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Monitoring the effects of disposal of fine sediments from maintenance dredging on suspended particulate matter concentration in the Belgian nearshore area (southern North Sea)

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ABSTRACT

The impact of continuous disposal of fine-grained sediments from maintenance dredging works on the suspended particulate matter concentration in a shallow nearshore turbidity maximum was investigated during dredging experiment (port of Zeebrugge, southern North Sea). Before, during and after the experiment monitoring of SPM concentration using OBS and ADV altimetry was carried out at a location 5 km west of the disposal site. A statistical analysis, based on the concept of populations and sub-sampling, was applied to evaluate the effect. The data revealed that the SPM concentration near the bed was on average more than two times higher during the dredging experiment. The disposed material was mainly transported in the benthic layer and resulted in a long-term increase of SPM concentration and formation of fluid mud layers. The study shows that SPM concentration can be used as an indicator of environmental changes if representative time series are available.

1. Introduction

The Water Framework Directive (2000/60/EC) and recently adopted EU Marine Strategy Framework Directive (2008/56/EC) (see e.g. Borja, 2005; Devlin et al., 2007) identifies human induced changes in the concentration of suspended particulate matter (SPM) as one of the main pollutants. Disposal of fine-grained dredged material at sea has a varying impact on the marine environment (Nichols, 1988; Bray et al., 1996; Hill et al., 1999; O'Connor, 1999; Smith and Rule, 2001; Lohrer and Wetz, 2003; Simonini et al., 2005; Lee et al., 2010) and constitutes an important problem in coastal zone management (OSPAR, 2008). Dredging activities can be classified as either maintenance or capital dredging. Maintenance dredging typically involves the periodic or continuous removal of sediments deposited in navigation channels and harbours as a result of natural processes. Capital dredging is associated with deepening or with construction activities and consists thus of civil engineering works limited in time. Very often, ports and navigation channels are situated in coastal or estuarine turbidity maximum areas and suffer from rapid sedimentation of fine-grained material (PIANC, 2008), necessitating frequent maintenance dredging and disposal operations. The effect of increased turbidity due to disposal operations on the ecosystem are well documented in low turbidity (<10 mg l^{-1}) waters (e.g. Orpin et al., 2004); but less obvious in coastal and estuarine areas where suspended particulate matter (SPM) concentration is high as well differences between minima and maxima. Dredging and disposal effects are site specific (Ware et al., 2010) and require the understanding of the site-specific dynamics in order to evaluate environmental impact of dredging and disposal works. In case of mainly non-cohesive material is the impact of disposal of dredged material at sea most significant at the seabed (Du Four and Van Lancker, 2008; Okada et al., 2009) and the impact on the environment may remain near-field and short-term (Fredette and French, 2004; Powilleit et al., 2006). When cohesive sediments are disposed then significant increases in turbidity may occur in the water column (Hossain et al., 2004; Van den Eynde, 2004; Wu et al., 2006) depending on the mode, timing, quantity, frequency of the disposal activity (Bolam et al., 2006).

The SPM dynamics control processes such as sediment transport, deposition, resuspension, primary production and the functioning of benthic communities (McCandliss et al., 2002; Murray et al., 2002). It varies as a function of seasonal supply of fine-grained sediments, the interaction between cohesive and non-cohesive sediments, biological activity, remote or local availability of fine sediments, advective processes, erosion, deposition, storms and human activities (Velegrakis et al., 1997; Bass et al., 2002;

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Schoellhamer, 2002; Le Hir et al., 2007; Fettweis et al., 2010). Deepening of channels and construction of ports increases deposition of fine-grained sediments and has as consequence an increase of maintenance dredging and thus an increase of SPM concentration in and around the disposal site (Truitt, 1988; Collins, 1990; Wu et al., 2006). During slack water and after storm periods fluid mud layers may be formed by settling of suspended matter or fluidization of cohesive sediment beds (Maa and Mehta, 1987; van Kessel and Kranenburg, 1998; Li and Mehta, 2000). Massive sedimentation of fine-grained sediments in harbours and navigation channel is often related to the occurrence of fluid mud layers (Fettweis and Sas, 1999; Verlaan and Spanhoff, 2000; Winterwerp, 2005; PIANC, 2008; Van Maren et al., 2009; De Nijs et al., 2009). Fluid mud is a high concentration aqueous suspension of fine-grained sediment with SPM concentrations of tens to hundreds of grams per litre and bulk densities of 1080–1200 kg m^{-3}; it consists of water, clay-sized particles and organic materials; and displays a variety of rheological behaviours ranging from elastic to pseudo-plastic (McAnally et al., 2007).

The aim of this paper is to present and discuss the impact of continuous disposal of fine-grained sediments on the SPM concentration and on the fluid mud dynamics in a shallow nearshore turbidity maximum area during a 1 month dredging experiment. The experiment took place in the port of Zeebrugge (Belgian coastal area, southern North Sea) in the framework of studies conducted by the Flemish Ministry of Public Works and Mobility to develop more cost effective methods for dredging fluid mud. Monitoring of the effects on SPM concentration was required as the dredged matter was disposed at sea at a location closer to the shore and the port compared to the existing disposal sites. Previous studies have used numerical simulations to investigate the spatial distribution of material disposed of in the sea (e.g. Gallacher and Hogan, 1998; Bai et al., 2003; Van den Eynde, 2004), but even with recent progress in sediment transport modelling (e.g. Sanford, 2008) limitations related to accurately simulating the dynamics of fluid mud layers and the interaction between the bed and the water column remain. In situ monitoring provides a good opportunity for investigating the impact of fine-grained matter dispersal behaviour and its fate due to disposal operations. In situ measurements of SPM concentration before, during and after the dredging experiment have been carried out at about 5 km from the disposal site together with sediment density and bathymetrical surveys at the dredging location and the disposal site. As the heterogeneity and complexity of the SPM concentrations are high, due to their natural high variability, statistical methods have been used to characterize temporal SPM concentration variation in a way that it can be used as indicator for changes induced by human activities.

2. Study area

The Belgian–Dutch nearshore area (southern North Sea, Fig. 1a) is shallow (<10 m Mean Lower Low Water Springs (MLLWS)) and characterised by sediment composition varying from pure sand to pure mud (Verfaillie et al., 2006). SPM forms a turbidity maximum between Oostende and the mouth of the Westerschelde (Fig. 1a). Measurements indicate variations in SPM concentration in the nearshore area of 20–70 mg l^{-1}; reaching 100–3000 mg l^{-1} near the bed; lower values (<10 mg l^{-1}) occur in the offshore (Fettweis et al., 2010). The most important sources of SPM are the French rivers discharging into the English Channel, coastal erosion of the Cretaceous cliffs at Cap Gris-Nez and Cap Blanc-Nez (France) and the erosion of nearshore Holocene mud deposits (Fettweis et al., 2007). Tides are semi-diurnal with a mean tidal range at Zeebrugge of 4.3 m at spring and 2.8 m at neap tide. The tidal current ellipses are elongated in the nearshore area and become gradually more semi-circular further offshore. The current velocities near Zeebrugge (nearshore) vary from 0.2 to 1.5 m s^{-1} during spring tide and 0.2 to 0.6 m s^{-1} during neap tide; more offshore they range between 0.2 and 0.6 m s^{-1} during spring tide and 0.1 and 0.3 m s^{-1} during neap tide. Flood currents are directed towards the Northeast and ebb currents towards the Southwest. Winds blow predominantly from the southwest and the highest waves occur during north-westerly winds. Significant wave heights in the nearshore area exceed 1.5 m during 10% of the time. The strong tidal currents and the low fresh water discharge of the Westerschelde estuary (yearly average is 100 m^3 s^{-1} with minima of 20 m^3 s^{-1} during summer and maxima of 600 m^3 s^{-1} during winter) result in a well-mixed water column with very limited salinity and temperature stratification.

