Journal of Coastal Research	SI 39	1564 - 1569	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Modelling of Fine-Grained Sediment Transport and Dredging Material Dumpings at the Belgian Continental Shelf

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ABSTRACT

VAN DEN EYNDE, D. And FETTWEIS, M., 2006. Modelling of fine-grained sediment transport and dredging material dumpings at the Belgian Continental Shelf. *Journal of Coastal Research*, SI 39 (Proceedings of the 8th International Coastal Symposium), 1564 - 1569. Itajaí, SC, Brazil, ISSN 0749-0208.

The Belgian coastal zone is shallow, well mixed and has a high hydrodynamic energy. In the coastal zone a turbidity maximum occurs, which is responsible for high dredging amounts. Every year about $10x10^6$ ton dry matter (TDM) is dredged for the maintenance of the harbours and the navigation channels. After dumping the matter is transported in suspension.

The amount of maintenance dredging works is depending on the local hydrodynamic conditions and of the natural sediment transport as well as the amount and frequency of the dumping and dredging works. In order to estimate the efficiency of the dumping sites the natural cohesive sediment transport has to be known. Numerical models can be used to simulate this natural sediment transport. The uncertainties or variability of the sediment transport measurement data are high, in contrast with the dredging and dumping data, which are well known. The natural sediment transport is partly formed by the continuous erosion and deposition during a tide, a neap-spring cycle and during storms. This article will focus on the results of numerical simulations of the sediment transport. In particular the natural sediment transport of mud, the effect of dumping of dredged matter and the efficiency of the dumping sites will be discussed. This discussion is preceded by an overview of the physical situation (hydrodynamics, sediment transport, dredging and dumping data) and a description of the numerical models used (hydrodynamic model, wave model and sediment transport model).

ADDITIONAL INDEX WORDS: *Sediment transport modelling, cohesive sediments, dredging, dumping, turbidity, North Sea, Belgian Continental Shelf.*

INTRODUCTION

The Belgian coastal waters are characterised by shallow waters, by a good vertical mixing and a high hydrodynamic energy. The sediment transport in the area is complex, which is apparent from the very dynamic sand banks at the coast and the high turbidity between Oostende and Zeebrugge. In this area the harbours of Oostende and Zeebrugge and the main fair channels are located. Therefore, every year, around $10x10^6$ ton dry material (TDM) is dredged.

More than 60% of the mud, that is dumped on the Belgian Continental Shelf (BCS) is originating from the harbours of Zeebrugge and Oostende. This mud is dumped back into the sea from which it is transported again, mainly in suspension. The dumping of this fine-grained material enhances locally the concentration of material in suspension and can disturb the nutrient dynamics in the water. A higher sediment concentration mainly influences the biota and the filter-feeding organisms. At the dumping sites itself, the benthos is disturbed due to the burial under the dumped material.

The selection of dumping sites with a high dumping efficiency, *i.e.* the ratio between the amount of material that stays at the dumping site and the amount of material that was dumped, is an important concern for the authorities. First of all, one has to avoid as much as possible, that the dumped material recirculates to the place where it was dredged initially. Further, it is important that the physical, chemical and biological effects, that are related to the dumping of the possibly contaminated dredging material, stay as localised as possible.

The knowledge of the natural sediment transport is essential for the evaluation of the dumping sites. Unfortunately, until now, the natural fine-grained sediment transport is not well known. The uncertainties in the measurements of the natural sediment transport is considerable (VAN LANCKER *et al.*, 2001).

Different research projects were started to investigate the dispersion of dumped dredging material in the Belgian coastal waters and to the sediment transport in the area more in general. In the present paper, some research is presented, which was executed with numerical sediment transport models. The natural sediment transport is simulated as realistic as possible first. Hereafter, the effect of the dumping of dredging material on the natural sediment transport and the efficiency of the dumping sites is investigated.

In a first section, the physical characterisation of the hydrodynamics and the sediment transport on the BCS is discussed and the numerical models are presented shortly. In the central part of the paper, some model results are presented and discussed before the conclusions are formulated. It must be emphasized that only the physical effects of the dumpings on the natural transport of sediments, *i.e.* the increase of turbidity, will be discussed. Biological and chemical effects are not treated here.

