Sediment resuspension during vessel manoeuvres in port areas: evidence from field observations

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Abstract

Purpose The increase in maritime traffic in the Bay of Koper (Gulf of Trieste, northern Adriatic Sea) has been made possible given the increase in the local port capacity and logistics, which, in turn, means an increase in the number of arrivals of larger vessels (which were the original motive for port expansion); this poses a potential risk for coastal environments due to the impact of the resuspension of bottom sediment which affects the physical and chemical characteristics of the water column. The aim of this work was to assess the magnitude of these perturbative events.

Materials and methods Turbidity (NTU) measurements were made using a CTD multiprobe during a vessel manoeuvre in the port navigational canal and in the entire Bay of Koper. In the highest turbidity zone, samples were collected from the surface water layer (0.5 m), at a depth of 6.0 m and 12.0 m. Total suspended solids (TSS) and suspended organic matter (SOM) were measured gravimetrically. TSS grain-size distribution was determined using a laser granulometer.

Results and discussion The effect of the vessel manoeuvre was evident on turbidity with a maximum value of 137 NTU (TSS = ~ 139 mg l^{-1}) and a sampled concentration of TSS of 37 mg l^{-1} (bottom layer) in the water column immediately after the ship manoeuvre. Grain-size analysis shows a spectrum of particles with a mode size between 22 and 88 µm (medium silt and very fine sand, respectively). The estimated resuspension mass of total suspended solids (TSS) was ~ 109 t in the restricted manoeuvre area extending about ~ 736 × 493 m and with an average depth of 15 m.

Conclusions The results demonstrated the significant impact of vessel manoeuvres on the measured parameters, the impact of which cannot be underestimated in terms of marine environmental protection and maritime traffic safety. Moreover, this impact is expected to increase in the near future.

Keywords Vessel manoeuvre · Turbidity · Total suspended solids · Suspended organic matter · Sediment resuspension · Northern Adriatic Sea · Bay of Koper

1 Introduction

Over the last few decades, there has been a rapid increase in the number of large vessel arrivals in ports where dredging operations periodically occur in the navigational canals which connect the deepest offshore areas with the port berth in the shallow basins. Panamax and postpanamax vessel (draught of mean 15 m) arrivals have consequentially amplified the negative impact on the marine environment. Various studies (Kelpšaitė et al. 2009; Kelpšaitė and Soomere 2009; Erm et al. 2011; Pindsoo et al. 2014) have assessed the deleterious aspects of marine traffic, which can be a potential source of pollution through, for instance, accidental oil spills, which have negative consequences for the marine environment (Lipej et al. 2006; Gabel et al. 2017).

Previous investigations in the Bay of Koper (Gulf of Trieste, northern Adriatic Sea; Fig. 1) have indicated that this impact is notable (Malačič et al. 2014). However, previous studies have omitted the potential risk of specific vessel manoeuvres. Among these, we consider vessels' changing directions with the help of tugs during the berthing process. The effects of this manoeuvre are easily observed in the uppermost layer (surface) of the water column. Increased