On average 4.46×10^6 ton dry matter (tdm) is dredged annually in the port of Zeebrugge to maintain navigation depth; this represents about 60% of the total amount of maintenance dredging in the Belgian nearshore area (Lauwaert et al., 2009). The dredged matter consists of muddy sediments and is disposed on the disposal sites S1 (47%), Zeebrugge Oost (44%) and S2 (9%), see Fig 1b. The sedimentation rate in the outer port of Zeebrugge is on average about 1.7 tdm m^{-2} per year. In 2007 and 2008, respectively, 0.7×10^6 and 0.3×10^6 tdm of sediments were dredged in the Albert II dock (Fig. 1b).

3. Materials and methods

3.1. Dredging experiment

Dredging with trailer hopper suction dredgers and open water disposal of the dredged material at designated locations, is inefficient for fluid mud and incur substantial costs (PIANC, 2008). An automatic method to intercept and pump away fluid mud using stationary pumping system was evaluated by Berlamont (1989) for mud from the port of Zeebrugge. A similar approach was adopted for the dredging experiment, except that a cutter suction dredger was used instead of stationary pumping systems. The experiment took place in the Albert II dock situated in the outer port of Zeebrugge between 5 May and 2 June 2009 (Fig. 1b). The dredger continuously dredged for periods of a few days up to a week at a fixed location and a fixed depth before being moved to another location. The dredged matter was pumped using floating pipelines over the harbour breakwater into the sea (see Fig. 1b). The pumping capacity was 3000 m^3 h^{-1}, resulting thus – using the average density of the pumped matter (including salt and sediment) of 1.055 t m^{-3} – in 60×10^3 tdm of sediments that have been disposed during the duration of the experiment. As the density recordings of the dredge material were inaccurate, this should be seen as an estimate. The aim of the experiment was to investigate whether the thickness of the fluid mud layer with a density lower than 1200 kg m^{-3} could efficiently be reduced. This density is derived from ship manoeuvrability studies that aided in the redefinition of the level of dredging required (Delefortrie et al., 2005; PIANC, 2008).

3.2. In situ monitoring

The monitoring during the disposal experiment is divided in near and far field measurements. The near field measurements consisted of bathymetrical surveys in the dock and at the disposal site and weekly mud density surveys in the Albert II dock (Fig. 1b). Density profile measurements were carried out in situ using a gamma-ray densitometer that was pushed in the mud layer. Bathymetrical surveys were performed daily with 33/210 kHz echo

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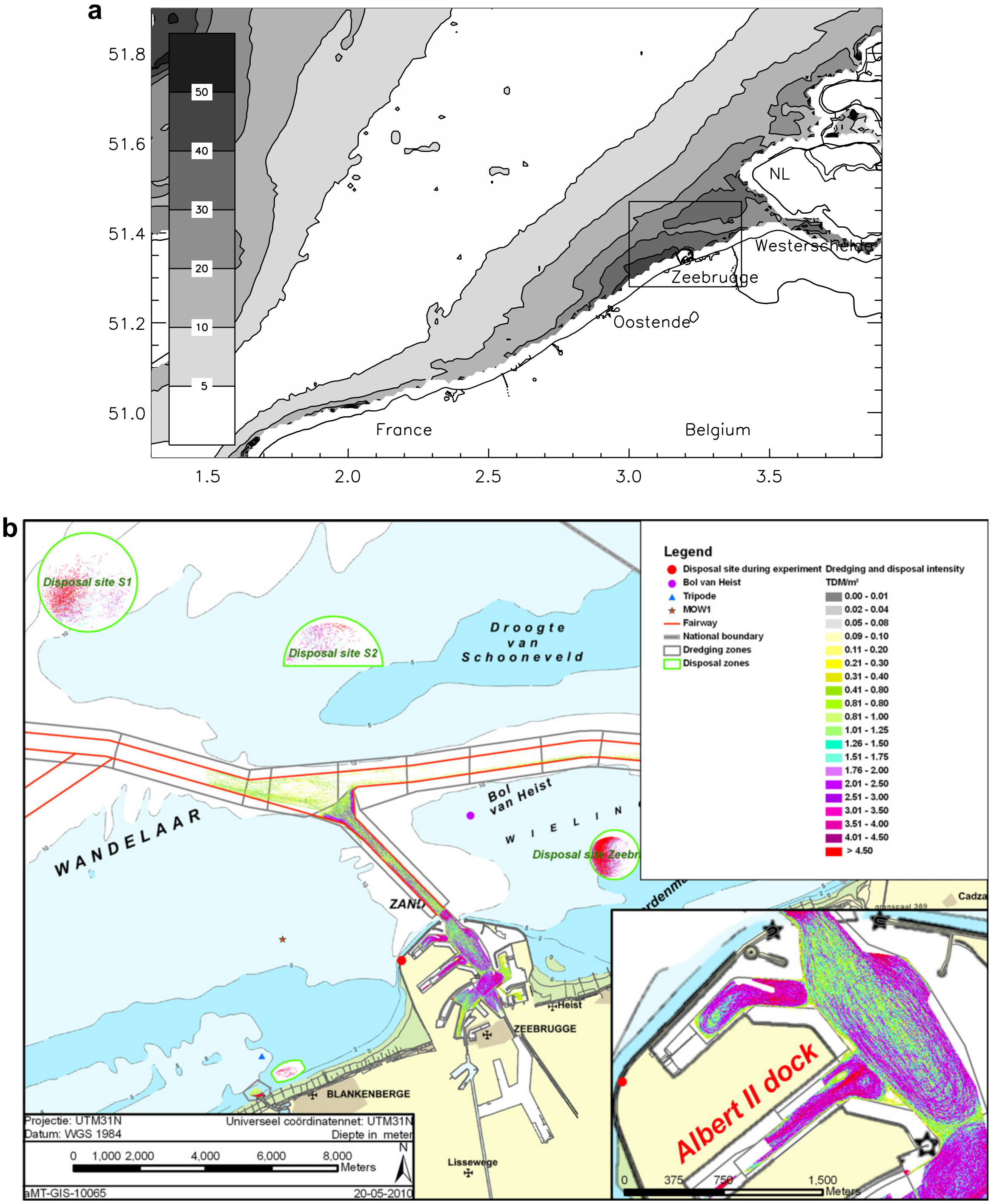

Fig. 1. (Above) Map of the southern North Sea showing the yearly averaged surface SPM-concentration (mg l^{-1}) in the southern North Sea, derived from the MODerate resolution Imaging Spectroradiometer (MODIS) images of 2003–2008 (Nechad et al., 2010); coordinates are in latitude (°N) and longitude (°E). (Below) Detail of the Zeebrugge area showing the measurement station at Blankenberge (blue triangle), the wave measurement station at Bol van Heist (purple dot), the location of the disposal site during the field experiment (red dot), the MOW1 site (brown star), the Albert II dock and the esisting disposal sites (green circles or half-circles). The background consist of bathymetry and of the dredging and disposal intensity (scale is from 0 to >4.5 tdm m^{-2}) for 2008. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sound measurements along fixed transects and weekly with multibeam.