HYDRODYNAMICS AND FINE-GRAINED SEDIMENT TRANSPORT AT THE BCS

Hydrodynamics and Sedimentology

The bathymetry of the BCS is shallow and irregular. The water depth varies between three and about forty meters, while the fair channels are dredged to about fifteen meters below mean sea level. The area of interest and the bathymetry of the modelled area are presented in Figure 1. The hydrodynamics of the Belgian coastal waters is mainly determined by tides, wind and wave activity. The tides are semi-diurnal and slightly asymmetrical. The mean tidal range at Zeebrugge is 4.3 m at spring tide and 2.8 m at neap tide. The tidal current ellipses are elongated in the coastal zone and become more elliptical further offshore (Figure 2). The current velocities can reach more than 1 m/s at spring tide. The water column in the area is well mixed during the entire year (DE RUIJTER *et al.*, 1987) and no stratification due to salinity or temperature gradients exists. The outflow (inflow) of the Westerschelde has a mean of 50,000 m^3/s during ebb (flood). The freshwater outflow is low and has a long-term (1949-1997) annual mean of 107 m^3/s. The winds and consequently also the waves are mainly from the south-west or

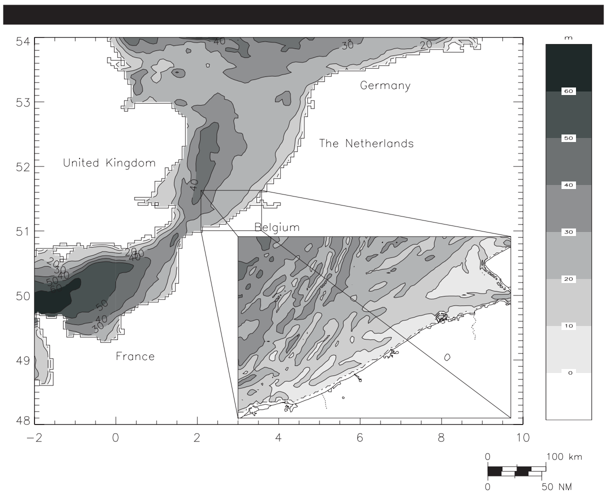


Figure 1. Bathymetry of the Southern Bight of the North Sea and the Belgian Continental Shelf.

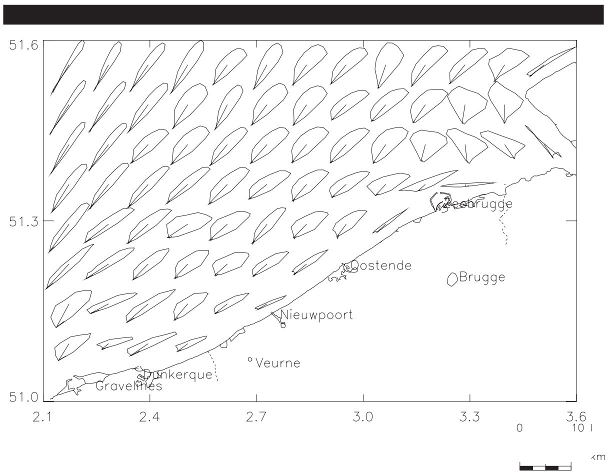


Figure 2. Current ellipses on the BCS, calculated with the hydrodynamic model MU-BCZ, for tides only and for mean tide.

from the north-east. The winds are for almost 90 % of the time below 5 Bft, while the significant wave height at Westhinder, 20 km out of the coast, is for 87 % of the time below 2.0 m. The residual transport of the water masses is mainly to the north-east.

The surface sediments on the BCS mainly consist of medium size sand to fine sand. Further from the coast, at water depths greater than 12 m, medium size sand is found with a median grain size up to more than 400 µm. Nearer to the coast and east from Oostende, more fine sand is found with a median grain size lower than 200 µm. In the eastern part, near the coast, large mud fields are found. These mud fields are partly correlated with the high turbidity zone between Oostende and Zeebrugge and in the mouth of the Westerschelde.