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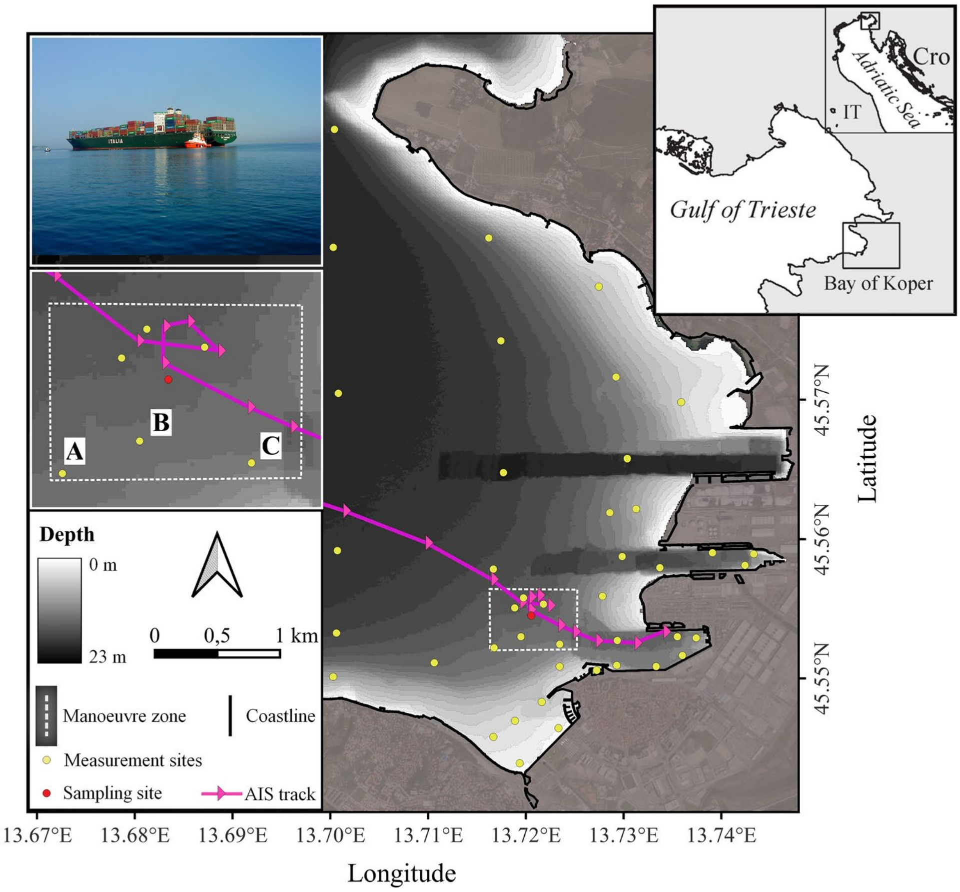

Fig. 1 The Bay of Koper is situated in the Gulf of Trieste (northern Adriatic Sea). The yellow dots mark the measurement sites (38), and the dashed line indicates the vessel manoeuvre zone (4 measurements and 1 sampling point—red). The S dot marks the sampling site where the discrete samples were taken at three depths: 0.5, 6.0 and 12.0 m. The square depicts the manoeuvre zone in the first port canal and the area used for TSS mass calculation

turbidity is a consequence of the resuspension of a considerable amount of sediment from the seabed to the surface layer due to the turbulence caused by the vessel propellers. Moreover, a vessel with minimum bed clearance during the manoeuvre at near maximum power generated by the propeller determines the acceleration of the water, which flows and erodes the seabed, thus damaging the benthic community in the much the same way as it causes damage to underwater structures. An estimation of the velocity which affects the seabed accounts for an excess of 8 m s^{-1} as reported by Hamill et al. (2001).

Increased turbidity can also result in low light penetration, vital not only for marine vegetation but also for the benthic community (Wolter and Arlinghaus 2003; Kucera-Herzinger et al. 2009). Resuspended particles can be transported and eventually deposited on the macro-/microphytes and can again destabilise the benthos (Wolanski 2007; Jones 2011). The contaminants previously accumulated in the sediments and involved in resuspension (Pavoni et al. 2021) can be transported far enough by coastal currents to ultimately enter the food chain. Strong turbulence at the bottom of the water column can not only erode the seabed but also cause the collapse of canal walls (Houser 2010). Suspended sediments can gradually be settled and accumulate, leading to modification of the morphobathymetry and in extreme cases reducing navigational safety (Guarnieri et al. 2021).

The impact of vessel manoeuvres in the studied area affects the entire water column and results in a high concentration of resuspended TSS (above 100 mg l^{-1}) at the surface layer (0.5 m depth). To verify this hypothesis, the present study is aimed at (1) assessing the spatial distribution of the TSS concentration after conducting turn manoeuvre assisted by tugs in three selected episodes, (2) analysing the distribution of TSS concentration and related grain-size spectra along the water column and (3) evaluating the total amount of TSS induced by the resuspension caused by the manoeuvre.

The expected results are important as they would provide the basis for further studies including the modelling of sediment resuspension. In addition, knowledge regarding the impact of frequent vessel manoeuvres is fundamental in order to assess potential damage to the canal walls or the port infrastructure, as well as the coastal marine environment in the Bay of Koper.