The far field monitoring was carried out at a fixed location near Blankenberge (51.33°N 3.11°E) situated about 1 km offshore and 5 km west of the disposal site (Fig. 1b) using a tripod which was developed for collecting time-series (up to 50 days) of SPM concentration and current velocity. The water depth at the site is about 6 m MLLWS and the sea bed consists of fine sand (D50 = 150 μm) with ephemeral mud patches on top. The tripod was deployed for 240 days during six measuring periods before, during and after the experiment, see Table 1. Of the data (17%) have been collected during or shortly after the field experiment. A SonTek 5 MHz

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Acoustic Doppler Velocimeter (ADV) Ocean, a Sea-Bird SBE37 CT system and two D&A OBS3 sensors were mounted on the frame, one at about 0.2 and the other one 2 m above bottom (mab). Field calibration of the OBS sensors has been carried out during several tidal cycles carried out in the nearshore area in order to obtain SPM concentration. A Niskin bottle was closed every 20 min, thus resulting in about 40 samples per tidal cycle. Three sub samples were filtered on board of the vessel from each water sample, using pre-weighted filters (Whatman GF/C). After filtration, the filters were rinsed once with Milli-Q water (±50 ml) to remove the salt, and dried and weighted to obtain the SPM concentration. A linear regression between all OBS signals and SPM concentrations from filtration was assumed. The measuring volume of the ADV was situated at 0.2 mab. The altimetry of the ADV was used to detect variation in bed level due to the occurrence of fluid mud layers. Decreasing distance between probe and bed boundary may correspond with the presence of fluid mud acting as an acoustic reflector. However, the boundary detection may also fail, due to attenuation of the signal before reaching the bottom (Velasco and Huhta, App. Note SonTek).

3.3. Statistical analysis

Variation in SPM concentration at Blankenberge is related to tides, storms, seasonal changes and human impacts. SPM concentration can be defined as a statistical population. We can consider the measured SPM concentration time series as sub-samples that are characterised by statistical properties, such as median, geometrical mean, standard deviation and probability density distribution. Fettweis and Nechad (2010) have shown that SPM concentration has a log-normal distribution. The probability density distributions of the different sub-samples, consisting of the different time series or other sub-samples, were therefore fitted using log-normal distributions, and the χ^2 test probability calculated to assess how well the distribution fits a log-normal one. By doing so statistical properties can be calculated so that inferences or extrapolations from the sub-sample to the population can be made. e.g. if the data series collected during different periods have similar log-normal distributions, geometric means and standard deviations, then we could conclude that – within the range of natural variability and measuring uncertainties – these data series represent similar sub-samples

Table 1
Tripod deployments at Blankenberge and the median and maximum significant wave height (H_s) during the measurement period. Period 6a corresponds with the dredging experiment.

	Start (dd/mm/yyyy hh:mm)	End (dd/mm/yyyy hh:mm)	Duration (days)	Median (max) H_s (m)
1	08/11/2006 14:30	15/12/2006 08:30	36.7	0.83 (2.76)
2	18/12/2006 10:47	07/02/2007 13:17	50.1	0.79 (2.96)
3	28/01/2008 15:38	24/02/2008 13:18	26.9	0.44 (2.82)
4	06/03/2008 09:09	08/04/2008 15:29	33.7	0.76 (3.03)
5	15/04/2008 08:58	05/06/2008 07:48	51.0	0.46 (1.69)
6	04/05/2009 09:59	15/06/2009 11:49	41.9	0.57 (1.89)
6a	05/05/2009 12:00	02/06/2009 07:00	27.8	0.55 (1.89)
6b	09/06/2009 00:00	15/06/2009 11:49	7.5	0.42 (1.12)

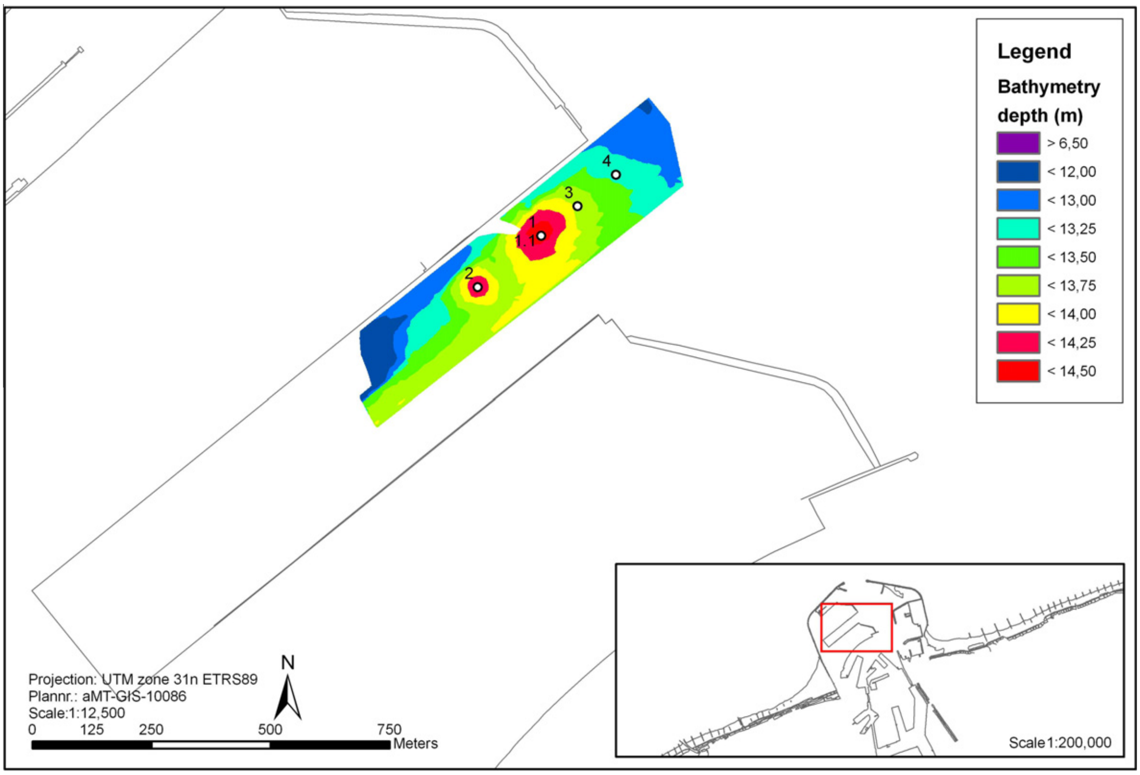

Fig. 2. Bathymetrical map of the 210 kHz echo soundings in the Albert II dock and the successive position of the cutter suction dredger (1–4) during the experiment. The bathymetrical survey was carried out when the dredger was operating in position 2. In position 1 a relict dredging crater is visible.

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of the whole SPM concentration population. Consequently, if disposal of dredged material has a significant impact on SPM concentration then this should be detectable in the differences between the statistical parameters of the sub-sample collected during the dredging experiment and of the whole population.

