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Use of optical and acoustic instruments to study the turbid plumes generated by three different types of dredges during dredging activities inside and outside of a port

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Abstract

Purpose The turbid plumes generated by different types of dredges have specific behaviours and diffusion patterns. The dredging of the Oil Port of Genoa Multedo (Italy) with three different dredges (grab, backhoe and trailing suction hopper) enabled us to study: the physical and hydrodynamic characteristics of the water column of the port and the area just outside it; the characteristics of the turbid plumes; and the different responses of our optical and acoustic instruments.

Materials and methods In the dredging operations, a vessel equipped with a vertical acoustic Doppler current profiler and a conductivity–temperature–depth probe with a turbidimeter followed the different dredges during their daily operations. Using the acoustic backscatter and turbidity data acquired during the dredging phase, we investigated the turbidity variations caused by the dredging operations to study the evolution of the plume generated by the three different dredges.

Results and discussion The grab plume was present only on the bottom up to a distance of 50 m from the grab, while at greater distances the turbidity fell to background values. The backhoe plume was present close to the bottom at a distance of 50 m from the dredging and, in the entire water column, at distances of 50–400 and 100 m inside and outside of the port, respectively. The trailing suction hopper dredge plume extended from the surface through the entire water column at distances from the dredging of 400 and 100 m inside and outside of the port, respectively. The highest values were found close to the bottom at distances from the dredging at 50 and 30 m inside and outside of the port, respectively.

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Conclusions The choice of a combined monitoring system is a good practical solution for studying the differences between the turbid plumes created by the three dredging tools (grab, backhoe and trailing suction hopper dredge) under different hydrodynamic conditions. Furthermore, two different types of instrument should give complementary information on different aspects of sediment resuspension during a dredging operation.

1 Introduction

The importance of sedimentary plumes during dredging should not be underestimated because this phenomenon can extend the impact well beyond the limits of the dredging activity (Hitchcock and Bell 2004). A key element in the evaluation and monitoring of a dredging plume is the choice of technique for measuring the total suspended solids (TSS). Several studies have suggested that acoustic backscattering (BS) and turbidity (Tu) may be suitable surrogate measurements for TSS (Thevenot and Kraus 1993; Wang et al. 2000; Hitchcock and Bell 2004; Chanson et al. 2008; Cutroneo et al. 2012). The most common practice worldwide to determine TSS and turbid plume diffusion is a combination of acoustic Doppler current profiler (ADCP) and turbidimeter systems and traditional water sampling techniques (HR Wallingford Ltd and Dredging Research Ltd 2003; Gartner 2004; Hitchcock and Bell 2004; Hoitink and Hoekstra 2005; Burt et al. 2007; Chanson et al. 2008; Defendi et al. 2010; Cutroneo et al. 2012). The use of an ADCP and a turbidimeter allow one to characterise the turbid plume created by the dredge in *real*

time because they provide immediate results; nevertheless, the acoustic and optical responses, respectively, have different characteristics and provide different results.

Depending on the different equipment used to carry out the dredging, the plume generated has different characteristics in terms of resuspended sediment quantity, vertical extension in the water column, horizontal spread around the dredge and resedimentation time (Pennekamp et al. 1996; Sanchez 2001; Sanchez et al. 2002; HR Wallingford Ltd and Dredging Research Ltd 2003; Palermo et al. 2003, 2004). In particular, the expected plume formed by the grab will display: a near-bed resuspension generated by grab impact and excavation; a columnar plume extending from the bed to the surface; and a surface plume of material escaping from the grab as it is pulled from the water and slewed towards the barge. Grab dredging is a discontinuous process, and each stage of each grabbing cycle will be characterised by different rates of sediment release, and the releases will occur sequentially.

The release mechanisms from the backhoe are generally similar to those from the grab and the plume will consist of the same three main components (HR Wallingford Ltd and Dredging Research Ltd 2003).

The trailing suction hopper dredge (TSHD) also has three main mechanisms of sediment release: the overflow from the hopper; the disturbance around the draghead; and the scouring of the bed caused by the main propellers and bow thrusters. However, the sediment released by the overflow will dominate the other mechanisms. The sediment release generated by the TSHD is continuous (van Rhee 2002; HR Wallingford Ltd and Dredging Research Ltd 2003; Spearman et al. 2003).

The characteristics of the plume generated by the dredging depend not only on the type of dredge and the dredging technique used, but also on the sensitivity of the bed material to resuspension, and the hydrodynamic conditions (water depth, current magnitude, waves; Hitchcock and Bell 2004).

The dredging of the Oil Port of Genoa Multedo (Italy) provided us with the opportunity to study the physical and hydrodynamic characteristics of the water column of the port and the characteristics of the plumes, and to investigate the different responses of optical and acoustic instruments. In this paper, we present data obtained during dredging experiments and the differences found in the characteristics of the diffusion of the plumes generated by the three different dredges used inside and outside the port. We present these results using two different instruments to highlight which kind of dredge produced the most important sediment dispersion.

2 Materials and methods

2.1 Application site, dredges and background

The Oil Port of Genoa Multedo (Fig. 1) has a surface area of 123,000 m^2; it is composed of a quay with an operative length of about 400 m and four wharves perpendicular to the coast. The deep-maintenance dredging began in July 2009 and finished in May 2010 with the removal of 40,000 m^3 of sediment, using a grab (orange peel grab), a backhoe (a mechanical dredger with a number of buckets of capacity 9.5–16.0 m^3) and a TSHD (a self-propelled vessel equipped with a hopper and a dredge installation to load and unload itself) with a capacity of 1,000 m^3, the overflow above the water surface and a trailing speed of 1.5 knots.

