The impact of disposal of fine-grained sediments from maintenance dredging works on SPM concentration and fluid mud in and outside the harbor of Zeebrugge

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Abstract The amount of sediments to be dredged and disposed depends to a large part on the suspended particulate matter (SPM) concentration. Tidal, meteorological, climatological, and seasonal forcings have an influence on the horizontal and vertical distribution of the SPM in the water column and on the bed and control the inflow of fine-grained sediments towards harbors and navigation channels. About 3 million tons (dry matter) per year of mainly fine-grained sediments is dredged in the port of Zeebrugge and is disposed on a nearby disposal site. The disposed sediments are quickly resuspended and transported away from the site. The hypothesis is that a significant part of the disposed sediments recirculates back to the dredging places and that a relocation of the disposal site to another location at equal distance to the dredging area would reduce this recirculation. In order to validate the hypothesis, a 1-year field study was set up in 2013–2014. During 1 month, the dredged material was disposed at a new site. Variations in SPM concentration were related to tides, storms, seasonal changes, and human impacts. In the high-turbidity Belgian near-shore area, the natural forcings are responsible for the major variability in the SPM concentration signal, while disposal has only a smaller influence. The conclusion from the measurements is that the SPM concentration decreases after relocation of the disposal site but indicate stronger (first half of field experiment) or weaker (second half of field experiment) effects that are, however, supported by the environmental conditions. The results of the field study may have consequences on the management of disposal operations as the effectiveness of the disposal site depends on environmental conditions, which are inherently associated with chaotic behavior.

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1 Introduction

Dredging operations in coastal areas are essential in order to maintain channels and harbors navigable for large vessels. These deepened areas—often protected by breakwaters—are not in equilibrium with the hydrodynamics, and as a consequence, sediments are quickly accumulating after removal, demanding thus for almost continuous maintenance works. The amount of sediments to be dredged depends to a large part on the suspended particulate matter (SPM) concentration. SPM concentration is highly variable in coastal areas due to tidal, meteorological, climatological, and seasonal forcings (Fettweis and Baeye 2015). These forcings have an influence

on the horizontal and vertical distribution of the SPM in the water column and on the bed and control the inflow of fine-grained sediments towards harbors and navigation channels (Mehta 1991; van Ledden et al. 2004; Van Maren et al. 2009; Vanlede and Dujardin 2014; Wan et al. 2014). Further to the natural variability, dredging and disposal influence the SPM concentration in the near and far field due to the operations itself and due to dispersal, transport and buffering of the disposed fine sediments (Smith and Friedrichs 2011; Decrop et al. 2015; Van Maren et al. 2015). Massive sedimentation of fine-grained sediments in harbors and navigation channels is often related to the occurrence of fluid mud layers (Verlaan and Spanhoff 2000; Winterwerp 2005; Kirby 2011; Van Maren et al. 2009). Fluid mud may be formed by fluidization of cohesive sediment beds or by the quick settling of larger SPM flocs during slack water resulting in an increase of the near-bed SPM concentration and the formation of lutoclines (Mehta 1991; van Kessel and Kranenburg 1998; Li and Mehta 2000; Becker et al. 2013). The particle-turbulence interactions and the stratification-induced turbulence damping contribute to the formation and stability of these layers (Le Hir et al. 2000; Toorman 2002; Winterwerp 2006).

The potential effects of the disposal of fine-grained sediments are relatively well described with respect to environmental issues, such as alteration of benthic and pelagic communities, decrease of water clarity, dispersion of pollutants and nutrients, and changing bathymetry and hydrodynamic processes (Smith and Rule 2001; Stronkhorst et al. 2003; Orpin et al. 2004; Simonini et al. 2005; Bolam et al. 2006; Du Four and Van Lancker 2008; Okada et al. 2009; Stockmann et al. 2009; Fettweis et al. 2011; Agunwamba et al. 2012; Bolam 2012; van Maren et al. 2015). Relatively less attention has been paid to the effect of disposal of fine-grained material on the dredging works itself (e.g., Kapsimalis et al. 2013). Depending on the location of the disposal site, significant amounts of the disposed matter may recirculate in suspension or as high concentrated benthic layers back to the dredging areas, increasing thus the volume to be dredged and disposed. A smart relocation of the disposal site that does not induce recirculation is a straight-forward way to decrease dredging volumes, costs, and environmental impact. In order to evaluate the impact of a relocation of disposal site in highly dynamic and turbid areas, continuous measuring stations are mandatory. With increasing implementation of long-term monitoring stations, an understanding of variations and short-term impacts became possible (e.g., Badewien et al. 2009; Garel and Ferreira 2011; Fettweis et al. 2011; Henson 2014; Jalón-Rojas et al. 2015).

The harbor of Zeebrugge, situated in the coastal turbidity maximum area along the Belgian coast (southern North Sea), is subject to high siltation rates and, as a result, huge maintenance dredging and disposal works are mandatory (Fettweis et al. 2011). The focus of the present study emerged from

numerical model results that have indicated that part of the disposed sediments quickly returned back to the dredging areas and that the mass to be dredged could be decreased by relocating the disposal site (Van den Eynde and Fettweis 2006). In the framework of studies conducted by the Flemish Ministry of Public Works and Mobility to reduce dredging costs, a 1-year field study was set up to validate the model results with in situ data. The field study consisted of 11 months "business as usual," i.e., disposing of the dredged material on the existing disposal site and of a 1-month period where an alternative disposal site without recirculation was used. An extensive monitoring campaign was set up during the field study which consisted of measurements in and outside the harbor of Zeebrugge of various oceanographic, meteorological, and sediment parameters (SPM concentration, current velocity, waves, salinity, temperature, tides, wind, bathymetry, density of mud layers) in order to estimate the impact of the relocation of the disposal site on the SPM concentration and on the fluid mud dynamics in and outside the harbor of Zeebrugge. A key element in the analysis is the use of environmental parameters that allowed establishing a representative baseline encompassing the major actors (tides, wind, waves) responsible for variabilities in SPM concentration and fluid mud thickness, as well as human activities such as ship maneuvering and dredging/disposal works.

2 The study site

The harbor of Zeebrugge is situated in the Southern Bight of the North Sea at the marine limit of influence of the Westerscheldt estuary (see Fig. 1). The relatively well-protected Southern Bight is mainly tidally dominated as compared with other shallow areas in the North Sea where wave influences are more pronounced (Fettweis et al. 2012b). The tides are semidiurnal and the mean tidal amplitude is about 3.6 m. The nearshore tidal current ellipses are elongated and vary on average between 0.2 and 0.8 m/s during spring tide and 0.2 and 0.5 m/s during neap tide at 2 m above the bed. The strong tidal currents and the low freshwater discharges result in a well-mixed water column. Slack water occurs around 3 h before and 3 h after high water (HW). Ebb (about 3 h after HW until about 3 h before HW) is directed towards the southwest (SW) and flood towards the northeast (NE). Maximum currents occur during flood around 1 h before HW; the peak currents during ebb are slightly lower and occur around LW. Southwesterly winds dominate the overall wind climate, followed by winds from the NE sector. Maximum wind speeds coincide with southwesterly winds; nevertheless, the highest waves are generated under northwesterly winds, due to a longer fetch. The waves have generally a period of about 4 s, lower frequency swell waves with a period of about 6 s are less abundant. The median significant wave height is 0.6 m
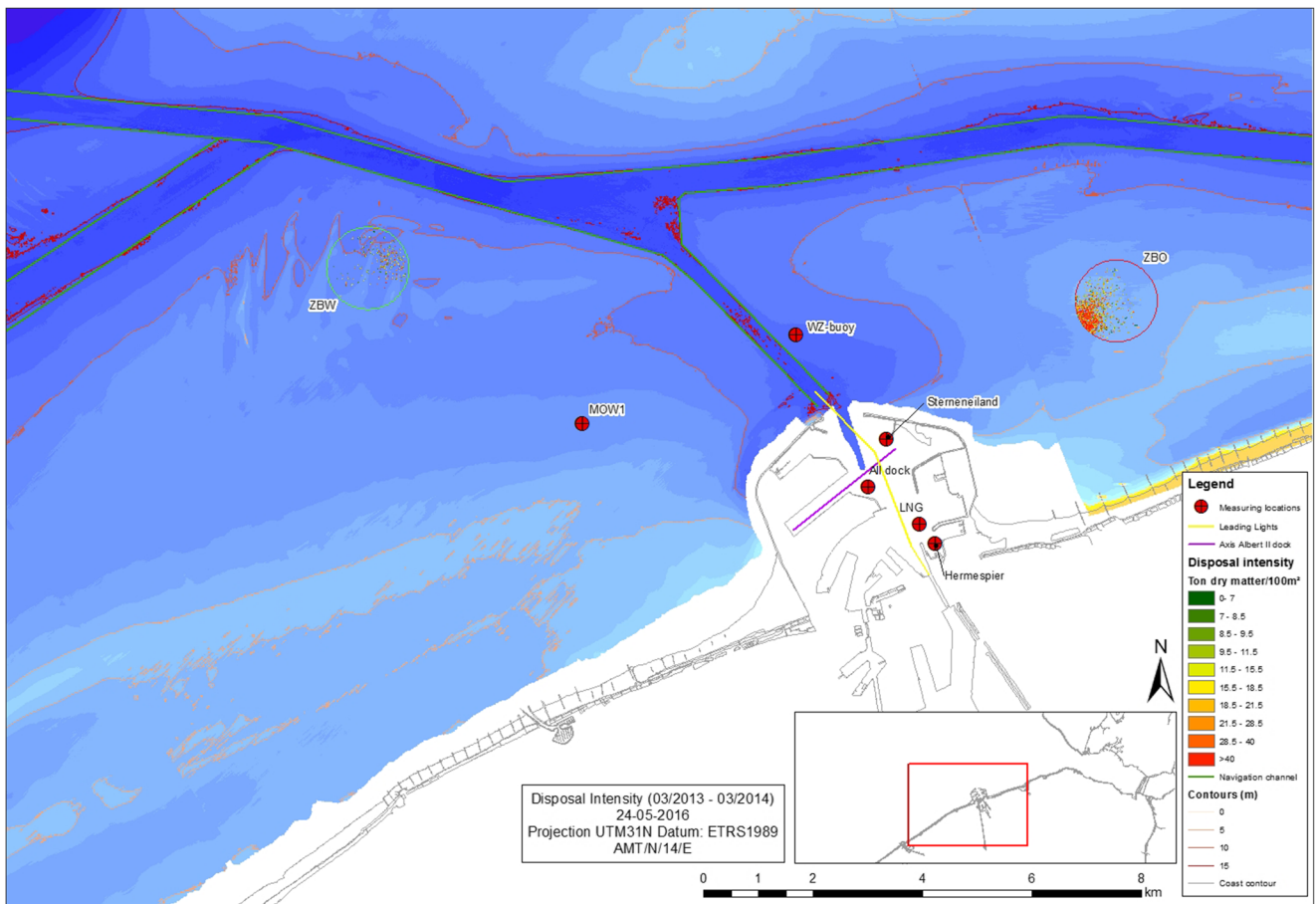
Fig. 1 Map of the Belgian coastal area (southern North Sea) showing the measurement stations outside (*MOW1*; *WZ buoy*) and inside the port of Zeebrugge (*Hermespier*, *LNG*, Albert II dock (*AII dock*), and *Sterneneiland*), the regular disposal site ZBO and the disposal site ZBW used during the field experiment. The background consists of bathymetry and of the dredging and disposal intensity during 2013

and the P90 percentile 1.2 m. The salinity is generally between 28 and 34, and changes in salinity are caused by the advection of marine and Scheldt water masses (Arndt et al. 2011; Fettweis and Baeye 2015). The residual alongshore currents at MOW1 (WZ buoy) (see the location of these stations in Fig. 1) are in 80 % (64 %) of the time directed towards the SW (i.e., in ebb direction) and salinity is then around 30. During the prevailing SW wind, salinity may increase up to 34 and marine water with generally lower SPM concentration enters the area; the residual alongshore current is then directed towards the NE. SW-NE direction corresponds with the alignment of the coastline.