It is well known that waves have an important impact on cohesive sediment transport processes on continental shelves (e.g. Green et al., 1995; Cacchione et al., 1999; Traykovski et al., 2007; Shi et al., 2008; Fettweis et al., 2010). In order to assess this effect, sub-samples of the SPM concentration data have been selected based on bottom wave orbital velocities. The wave orbital velocity at the bottom was calculated from significant wave height measured at the station "Bol van Heist" (Fig. 1b), the measured water depth and the JONSWAP spectrum of waves (Soulsby, 1997). Sub-sampling of the data series allows filtering out the effects of random storms from the harmonic SPM concentration variations caused by tides. The statistical properties of sub-samples representing good (stormy) weather conditions can thus be calculated and the SPM concentrations can be correlated with sea state conditions.

The statistical analysis is based on the assumption that the data collected before and after the dredging experiment (periods 1–5 and 6b in Table 1) are representative for the SPM concentration at this location. 15%, 38% and 47% of the measurements are situated in autumn, winter and spring, respectively. As the SPM concentration is highest during autumn and winter and lowest during spring and summer (Fettweis et al., 2007; Dobrynin et al., 2010), the measurements are well distributed over the high and low SPM concentration periods. The median significant wave height (H_s) during the tripod measurements (measured at the wave station "Bol van Heist", Fig 1b) was 0.54 m, with 0.50 m, 0.61 m and 0.53 m during spring, autumn and winter, respectively. These values correspond well with the median H_s during the period 2006–2009 of 0.50 m (whole the period), 0.48 m (spring), 0.62 m (autumn) and 0.60 m (winter), supporting thus the assumption of representativeness.

4. Results

4.1. Near field monitoring

The dredging effort caused rapid (order of hours) formation of cone formed craters centred on the cutter head location (Fig. 2), which disappeared again after relocation of the cutter. Influx of sediment related to shipping activities and spring tide caused at some occasions the filling-up of the crater during a short period. The dredging caused a local deepening of the 1200 kg m^{-3} density surface, however the influence remained local and did not significantly changed the depth of the fluid mud density field in the dock, therefore the evaluation of the dredging experiment was negative in terms of efficiently reducing the thickness of the fluid mud layer (see Lauwaert et al., 2009).

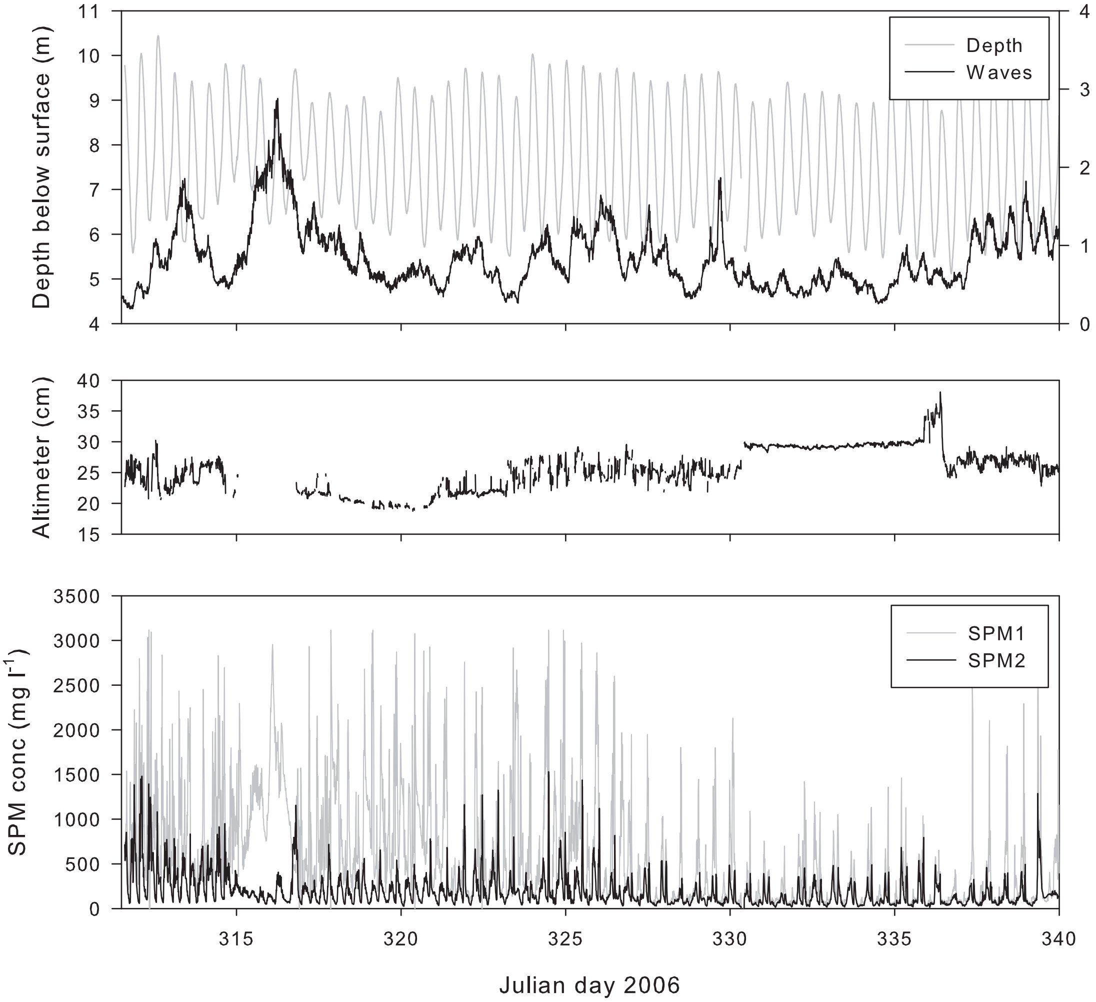

Fig. 3. Tripod measurements of 8 November–6 December 2006 (part of measuring period 1). From up to down: depth below water surface (m) and significant wave heights at Bol van Heist; ADV altimetry; and SPM concentration derived from OBS at 0.2 mab (SPM1) and 2 mab (SPM2). Saturation of the OBS is at 3.2 g l^{-1}.

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4.2. Far field monitoring

The time series for periods 1, 5 and 6 are shown in Figs. 3–5. Generally, the SPM concentration signal is dominated by quarter-diurnal variations due to ebb–flood. The data show that the maximum SPM concentrations during a tidal cycle were sometimes up to 50 times higher than the minimum concentrations. The spring-neap tidal signal is often overprinted by wave effects and can only be identified clearly during calm meteorological conditions. The very high SPM concentrations measured near the bed during winter and autumn are related to storms and suggest that high concentrated benthic suspension layers have been formed that may stay for a few days. The ADV altimetry data show quarter-diurnal variations in bed level during periods with SPM concentration; this is explained as formation and resuspension of fluffy layers during slack waters.

Period 1 is characterized by the occurrence of different storms (Fig. 3). On 12–13 November (days 316–317), a NW storm generated significant wave heights of about 2.8 m. The highest SPM concentrations were registered only about one day after the storm by the OBS at 0.2 mab and about two days after by the OBS at 2 mab (Fig. 3). The OBS data at 0.2 mab are characterised by very high minima in SPM concentrations (>0.8 g l^{-1}). The OBS at 2 mab measured an increase in SPM concentration only during a short period after the storm. This indicates that vertical mixing was limited. ADV altimetry shows a vertical rise of the acoustic reflective boundary after the storm (days 317–321) indicating the formation of a fluid mud. Its appearance coincided with low wave activity and decelerating currents associated with neap tide. The fluid mud layer disappeared around day 321 due to higher wave activity and accelerating currents. The altimetry signal shows then a bed boundary fluctuating with the quarter diurnal tidal currents; the change in altimeter height on day 336 is probably caused by erosion of the sandy bed. During the deposition event on day 344, the sea floor as detected by the ADV altimetry raised about 10 cm, due to formation of fluid mud.