Before the beginning of the dredging, we characterised the water column inside and outside the Port during a summer campaign of measurements and determined the background values in terms of Tu. The TSS values found inside and outside the Port were similar but relatively higher outside the Port; the Tu range was 6–12 and 5–10 FTU inside and outside the Port respectively, and BS maximum was 210 and 200 dB, respectively.

2.2 Portable system

A Teledyne RDI 600-kHz Workhorse® over-the-side-mounted V-ADCP with bottom-track function was used to collect the
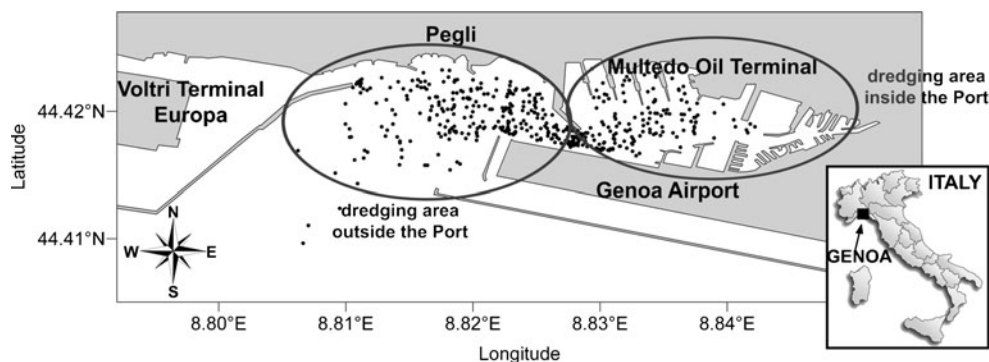

Fig. 1 Map of the Multedo Oil Terminal, Genoa, Italy. The *black dots* indicate the 439 sites where conductivity–temperature–depth (CTD) measurements were carried out during the dredging phase. The Terminal and its approach channel are flanked by the runway of Genoa Airport, the beaches of Genoa Pegli and the Voltri Terminal Europa container port. Dredging was carried out both inside and outside the Port (*grey ellipses*)

current velocity, direction and BS data. The RDI software "WinRiver® II" was used to collect and display the data. Navigation data received from an external global positioning system were collected and used in the data post-processing.

The hydrological data were collected using a conductivity–temperature–depth (CTD) multiparametric probe equipped with a turbidimeter (0–200 FTU). Before the beginning of the dredging, the probes were factory adjusted to obtain comparable results. >At the beginning of the dredging, the TSS concentrations in the water samples were matched to the turbidity data to calibrate the turbidity sensor response (Cutroneo et al. 2012); the linear regression of the data (turbidity versus TSS) yielded a good correlation ($R^2=0.90$). Moreover, the Tu data were matched to the BS data to calibrate the acoustic response in three different situations. The calibration of the data (BS versus Tu) with exponential regression yielded $R^2=0.8065$ for the grab (Fig. 2a), $R^2=0.6844$ for the backhoe (Fig. 2b) and $R^2=0.8225$ for the TSHD (Fig. 2c).

During the dredging, BS was used both as a surrogate measure of Tu and to identify and follow the plume in real time.

2.3 Data collection

During the dredging, CTD measurements at 439 stations were used, and the ADCP was used continuously to investigate the plume dispersion. The survey vessel collected profiles perpendicular to the plume axis at increasing distances downstream from the dredges, or along spiral courses around them, reaching distances with background levels of TSS, and produced a series of profiles of the status of the plume and its dispersion.

3 Results

Given the sheer quantity of data acquired during the 10 months of work, we present only a few of the most representative situations that emerged during the study, the different methods applied for data processing to better evaluate the different instrument responses, a discussion of what the responses of the different instruments highlighted and the difference in the plumes generated by the three different kinds of dredge.

3.1 The grab: an experiment with a linear route

This exercise was undertaken with both CTD and ADCP profiles (Fig. 3) with a gentle northeast wind and a calm sea, and the grab working inside the port. In the Tu section (Fig. 3), the maximum values were present close
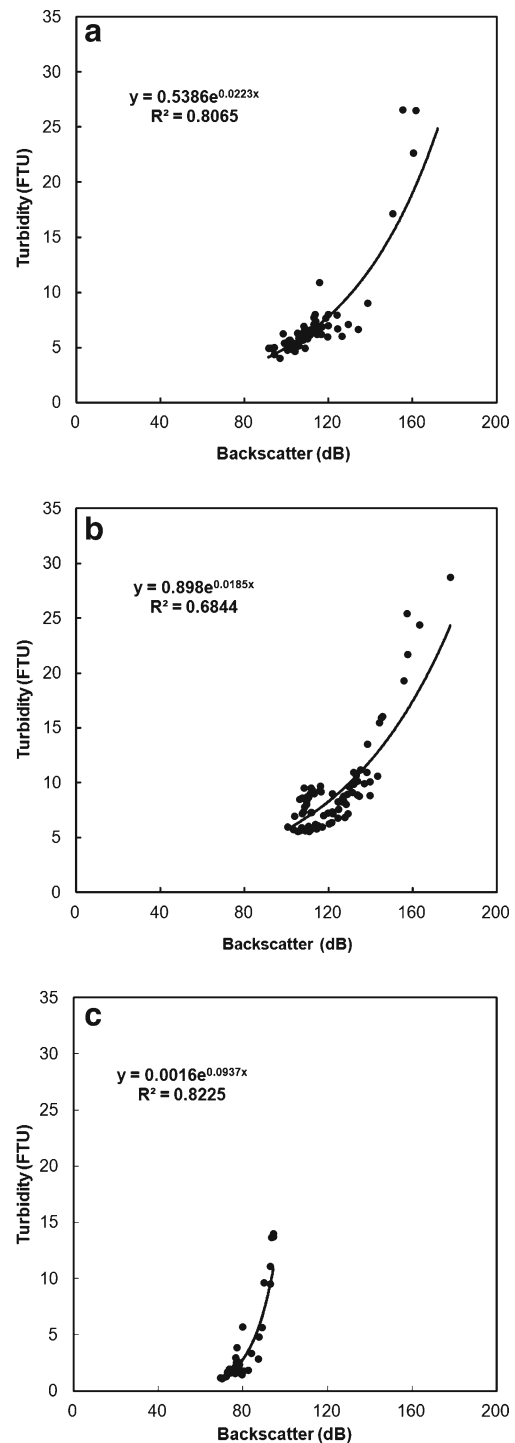