The harbor is situated in a coastal turbidity maximum area with SPM concentrations between 0.02 and more than 0.1 g/l at the surface and between 0.1 and more than 3 g/l near the bed; lower values (<0.01 g/l) occur offshore (Baeye et al. 2011; Fettweis et al. 2012b). The SPM concentration, floc size, and settling velocity have a distinct seasonal signal (Fettweis and Baeye 2015). An acoustic detection method using ADV and ADP altimetry revealed bed boundary level changes of up to 0.2 m in the nearshore area during tidal and spring-neap cycles, suggesting the occurrence of lutoclines

and possibly of fluid mud layers (Baeye et al. 2012). The occurrence of brownish-colored fluffy layers on top of consolidated black and anoxic mud deposits of Holocene age, intercalated with thin sandy layers, have frequently been observed in Van Veen grab and box core samples taken in the vicinity of the harbor.

The outer port of Zeebrugge is reclaimed from the sea and is protected from it by two breakwaters, each about 4 km in length (Vanlede and Dujardin 2014). The harbor mouth is in open connection to the sea. The open water surface is 6×10^6 m^2, which gives a tidal volume of 24×10^6 m^3. The cross-sectional surface between the harbor and sea is about 12,000 m^2. The sediment exchange between the harbor and the sea is caused mainly by horizontal and to a lesser extent vertical exchange at the harbor mouth (Vanlede and Dujardin 2014). Most horizontal sediment exchange occurs from 2 h before high water to high water. Around that time, the flood flow in the North Sea (directed northeastward along the Belgian coast) drives a primary gyre in the harbor. The high SPM concentrations result in an average siltation rate of 3.6×10^6 tons dry matter (TDM) per year, which is dredged and disposed on the authorized disposal site ZBO (Fig. 1)

(Lauwaert et al. 2009). Because of the high sediment retention in the harbor, the sediment concentration in the outflowing water is lower than that in the inflowing water.

3 Methodology

The field study lasted for 1 year (between January 2013 and March 2014) and consisted of 11-month disposing of the dredged material on the existing disposal site ZBO, which induces recirculation of the disposed material back to the dredging sites and of a 1-month period (further called field experiment) with disposal on an alternative site (ZBW) with more limited recirculation (see Fig. 1). The fine-grained dredged sediments ($D_{50} < 10$ μm) from the harbor of Zeebrugge consist of 20–40 % clays, 20–40 % quartz, 20–30 % carbonates, and 1–7 % organic material (Adriaens 2015). In total, about 3×10^6 TDM have been dredged and disposed during the period March 2013–March 2014. During the 1-month field experiment, 0.41 million TDM (14 % of the yearly amount) were disposed on the ZBW site. The disposal on site ZBW occurred between 21 October 2013 and 20 November 2013. The 11-month period of disposal on site ZBO (further called disposal as usual) was situated between February 2013 and March 2014. Besides the monitoring station MOW1, where data are available since 2005 (Fettweis and Baeye 2015), a second station (WZ buoy) outside the harbor and four inside the harbor were installed during the field study.

3.1 Monitoring stations for SPM concentration outside and inside the port

Current velocity, salinity, SPM concentration, and altimetry were collected with tripods at MOW1, located about 5 km offshore, and at WZ buoy located at about 2 km from the harbor entrance (Fig. 1). Both measuring stations are situated in the influence zone from dispersion of dredged material disposal at ZBO (Van den Eynde and Fettweis 2006). The instrumentation suite consisted of a point velocimeter (5 MHz ADVOcean velocimeter), a downward looking ADP profiler (MOW1, 3 MHz SonTek Acoustic Doppler Profiler; WZ buoy, 2 MHz Aquadopp current profiler), two D&A optical backscatter point sensors (OBS3+), a Sequoia LISST-100X, and a Sea-bird SBE37 CT. The data were collected in bursts every 10 or 15 min for the OBS, LISST, and ADV, while the ADP was set to record a profile every 1 min; later on, averaging was performed to a 15-min interval to match the sampling interval of the other sensors. The OBSs were mounted at 0.2 and 2 m above bed (mab). The tripods were moored between 3 and 6 weeks and then replaced with similar tripod systems to ensure continuous time series.

Inside the port current velocity, salinity and SPM concentration were measured at four locations (Sterneneiland, Albert II dock, LNG and Hermespier, see Fig. 1) at two points in the water column, respectively about 2 m below MLLWS and about 2 mab. The instrumentation suite consisted of a point velocimeter (Aquadopp), an OBS3+, and a CT probe (Valeport 620). At Hermespier ,the instrumentation was mounted on a fixed cable, attached to the gangway of the pier and a concrete anchor at the bottom. The other three measuring locations were equipped with two concrete anchors connected by a 50-m steel cable; the measurement devices were attached to the first, 300 kg anchor, a localization buoy to the second, 1000 kg anchor. The instruments were kept at the desired depth by an underwater buoy, positioned just below MLLWS, and a second flotation buoy at the water surface. The data were collected every 10 min (average value of 60 s bursts). To reduce data gaps to a minimum, the measurement devices were retrieved and cleaned every 3 weeks. After some functionality checks, the measuring suite was then lowered again.

3.2 Top sediment layer outside and inside the port

Recently, applications in fine-grained sediment environments have been documented where the ADV altimeter was used to elucidate the high concentrated mud suspension (HCMS) or fluid mud layer dynamics (see Baeye et al. (2011)). The acoustic signal of the ADV records the distance between the measuring volume and the sea floor at both stations outside the port. This distance varies as a function of settling of the tripod, variation in bathymetry (erosion/deposition) and the presence of lutoclines or sharp gradients in the SPM concentration that act as reflector for the acoustic signal. The variation in altimetry can thus be used as a proxy for the dynamics of HCMS or fluid mud layer.

The thickness of the top mud layer inside the harbor was measured with a dual-frequency echo sounder on a regular basis. Besides the two weekly measurements along the central axis of the outer harbor (leading lights line in Fig. 1), a daily survey of the axis of the Albert II dock (axis Albert II in Fig. 1) was conducted during the field study. The 210-kHz reflector is considered to be the top of the mud layer, while the 33-kHz reflector is interpreted to be the hard sandy bottom.

3.3 SPM concentration from optic and acoustic sensors

The SPM concentration was derived from optical (OBS and LISST) and acoustical instruments (ADP). The OBS voltage readings were converted into NTU using Amco clear and then into SPM mass concentration (g/l) by calibration against filtered water samples collected during one (WZ buoy, inside the harbor points) and four tidal cycles (MOW1). A linear regression was used to fit a straight line between the OBS signal (in

NTU) and the filtered SPM concentration (g/l; see Fig. 2). The stability of the OBS was further controlled by calibrating them against Amco clear solution before and after the field study. The measuring range was set to 1.5 or 3 g/l depending on the sensor. During high-energy conditions, near-bed SPM concentrations at MOW1 and WZ buoy were regularly higher than 1.5 or 3 g/l. Under these circumstances, the OBS saturated and underestimated the actual SPM concentration. The OBS at 0.2 mab was in saturated state during about 2.3 % of the time at MOW1 and 3.2 % of the time at WZ buoy. Although this represents a relatively short period of time, it may significantly affect the mean SPM concentration, e.g., an underestimation of the peak SPM concentration during saturation by 2 g/l results in an underestimation of the mean SPM concentration in summer by 60 mg/l and in winter by 30 mg/l (Fettweis and Baeye 2015).

The LISST 100X uses laser diffraction technology to measure particle size and volume concentration in 32 logarithmically spaced size groups over the range of 2.5–500 mm (Agrawal and Pottsmith 2000). The volume concentration of each size group is estimated with an empirical volume calibration constant, which is obtained under a presumed sphericity of particles. The total SPM volume concentration (units: ml/l) is the sum of the 32 volume concentrations per size class and has been used in the study. As cohesive sediments occur as flocs in suspension, the SPM volume concentration is not equal to the SPM mass concentration. The uncertainty of the instrument is related to the characteristics of the particles occurring in nature (particles smaller and larger than the size range; non-spherical particles), which affects the estimated size and volume distribution (Mikkelsen et al. 2006; Andrews et al. 2010).

The ADP profilers at both locations were attached at 2.3 mab and down-looking, measuring current and acoustic intensity profiles with a bin resolution of 0.25 m starting at 1.8 mab. The backscattered acoustic signal strength, from ADP, was used to estimate SPM concentrations. After conversion to decibels, the signal strength was corrected for geometric spreading and water and sediment attenuation (Thorne and Hanes 2002). The upper OBS-derived SPM concentration estimates were used to calibrate the ADP's first bin. The different sensitivity of acoustic and optic sensors to changes in the SPM particle size and characteristic is reflected in the correlation coefficient between the ADP backscatter (dB) and the OBS-derived SPM concentration of $R^2 = 0.53$. The R^2 is better for the lower SPM concentrations and the regression model thus accounts for less variance for the higher SPM concentrations.

3.4 Data classification, ensemble averaging

The number of data at WZ buoy comprises 254 (OBS), 310 (Aquadopp), and 320 LISST tidal cycles, and at MOW1, about 1390 (LISST) and 2430 (ADP, OBS) tidal cycles were collected during different seasonal, tidal, and meteorological conditions. To every tidal cycle classification, parameters were assigned that take into account seasons, tidal range, alongshore current, and the significant wave height. Each tidal cycle starts at high water (HW) and finishes at the following HW and was resampled to obtain 50 data points per cycle (i.e., every 15 min). The tidal cycles of each class were then ensemble averaged, and the standard error was calculated. The standard error estimates how far the sample mean is likely to be from the population mean and will decrease with increasing sample size.