2 Materials and methods

2.1 Site description

The Bay of Koper (Slovenia) occupies the SE part of the Gulf of Trieste, located in the northern Adriatic Sea, and is defined as a large, open bay with the deepest point being 23 m in the western open part (Malačič et al. 2014). The tidal range is ± 0.6 m and the circulation is mainly affected by meteorological and river discharge forcing (Malačič et al. 2014; Soczka Mandac 2014). The coast is densely populated, which results in significant inputs of organic and inorganic contaminants (Turk and Potočnik 2001; Turk et al. 2013). The main source of contamination is attributed to port activities (located in the western part) and to inflow from the Rižana River (Orlando Bonaca et al. 2008). The supply of riverine material into the Bay of Koper is mainly attributed to the Rižana River (Ogorelec et al. 1987; Faganeli and Turk 1989; Soczka Mandac and Faganeli 2015), whereas secondary inputs are provided by the Badaševica stream (Soczka Mandac et al. 2014). Local media and scientific reports (Malačič 1993; Malačič et al. 2014) indicate that contaminants are deposited on the seabed.

2.2 Measurements

The survey was performed on 25th July 2013 with a launch (8 m long) in the Bay of Koper at 38 measurement sites. Additional four measurements were taken at one sampling site in the first basin canal (marked S) at the location (Fig. 1) where the turning manoeuvres of the container vessel Ital Universo (IMO: 9,196,993) (Marine Traffic 2017) were executed with two tugs. The survey area of 5600 × 4030 m was restricted to the bay and to the manoeuvre zone at a width of 740 × 500 m and a depth of 15 m in the first of the three canals belonging the port of Koper (Fig. 1). The turbidity was profiled along with conductivity, temperature and depth using a CTD multiprobe (Hydrolab Datasonde model 4a) with an optical turbidity sensor (ISO 7027 compliant), which measures the light backscatters at a wavelength of 860 nm ± 10 nm (Hydrolab corporation 1998). An optical turbidity sensor was calibrated between 0 and 400 NTU. The CTD multiprobe was manually lowered from the water surface to the seabed, recording temperature, conductivity and turbidity at the rate of 1 Hz.

Discrete water samples for the determination of total suspended solids (TSS) were simultaneously collected at three selected depths of 0.5, 6.0 and 12.0 m from the sampling site (marked with S) in the area where the vessel manoeuvres took place (Fig. 1) using a 5-l Niskin bottle sampler. The water subsamples (1 l) were immediately transferred to polyethylene bottles, stored in a portable fridge and filtered within 4 h in a laboratory. One litre of water subsample was filtered through a pre-weighed Whatman GF/F glass-fibre filter (47 mm diameter, 0.7-µm pore size) pre-ignited at 480 °C for 3 h (Strickland and Parsons 1972). Filters with particles were washed several times with Milli-Q water to remove salts and oven-dried at 60 °C (Aurodent typ 830 nf). Filters were frozen after the net weight (TSS) was recorded. For suspended organic matter (SOM) determinations, the filters were successively ignited in an oven at 480 °C for 4 h and weighed. The difference between the TSS quantity and the residue after ignition was considered to be SOM.

The regression model (1) between turbidity and total suspended solids explained in detail in a previous publication (Soczka Mandac and Faganeli 2015) was adopted to estimate the TSS concentration from the turbidity data. The model was obtained from the analysis of measurements and sampling data from the Bay of Koper and local rivers.

$$\mathrm{TSS}\ (\mathrm{mg\ l^{-1}}) = 1.01\ (\mathrm{NTU}) + 0.91 \tag{1}$$

An additional 1-l water subsample from each sampling depth (0.5, 6.0 and 12.0 m at sampling site S) was filtered using Millipore HA filters (diameter 47 mm, 0.45-µm pore size) for particle size analysis of the TSS. The TSS collected was resuspended in distilled water (Turritto et al. 2018) and subsequently analysed using a Malvern Mastersizer 2000 laser granulometer, in accordance with Grangeon et al. (2012).

The profiles of TSS concentrations were averaged (1.0 m) and on each layer, spatially interpolated using cubic splines (Matlab 2015). Previous optimal analysis (Diva Matlab 2014) was tested for spatial interpolation, which is widely used in oceanography. The results of the optimal analysis show various artefacts in spatial distribution; the cubic spline interpolation method was used in this case.