Period 5 (April–June 2008) was characterised by low meteorological disturbances. SPM concentration follows tidal and neap-spring tidal signal with higher SPM concentration around days 108–114, 124–130 and 142–144 (Fig. 4). A clear shift between the signal of the OBS at 0.2 mab and at 2 mab is observed from day 132 on (May 2008). The highest SPM concentrations occur at 0.2 mab during neap tide, whereas at 2 mab the highest values are around spring tide, indicating that SPM was deposited during neap tide and resuspended during spring tide. The acoustic bed boundary remained at the same distance after stabilization of the tripod at the beginning of the deployment. Deposition and consecutive resuspension occurs as temporal events coinciding with the ebb–flood tidal signal during neap tides and the availability of SPM. During the deposition events, the sea floor as detected by

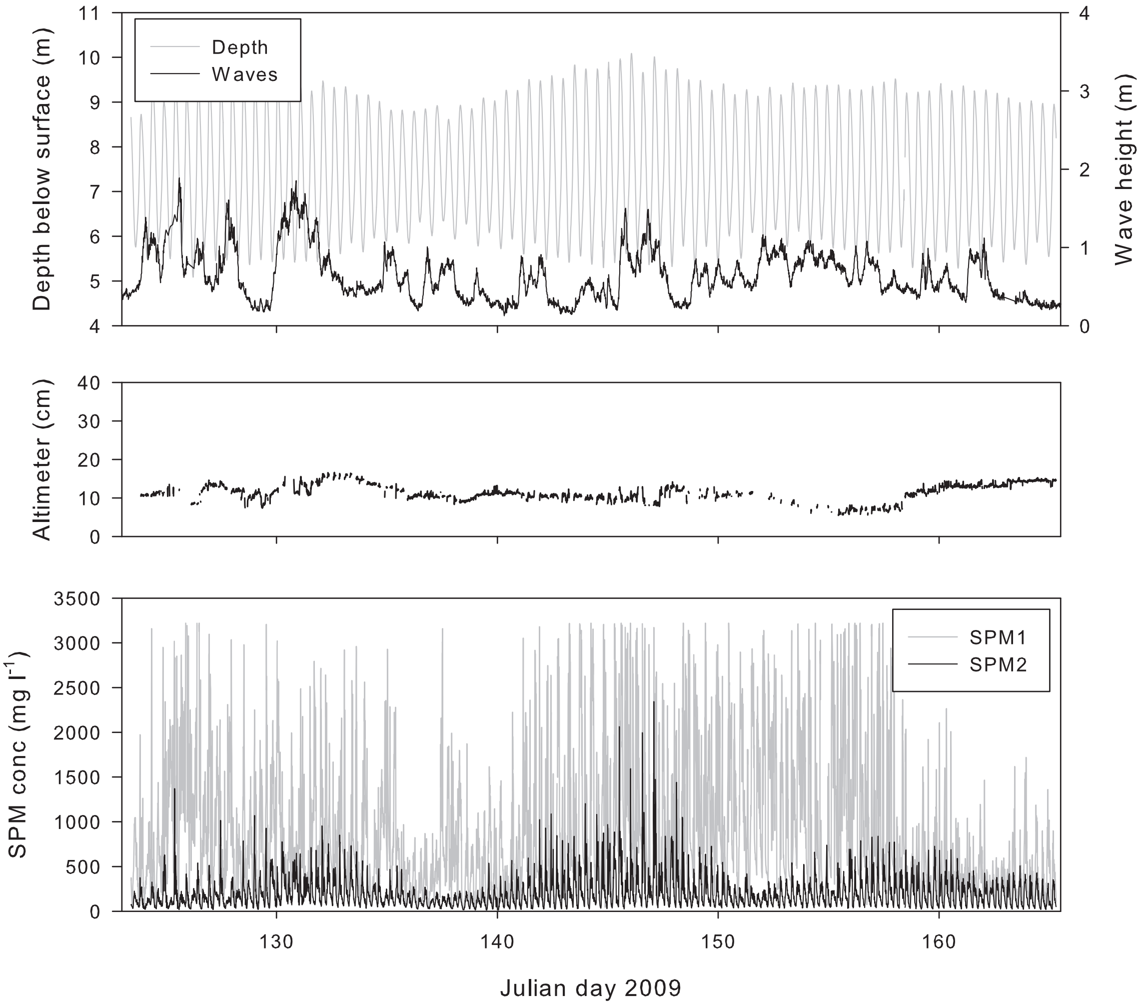

Fig. 4. Tripod measurements of 15 April–23 May 2008 (part of measuring period 5). From up to down: depth below water surface (m) and significant wave heights at Bol van Heist; ADV altimetry; and SPM concentration derived from OBS at 0.2 mab (SPM1) and 2 mab (SPM2). After day 142, no SPM1 data are available. Saturation of the OBS is at 3.2 g l^{-1}.

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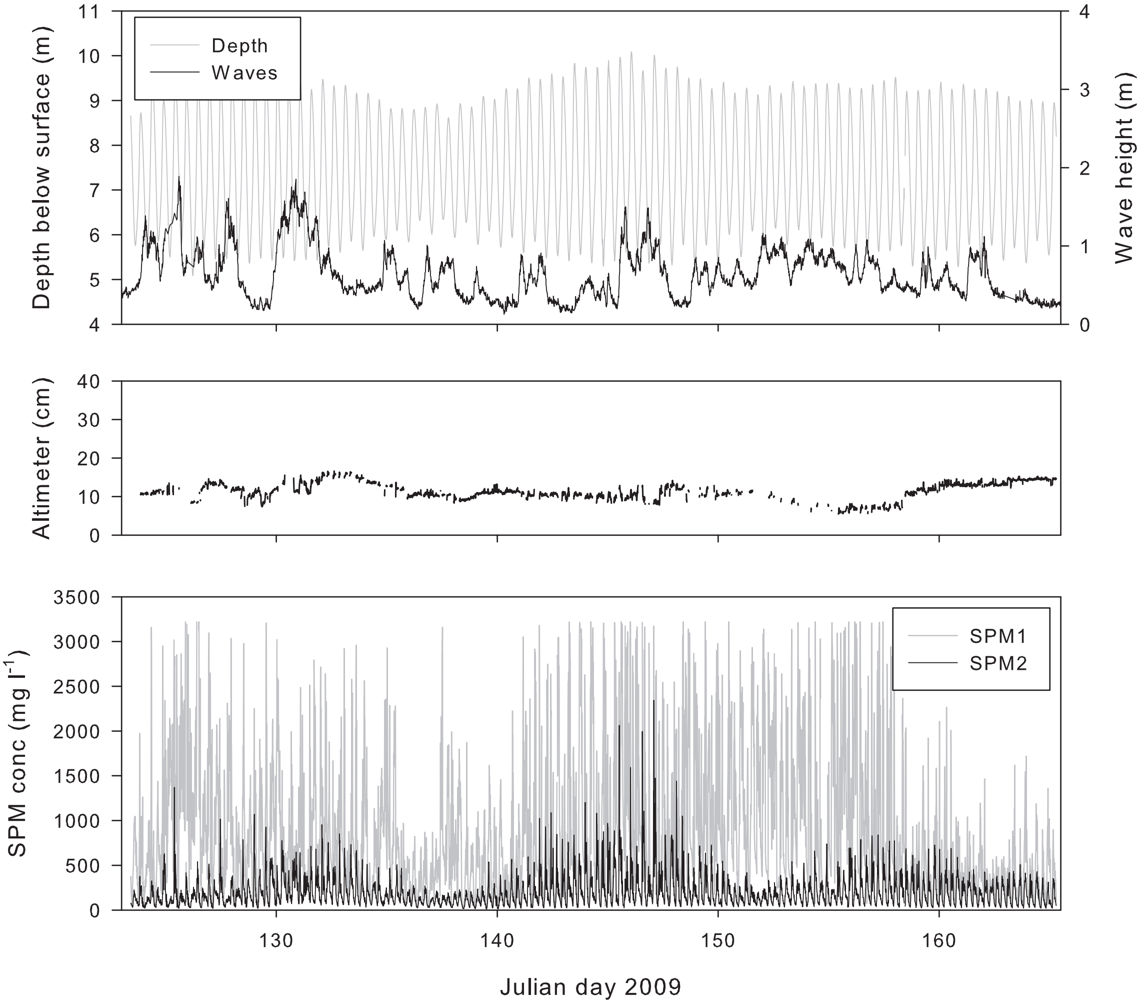