The tidal range was calculated from the harmonic tidal signal and then grouped according to the P66 (3.95 m) and P33 (3.31 m) percentiles into a spring tide (SP; >P66), mean tide (MT; P66-P33), and neap tide (NT; <P33). The influence of weather systems on SPM concentration was investigated by grouping the tidal cycles according to the residual alongshore

Fig. 2 Calibration of OBS output (NTU) versus filtered water samples (*MOW1*) during four tidal cycles (one in January and April and two in November). The *errorbars* indicate the standard deviation of three replica filtrations (*y*-axis) and 30 s of OBS measurements prior to the closure of the Niskin bottles (*x*-axis)
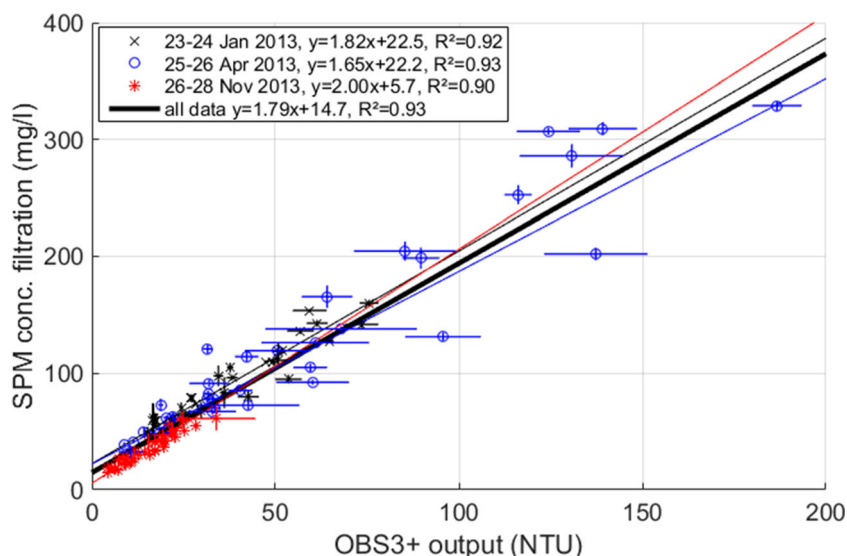
flow and the significant wave height. For each tidal cycle, the residual alongshore flow (U_a) was calculated using the ADP current velocity data at 2 mab. Subsequently, the tidal cycles were classified in terms of the direction and strength of this residual alongshore current into a SW-ward directed ($U_a < -0.09$ m/s) and a NE-ward directed ($U_a > 0$ m/s); SW-NE direction corresponds with the alignment of the coastline. The P50 percentile of residual alongshore currents is $U_a = -0.06$ m/s; a $U_a < -0.09$ m/s corresponds with the P33 percentile and a $U_a > 0$ m/s with the P80 percentile of all values. The influence of wave systems was looked at by grouping the data into tidal cycles with significant wave heights (H_s) < 0.60 m (<P50) and H_s > 1.2 m (>P90).

4 Results

4.1 SPM concentration outside and inside the port

The 2013 time series at MOW1 and WZ buoy of SPM concentration derived from OBS, LISST, and ADP and some additional parameters (H_s, U_a, salinity, and altimetry) are shown in Figs. 3 and 4. Less data are available at the WZ buoy location due to frequent failure of the instrumentation and collision of ships with the frame. The influence of neap-spring cycle is more pronounced in the SPM concentration derived from the ADP than the OBS. At 2 mab, the peak in the low-passed filtered SPM concentration from both the ADP
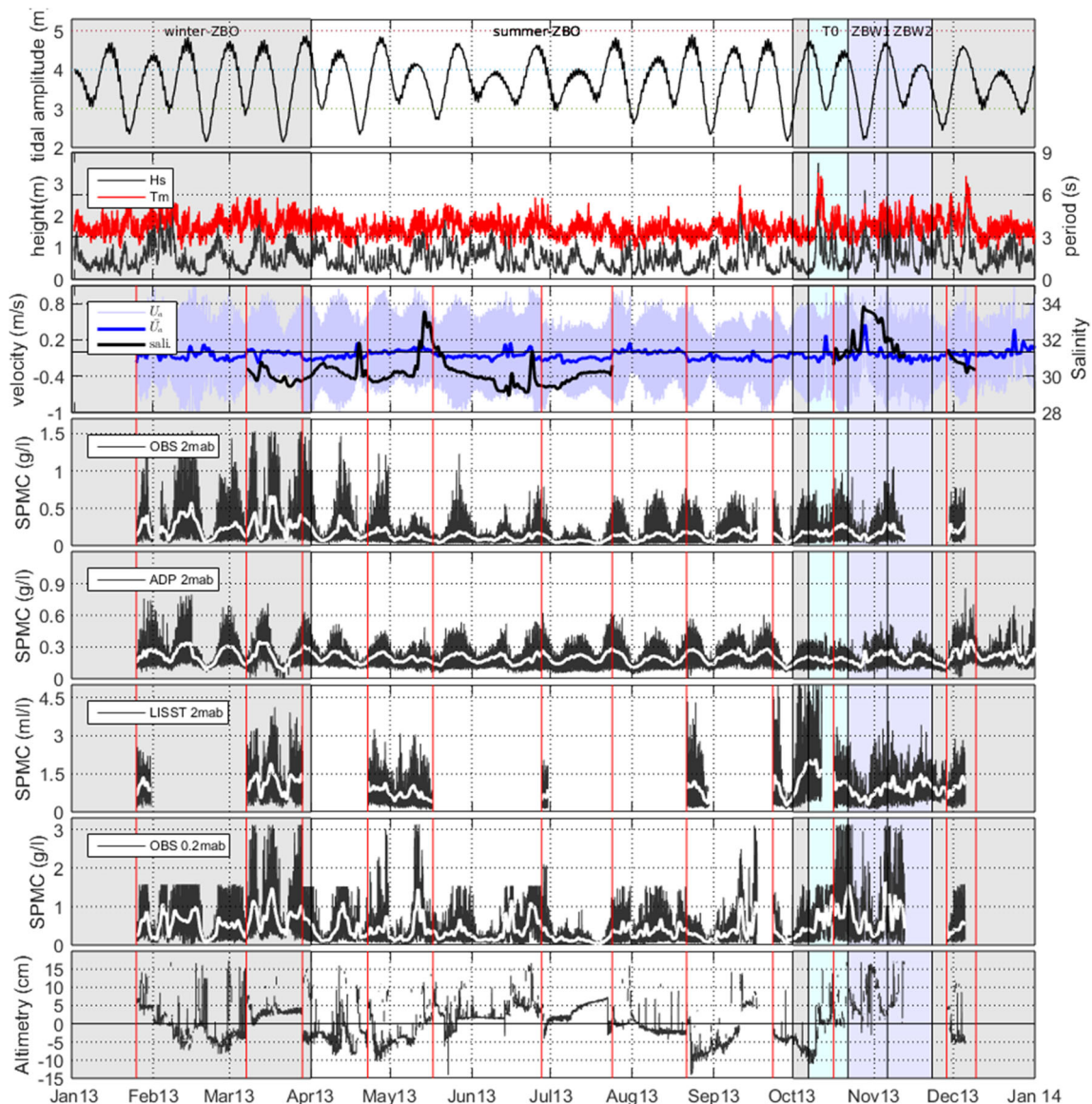
Fig. 3 MOW1 location, 1 January 2013–31 December 2013 time series of tidal amplitude, significant wave height (H_s) and mean wave period (T_m), alongshore currents (U_a), residual alongshore currents (positive is towards the NE, negative towards the SW), and salinity; SPM mass and volume concentration at 2 and 0.2 mab (SPMC) for ADP and OBS, and altimetry (decrease: erosion, increase: accretion). Red lines indicate the start/end of a tripod deployment
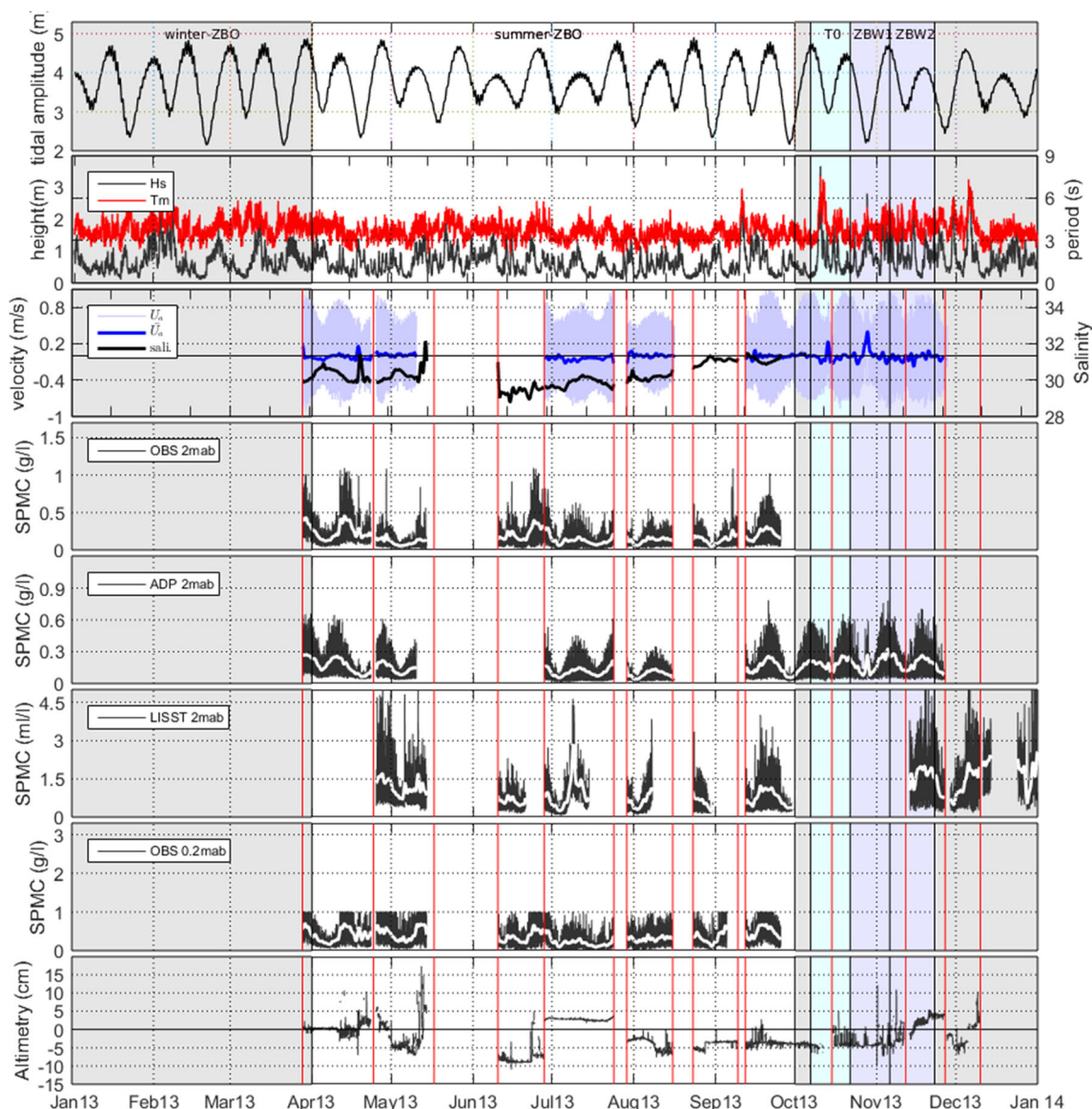
Fig. 4 Same as Fig. 3, but for WZ buoy

and the OBS corresponds generally well with the peak in tidal amplitude, which is not the case closer to the bed where the SPM concentration is more influenced by near-bed SPM dynamics, such as wave induced resuspension, or formation of HCMS. The quality of the correlation of low-pass filtered OBS-derived SPM concentrations with tidal amplitude is low for several periods at MOW1. This is the case around days 33, 45, 60, 72, 293, and 312, which have a lower low-passed filtered SPM concentration than expected from tidal amplitude. This can be explained by the direction of the residual alongshore currents, by an apparent low SPM concentration due to the fact that waves disturbed the signal, by saturation of the OBS at 0.2 mab, and by possible changes in sediment composition or the formation of fluid mud layers and a reduction of the vertical mixing.