Natural Sediment Transport

A quantitative analysis of the natural sediment transport can be assessed by the interpretation of the sediment transport on a larger scale basis. From this analysis, it follows that the major part of the fine-grained sediments transport, along-shore the Belgian coast, are from the Dover Strait and from the English coasts (IRION and ZÖLLMER, 1999; FETTWEIS and VAN DEN EYNDE, 2003). The values of the sediment input in the southern North Sea, which can be found in literature, vary between 2.5 and 58 $x10^6$ ton/year. Recent data give values of $44.4x10^6$ ton/year. Residual current and residual SPM transport data suggest that about half of the SPM flux through the Dover Strait is deviated towards the south-eastern coastal zone of the North Sea (MCMANUS and PRANDLE, 1997). Therefore the SPM transport along the Belgian coastal zone is estimated as $22.2x10^6$ ton/year. A smaller part of the mud at the BCS finds its origin in the tertiary and quaternary clay layers. BASTIN (1974) estimated that this erosion was less then $2.4x10^6$ ton/year.

Anthropogenic Influences

Over the last ten years, the fair channel to Zeebrugge and the Westerschelde were systematically deepened and as a result the amount of dredging increased. The dredging works, together with the dumping at sea are actually the most important anthropogenic disturbances.

Yearly around $10x10^6$ ton of dry material is dredged for the maintenance of the fair channels (46 %) and the harbours (54 %). 90 % of the dredged matter consists of fine-grained sediments (mud). In the harbours almost 100 % mud is dredged, whereas in the fair channels, the dredging material contains about 25 % sand. The dredged matter is dumped at sea, at mainly two dumping sites: 50 % on B/1 en 30 % on B/6. The amount of material dredged and dumped is of the same order of magnitude as the natural residual sediment transport on the BCS. The dredging and dumping of the maintenance dredging works can not be considered as a source of mud, because they only displace the sediments over a short distance. Further it is important to stress the fact that the higher turbidity at the Belgian eastern coast is a natural phenomenon, which was amongst others already described by VAN MIERLO (1899). The dumping of the sediments at the B/1, B/2 and B/6 dumping sites only has an influence on the local concentration of the matter in suspension.

DESCRIPTION OF THE NUMERICAL MODELS

Introduction

The applications which are discussed here, were executed with the two-dimensional sediment transport model MU-STM. The currents and the water elevations were calculated with the two-dimensional hydrodynamic model MU-BCZ while the wave climate was calculated with the MU-WAVE model. Each of these models will be shortly described.

A two-dimensional hydrodynamic model can be used since the water column is well mixed over the entire year and since no important temperature or salinity gradients occur in the area. Further validation exercises, not discussed in this paper, showed that the two-dimensional model gives satisfying results. This was *e.g.* shown in simulation of different tracer experiments (VAN DEN EYNDE, 2003).

Hydrodynamic Model MU-BCZ

The two-dimensional hydrodynamic model MU-BCZ calculates the depth-integrated currents and the water elevations under influence of tides and meteorological effects. The model solves the classical shallow-water wave equations together with a continuity equation. The equations are solved using an explicit finite difference method on an Arakawa-C model grid. The bottom current is calculated by a quadratic friction law.

The model is implemented on a model grid that covers the BCS and the Flemish Banks, using a resolution of 25” x 40” (about 750 m x 750 m). At the open sea boundaries, the model is coupled with MU-STORM, an hydrodynamic model for the entire North Sea and Channel (ADAM, 1979). Four semi-diurnal (M_2, S_2, N_2, K_2) and four diurnal (O_1, K_1, P_1, Q_1) components are used to calculate the water heights at the open sea boundaries. The inverse barometric effect is incorporated in the model to account for the meteorological conditions. At the outflow of the Schelde estuary, the model is coupled with a one-dimensional hydrodynamic model of the Schelde and its main tributaries.

Wave Model MU-WAVE

For the calculation of the waves, the MU-WAVE model (VAN DEN EYNDE, 1992) is used. The core of the model consists of the second generation wave model HYPAS (GÜNTHER and ROSENTHAL, 1985), which combines the independent calculation of the swell energy for different frequencies and directions using a ray technique, with a parametric wind sea model which uses the JONSWAP parameters and the mean wind sea direction as prognostic variables. A Lax-Wendrof scheme is used to solve the equations.