Fig. 2 Correlation results of backscatter (dB) versus turbidity data in the case of **a** the grab, **b** the backhoe and **c** the trailing suction hopper dredge (TSHD)

to the bottom (30 FTU max) while the BS section (Fig. 3) shows a plume extending through the entire water column, with a maximum value of 200 dB ca. at depths <3 m; these values in line with the background. From the site of dredging, relatively low values (<6 FTU and <135 dB)

Fig. 3 Vertical transect of turbidity (FTU; *upper plot*) and backscatter signal (dB; *lower plot*) inside the port near the grab (*black triangle* in the map and above Station 3 in the turbidity section); the *y*-axis scale is exaggerated
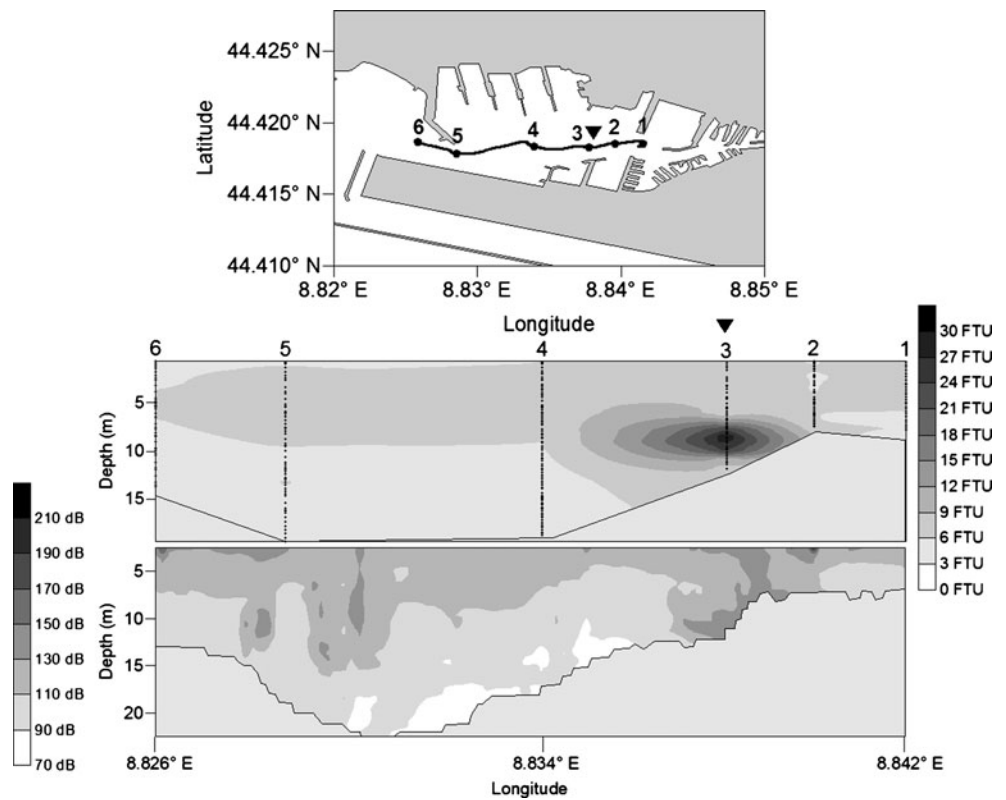

Fig. 4 Horizontal distribution of the backscatter signal (contour; in decibels) and the current (vectors; in centimeters per second) in the surface layer (2.7 m deep) recorded by the vessel-mounted acoustic Doppler current profiler (ADCP) along a spiral transect (*small map upper right*) around the backhoe (*white triangle*). The wind intensity is shown in the rose diagram (*upper left*)
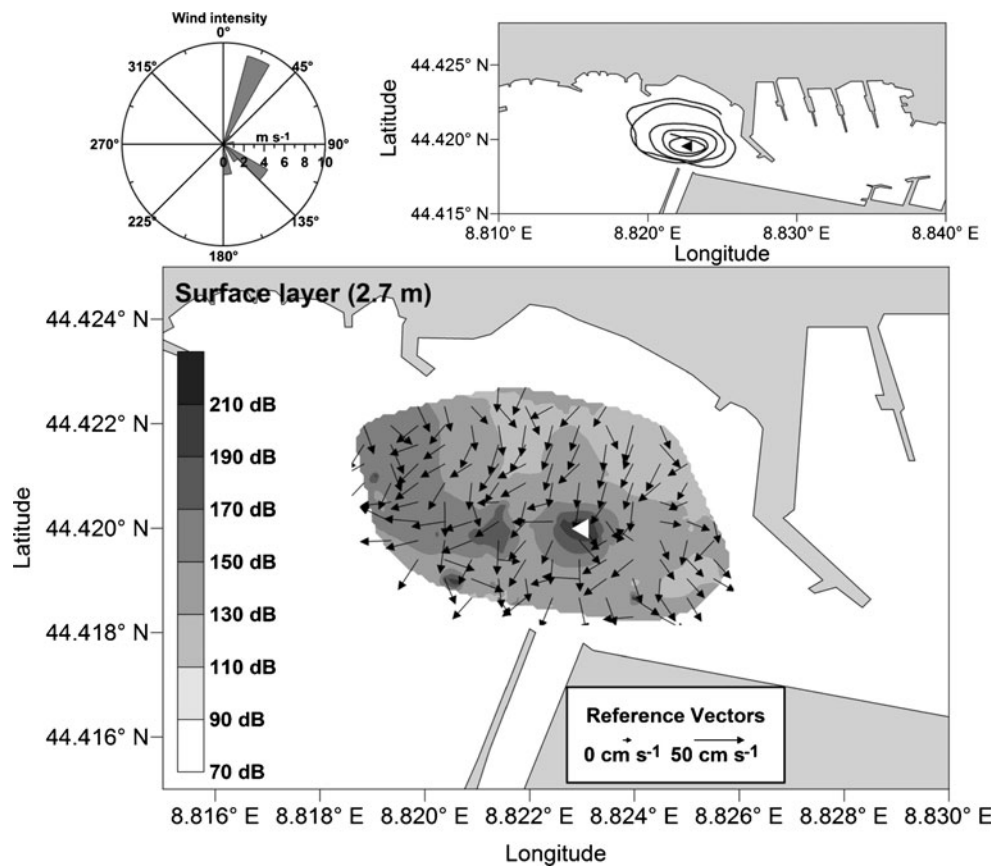
spread in the direction of the entrance to the port to a depth <15 m.