A spatial survey in the Bay of Koper was initially performed at two measurement sites (A and B) and at measurement site C in order to verify the possible presence of suspended particles in the water column prior to the vessel manoeuvre; sampling took place at the remaining sampling sites after the manoeuvre. The average turbidity at sampling site A along the whole water column (~ 12.0 m) was 1.2 NTU, due to the low concentration of suspended solids. From this evidence, we assumed that no sediment resuspension had occurred and, consequently, no samples were collected at this point. Measurement sites B and C were excluded from further analysis.

Measurements at four sites in the manoeuvre zone were conducted 3 min after the tugs disengaged and left the manoeuvre area. Three turbidity profiles were recorded:

at the eastern, southern and western sides of the quadrant (Fig. 1), respectively, whereas a fourth was accomplished in the northern part. The fourth profiling included sampling at the three selected depths (Fig. 1 sampling point *S*). During the prolonged measuring periods, a Niskin bottle was lowered to the measuring depth and 5 l of water samples was collected.

3 Results

In the entire Bay of Koper, the TSS values calculated from the mean turbidity values in the surface layer (0.5 m) varied from ~ 1 to 5 mg l^{-1}. The spatial interpolation of the TSS concentration values in the entire bay and manoeuvre zone (Fig. 2) demonstrated that slightly high TSS values could be observed in the coastal sector at the western and southern sides of the bay, as well as in the port area (TSS = ~ 10 mg l^{-1}). Conversely, in the manoeuvre zone, the TSS concentration profiles were notably higher than in the rest of the bay, ranging from ~ 1 to 37 mg l^{-1}, in the surface layer, i.e. 0.5 m (Fig. 2). High concentrations of TSS in the surface layer were due to the high velocities that resuspend sediment particles from the seabed along the ~ 13.0-m depth of the water column upwards to the sea surface.

The water column profiles (Fig. 3) showed turbidity values in the entire bay ranging from ~ 0 to 137 NTU. The turbidity mean value at the four measurement and sampling sites were 10.6 ± 14.5 NTU (maximum 30.4 NTU) in the surface layer (0.5 m), whereas it reached 21.6 ± 17.8 NTU and 19.5 ± 15.5 NTU at 6 m and 12.0 m, respectively. The mean turbidity value of four profiles accounted for 18 ± 7.2 NTU and was highly variable in the entire water column. The high variability was also observed at the three sampling depths at sampling point *S* (Fig. 1): turbidity fell within a range from ~ 0 to 137 NTU (0.5 m), from 6.5 to 94.1 NTU (6 m) and from 1.5 to 40 NTU (12 m). Higher turbidity values (~ 80 NTU) were observed at a depth of ~ 13 m (Sampling profile, Fig. 3).

Considering the turbidity profiles, the calculated concentrations of TSS in the water column varied from ~ 1 to ~ 139 mg l^{-1}. The average TSS concentration of the four profiles in the manoeuvring zone (Fig. 1) was ~ 20 mg l^{-1} (Fig. 2) taking into account the entire water column, from 0.5 to 13 m. The highly variable turbidity values were determined by the strong currents and eddies caused by the three