The effect of tidal amplitude, seasons, waves and residual alongshore current on the OBS-derived SPM concentration during a tide at MOW1 is shown in Fig. 5 and Table 1. The tidal ensembles indicate that the mean SPM concentration at 0.2 mab during summer (winter) is about 13 % lower (higher) than the mean SPM concentration during the whole year. The seasonal difference is more pronounced at 2 mab where the difference with the mean during the whole year is ±25 %. The tidal-averaged SPM concentration at 0.2 and 2 mab during winter spring (neap) tide increases (decreases) by about 25 % with respect to the tidal-averaged SPM concentration during all tides in winter. During a NE-ward-directed residual alongshore current (P10) in winter, the tidal-averaged SPM concentration decreases by 20 % at 0.2 mab and 13 % at 2 mab, with respect to the tidal-averaged SPM concentration
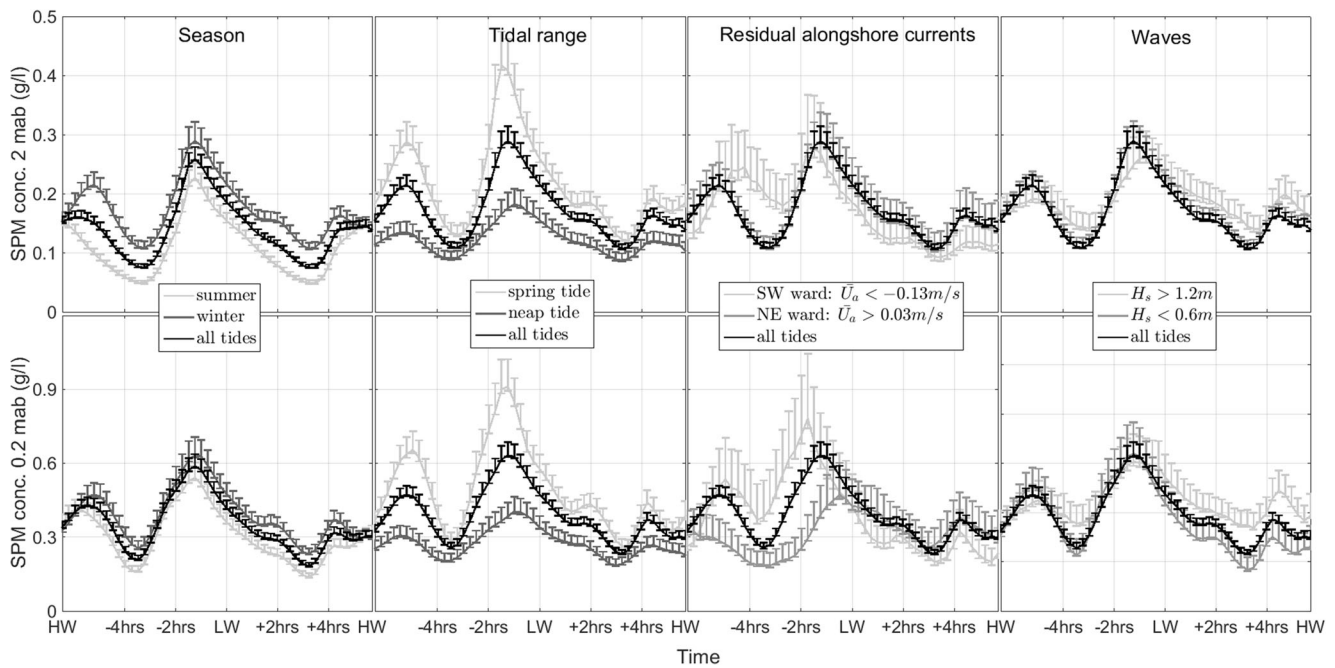
Fig. 5 MOW1 (2005–2013), ensemble-averaged OBS-derived SPM concentration at 2 and 0.2 mab during a tidal cycle as a function of season, tidal amplitude, direction of the residual alongshore current, and significant wave heights. The data grouped according to tidal amplitude, residual alongshore current, and significant wave heights are for winter period. The *error bars* are the standard errors. Slack water occurs around 4 to 3 h before and 3 h after LW

in winter. During SW-ward-directed residual alongshore current (P90), the values are almost equal to the tidal-averaged SPM concentration in winter. Low (high) wave conditions result in a decrease (increase) of the tidal-averaged SPM concentration by 9 % (16 %) at 0.2 mab and by 8 % (11 %) at 2 mab. The results show that high waves and negative residual alongshore flow direction induce the highest variations near the bed (0.2 mab), whereas seasonal effects are more pronounced higher up in the water column. The effect of tidal

Table 1 Geometric mean and multiplicative standard deviation (multiplied divided: */) of the OBS-derived SPM concentration (mg/l) at MOW1 (2005–2013) during different tidal ranges (neap tide, spring tide), residual alongshore current directions (SW-ward, NE-ward: P10 and P90 of all values) and significant wave height. The results of tidal range, residual alongshore current, and significant wave heights are for winter period

|	0.2 mab	2 mab
All tide	332*/1.36	131*/1.41
Summer	288*/1.44	100*/1.57
Winter	374*/1.31	165*/1.31
Neap tide	268/1.23	120*/1.22
Spring tide	460*/1.39	203*/1.38
SW-ward	361*/1.47	159*/1.39
NE-ward	303*/1.30	127*/1.27
$H_s < 0.6$ m	341*/1.43	147*/1.40
$H_s > 1.2$ m	432*/1.18	183*/1.19

range is similar near the bed and in the water column. The results indicate that SPM concentration is mainly tidally dominated, but the occurrence of storms will impact the shallow regions through resuspension and by advection. Figure 5 shows the effect of one parameter separately and gives a result that incorporates the average for the other parameters. The relatively low effect of high waves is thus hidden in the average over all tidal ranges. If we look at high wave condition during several tidal ranges, then the effects are more pronounced, i.e., strong increases of the SPM concentration near the bed during both neap and spring tidal condition and a decrease of wave effects at 2 mab, which is more pronounced during neap than spring tide. The effect of waves on different residual alongshore regimes is similar. Near the bed, the effects of alongshore residual current, as described above, is overprinted by the wave effects, in contrast with the situation at 2 mab, where the effect of residual alongshore current direction is more dominant than waves effect.

The SPM concentration time series inside the port are shown in Fig. 6. Data gaps are mainly caused by insufficient power supply and fouling. All stations show higher SPM concentration in the lower measurement point, except for Hermespier, where the difference in median value is not significant (Table 2). SPM concentrations are higher in winter (October–March) compared with summer (April–September), except for location Sterneneiland. This is probably caused by some exceptionally deep moorings during summer, leading to approximately the same depth for the upper
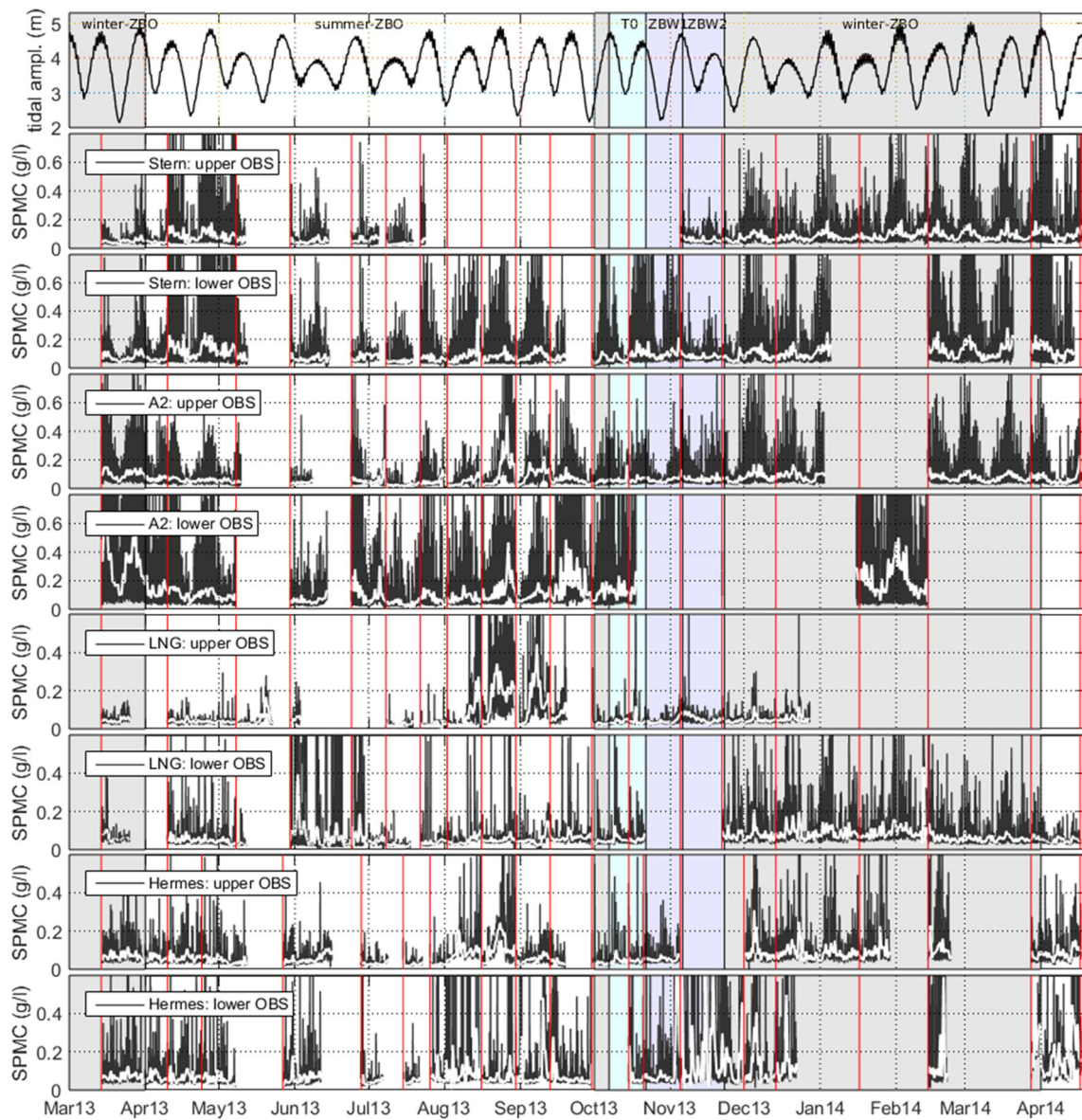
Fig. 6 1st March 2013–15th April 2014 time series of SPM concentration at two levels and in the four locations inside the harbor. *Red lines* indicate the start/end of a deployment

measurement point as the lower measurement point in winter. Sterneneiland and Albert II dock show significantly higher SPM concentrations during spring tide than during neap tide, in contrast to LNG and Hermespier (Table 2). The SPM concentrations at the two locations closest to the harbor mouth