3.2 The backhoe: an experiment with spiral and linear routes

To study the dispersion of the plume during the dredging made by the backhoe, we performed an ADCP spiral transect around the dredge. In the horizontal distributions shown in Figs. 4 (surface layer) and 5 (bottom layer), we have highlighted the relationship between currents and sediment dispersion. With a northeast wind and calm sea, the plume tended to spread towards the west and northwest in both the surface and bottom layers, influenced by a clockwise and an anticlockwise current, respectively. The maximum current magnitude and BS values were found in the surface layer (50 cm s^{-1} and 205 dB, respectively), while in the bottom layer the values were somewhat lower (max 49 cm s^{-1} and 185 dB, respectively). Therefore, the plume had maximum values in the surface layer (210 dB), spread through the water column to the sea bottom and was not homogeneous, due to the presence of intervals with relatively low BS (<170 dB).

The distribution of Tu along a linear transect across the dredging area (Fig. 6) highlighted the high Tu increase close to the bottom, near the dredging point (55 FTU max at Station 11); in the rest of the section, values were <10 FTU.

3.3 The TSHD: an experiment with a linear route perpendicular to the dredge wake

We performed a transect across the dredge course with both the CTD and ADCP in continuous operation, immediately after the passage of the dredge, to sample the plume with the highest possible concentrations. Generally, the distributions of the CTD and ADCP data (Fig. 7) had a similar trend, with the maximum TSS values in the surface layer at Station 4 and a

tendency to spread towards Station 2, without involving the bottom layer. Three differences between the two sections can be highlighted: (1) in the CTD profile the heart of the plume was centred at a depth of 5 m with 28 FTU max, while in the ADCP section the plume was more superficial, with a maximum of 184 dB at a depth of ~1 m; (2) in the CTD section the vertical diffusion of the plume was only restricted to intermediate depths, centred around a 5-m depth, and reached the bottom with relatively low Tu values (<6 FTU), in the ADCP section the sediment distribution in the water column was more evident and reached the bottom with intermediate and high BS values (>120 dB); and (3) the plume extension, which moved southwards in the surface layer (Stations 2 and 3), was more evident in the ADCP section and had maximum BS values (>155 dB), while it was less evident in the CTD section which had low Tu values (<9 FTU).

3.4 General results

The Tu data were analysed to determine the characteristics of the plumes created by the three dredges to highlight the eventual differences in their spread in the inner part of the port (area with reduced dynamics) and outside the port (area subject to strong currents and wave action).

Figure 8 shows that the Tu generated by the grab generally had low values (5–8 FTU) and that the maximum values (27 FTU) were present only close to the bottom at a distance of 50 m from the grab. The typical Tu profile measured close to the grab usually had low values in the water column with an increase in the bottom layer, but values were <12 FTU 10 m from the grab.

During the backhoe dredging inside the Port (Fig. 9a), the Tu max (117 FTU) was recorded close to the bottom at a distance of 50 m from the dredge; at this distance, the Tu remained <15 FTU in the overlying water column. At 50–