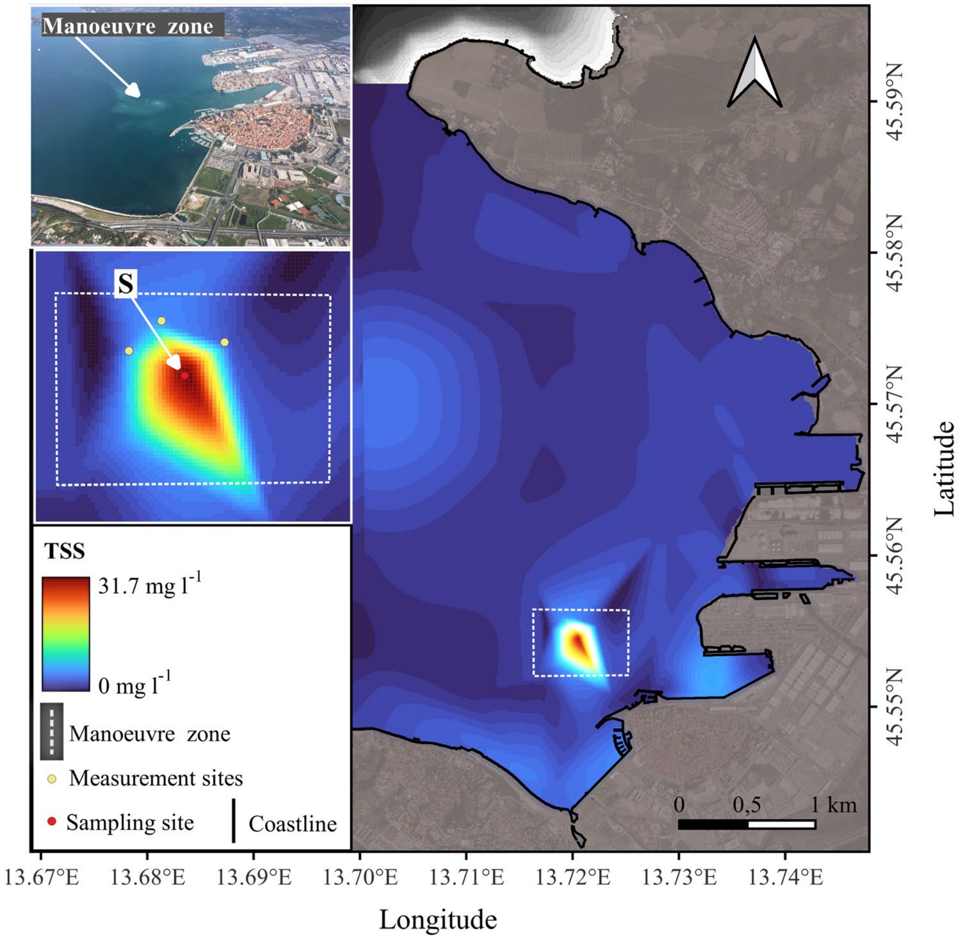

Fig. 2 Spatial distribution of TSS concentrations in the bay. The rectangle in the navigation canal limits the manoeuvre zone. The top left photo is an example of the effect of the manoeuvre at the studied site. The left square shows the detail of the vessel manoeuvre zone and a high TSS concentration of 31.7 mg l^{-1} after the vessel manoeuvre