Fig. 5. Tripod measurements of 4 May–15 June (measuring period 6). The field experiment lasted from 5 May until 2 June. From up to down: depth below water surface (m) and significant wave heights at Bol van Heist; ADV altimetry; and SPM concentration derived from OBS at 0.2 mab (SPM1) and 2 mab (SPM2). Saturation of the OBS is at 3.2 g l^{-1}.

Table 2
Median (D50) and geometric mean SPM concentration (x^*) in mg l^{-1} during the six deployments (Table 1) together with the χ^2 test probability (p) compared with a lognormal distribution and the multiplicative standard deviation (s^*). 1–5, 6b correspond with all the data before and after the dredging experiment (6a).

Data	0.2 mab								2 mab							
	1	2	3	4	5	6a	6b	1–5, 6b	1	2	3	4	5	6a	6b	1–5, 6b
D50	341	288	199	321	280	672	345	281	137	143	116	150	106	150	158	131
x^*	340	308	183	290	258	612	319	279	144	149	105	150	102	150	135	128
s^*	2.9	3.0	2.4	3.0	2.7	2.6	2.2	2.9	2.3	2.3	2.5	2.5	2.4	2.3	2.3	2.4
p	1.00	0.57	0.77	0.96	0.82	0.99	0.37	0.93	0.93	0.94	0.59	0.99	0.94	0.99	0.12	0.99

the ADV altimetry raised on average by 10 cm, due deposition of mud. From day 140 on SPM concentration decreased, resulting in no increase of the acoustic bed boundary.

May 2009 was marked by alternating W–SW and E–NE and relatively high wave conditions as compared to a similar period in May 2008 (Table 1, Figs. 4 and 5). During the experiment the SPM concentration at 0.2 mab was strikingly high, with tide-averaged values ranging from 0.3 to 1.6 g l^{-1}. These high values remained until 1 week after the end of the dredging experiment before decreasing to tide averaged values lower than 0.5 g l^{-1}. The high SPM concentrations in May 2009 are only partially due to higher waves. SPM concentration at 2 mab differs from the near-bed one, and reveals a dynamic controlled by tidal and neap-spring tidal variation, whereas near the bed high concentrated benthic suspension or fluid mud layers have dominated the sediment dynamics. The ADV altimetry revealed also the decrease in acoustic bed boundary of 8–10 cm during neap tide (for days 134–139 and 153–159). For both periods mud was deposited because favourable hydro-meteor conditions prevailed (i.e. low wave activity and decelerating currents); the mud layers remained during several days. After cessation of the disposal operations, the SPM concentrations at 0.2 mab remained still very high during 1 week and disappeared together with the fluid mud layer.

4.3. Statistics of SPM concentration

For each of the six measuring period probability distributions were constructed for SPM concentration at 0.2 and 2 mab together

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with fitted lognormal distributions. The geometric mean (x^*), median (D50) and multiplicative standard deviation (s^*) of these distributions, together with the χ^2 test results are shown in Table 2, some of the distributions are presented in Fig. 6. If the χ^2 test probability is low ($p < 0.05$), then the distribution would not correspond with a log-normal one. The results confirm that all distributions are log-normally distributed. The results show that the mean SPM concentration during autumn and winter (periods 1, 2, 3 and 4) is generally higher than during spring (period 5). The mean and median SPM concentration at 0.2 mab during the field experiment (period 6a) is significantly higher than during any of the other periods, whereas at 2 mab the same order of magnitude is