The model is implemented on two coupled grids. In the entire North Sea a model with a resolution of 50 km x 50 km is used, while in the Southern Bight the resolution is 5 km x 5 km.

SEDIMENT TRANSPORT MODEL MU-STM

The Numerical Model

The two-dimensional sediment transport model MU-STM is a Lagrangian model, based on the Second Moment Method (DE KOK, 1994). In this method, all the material in a grid cell is represented by one rectangular mass, with the sides parallel to the direction of the model grid, and characterised by its zeroth order moment (the total mass), its first order moments (the mass centre) and its second order moments (the extension of the mass). The advection in the model grid is performed by the advection of each of the sides of the rectangle. The diffusion is done by enlarging the extension of the rectangle. After each time step all material in a grid cell is recombined and represented by one new rectangle with the same zeroth, first and second order moments.

The model can account for different sediment classes. In the present application, only mud, defined as the fraction smaller then 63 µm, is taken into account.

Erosion, Sedimentation and Consolidation

The behaviour and the transport of the sediments is determined by the erosion, sedimentation and resuspension of the material. These processes are governed by the bottom friction. In the MU-STM model, the bottom friction is parameterised, using an adapted formulation of the BIJKER (1966) formulae. This is a simple equation to calculate the bottom friction under the influence of the prevailing currents and waves.

The erosion is modelled following Ariathurai-Partheniades (ARIATHURAI, 1974), while the sedimentation is calculated using the formula of KRONE (1962). The amount of material that is eroded is therefore a function of the erosion constant M [kg/m²/s] and of a critical bottom stress for erosion τ_s [Pa], while the sedimentation depends on the fall velocity of the sediment particles w_s [mm/s] and of a critical bottom stress for deposition τ_d [Pa].

In this model, the critical bottom stress for erosion is made dependent on the consolidation of the deposited material. The consolidation model is based on the work of HAYTER (1986), LE NORMANT (1995) and WILLIAMSON and TORFS (1996). The bed is divided in different "active layers", which are represented by a dry density and an age. If the sediment in the layer obtains a certain critical age, the sediment falls in the next layer with a higher density. Below the active layers, a "bottom layer" is present. No material can be deposited in this bottom layer. If no material is present in the active layers however, material can be eroded from this bottom layer, taking into account the percentage of mud in the bottom. As such, the bottom layer could be a source of sediments. The percentage of mud in each grid cell was calculated by an distance weighted interpolation, using grain size distributions of about 1400 bottom samples.

In the model, the critical bottom stress for erosion varies between 0.5 Pa for loosely deposited mud and 0.79 Pa for consolidated mud after 48 hours. The critical erosion stress of the bottom layer is set to 5.0 Pa, which reflects the fact that the tertiary and quaternary clay layers are difficult to erode. For 100 % mud, the erosion constant M is set to 0.00012 kg/m^2/s. For sediments with a lower percentage of mud (only in the bottom layer) this erosion constant is multiplied with the mud fraction. The fall velocity is set constant and equal to 2 mm/s. This rather high value implicitly accounts for flocculation processes (BRENON and LE HIR, 1999) and agrees with recent measured values of the *in situ* fall velocity. The critical bottoms stress for deposition has a value of 0.5 Pa. This high value promotes the deposition of the sediments.

The model was validated by comparing the model with *in situ* measurements and by simulating radioactive tracer experiments (VAN DEN EYNDE, 2003).

Boundary Conditions and Initial Conditions

Knowledge of the concentration of the material in suspension at the model boundaries is important. The implementation of realistic boundary condition is critical for the long-term model calculations and for setting up of a sediment balance. Only then the natural sediment transport can be estimated and the effect of dumping activities can be evaluated. The sediment concentration at the boundaries is determined using the measurements of the MUMM Monitoring Programme 1976-1996 and using measurements found in literature. A seasonal variation on the boundary conditions is applied, with higher concentrations in winter and lower ones in summer. In the bottom layer, an unlimited amount of material is present, which represent the tertiary and quaternary clay layers.