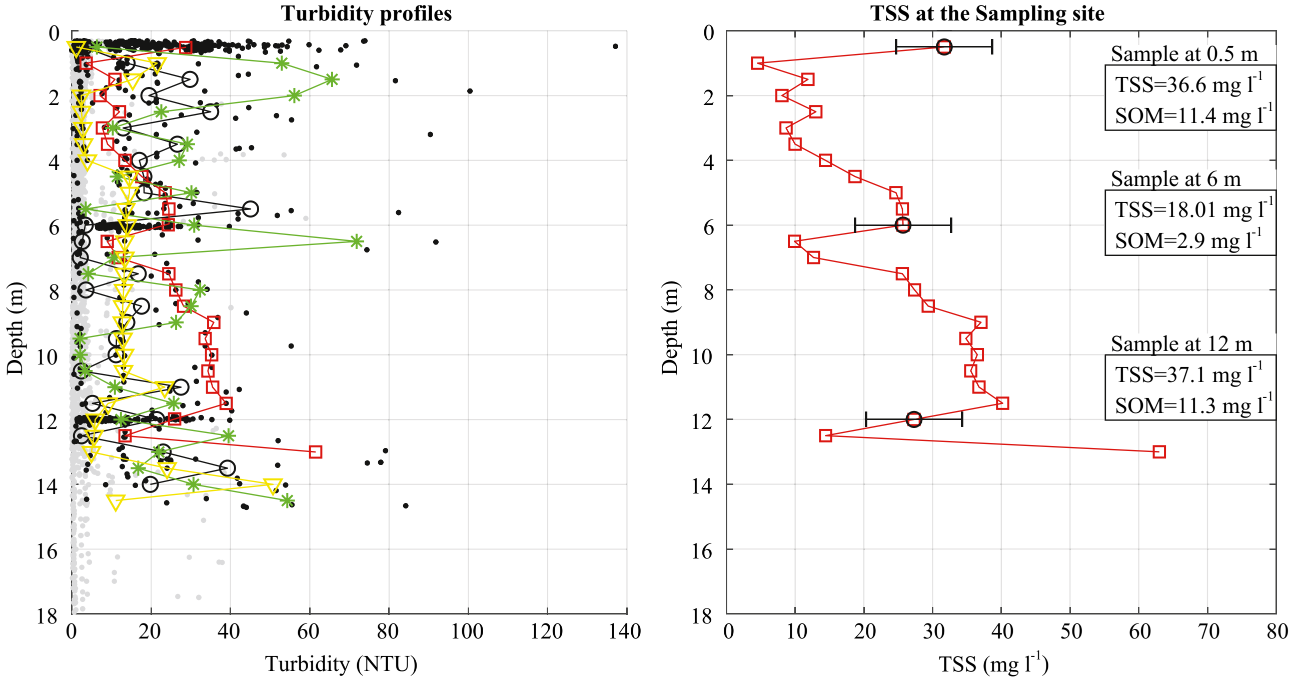

Fig. 3 The graph on the left represents turbidity profiles at the manoeuvre zone and all turbidity measurements in the bay (grey dots) and at the manoeuvre zone (black dots). The four lines show the mean turbidity profiles at 0.5 ± 0.1 m intervals in the manoeuvre zone. TSS concentration profile (redline with squares) at sampling point *S* in the manoeuvre zone is calculated from the turbidity (NTU) measurements and presented values at the three sampling depths (black error dots). The mean concentration of TSS in the surface (0.5 m) layer is 31.7 mg l^{-1} (STD = 14.9, *n* = 365) and 25.7 mg l^{-1} (STD = 14.6, *n* = 272) at 6.0 m and 27.3 mg l^{-1} (STD = 13, *n* = 194) in the bottom layer (12.0 m). The TSS values in the right boxes show concentrations of the discrete samples at the three sampling depths

steering vessels involved in the manoeuvre. A possible explanation for the highest turbidity values recorded could be the production of bubbles (cavitation air). In order to minimise this effect, turbidity values above 400 NTU (*n* = 15) were henceforth excluded from the data.

The TSS values calculated from the turbidity values at the sampling point (Fig. 3) and those obtained from the water sample concentrations (Fig. 3) in the surface layer showed a positive correlation. The difference between the two sets of values revealed that the concentrations in the collected water samples were, respectively, ~ 5 mg l^{-1} higher (surface layer), ~ 7 mg l^{-1} lower (6.0 m) and ~ 11 mg l^{-1} higher than the concentrations extrapolated from the corresponding NTU values. More significant discrepancies between the TSS values from turbidity measurements (Fig. 3) and the actual TSS concentrations were found at 6.0 m (~ 7 mg l^{-1}) and at 12.0 m (~ 11 mg l^{-1}). Such discrepancies may be attributed to the turbidity fluctuations in the layers and false turbidity reading (Hydrolab corporation 1998).

Very similar grain-size spectra (Fig. 4) were obtained for the surface (0.5 m) and mid-depth (6.0 m) samples consisting predominantly of silt (76.0 and 77.2%, respectively) and by sand (17.7 and 16.4%, respectively) and clay (6.4% in both samples). Conversely, the grain-size distribution in the deepest TSS sample (12.0 m) showed the highest content of sand (54.1%) followed by silt (43.3%) and clay (2.6%) as a consequence of the notable resuspension of the surface sediment particles due to the vessel manoeuvre. The mode size ranges between 3.50 phi (88 μm) for the sample taken at a depth of 12 m and 5.5 phi (22 μm) corresponding to the sample taken at a depth of 6 m. This distribution indicated that the resuspension of the finest particles (silty and clayey) occurred throughout the entire water column, whereas sandy particles were prevalently resuspended at the bottom.

The organic fraction in all samples was around 17% (mean SOM = 8.5 ± 4.3 mg l^{-1}). In the surface layer, where the highest concentration of TSS was detected (11.4 mg l^{-1}), the organic fraction was 13% of the TSS. In the 6.0-m-depth layer, SOM concentration was 2.9 mg l^{-1} corresponding to 20% of the TSS, whereas, at the depth of 12.0 m, the organic fraction accounted for 18% and SOM concentration about 11.3 mg l^{-1}.

The calculated volume of 4.8×10^6 m^3 defined as 736 m long × 493 m wide × 15 m depth of the manoeuvre zone (Fig. 1) and the mean concentration (20 mg l^{-1}) of the four TSS profiles in the area were used to roughly assess the resuspended amount of TSS, which accounted for ~ 109 t.