(Sterneiland and Albert II dock) show a clear correlation with the tide, with highest SPM concentrations around high water (Fig. 7), indicating the period of inflow of sea water with high SPM concentration towards the harbor. At LNG this correlation is less pronounced and for location Hermespier there is no

Table 2 Median and its 95 % confidence interval of SPM concentrations (mg/l) inside the harbor: seasonal and tidal variations (spring tide–neap tide)

	Summer		Winter		Neap tide		Spring tide	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Sterneneiland	66 ± 6	81 ± 6	73 ± 4	88 ± 5	66 ± 4	71 ± 4	93 ± 7	105 ± 8
AII dock	54 ± 4	86 ± 8	73 ± 4	164 ± 30	51 ± 4	106 ± 14	76 ± 6	135 ± 22
LNG	38 ± 6	50 ± 3	43 ± 2	71 ± 4	40 ± 4	60 ± 5	39 ± 8	56 ± 4
Hermespier	54 ± 5	61 ± 5	68 ± 5	86 ± 14	60 ± 6	68 ± 10	62 ± 6	67 ± 7

Fig. 7 Albert II dock, ensemble-averaged OBS-derived SPM concentration at 2 m below water surface during a tidal cycle in winter (*upper*) and summer (*lower*) as a function of tidal range. The *error bars* are the standard errors. Slack water outside the harbor occurs around 4 to 3 h before and 3 h after LW
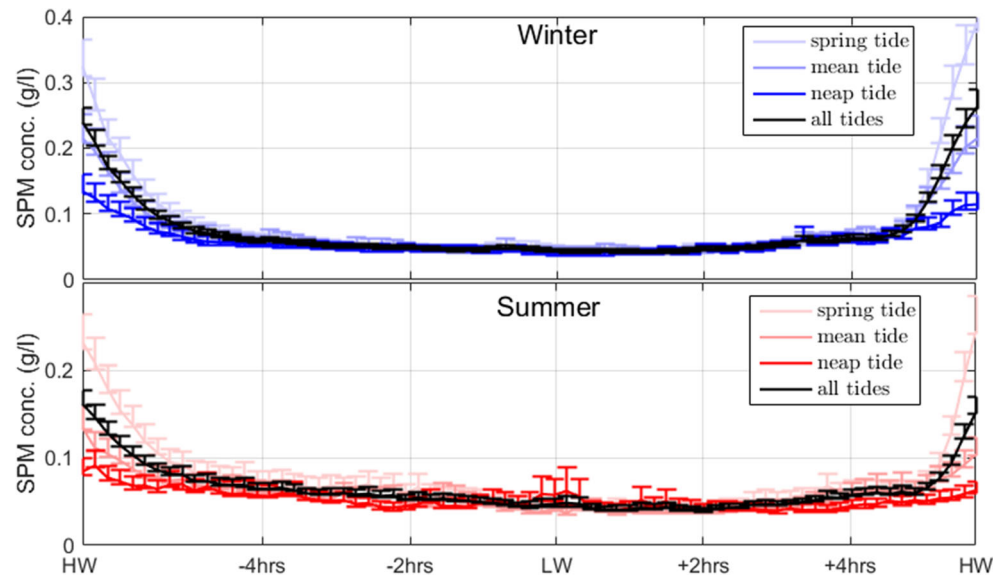
significant difference between high water and low water SPM concentrations. The SPM concentration in all locations inside the harbor correlates highly with the current velocity. Whilst the measurements outside the harbor show a peak around maximum ebb and flood flow, only the flood peak is observed in the harbor. The peak in SPM concentration during maximum flood velocity is simultaneously outside the harbor and at location Stern.

4.2 Fluid mud outside/inside the port

The 2013 time series at MOW1 and WZ buoy of the 5-MHz altimetry signal of the ADV are shown in Figs. 3 and 4. The seafloor varied between −14.8 and 17.4 cm (MOW1) and −9.2 and 17.4 cm (WZ buoy) and shows low- and high-frequent variations. In general, the low-frequent variations in altimetry are more pronounced during strong variations in residual alongshore current associated with storms. The high frequent

variations are often associated with the formation and resuspension of HCMS at slack water; these variations reach up to about 15–20 cm. The ensemble-averaged altimetry (Fig. 8) shows an increase around slack water at both locations. At MOW1, the accretion is more pronounced around the slack water after HW than that after LW. The resuspension of this material results in a peak in SPM concentration during ebb that is higher than during flood (Fig. 5). At the WZ buoy, the variations in altimetry are less pronounced and the seafloor thus more stable.

Inside the port, a mud layer up to 3.5 m thick exists, whereas at the harbor entrance (−500–0 m in Fig. 9), the thickness of the mud layer is about 0.5 to 2 m. Maximum thickness is located around the entrance of the Albert II dock; deeper in the harbor the thickness of the mud layer again decreases. However, Fig. 9 also shows that the variation of the 210 kHz altimetry is largest at the entrance and deeper in the harbor. For the whole period of the field study, the variation in

Fig. 8 Ensemble-averaged ADV altimetry signal outside the port. The altimetry is indicated with respect to the mean altimetry. The *error bars* are the standard errors. Slack water occurs between 4 and 3 h before and 3 h after LW. The variations in altimetry are a proxy for the HCMS or fluid mud dynamics
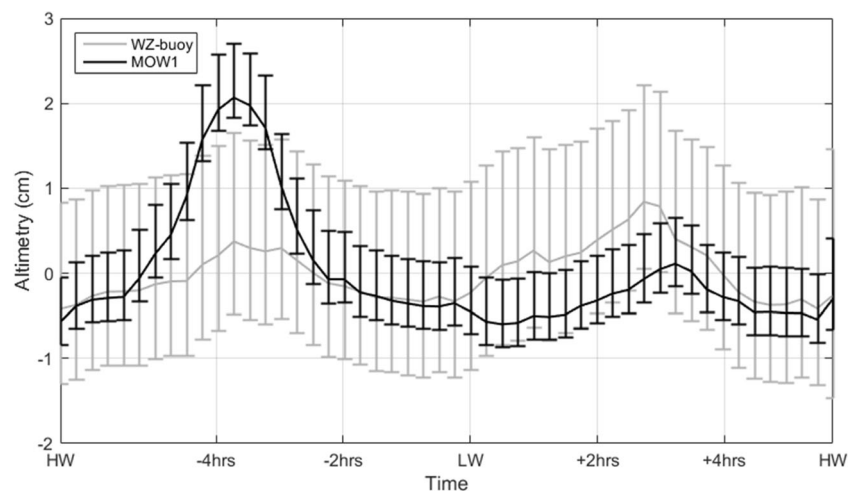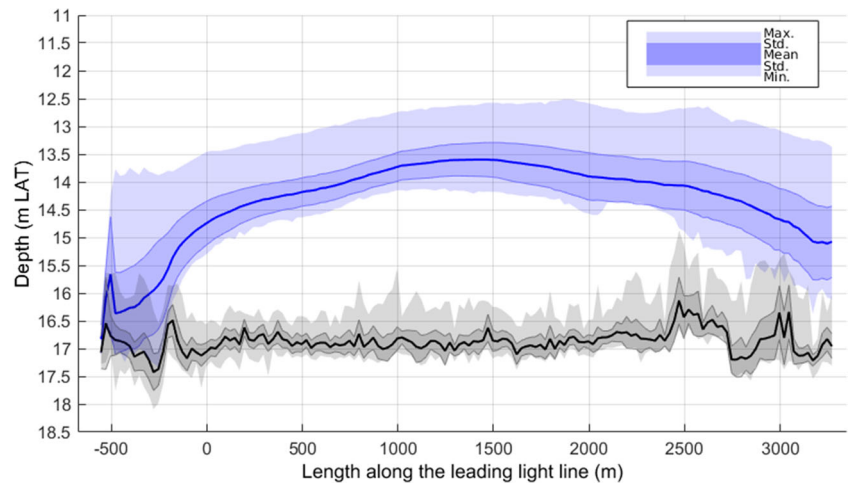
volume between the 210- and 33-kHz reflector has been calculated, based on both transects (leading light line and axis Albert II dock). In order to obtain a natural variability of the mud volume, the observed volume changes were corrected for the dredging works conducted during the period between two consecutive soundings (see Fig. 10). In winter, the mud volume is the largest; during spring and summer, the volume gradually decreases to reach a minimum at the beginning of autumn. This confirms what already was shown in Fig. 9 namely that the dome shape of the mud layer along the leading light line (Fig. 1) is more or less constant in time but moves up and down as a whole. Some differences in mud volume variation exist within the harbor, but all locations confirm that the thickness of the mud layer is higher in winter than in summer.

Figure 10 confirms generally that the increase of the mud volume is higher during spring tide than during neap tide, since more sediment is imported into the harbor. However, other variations (seasonal, storms) partially mask this neap-spring signal so that no statistical confirmation exist that the mud volume during or just after spring tide is higher than during neap tide.

4.3 SPM concentration during the field experiment

In order to take spring-neap cycles, seasonality and meteorology as much as possible into account, the evaluation of the field experiment was based on a 15-day period prior to the field experiment (T0: 06–20 October 2013), a 15-day period
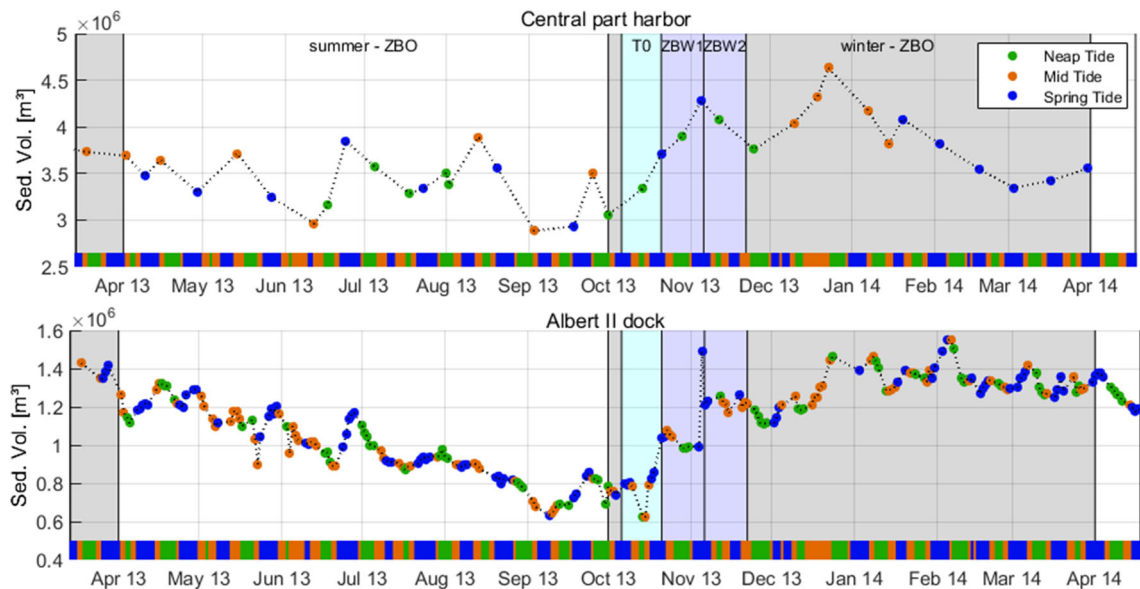
Fig. 10 Natural evolution of the mud volume in the central part of the harbor and in the Albert II dock. The volume changes are calculated from two weekly transects along the leading light line (see Fig. 1) and from daily transects along the axis of the Albert II dock and have been corrected for the dredging works conducted during the period between two consecutive soundings