Fig. 5 Horizontal distribution of the backscatter signal (contour; in decibels) and the current (vectors; in centimeters per second) in the bottom layer, recorded by the vessel-mounted acoustic Doppler current profiler (ADCP) along a spiral transect around the backhoe (*white triangle*)
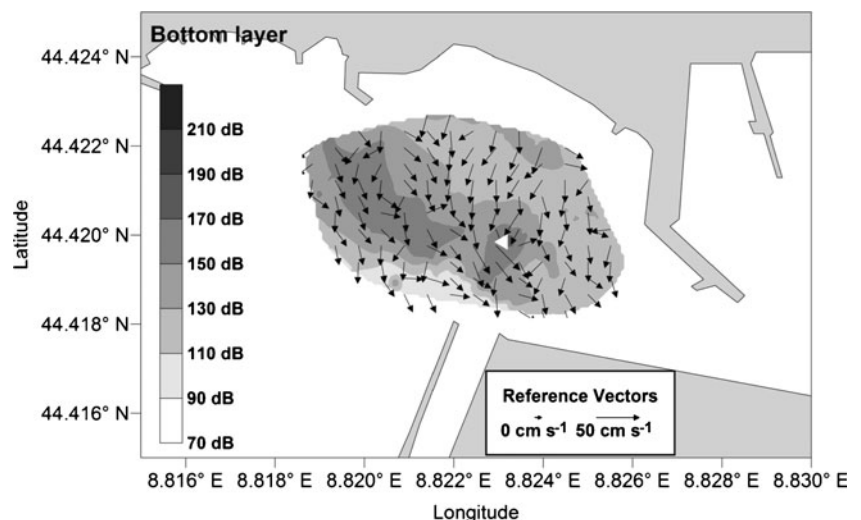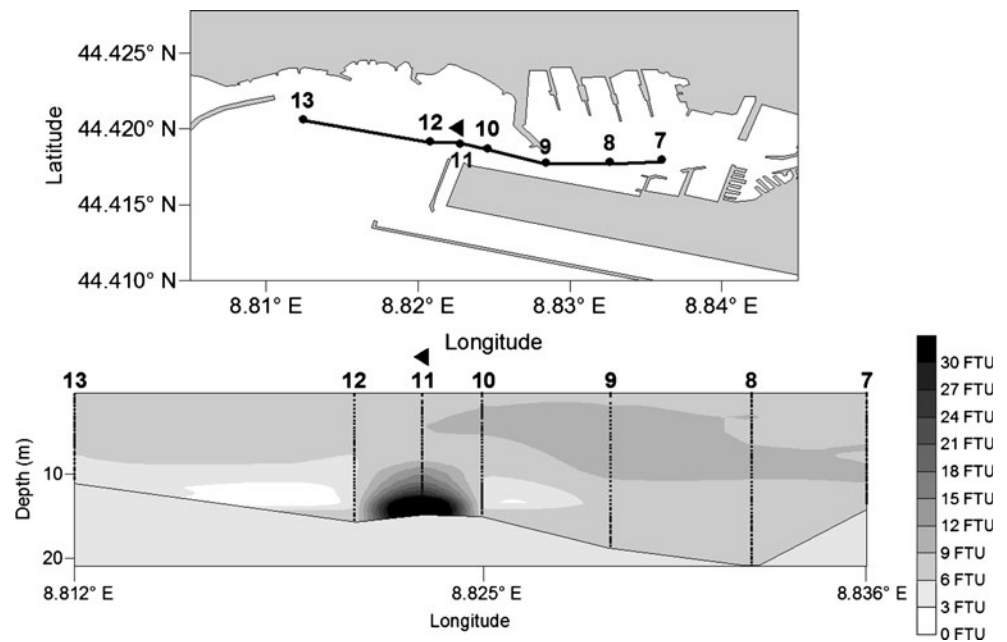
Fig. 6 Vertical profile of the turbidity (FTU) across the area of backhoe dredging (*black triangle* in the map and above Station 11 in the section). The near-bottom plume is evident at Station 11; the scale indicated has a maximum of 20 FTU to highlight the turbidity variation around the dredge, but the maximum value reached on the bottom below the backhoe was ca. 55 FTU

400 m, the Tu was 15–25 FTU in the entire water column, while at distances greater than that the Tu was 10 FTU. Outside the Port (see Fig. 9b), the maximum Tu recorded at a distance of 50 m was 58 FTU, close to the bottom, while it was <10 FTU in the remaining part of the water column. At a distance of 100 m from the backhoe, we only observed 10–15 FTU in the entire water column, and at distances greater than that, the values remained <10 FTU.

The Tu measured around the TSHD inside the Port (Fig. 10a) showed relatively high values (>30 FTU, 50 FTU max) only near the bottom, at a distance of 50 m, measured in the wake of the dredge about 70 seconds after its passage. At this distance, besides the bottom Tu, a subsurficial turbid layer was identified at a depth of 5 m with values reaching 25 FTU. At a distance of 400 m from the dredge, the Tu fell below 17 FTU from a depth of 2.5 m to the