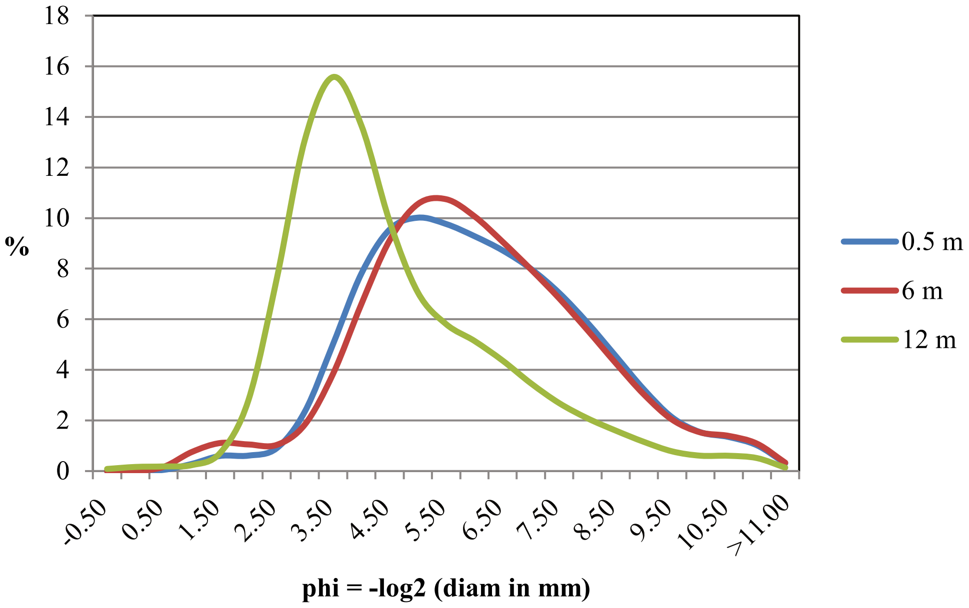

Fig. 4 Grain-size spectra of the samples collected at sampling point *S* at the three selected depths (0.5, 6.0 and 12.0 m)

4 Discussion

Previous investigations of maritime traffic impact on the resuspension of bottom sediments in the Bay of Koper reported high levels of turbidity (> 100 NTU) near the vessel departure route (Malačič et al. 2014), whereas similar high turbidity values and comparable grain-size distributions in the surface (0.5 m) and the middle layers (6.0 m) were found in this study. Comparing our results to those obtained from sediment remobilisation induced by the passage of commercial vessels in the Venice Lagoon shows that high concentrations of suspended sediment above 400 mg l^{-1} were observed by Rapaglia et al. (2015). Also, Gelinas et al. (2013) reported high suspended sediment values due to remobilisation induced by the passage of commercial vessels exhibiting concentrations above 380 mg l^{-1}. Pavoni et al. (2021) observed a clear increase in turbidity values immediately after a ship had passed the navigation channel approaching the Port of Monfalcone in Panzano Bay (northern part of the Gulf of Trieste) but the maximum values (20–25 NTU) were recorded at approximately 7-m depth and about 30 min after the ship had sailed past the sampling area. In Panzano Bay, at depths greater than 6–7 m, as in the entire area of the mid-Gulf, bottom sediments belonging to the delta front of the Isonzo River are muddy and prevalently silty (Brambati et al. 1983).

Clarke et al. (2015) found high concentrations of resuspended sediment (~ 90 mg l^{-1}) in the surface layer (1.0 m), as well as other layers in Newark Bay (USA) after vessel manoeuvres, which are similar to the TSS values found in this study, and also stated that the various sediment concentration distribution patterns in the acoustic Doppler current profiler measurement results are associated with different vessel types. Sediment resuspension from cruise ships off Bermuda Island (Caribbean Sea) can produce turbidity levels in the plumes up to 50 NTU (80 mg l^{-1}), but turbidity rapidly decreased to background levels (< 1 NTU) over ~ 4–6 h (Jones 2011). Particle size analysis in the same work revealed that the plumes were composed of very fine sediments with a median diameter between < 5 and < 200 µm. Higher values in the northern Adriatic examples may be attributed to larger vessels, lower ship clearance, shallower water and different bottom sediment grain-size characteristics. In this context, the grain-size distribution of the surface sediments in Panzano Bay and in the Venice Lagoon is not dissimilar from the central part of the Bay of Koper, consisting prevalently of silty particles associated with a minor sandy (i.e. sandy silt) and clayey component (i.e. clayey silt), respectively (Ogorelec et al. 1991; Brambati et al. 1983; Zonta et al 2018). Nevertheless, the present results have demonstrated the significant impact of vessel manoeuvres on the entire water column. Due to the high level of turbulence in the manoeuvre zone, the measurements were affected by a negative influence from the rapid fluctuation of turbidity and current velocities, which suggest a need for caution in assessing the obtained gross mass values.