Table 3   Subperiods used for (statistical) analysis

|	
Summer	April–September
Winter	January–March, October–December
Winter ZBO	Winter except 21 October 2013–21 November 2013
T0	6 October 2013–20 October 2013
ZBW	21 October 2013–21 November 2013
ZBW1	21 October 2013–05 November 2013
ZBW2	06 November 2013–21 November 2013
Winter 1	28 January 2013–13 February 2013
Winter 2	17 December 2013–31 December 2013
Winter 3	16 February 2014–03 March 2014
Summer 1	12–26 April 2013
Summer 2	25 June 2013–10 July 2013

during the winter 2013 (Winter 1) and the winter 2013 with disposal on ZBO (winter ZBO); the field experiment (ZBW) was divided in two 15-day period (ZBW1, ZBW2), see Figs. 3, 4, and 6 and Table 3. A comparison of the ensemble averaged SPM concentrations during these different periods as well as during winters of 2005–2012 is shown in Fig. 11 and Table 4 for the MOW1 station. Similar results have been found at the WZ buoy location for the ADP-derived SPM concentrations. The data indicate that the SPM concentration was higher during the 2013 winter with disposal on ZBO than during the previous winters. The data also show that the difference between T0 and ZBW1 is more pronounced during ebb and at the beginning of flood. The disposal site ZBO is situated in ebb direction of the measurement sites and the decrease in concentration is thus in line with expectations. Further, the ZBW2 period is more similar with the T0 than the ZBW1 period. The averaged values (Table 3) show that

variations in SPM concentrations due to waves, seasons, or disposal are more visible in the near-bed layer than higher up in the water column.

5 Discussion

The results based on time series measurements at two fixed location outside the port and 4 stations inside the port and on echo soundings and density measurements inside the port before, during and after the relocation of a disposal site did not indicate unambiguously that the relocation resulted in a decrease of the SPM concentration outside and a reduction of the siltation inside the port. The main reason for this is that the most important changes in SPM concentration at MOW1 are due to tidal range (70 % higher during spring than neap tide), waves (27 % at 0.2 mab and 24 % at 2 mab higher during high (>1.2 m) than low (<0.6 m) waves), seasons (30 % at 0.2 mab and 65 % at 2 mab higher in winter than summer) and residual alongshore flow (19 % at 0.2 mab and 25 % at 2 mab higher during SW-ward than NE-ward directed residual alongshore), see Table 1. The numerical model results suggest that after relocation of the disposal site to ZBW the tidal and vertical averaged SPM concentrations decrease from about 10 to 2 mg/l at MOW1 and from about 15 to 3 mg/l at WZ buoy (Van den Eynde and Fettweis 2014). As SPM concentration is not uniformly distributed in the water column, it is expected that the decrease at 2 mab is about a factor two larger (Fettweis and Nechad 2011). The effect of disposal at MOW1 as estimated by the model represents about 10 % of the tidal averaged SPM concentration at 2 mab and is thus lower than the variations caused by natural forcings. Due to the fact that the

Fig. 11 MOW1, ensemble-averaged OBS-derived SPM concentration at 2 and 0.2 mab during a tidal cycle for different periods in winter
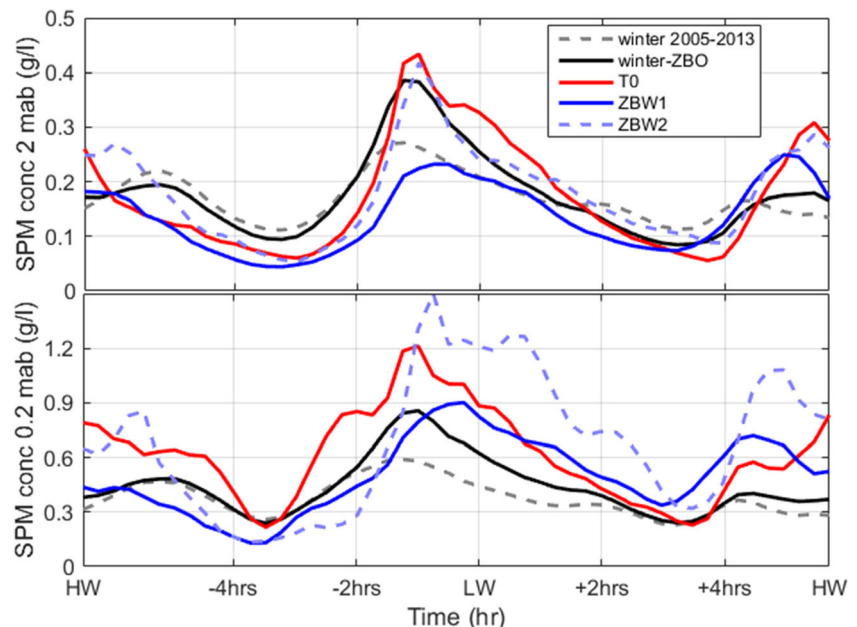
Table 4 Geometric mean and multiplicative standard deviation (multiplied divided: *) of the ADP and OBS-derived SPM concentration (mg/l) at MOW1 and of the ADP-derived one at WZ buoy at two heights above the bed and during different periods. The OBS derived SPM concentration at MOW1 is shown during low and high wave conditions

	ADP	OBS	OBS ($H_s < 0.6$ m)	OBS ($H_s > 1.2$ m)	ADP-WZ buoy
2 mab					
Summer	78*/1.71	85*/2.20	86*/2.29	102*/2.01	97*/2.13
Winter ZBO	91*/1.78	172*/2.23	176*/2.32	152*/1.93	141*/2.10
T0	74*/1.61	148*/2.09	149*/2.21	141*/1.88	150*/2.12
ZBW	70*/1.70	128*/2.08	129*/2.09	148*/1.94	149*/2.05
ZBW1	67*/1.76	117*/2.09	116*/2.00	146*/2.02	131*/2.04
ZBW2	73*/1.63	159*/1.98[1]	172*/1.86	155*/1.77	166*/2.02
0.2 mab					
Summer	504*/1.54	217*/2.54	199*/2.47	372*/2.72	856*/1.86
Winter ZBO	469*/1.62	410*/2.43	383*/2.48	430*/2.34	1161*/1.72
T0	496*/1.41	571*/2.26	477*/2.78	700*/2.06	1246*/1.71
ZBW	504*/1.61	462*/2.89	405*/3.11	623*/2.67	1213*/1.63
ZBW1	488*/1.72	426*/2.60	404*/2.86	275*/2.41	1106*/1.65
ZBW2	518*/1.50	555*/3.50	409*/3.80	748*/3.20	1307*/1.60

model is a simplification of reality these values should be interpreted as an estimate.

In order to detect these changes, the evaluation of the field experiment was based on statistical testing together with an analysis of the environmental conditions. The null hypotheses to be tested are: (1) the SPM concentration at the measuring locations outside the harbor is the same during the field experiment (ZBW) and during disposal as usual (T0, winter ZBO) and (2) the siltation in the harbor during the field experiment (ZBW) is the same as during disposal as usual (T0, winter ZBO). The evaluation of the null hypothesis is based on Wilcoxon's and Welch's tests (Motulsky 2014). The former one tests the null hypothesis that there are no differences in the populations and can be applied for non-normal distributed data and if the variable is measured before and after an intervention. The latter one is an adaptation of the one-sided t test and tests the hypothesis that two populations have equal means.

5.1 Statistical analysis outside the port

The evaluation of the first null hypothesis is based on Wilcoxon's test (see Table 5). The P values, which are the

Table 5 MOW1: Wilcoxon's test statistics (P value) between the OBS-derived SPM concentrations at 0.2 mab (2 mab) during different periods

	Winter ZBO	T0	ZBW1	ZBW2
T0	<0.01 (<0.01)	–	–	–
ZBW1	0.21 (<0.01)	<0.01 (<0.01)	–	–
ZBW2	<0.01 (<0.01)	0.03 (0.01)	<0.01 (<0.01)	–
Winter 1	0.61 (<0.01)	<0.01 (<0.01)	0.60 (<0.01)	<0.01 (<0.01)

probability of obtaining results equal or more extreme than what was actually observed, when the null hypothesis is true, indicate that the mean SPM concentration during winter ZBO and ZBW1 and winter ZBO and ZBW2 are—depending on the height of the OBS above the bed—not always statistically different, and therefore the null hypothesis fails partially to be rejected. Further, due to the fact that various forcings change SPM concentration, 15-day periods within the winter of 2013 can be found to have statistically different means than the winter ZBO (e.g., T0) although no change in disposal has occurred. Also 15-day periods with different disposal strategies have statistically similar mean SPM concentrations (e.g., Winter 1 and ZBW1). Another way of statistically looking at the data is to calculate the probability that the SPM concentration during a certain period is higher/lower than during another period. This was done by randomly sampling the population of SPM concentration during the selected periods and to compare the values. The results indicate that the probability of having a higher OBS-derived SPM concentration during the field experiment than during T0 is 45 % (ZBW1, 41 %; ZBW2, 53 %) at 0.2 mab and 44 % (ZBW1: 35 %; ZBW2: 53 %) at 2 mab. The probability distributions of the OBS-derived SPM concentrations are shown in Fig. 12. The geometric mean SPM concentrations are within one standard deviation of each other and illustrate that the natural variability of SPM concentration is higher than the human induced one at the measuring locations.