MODEL SIMULATIONS AND RESULTS

The Natural Situation

The natural situation was simulated for the entire year 1999. At the start of the simulations, no material is present in the active bed layers. An initialisation run of one month was performed to calculate the initial conditions for the material in suspension.

In Table 1 a mass balance for the simulation of the natural sediment transport for the entire year 1999 is presented. The results correspond reasonable with the values found in literature. Also the sedimentation of mud in the model has the correct order of magnitude. The value however is smaller than the yearly amount of dredged material. This probably is caused by the fact that the harbours, which are important sediment sinks, are not represented in the model.

More information on the simulation of the natural sediment transport on the BCS can be found in FETTWEIS and VAN DEN EYNDE (2003), where also some sensitivity tests to different model parameters are presented.

In Figure 3 (a), the tidal averaged mud concentrations at spring tide are shown. The turbidity maximum in front of Zeebrugge and at the mouth of the Schelde estuary is clear. The existence of mud fields and the turbidity maximum in the area with high hydrodynamic energy has been the subject of many studies. Most of the studies use an "hydrodynamic trap" as explanation, in which the material, coming from the French coastal waters, is trapped. This trap could have the form of a gyre or of a diverging or converging residual currents pattern (*e.g.* NIHOUL, 1975; GULLENTOPS *et al.*, 1976; MALHERBE, 1991). Based on model results a different explanation is proposed by FETTWEIS and VAN DEN EYNDE (2003), where the turbidity maximum is created by the input of material in suspension through the western boundary, the specific hydrodynamic conditions and the decrease in magnitude of the residual water transport vectors from the French/Belgian border to Zeebrugge. The turbidity maximum therefore seems to be a congestion of mud and not a mud trap. The existence of the mud fields in the area is related to the turbidity maximum.

DISPERSION OF DUMPED MATERIAL AT SEA

Continuous Dumpings

Simulations of continuous dumpings at the three dumping sites B/1, B/2 and B/6, were executed for the year 1999. The dumpings were corrected to account only for the mud fraction. The dumpings were simulated in the model by inserting the amount of dumped mud into suspension.

Table 1. *Mass balance (in 10^6 TDS) for 1999 from the simulation of the natural situation (nat.) and from the simulation with dumpings of dredging material (dump). In-W: the material entering at the western boundary, In-Eros: erosion from the bottom layer; In-Sch: material entering the BCS from the Schelde; Out-N: material leaving the model grid through the Northern and Eastern boundary: Out-Dep: material deposited at the bottom; Dump: material entering the model from dumpings; Susp: material in suspension.*

	In			Out		Dump	Susp
	W	Eros	Sch	N	Dep		
Nat	17.2	1.0	0.3	-15.8	-3.5	-	-0.8
Dump	17.1	1.0	0.1	-21.9	-3.5	6.4	-0.8

The simulation can only give a first indication of the processes that are taking place, since in the model new material is inserted in the system. In reality, during maintenance dredging works, the material is only displaced over a certain distance. Only during the deepening works, new material is dredged and dumped. Since the material during deepening works mainly consist of sand, the influence on the turbidity and on the fine-grained sediment transport will be limited.

The mass balance from the simulation with the dumpings is presented in Table 1. One can conclude that almost 100 % of the dumped material leaves the model grid through the northern boundaries. The dumpings can temporarily also enhance the deposition of mud in the neighbourhood of the dumping sites, in the fair channels and in the coastal area near Zeebrugge (see Figure 4).

The tidal averaged mud concentration with and without dumpings, together with the differences between them, are presented in Figure 3. The model simulation show that the dumpings on the B/1 dumping site increases the concentration in an area with a diameter of 20-40 km. The tidal averaged concentration increases with 50-100 mg/l, depending on the dumping frequency and amount of dumpings.

In the neighbourhood of the dumping site B/6, the differences in turbidity with and without dumpings are less pronounced. The results further show an increase in deposition in the north of the Vlakte van de Raan (Figure 4).

A part of the deposited mud is resuspended during spring tide which causes an increase in turbidity and extension of the turbidity maximum area. In contrast to the large amount of mud dumpings, the deposited material in the fair channels hardly increases, when compared with the situation without dumpings. One can conclude that the material has left the model grid.