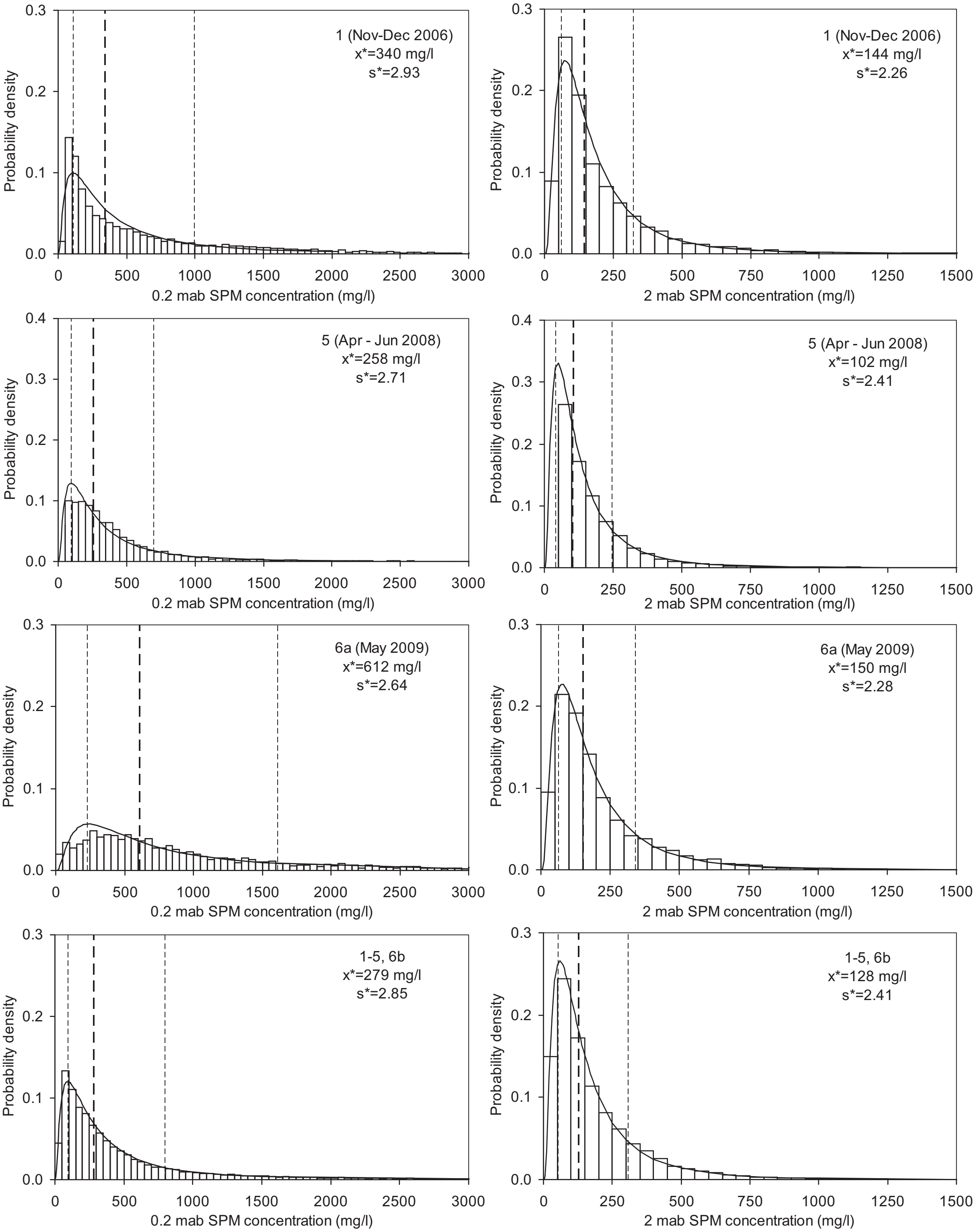

Fig. 6. Probability density distribution of the SPM concentration data at 0.2 mab (left) and 2 mab (right) for periods 1, 5 and 6a (during dredging experiment) and all data except those during the dredging experiment (1–5 and 6b) and the corresponding log-normal probability density functions (periods 2–4 are not shown), see Table 1. The data are binned in classes of 50 mg l^{-1}, the dashed lines correspond to the geometric mean x^* times/over the multiplicative standard deviation s^*.

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Table 3
Median (D50) and geometric mean SPM concentration (x^*) in mg l^{-1} during the six deployments (see Table 1) and wave orbital velocities $U_w < 0.03$ m/s. Also shown is the χ^2 test probability (p) of the distributions compared with a lognormal one and the multiplicative standard deviation (s^*). 1–5, 6b correspond with all the data before and after the dredging experiment (6a).

Data	0.2 mab								2 mab							
	1	2	3	4	5	6a	6b	1–5, 6b	1	2	3	4	5	6a	6b	1–5, 6b
D50	184	310	206	217	259	559	306	250	91	209	137	126	113	141	130	134
x^*	221	341	181	203	239	470	269	237	103	196	116	127	103	142	121	124
s^*	2.7	2.5	2.3	3.3	3.1	3.0	2.2	2.8	2.5	2.1	2.5	2.8	2.6	2.4	2.3	2.6
p	0.02	1.00	0.49	0.59	0.84	0.99	0.38	0.95	0.18	0.66	0.32	0.83	0.70	0.99	0.11	0.86

Table 4
Median (D50) and geometric mean SPM concentration (x^*) in mg l^{-1} during the six deployments (see Table 1) and wave orbital velocities $U_w > 0.3$ m s^{-1}. Also shown is the χ^2 test probability (p) of the distributions compared with a log-normal one and the multiplicative standard deviation (s^*). 1–5, 6b corresponds with all the data before and after the dredging experiment (6a). For periods 5 and 6b, not enough data correspond with these wave conditions to give statistical meaningful values.

Data	0.2 mab								2 mab							
	1	2	3	4	5	6a	6b	1–5, 6b	1	2	3	4	5	6a	6b	1–5, 6b
D50	763	197	98	303	–	595	–	244	178	117	57	167	–	177	–	130
x^*	609	237	115	288	–	651	–	270	197	114	61	162	–	169	–	129
s^*	2.5	2.6	2.2	2.5	–	2.1	–	2.8	2.0	1.8	2.0	2.1	–	2.2	–	2.1
p	1.00	0.09	0.07	0.98	–	0.99	–	0.52	0.13	0.40	0.08	0.37	–	0.46	–	0.91

observed than during a winter situation (periods 1, 2 and 3). During the field experiment (5 May–2 June) the mean increased to 612 mg l^{-1} (0.2 mab), i.e. more than twice the mean value before and after the experiment; but remained nearly similar at 2 mab (150 vs. 128 mg l^{-1}).

The results of sub-sampling the SPM concentration data using as selection criterion a bottom wave orbital velocity (U_w) smaller than 0.03 m s^{-1} and bigger than 0.3 m s^{-1} are shown in Tables 3 and 4. The χ^2 test probability is for some periods lower than 0.05, this is due to the fact that the sub-sample does not contain sufficient data. An U_w of 0.03 m s^{-1} (0.3 m s^{-1}) corresponds to a significant wave height of about 0.5 m (1.5 m) in 8 m water depth. The results show that the mean SPM concentration at 0.2 mab is generally lower during low wave activity, except for periods 2 and 3, whereas at 2 mab no clear relation can be observed. Before and after the field experiment, lower wave influence is not significantly changing the mean SPM concentration at 2 mab. The low mean SPM concentration during measuring period 3 is the result of calm weather ($H_s = 0.46$ m). The correlation between median SPM concentration and SPM concentration during higher wave action ($U_w > 0.3$ m s^{-1}) is only obvious for periods 1 and 6 (Table 4). For the other periods, the mean has similar values (periods 4 and 5) or is even lower than the mean for all data (Table 2).

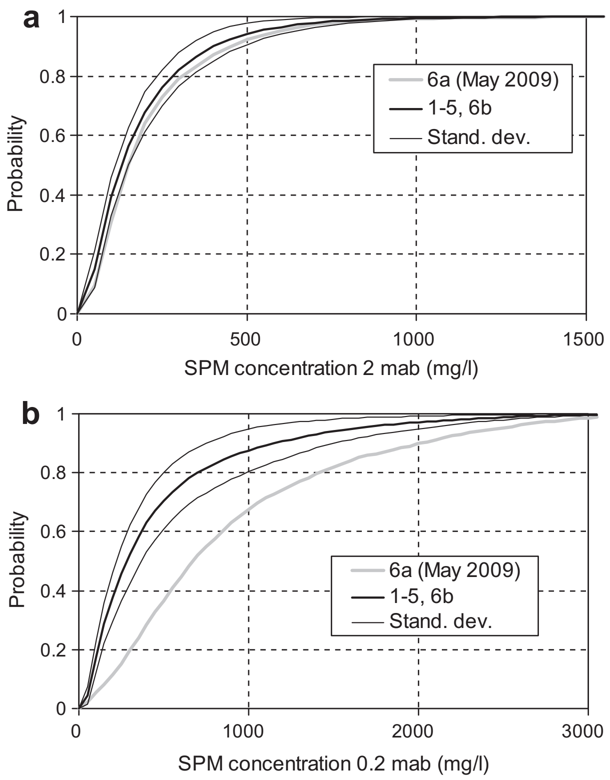

Fig. 7. Cumulative probability distribution of SPM concentration measured at 2 mab and 0.2 mab. The black line (1–5, 6b) shows the data not collected during the field experiment ± one standard deviation (thin black lines) and the grey one during the field experiment (6a), see Table 1.