Statistical testing is based on the assumption that the sample is representative for the whole population. The large data set available at MOW1 (2005–2013) can be seen as a representative subsample of the whole population of SPM concentration with disposal on site ZBO. However, some doubts can be formulated, given the large variability due to random and

Fig. 12 Probability distribution of SPM concentration measured at MOW1 at 2 and 0.2 mab. The *black line* shows geometric mean SPM concentration for the winter data with disposal on ZBO. The *blue* and *red lines* are geometric mean SPM concentration for the T0 period and ZBW1 period, respectively. The *dashed lines* are the mean multiplied and divided respectively by one standard deviation. The higher probability around 1.5 g/l is due to saturation of the lower OBS
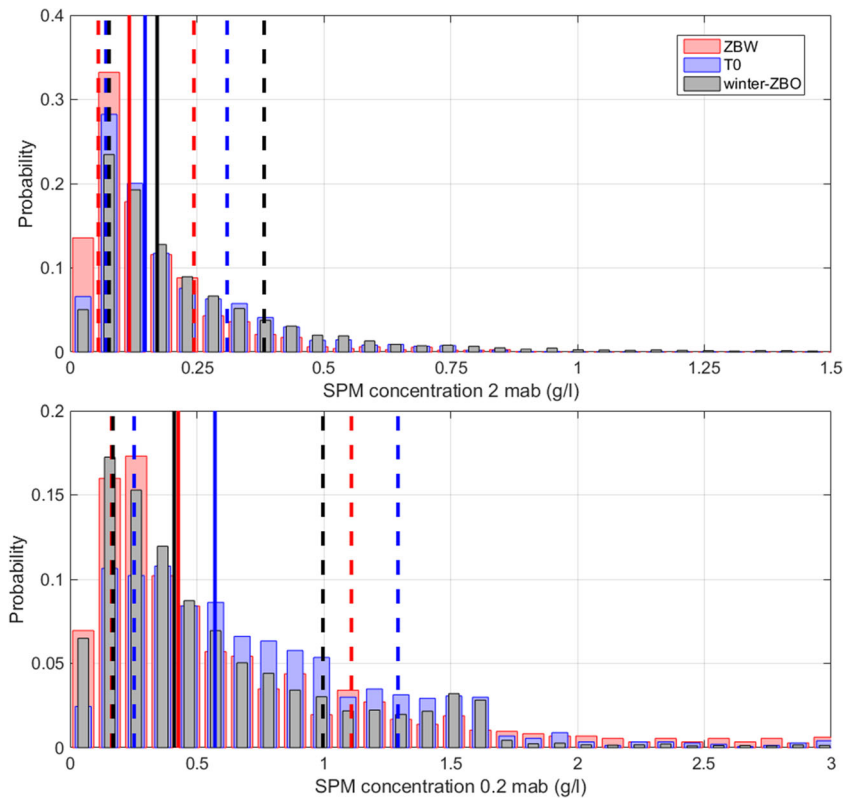
natural forcings, that the 1-month period with disposal on ZBW is a representative subsample. Further, statistical testing assumes that the samples are independent if they come from unrelated populations and the samples do not affect each other. These assumptions are not guaranteed within our experiment as it is not only the forcings that influence SPM concentrations but also the sediment availability that is depending on the previous history.

5.2 Environmental analysis outside the port

Because SPM dynamics are highly variable on a multitude of time scales, establishing a baseline framework for a particular location is only possible with repeated and continuous observations, e.g., multiple years of data are required to characterize the typical range in seasonal amplitude and timing of events

Table 6 Mean and standard deviation of wind velocity (m/s), residual alongshore current at MOW1 (U_a, negative is SW-ward, positive is NE-ward) and significant wave height (H_s) during different periods in 2013. Wind velocity and wave height are given as geometric mean and mutliplicative standard deviation (multiplied divided: */)

	Winter ZBO	T0	ZBW1	ZBW2
Wind (m/s)	7.8*/1.78	6.2*/2.52	11.2*/1.29	8.5*/1.63
U_a (cm/s)	−4.4 ± 7.1	−6.3 ± 8.1	+1.4 ± 13.4	−9.7 ± 4.3
H_s (m)	0.64*/1.91	0.65*/1.91	0.79*/1.79	0.79*/1.70

(Henson 2014). The argument to favor that the relocation of the disposal site has had a measurable effect on SPM concentration is held in the long-term data series that allowed quantifying the variability associated with the main forcing mechanisms (see Figs. 5 and 12; Table 1).

The field experiment (ZBW) was characterized by variable wind velocities from mainly W to SW direction. The wind velocities were higher during the field experiment than during the 2013 winter with disposal on ZBO. This resulted in strongly variable residual alongshore currents and a higher frequency of strong negative and positive residual alongshore currents and also higher significant wave heights than during the 2013 winter with disposal on ZBO (see Table 6). The OBS-derived SPM concentrations at 0.2 and 2 mab were during the first 15 days of the field experiment (ZBW1) lower in both stations outside the port than during T0. The mean in situ OBS-derived SPM concentration at MOW1 was about 140 mg/l at 0.2 mab and about 30 mg/l at 2 mab lower during ZBW1 than during T0. This equals a reduction of the averaged SPM concentration by 20 % during ZBW1, which is larger than the model results. The effects during ZBW2 were lower (−15 mg/l at 0.2 mab and +30 mg/l at 2 mab), and correspond with a reduction by about 8 % (0.2 mab) and an increase by about 7 % (2 mab) as compared with T0, which is thus less than predicted by the model. The different results for ZBW1 and ZBW2 were triggered by the occurrence of two storm periods with high waves during ZBW2 and by the differences in residual

alongshore currents (ZBW1: U_a = +1.4 cm/s; ZBW2: U_a = −9.7 cm/s), see Table 6. If we consider only data measured during low wave activity (H_s < 0.6 m) then the 0.2 mab OBS-derived SPM concentration at MOW1 during ZBW1 (ZBW2) is about 40 % (15 %) lower than during T0 (Table 4). Same results at 2 mab are not conclusive as wave influences are mainly concentrated in the near-bed layer and thus other forcings (tidal range) dominate more the signal at 2 mab (Fettweis and Baeye 2015). The positive (NE-ward directed) residual alongshore currents during ZBW1 explain the larger decrease in SPM concentration during ZBW1 than during ZBW2, when SW-ward directed residual alongshore currents were prevailing.

The results from the LISST-derived SPM volume concentration at MOW1 during different periods support those of the OBS but are more pronounced. The mean ADP-derived SPM concentration during ZBW1 indicate a decrease of about 2 % at MOW1 and 10 % at WZ buoy as compared with the T0 period. The differences are thus less pronounced and are probably caused by the higher uncertainty in the ADP than the OBS-derived data, due to the fact that the model is a simplification of reality and that the echo intensity of the backscattered acoustic signal gives a good indication of SPM concentration variation if the particle size distribution and characteristics remain the same (Thorne and Hurther 2014; Rai and Kumar 2015). This is not the case for tidal environments where fine-grained sediments are subject to flocculation and where cohesive and non-cohesive sediments can both be in suspension (Baeye et al. 2011; Fettweis et al. 2012a; Ha et al. 2011). The different sensitivity of acoustic and optic sensors to changes in the SPM particle size and characteristic and the higher uncertainty of the acoustic-derived SPM concentration is reflected in the low correlation coefficient (R^2 = 0.53) between the ADP backscatter (dB) and the OBS-derived SPM concentration. The measured changes in the SPM concentration derived from solely the ADP are thus below the estimated accuracy and are hence not statistically meaningful. The results of all sensors are, however, in line with the fact that the positive (NE-ward directed) residual alongshore flow was responsible for the lower SPM concentration during ZBW1 than T0, and that the higher waves together with a stronger negative residual alongshore flow were responsible for the almost similar SPM concentration during ZBW2 and T0.

5.3 Analysis of SPM concentration and thickness of the mud layer inside the port

All measurement locations inside the harbor show increasing SPM concentrations for T0 over ZBW1 to ZBW2 (Table 7). A t test for non-normal distributions (Wilcoxon's test) was used to investigate whether these increases are statistically significant at a 95 % confidence level. The null hypothesis of this test is that the mean values of the populations are identical. In addition, a Welch test (one-sided t test) was used to calculate the confidence interval around the difference between the mean of the populations (Welsh difference) at the same confidence level as the Wilcoxon test.

Seven 15-day periods were investigated: T0, ZBW1, ZBW2, and two periods with comparable meteorological conditions as ZBW1 and ZBW2, both in summer (summer 1, summer 2) and winter (winter 2, winter 3; see Table 3). Under equal meteorological circumstances, one would expect SPM concentrations to rise from summer conditions, over T0 to winter conditions. Due to the use of an alternative disposal site, SPM concentrations during ZBW1 and ZBW2 should be lower or at least should not rise as much as between T0 and typical winter conditions. The tests show low P values results for most locations, indicating that the mean SPM values are significantly different (Table 8). In contrast to what was expected, especially when comparing the first half of the experiment, the mean of the summer population is only slightly lower or even higher (summer 1) than the mean of the T0 period. This could indicate that meteorological influences are as important as seasonal variation. For the other populations a steady increase of mean SPM concentrations can be observed for T0 over ZBW1 and ZBW2 to similar winter conditions. Only for the location LNG Upper it can be proved that the mean SPM concentration during the experiment was at least 1.7 mg/l lower than during T0 and 17.4 mg/l lower than during winter. For most other locations, the increase in mean SPM concentration from ZBW1 and ZBW2 to similar winter conditions is of the same order of magnitude as the increase from T0 to winter conditions. This gives the impression that the field experiment caused a (relative) decrease of SPM concentrations inside the harbor. However, the statistical tests are not conclusive, because of the large spread on the confidence intervals. Meteorological and seasonal differences probably have a bigger influence on the observed SPM concentrations inside the harbor than the use of an alternative disposal site.

Table 7 Geometric mean and multiplicative standard deviation (multiplied divided: */) of the SPM concentration (mg/l) at the four measurement locations inside the harbor at two heights above the bed and during different periods

	Sterneneiland		AII dock		LNG		Hermespier	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
T0	No data	62.0/*1.8	49.0/*1.8	80.1/*2.3	35.4/*1.4	47.1/*1.5	38.8/*1.6	54.0/*1.7
ZBW1	No data	75.4/*1.7	51.8/*1.6	No data	34.6/*1.3	No data	48.6/*1.4	68.7/*2.1
ZBW2	57.1/*1.5	77.3/*1.5	57.3/*1.7	No data	49.9/*1.6	No data	No data	104.7/*2.6

Table 8 Wilcoxon's and Welch's test statistics for SPM concentration measurements inside the harbor and for different periods (infinity (imf))