Figure 5 shows during a period of 16 days, spring tide at day 78, the evolution of concentration of material in suspension, with and without dumping at the dumping site B/1 and at the station MOW1, its position is indicated in Figure 4 (c). Also the dumpings itself and the amount of dumped material is shown. We must emphasise the fact that the concentrations are averaged over the entire grid cell. A dumping of 1000 tons of mud at a water depth of 15 m therefore creates an increase of concentration of 120 mg/l. From the figures, it is apparent that during periods with many dumpings, the concentration of the material in suspension strongly increases, especially at the dumpings sites.

Efficiency of Dumping Sites

The dumping site B/6 lies nearby the dredging sites, *e.g.* the harbour of Zeebrugge, and part of the dumped material therefore recirculates to the place where it was dredged. From simulations and from tracer experiments, it is shown that also part of the material that is dumped at B/1 recirculates to the coastal waters (VAN DEN EYNDE, 2003). The efficiency of the present dumping sites therefore is limited. One can ask therefore the question, whether the amount of material to be dredged could be decreased by selection of different dumping sites?

The ratio between the amount of material, that is yearly dredged and dumped, and the amount of material entering the BCS naturally, gives an indication on the influence of the location of the dumpings sites on the amount of material, to be dredged. A large ratio is an indication that the dredging process is important in the Belgian coastal waters. If this ratio is small, on the other hand, the dumping of dredged matter is negligible compared to the natural mud transport in the area. In the latter case, the exact position of the dumping sites is not important.

The ratio is calculated using the data on the dredging activities, which are well known, and the estimated residual sediment transport at the BCS, which has large uncertainties, as already mentioned. Using the input data from literature, a ratio (dumpings/input) is calculated of 0.29. Using the model results, a ratio (dumpings/input+erosion+dumpings) of 0.26 is obtained. These values indicate that an important part of the natural mud is involved in the dredging activities. By choosing more efficient dumpings sites, farther out of the coast, the amount of matter to be dredged could decrease. However, also the longer distance to be sailed and the larger biological and chemical impact, compared to the dumping of the material in an environment with a natural high turbidity, must be taken into account. On the other hand, the high sediment input at the BCS and the existence of the natural turbidity maximum will be responsible for a continuous siltation of the harbours and the fair channels.

PHYSICAL EFFECTS OF DUMPINGS OF DREDGING MATERIAL

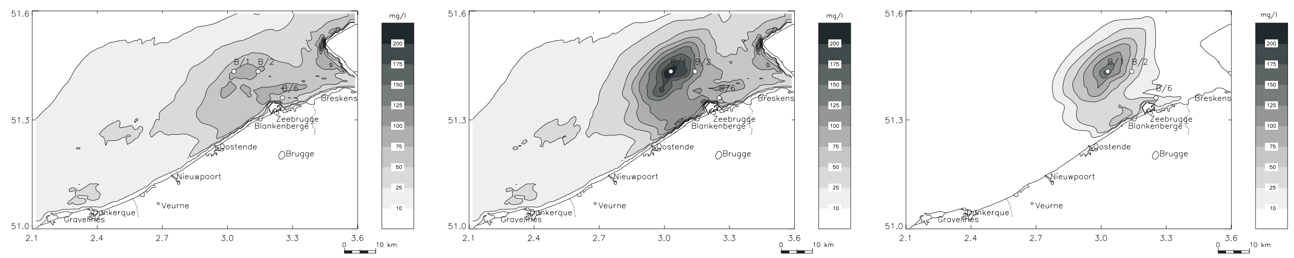
In the present article, an overview is given of the modelling of the natural and the anthropogenic influenced mud transport. Following conclusions can be draw:

The hydrodynamic conditions create a natural turbidity maximum at the east coast of the BCS. This turbidity maximum can be described as a congestion of the matter coming from the west and flowing to the north-east.

As a consequence of the higher turbidity, locally mud depositions occur.