Our SOM data were in the range of the reported seasonal concentrations in this area from previous investigations (Ogorelec et al. 1987; Soczka Mandac et al. 2014; Soczka Mandac and Faganeli 2015). The data were used to estimate the influence of the river discharge and corresponding fluvial material on the analysis of the vessel resuspension, as high concentrations of SOM were previously observed in the river and relatively lower in the bay area (Soczka Mandac and Faganeli 2015).

In addition, the concentration of TSS in the water column is expected to vary considerably due to vessel dimensions, draught, the number of tugs involved in manoeuvres and manoeuvre dynamics. Therefore, cooperation with port authorities, pilots and tug masters is needed to obtain broader information regarding the dynamics during manoeuvring. Tug propulsion while bulking the vessel affects the water-submerged jets (Clarke et al. 2007, 2015; Absalonsen 2014) resulting in a complex water mixing in the manoeuvre zone; consequentially, part of the resuspended material may be transported into the bay by currents over a short time period (< 1 h); thus, the profiling and sampling techniques adopted in this study can be spatially limited. As the presented vessel manoeuvre using tugs in the study area is a common procedure in the port of Koper and ports in general, new solutions to reduce sediment resuspension are studied and discussed by Srše et al. (2022). If those suggested solutions for mitigating resuspension are implemented, an extended measurement methodology is recommended to cover the spatial area.

To overcome the above-mentioned limitations of this study and to conduct a holistic measurement campaign, further research should incorporate the use of a multibeam sonar (Colbo et al. 2014) and an acoustic Doppler current profiler (Cutroneo et al. 2013; Hongmei et al. 2014; Clarke et al. 2015; Venditti et al. 2016) to estimate the TSS concentrations in the water column over a wider area. Remote sensing offers various useful tools to study TSS concentration, for example with drones (Sáenz et al. 2015) or satellites (Dorji et al. 2016). A combination of remote sensing and in situ measurements/sampling would provide a more holistic approach to evaluate the TSS concentration distribution in the studied area. The obtained data would be useful to validate and calibrate a numerical model (Wang et al. 2016; Guarnieri et al. 2021) and, subsequently, to simulate the TSS concentration transport in the bay.

Finally, as the study is, in part, necessitated by the increasing size of vessels arriving in the Port of Koper, scientists must be included in some manner in broader decision-making processes on local and national levels to prevent possible negative impacts on natural resources (Edgerton 2021; Othman et al. 2022). Economic decisions must include long-term environmental costs that are more difficult to evaluate, but play a significant role in long-term decision-making and lean less toward short-term profit/loss calculations.

5 Conclusions

The study has shown that the impact of vessel manoeuvres on the resuspension of sediment from the sea bottom to the surface layer in the area in the Port of Koper is far from negligible. Turbidity profiles showed the fluctuation of the parameter, attributed to high velocities and eddies in the entire water column. The analysis of the grain-size spectra of the TSS depicts similar grain-size distribution at the surface and at mid-depths of the water column, mainly silty particles, whereas at the bottom the high concentration of the sandy component is evident. The estimation of the suspended solid mass indicates that the quantity of resuspended sediment following a vessel manoeuvre is noticeable and possibly greatly underestimated. Considering the limited number of studies on this specific subject in the presented site and elsewhere and the lack of data available, this information may be relevant for further research, for example in numerical modelling, and for the assessment of the impact of marine traffic on environmental conditions in coastal areas, in particular the dispersion of contaminants associated with suspended sediment particles in the water column. Such environmental impact should be taken into account in decision-making at the national level, and care should be taken to prevent further degradation.

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