Fig. 7 Vertical profile of the turbidity (in FTU; *above*) across the wake of the trailing suction hopper dredge (TSHD; *black line* in the map). The plume is evident at a depth of 5 m at Station 4; the vertical profile of the acoustic Doppler current profiler (ADCP) backscatter (*below*) along the same section: the plume is *highlighted* in the surface layer
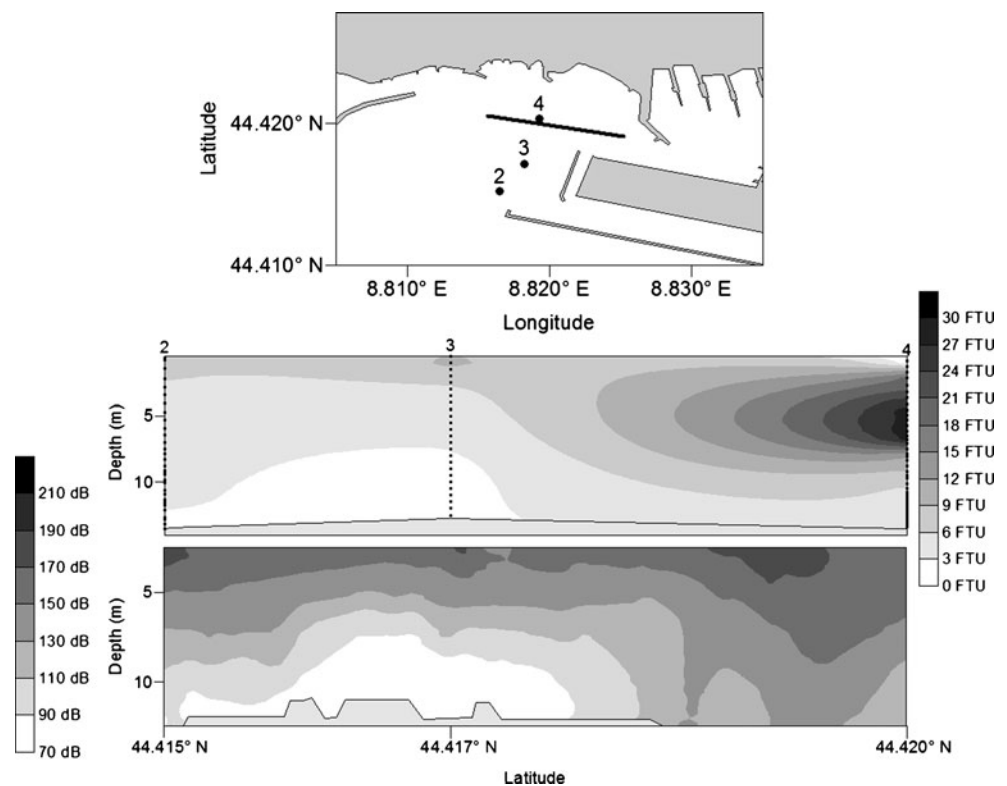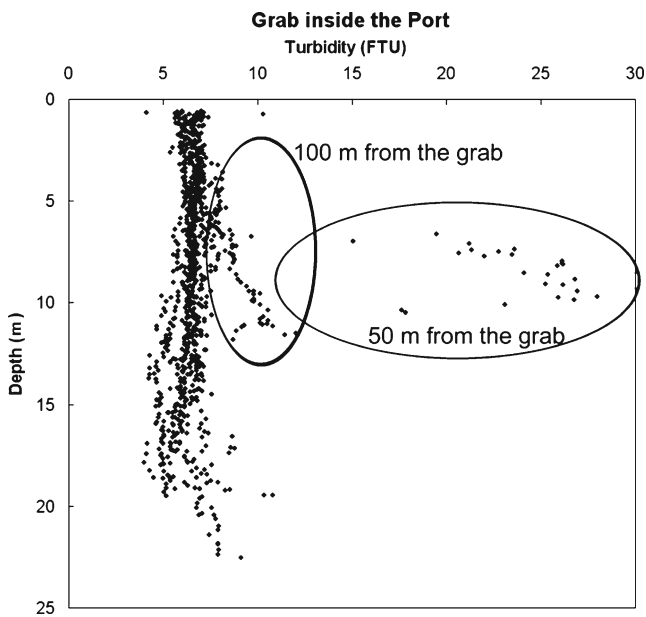
Fig. 8 Turbidity values (*x*-axis; FTU) measured in the water column (*y*-axis; depth in meters) around the grab during the dredging inside the Port

Fig. 9 Turbidity values (*x*-axis; FTU) measured in the water column (*y*-axis; depth in meters) around the backhoe during the dredging inside and outside the Port (**a** and **b**, respectively)

bottom (surface values <10 FTU). Further from the TSHD, the mean Tu was <10 FTU and constant in the entire water column.

Outside the Port (see Fig. 10b), we distinguished two different types of Tu behaviour, the first along the dredging route and the second in the Tu development area around the dredge. In the first case, the turbid layer was present only on the bottom, while at a distance of 30 m (43 minutes after the passage of the dredge) Tu had maximum values 97 FTU and at a distance of 50 m (25 minutes after the passage of the dredge) had values <40 FTU, which fell below 15 FTU at greater distances. In the Tu development area around the TSHD, the second case, we had relatively high values on the surface (max. 36 FTU) at a distance of 50 m from the dredge and low values in the deep layer (<10 FTU). At 100 m from the TSHD, the maximum values were <20 FTU at a depth 2.5–5 m, and close to the bottom were <10 FTU; at greater distances, the surface values were <15 FTU and at 200 m were <10 FTU in the entire water column.

4 Discussion

An increase in sediment near the bottom (30 FTU max) was noted at a distance of 50 m from the grab, although in the rest of the water column the values were similar to the background (5–8 FTU). At a distance of about 100 m, Tu never exceeded 12 FTU, values comparable to the background.