	Sternenland		AII dock		LNG		Hermespier	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Summer 1—T0								
Wilcoxon P	No data	<0.05	<0.05	0.09	<0.05	0.64	<0.05	<0.05
Welch P	No data	<0.05	<0.05	<0.05	0.07	0.35	<0.05	0.15
Welch diff (mg/l)	No data	$32.9 < \Delta x < \mathrm{Inf}$	$-\mathrm{Inf} < \Delta x < -0.2$	$-\mathrm{Inf} < \Delta x < -14.6$	$-0.2 < \Delta x < \mathrm{Inf}$	$-2.5 < \Delta x < \mathrm{Inf}$	$16.2 < \Delta x < \mathrm{Inf}$	$-\mathrm{Inf} < \Delta x < 3.3$
T0—ZBW1								
Wilcoxon P	No data	<0.05	<0.05	No data	0.12	0.12	<0.05	<0.05
Welch P	No data	<0.05	0.21	no data	<0.05	0.12	<0.05	<0.05
Welch diff (mg/l)	No data	$-\mathrm{Inf} < \Delta x < -8.5$	$-1.4 < \Delta x < \mathrm{Inf}$	No data	$1.7 < \Delta x < \mathrm{Inf}$	$-\mathrm{Inf} < \Delta x < 1.2$	$-\mathrm{Inf} < \Delta x < -7.0$	$-\mathrm{Inf} < \Delta x < -35.7$
ZBW1—winter 2								
Wilcoxon P	No data	<0.05	<0.05	No data	<0.05	<0.05	<0.05	<0.05
Welch P	No data	0.36	<0.05	No data	<0.05	<0.05	<0.05	<0.05
Welch diff (mg/l)	No data	$-4.7 < \Delta x < \mathrm{Inf}$	$-\mathrm{Inf} < \Delta x < -23.0$	No data	$-\mathrm{Inf} < \Delta x < -17.4$	$-\mathrm{Inf} < \Delta x < -30.2$	$-\mathrm{Inf} < \Delta x < -34.4$	$-\mathrm{Inf} < \Delta x < -12.9$
T0—winter 2								
Wilcoxon P	No data	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Welch P	No data	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Welch diff (mg/l)	No data	$-\mathrm{Inf} < \Delta x < -8.2$	$-\mathrm{Inf} < \Delta x < -21.5$	$-\mathrm{Inf} < \Delta x < -99.9$	$-\mathrm{Inf} < \Delta x < -13.9$	$-\mathrm{Inf} < \Delta x < -33.5$	$-\mathrm{Inf} < \Delta x < -42.9$	$-\mathrm{Inf} < \Delta x < -63.5$
Summer 2—T0								
Wilcoxon P	No data	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Welch P	No data	0.32	<0.05	<0.05	<0.05	0.34	<0.05	<0.05
Welch diff (mg/l)	No data	$-\mathrm{Inf} < \Delta x < 2.9$	$-\mathrm{Inf} < \Delta x < -3.4$	$-\mathrm{Inf} < \Delta x < -9.9$	$-\mathrm{Inf} < \Delta x < -18.9$	$-\mathrm{Inf} < \Delta x < 3.7$	$-\mathrm{Inf} < \Delta x < -9.9$	$-\mathrm{Inf} < \Delta x < -3.5$
T0—ZBW2								
Wilcoxon P	No data	<0.05	<0.05	No data	<0.05	No data	<0.05	<0.05
Welch P	No data	0.07	<0.05	No data	<0.05	No data	<0.05	<0.05
Welch diff (mg/l)	No data	$-\mathrm{Inf} < \Delta x < 0.5$	$-\mathrm{Inf} < \Delta x < -5.2$	No data	$-\mathrm{Inf} < \Delta x < -15.3$	No data	$-\mathrm{Inf} < \Delta x < -10.4$	$-\mathrm{Inf} < \Delta x < -110.7$
ZBW2—winter 3								
Wilcoxon P	<0.05	<0.05	<0.05	No data	No data	No data	<0.05	<0.05
Welch P	<0.05	<0.05	<0.05	No data	No data	No data	<0.05	<0.05
Welch diff (mg/l)	$-\mathrm{Inf} < \Delta x < -36.6$	$-\mathrm{Inf} < \Delta x < -38.6$	$-\mathrm{Inf} < \Delta x < -8.1$	No data	No data	No data	$-\mathrm{Inf} < \Delta x < -35.7$	$21.5 < \Delta x < \mathrm{Inf}$
T0—winter 3								
Wilcoxon P	No data	<0.05	<0.05	No data	No data	<0.05	<0.05	<0.05
Welch P	No data	<0.05	<0.05	No data	No data	<0.05	<0.05	<0.05
Welch diff (mg/l)	No data	$-\mathrm{Inf} < \Delta x < -42.8$	$-\mathrm{Inf} < \Delta x < -16.5$	No data	No data	$-\mathrm{Inf} < \Delta x < -2.2$	$-\mathrm{Inf} < \Delta x < -50.9$	$-\mathrm{Inf} < \Delta x < -60.5$

Fig. 13 Mud volume in the central part of the harbor and in the Albert II dock (see Fig. 1) during different periods (see Table 3). The mud volume has been calculated from the differences between the 33- and 210-kHz echo soundings
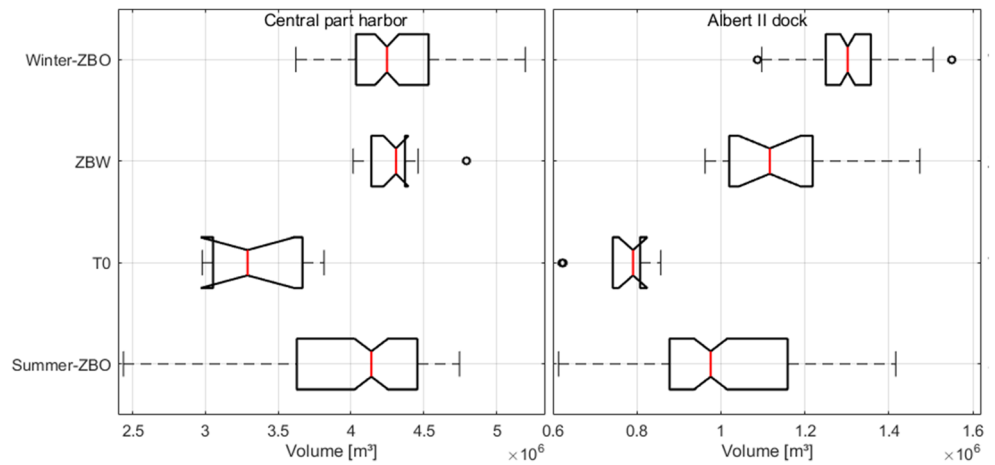
Figure 13 shows that the mud volume in the harbor (defined as the difference between the 33- and 210-kHz echo soundings) during the T0 period was exceptionally low. This could provoke higher sedimentation rates during the period thereafter (ZBW1). The distribution of the mud volume changes per day in the Albert II dock is shown in Fig. 14 for different periods with respect to the mud volumes during periods ZBW1 and ZBW2. The figure shows that no significant increase was seen in the rates of mud volume accretion during the first half of the field experiment. During the second half of the experiment (ZBW2) even a slight (although statistically not significant) decrease can be observed in the Albert II dock, which could point to a lower sedimentation in the harbor of Zeebruges due to the relocation of the disposal site.

6 Conclusion

The use of optical and acoustical sensors to detect changes in SPM concentration has enhanced system understanding of the present state and helped in estimating the direction of changes induced by the relocation of a disposal site. The use of different sensors (optical, acoustical backscatter) has also revealed the big differences in outcome that are a consequence of the fact that measurements are inherently associated with uncertainties. Positive is that the different sensors show the same trends, but the uncertainties due to the sensors itself are not fully quantified. The latter is especially relevant for the acoustic backscatter sensors, where more research is needed to develop well defined methodologies to invert backscattered signal to SPM concentration values in cohesive sediment environments (Rai and Kumar 2015).

The big issue for this and most other monitoring programs of SPM concentration and harbor siltation is to differentiate between anthropogenic impact and natural variations. The field experiment is somewhat different because the normal situation includes the human impact. The 1-month experiment, with relocation of the disposal site and reduction of the effects of disposal on the SPM concentration at the measuring locations, provides thus a glimpse on a more natural situation. Nevertheless, the method to assess the impact of the cessation of disposal or of the disposal on coastal ecosystem

Fig. 14 Mud volume changes in the Albert II dock (m³/day) during the first (*left*) and second parts (*right*) of the field experiment as compared with other periods
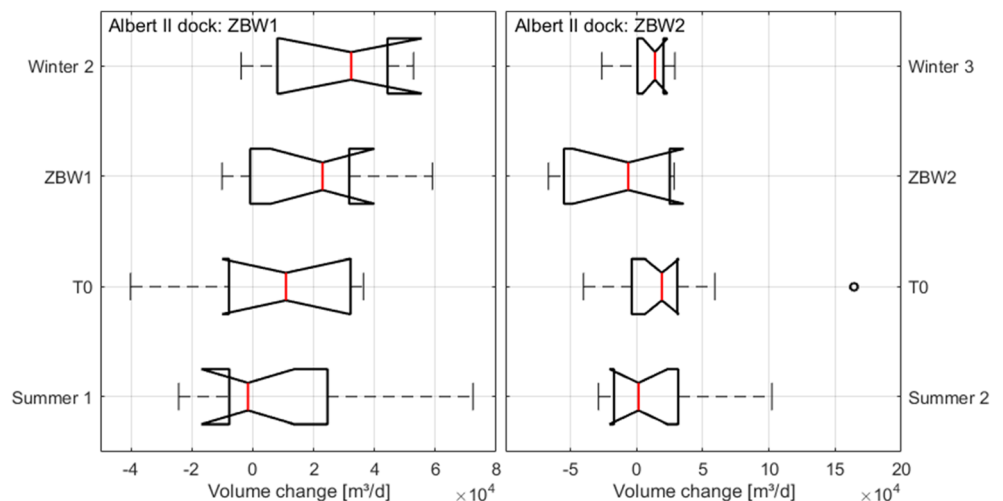
and on harbor siltation is the same and is based on the understanding of the variability of the major processes that modulate the SPM concentration outside and the fluid mud layer inside the port. This can only be achieved when long-term time series exist that encompass to a certain degree also spatial variability. Quantifying the variability of SPM concentration is crucial to elucidate the processes that have an influence (tides, tidal range, alongshore flow, waves, seasons), to understand the typical range of the variability, and to identify anomalous natural or human induced events.

In the high-turbidity Belgian near-shore area, the natural forcings are responsible for the major variability in the SPM concentration signal, while disposal has only a smaller influence. The mean SPM concentrations at MOW1 is about 10 % higher when the dredged matter is disposed at ZBO site; this represents a probability of 55 % to have higher SPM concentration than using the alternative (ZBW). The results emphasize that tidal range, random events and seasons have a stronger influence on the SPM concentration signal than the relocation of the disposal site. The conclusion from the measurements is that the SPM concentration decreases after relocation of the disposal site, but indicate stronger (first half of field experiment) or weaker (second half of field experiment) effects that are, however, supported by the environmental conditions. Inside the harbor, the influence of relocation of the disposal site on SPM concentration and mud volumes is even more attenuated by seasonal and random effects. As a consequence, a statistical significant difference in SPM concentration or mud volume inside the harbor could not be found. The statistical tests also revealed that the duration of the field experiment was too short (1 month) to separate the effect of the relocation of the disposal site from the data with clear statistical significance.

Decision-makers should be aware that typical monitoring programs that follow the classical time-limited "before/after and during" approach, with a relatively short "during" period, will very often not provide unambiguous conclusions, but rather conclusions that indicate a probability of the (environmental) impact. In other words our results indicate that on the long run and with the assumptions that the forcings as well as the geometry and bathymetry of the port will not change, a reduction of the dredging volumes is to be expected when disposal site ZBW will be in use. The results of the field study may have consequences on the management of disposal operations as the effectiveness of the disposal site depends on environmental conditions, which are inherently associated with chaotic behavior. Changes in hydrodynamics, e.g., that are induced by changes in weather types, influence the direction of the residual currents and thus also of the residual SPM transport. A disposal site that is efficient during most of the time may induce recirculation of the disposed matter back to the dredging places during other weather types. Disposal strategies should therefore allocate sites in a flexible way based on short-term predictions of environmental conditions and sediment dynamics. Developments in line with a flexible disposal strategy should encompass the recalibration and validation of the numerical model in order to obtain results over long periods of time that show the optimal use of disposal sites for forecasted weather conditions.

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