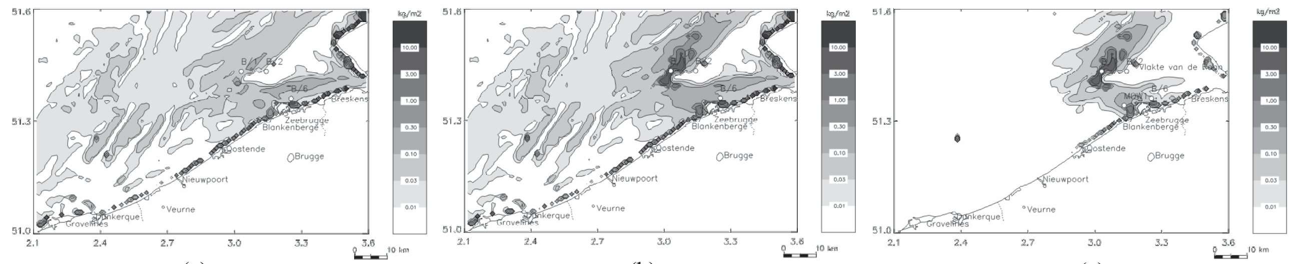
By the dumping of dredged material, the mud concentration can increase.

Recirculation of the dumped material is more important



(a) (b) (c)

Figure 3. Tidal averaged concentration of material in suspension during spring time (March 20th, 1999). (a): natural situation. (b): natural situation + dumpings at dumping sites B/1, B/2 and B/6. (c): difference between the two.



(a) (b) (c)

Figure 4. Tidal averaged concentration of material deposited at the bottom one day before spring time (March 19th, 1999). (a): natural situation. (b): natural situation + dumpings at dumping sites B/1, B/2 and B/6. (c): difference between the two.

from dumping site B/6 than from dumping sites B/1 and B/2. Since a natural turbidity maximum exists, it seems that the matter to be dredged will not change significantly afterdisplacement of the dumping sites.

ACKNOWLEDGEMENTS

This research was financed by the Coastal Waterways Division of the Ministry of the Flemish Community.

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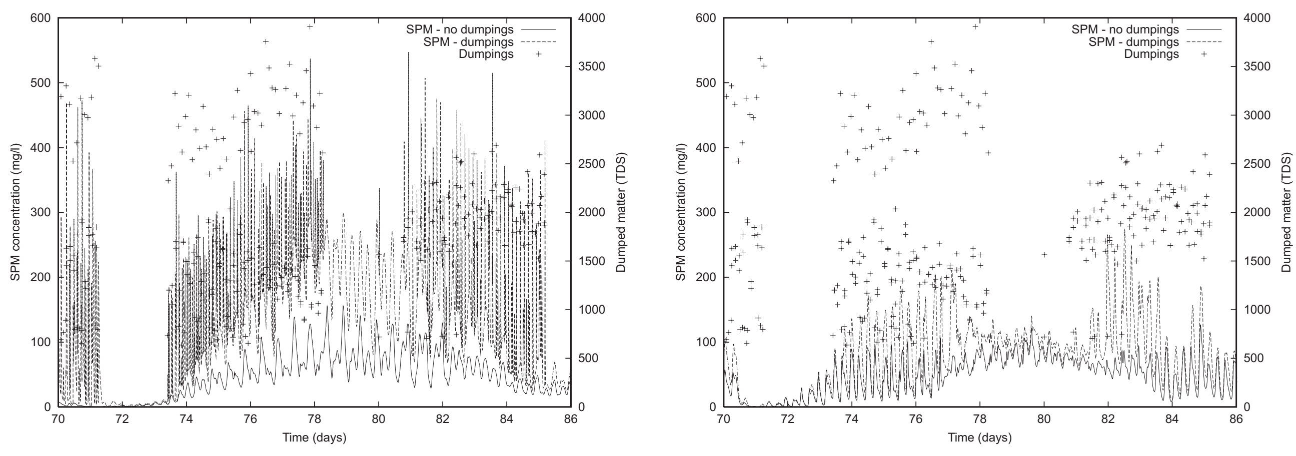

Figure 5. Concentration of material in suspension with and without dumping, and amount of dumped matter. (a): Dumping site B/1. (b): Measuring stations MOW1.

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