The analysis of the distribution of the backhoe plume at different depths (Figs. 4 to 5) allowed us to follow its spread and observe that the plume developed discontinuously. This
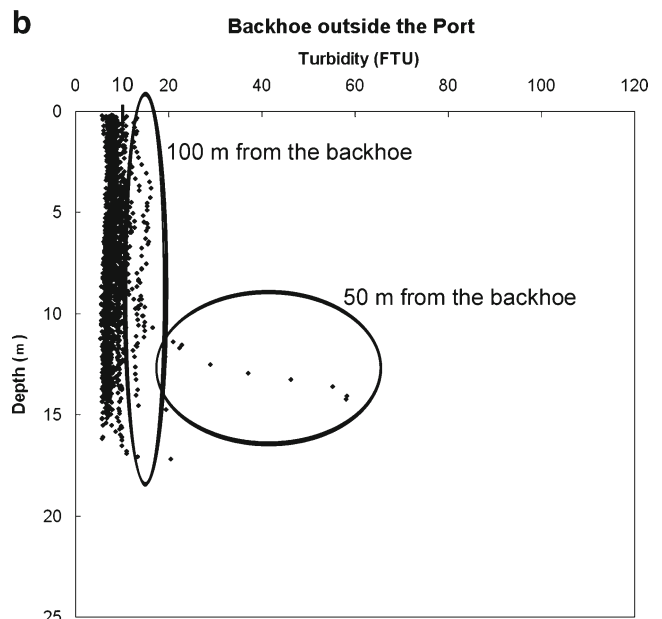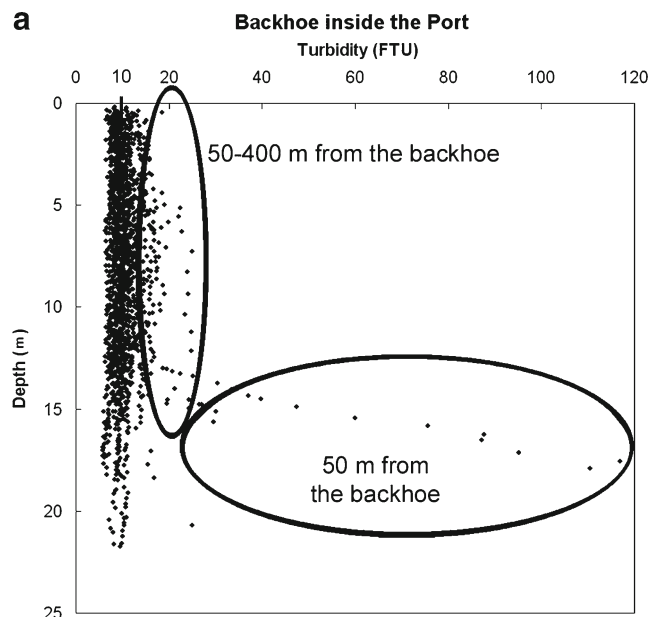
characteristic was due to the type of mechanical work done by the excavators of the backhoe. Along the cross-section made through the plume downstream from the dredge (Fig. 6), only one of the three main components of the backhoe plume could be seen, i.e. the resuspension of the sediment due to the impact of the excavator on the bottom. This could be due to the characteristics of the dredged sediment that, because it was relatively cohesive, was not lost during the raising from the bed to the surface of the water column. The analysis of the Tu generated by the backhoe revealed that relatively high concentrations only occurred close to the bottom with values
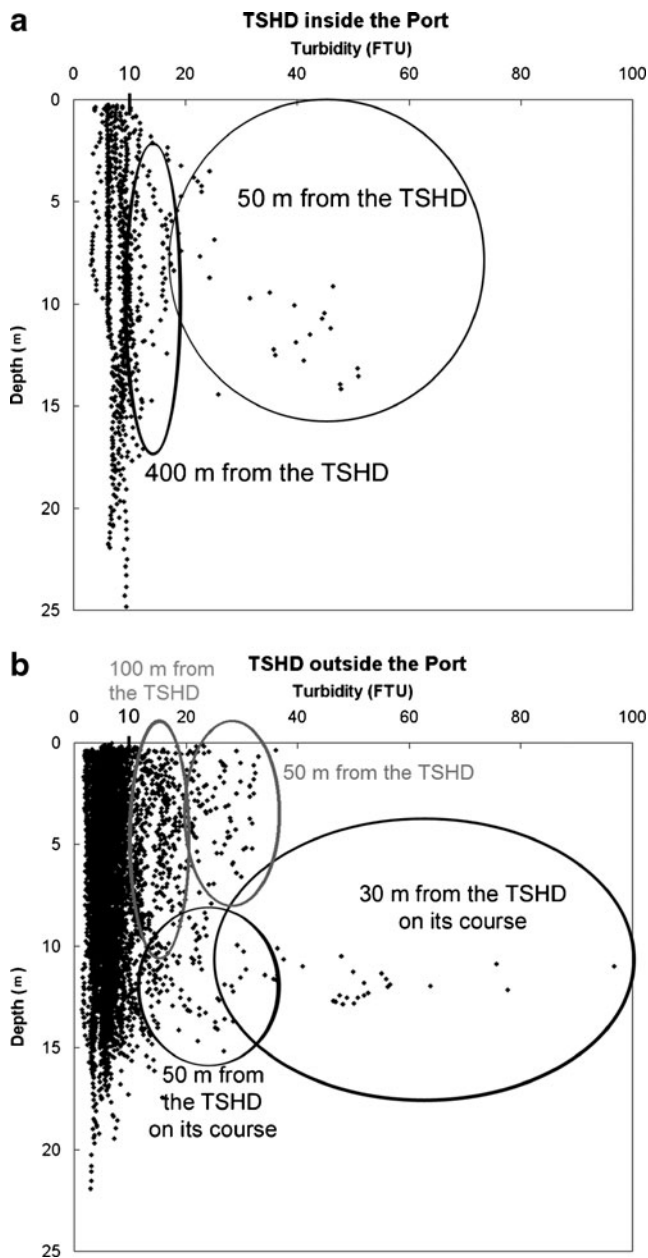
Fig. 10 Turbidity values (*x*-axis; FTU) measured in the water column (*y*-axis; depth in meters) around the trailing suction hopper dredge (TSHD) during the dredging inside and outside the Port (**a** and **b**, respectively)

reaching up to approximately 120 and 60 FTU inside and outside the port, respectively.

The main differences found in the turbidity produced by the TSHD (Fig. 10b) are most likely due to the presence and absence of overflow and to the more or less rapid dispersion of the overflow plume. During measurements along the dredging route outside of the port, the overflows were not present or had already spread, and only the bottom turbidity was highlighted. On the contrary, inside the port, the overflow turbidity remained longer in the dredging area due to the calm water column conditions.

The acoustic measurements did not show the plume generated near the bottom by the action of the TSHD draghead, probably due to the distance from the source and to the bottom blank layer in the acoustic measurements, while the measurements clearly showed the plume generated from the overflow. We identified a turbid layer just below the surface with the turbidimeter and the maximum concentration in the surface layer with the ADCP. More detail on the horizontal spread of the turbid layer was given by the ADCP.