The cumulative frequency distributions of SPM concentration are shown in Fig. 7. The probability to have a SPM concentration at 0.2 mab higher than the median SPM concentration during the field experiments is on average 0.21 (periods 1–5, 6b), with 0.06 (period 4) and 0.30 (period 1) being the two extreme probabilities. At 2 mab the probabilities are on average higher (0.43: periods 1–5, 6b) and the extreme values are closer together (period 5: 0.32–0.52: period 6b).

5. Discussions

In this study, the results based on time-series measurements at a fixed location before, during and after an experimental disposal of dredged matter, indicated a significant higher SPM concentration during the disposal. Below we argue that the increase is not due to natural variability. The probability of having a SPM concentration higher than the median SPM concentration at 0.2 mab during the field experiment is low.

5.1. Wave influence

SPM transport on many shelves is mainly controlled by currents and waves and high concentrated mud suspensions or fluid mud layers are formed in wave-dominated areas (Li and Mehta, 2000). The correlation between median SPM concentration and SPM

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concentration during higher wave action ($U_w > 0.3$ m s^{-1}) is only obvious for periods 1 and 6a (Table 4). For the other periods, the median has a similar value (period 4) or an even lower value than the median for all wave conditions (Table 2). This is in contrast with observations made at MOW1 (Fig. 1) situated about 7 km offshore and at a water depth of about 10 m MLLWS, where the median SPM concentration was clearly correlated with wave orbital velocity (Fettweis and Nechad, 2010). The differences in median SPM concentrations as a function of wave orbital velocity cannot be explained by the further offshore location and thus lower wave influence (Harris and Wiberg, 2002) or differences in wave climate during the measurements. It points to our opinion to a time lag occurring between waves and SPM concentrations at Blankenberge and thus to mainly advection of suspended matter from elsewhere as SPM source rather than local erosion. The mainly non-local sediment availability together with the fact that the median SPM concentration during the dredging experiment (period 6a) was always higher (also for the sub-samples with $U_w > 0.3$ and $U_w < 0.03$, see Tables 2–4) than during the other periods, strengthen the argument that the high SPM concentration during this period was caused significantly by the disposal of dredged material.

As the median H_s during the dredging experiment (period 6a) was higher than during the same season in 2008 (Table 1) we could explain the high SPM concentrations during May 2009 (Fig. 5) as being partially due to higher wave activity. Increase in SPM concentrations remained, however, limited to the near bed, suggesting that vertical mixing due to waves was low. Fettweis et al. (2010) report that wave effects on SPM concentration are starting to become significant when H_s exceeds 2 m as the thick packages of Holocene and recent muddy sediments, found in the area, are then eroded. It is therefore not very likely that the May 2009 storms (maximum $H_s < 1.8$ m) have eroded sufficient sediments to explain the increase in SPM concentrations.

5.2. Ebb–flood dynamics

During a tidal cycle, several peaks in SPM concentration are observed; generally, two peaks occurred during ebb and one during flood. The first ebb peak is generally lower and occurred when the increasing current velocity has reached a critical value for resuspending the fluffy layer. The second one occurred at the end of ebb and is a consequence of settling. This is confirmed by the fact that the SPM concentration peak at 0.2 mab is generally observed after the peak at 2 mab. Maxima in SPM concentration during flood occurred generally after slack water and point thus to resuspension; the SPM concentration at 2 mab occurred after the peak at 0.2 mab. The mean of the SPM concentration maxima during a tide was at least 1.7 times higher during the dredging experiment than during the other periods (0.2 mab: 2670 mg l^{-1} vs. 1566 mg l^{-1}; 2 mab: 941 mg l^{-1} vs. 552 mg l^{-1}), whereas the mean of the minima was similar (0.2 mab: 109 mg l^{-1} vs. 99 mg l^{-1}; 2 mab: 35 mg l^{-1} vs. 40 mg l^{-1}). These processes of resuspension and rapid deposition have also been identified in the ADV altimetry data. The OBS measurements indicated that the SPM concentration was generally higher during ebb at 0.2 mab, whereas at 2 mab it was generally higher during flood. This was more pronounced during measuring period 6a, where the highest peaks at 0.2 mab occurred more frequently during ebb than flood. The SPM during the disposal experiment was thus concentrated in the near bed layer rather than being well mixed in the water column, as was also observed by others (e.g. Wu et al., 2006; Siegel et al., 2009). The ebb-dominance of the near-bed SPM concentration indicates that SPM transport of fine sediments was from the disposal site towards the measurement location; the measurement location is situated in ebb direction of the disposal site. The SPM concentration and altimetry data both suggest that a lutocline or benthic plume was formed during the field experiment and that the fate of the fluid mud layer was controlled by the differences in bottom shear stress during neap and spring tidal periods.

5.3. Impact of disposal

The natural variability of SPM concentration in the area is very high, which is indicated by the high multiplicative standard deviations of the probability distributions (Table 2). Orpin et al.; (2004) argue that the natural variability of the system could be used to define the limits of acceptable turbidity levels during dredging or disposal operations. Such an approach assumes that a short-term increase (several hours) that falls within the range of natural variability will not have any significant ecological effect. Orpin et al. (2004) developed this strategy for coral communities, which are much more sensitive to turbidity than the *Macoma balthica* community found in the high turbidity area of the study site (Degraer et al., 2008). Changes in species density or faunal community may be attributable to changes in sediment composition and increased SPM concentration. Nevertheless, applying the same trigger to indicate acceptable upper limits of SPM concentration in the water column (2 mab) indicates that the increase is within natural variability of the system. However, we found that the cumulative frequency of SPM concentration at 0.2 mab during the dredging experiment was not included within one standard deviation of the curve for all the data not collected during the field experiment (Fig. 7), showing that significant change in turbidity and possibly bed sediment composition over a large area occurred. The results suggest that if the site would be used as permanent disposal site for maintenance dredging work then the SPM concentration in the near bed layer together with deposition of mud would increase and might thus negatively affect the macrobenthos of a larger area. Van Hoey et al. (2009) report that on the disposal site Zeebrugge Oost (Fig 1), situated west of the port, lower macrobenthos and epibenthos densities were found than elsewhere in the area.

6. Conclusions

Harbour authorities worldwide are obliged to dredge their major shipping channels, and subsequently to dispose the dredged spoil offshore. In this study an analysis method, based on the concept of statistical populations, was applied to evaluate the effects of disposal operations on SPM concentration in the Belgian nearshore area. The method provides a tool to account for the complexities associated with natural dynamics and the need to evaluate quantitatively human impact. SPM concentration can be used as an indicator of environmental changes if sufficiently long time series are available that are representative of the natural variability. The major site specific conclusions of the study are:

1. The area has a very high natural variability of SPM concentration (min–max: 10–3300 mg l^{-1}).
2. The SPM concentration near the bed (0.2 mab) was exceptionally high (median was more than two times higher) during the dredging experiment. Waves were not identified as being responsible for the high SPM concentrations.
3. The disposal site was situated in ebb-direction of the measuring location. During the experiment, a generally higher SPM concentration near the bed during ebb and at 2 mab during flood was observed, suggesting that the disposed material was mainly transported in the benthic layer. The time lag between high wave heights and high SPM concentration suggests further that the SPM has been advected towards the measuring location rather than eroded locally.

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4. The disposal results in a long-term increase of SPM concentration near the bed at the measuring location. This together with ADV altimetry suggest that fluid mud layers have been formed during whole the disposal experiment rather than being limited to neap tidal or storm conditions as observed during the other periods.

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