The high surface concentrations measured by the ADCP near the dredges could also be due to the presence of air bubbles created by the impact of the backhoe and the grab on the water surface, and the water flow around the hull of the TSHD and the bubbles created during the overflow, as verified by Burt et al. (2007). Also, the differences found in this case could due to the fine mean grain size of the overflow sediment, which was monitored better by the ADCP (Vousdoukas et al. 2011).

In general, the Tu values found within the port were higher than those measured outside, and, in particular, the maximum values close to the bottom were greater in the case of the backhoe. This difference may be due to the different current intensities inside and outside the port basin. Due to the structure of the basin (only one entrance to the port) and the presence of the wharves which block water movement, the currents in the port (20 cm s^{-1} mean max in the surface and <10 cm s^{-1} on the bottom) are generally lower than those outside (mean values during the dredging were 50 cm s^{-1} max in the surface layer and <15 cm s^{-1} on the bottom) where there is unhindered circulation, which is typical of open seas.

The low hydrodynamics in the port can lead to an accumulation of sediment and resuspension, especially for the backhoe which always operates in a narrow area of the bottom, and generates an increase in Tu, prolonging the time of sedimentation. On the contrary, outside of the port, the free circulation of water masses leads to a more rapid dispersion of the Tu, producing Tu values lower than those recorded in the port.

During the dredging of the Port of Genoa (Cutroneo et al. 2012) with current speeds <20 cm s^{-1}, the surface background values (<10 FTU) were re-established 100 m from the TSHD and at a distance of 200 m close to the bottom. In the case considered in the present study, within the Oil Port with currents <20 cm s^{-1}, at a distance of 400 m, there were still values slightly higher than the background (<20 FTU), indicating the greater persistence of the Tu.

This phenomenon can also be confirmed by the differences in the spread and persistence of the plume generated by the backhoe; in fact, in Cutroneo et al. (2012), background Tu values were detected at a distance of 100 m from the backhoe, while in this study we found background values at distances greater than 100 m outside of the port and greater than 400 m inside of the port, which indicate that the plume characteristics found during the dredging of the Port of Genoa are more similar to those found outside the Oil Port than those found inside of it.

During the mining of marine aggregate from a small licence off the south coast of the UK, made by a TSHD with 2,300-t capacity, Hitchcock and Bell (2004) found that the plume immediately sank to the seabed close to the dredge and spread laterally downstream from the operation with a current speed of 3 m s^{-1}. Hitchcock and Bell (2004) found a rapid reduction in BS at a distance of 300 m in the surface layer and a return to background levels at 500 m, while in the bottom layer a dense plume extended more than 800 m from the dredging site. The extension of the plume in this case was explained by the current speed of 3 m s^{-1}, which was very high compared with the values found at Genoa Multedo and allowed the transport of sediments over a much larger area.

During the dredging of the Norfolk and Baltimore Ports (USA) in the central part of Chesapeake Bay, North America's largest estuary, with a hopper dredge, Maynard et al. (1990) found two plumes, one in the surface layer, produced by overflow, and one near the bottom, produced by draghead agitation and rapid settling from the upper plume. In that case, the upper plume had an extension of 5,200 m from the point of discharge with a total impact area of 5.7 km^2, while the sediment concentrations reach 400 times the normal background values at a distance <300 m from the dredge and eight times the background values at >300 m. These results and those found in other cases of dredging in the world (i.e. Hitchcock and Bell 2004) are much higher than those found at Genoa Multedo (where the maximum sediment concentration near the dredge was only six times the background values), because of higher background concentrations, much larger areas and volumes involved, and perhaps differences in the size of sediments involved (not considered in this work) and greater hydrodynamics influenced by stronger tidal currents, which are negligible in Genoa. The magnitude of the impact was therefore much smaller, both in terms of spatial extent and in terms of plume intensity. This, plus the differences found in TSS concentrations during the dredging of the two areas of the Port of Genoa, highlight the fact that TSS variations and their impact are site-specific, depend on the background values and require an understanding of the site-specific dynamics in order to evaluate the environmental impact of dredging. Finally, to correctly determine the possible impact of the TSS variations on the vulnerable ecosystems present near the dredging area, it is necessary to know what the tolerance levels of the species present are, as highlighted by Orpin et al. (2004), Palermo et al. (2006), Ware et al. (2010) and Fettweis et al. (2011).

5 Conclusions

Optical and acoustic instruments used to monitor the evolution of a turbid layer often give different results, even when inter-calibrated, so that it is convenient to use both at the same time so as to obtain a more complete overview of the development of turbidity. The use of the parameter "turbidity" tends to give underestimations of the diffusion of the plume, and this may be due to the discontinuity of characteristics associated with this measurement (vertical profiles carried out at single stations, separated from each other in terms of time and space).

On the contrary, the use of an ADCP allows the investigator to identify the real extension of the plume along the route followed by the control boat and vertically, in the water column. This instrument, however, cannot give information on the actual bottom and surface situations (defined as "blank" areas where the instrument, due to physical and hardware issues, cannot function) and therefore returns a partial image of the water column, excluding two relatively important layers from the point of view of our understanding of turbidity dynamics.

The dynamics of the area involved in the dredging play an important role in spreading the sediment plume and also in the persistence of turbidity in the water column. This effect is more evident in the case of the plume generated by the mechanism of surface TSHD overflow and the impact of the backhoe excavator on the bottom. Conversely, the sediment dispersion generated by a grab is too discontinuous to generate turbidity persistence, especially in calm conditions.

The intensity of the plume and its extension, measured during the dredging of the closed basin of the Port of Genoa Multedo, were much lower than those studied during the dredging of many other harbours in the rest of the world.

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