

# The use of a combined monitoring system for following a turbid plume generated by dredging activities in a port

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## Abstract

**Purpose** The potential negative effects of dredging on a sensitive marine environment (e.g. phanerogamic meadows, beaches, benthic populations) can be justification for restrictions on the dredging project or the creation of a dredging monitoring plan. The dredging of the Port of Genoa (Italy) provided the opportunity to study the concentration of total suspended solids, the physical characteristics of the water column, and the winds and currents determining the hydrodynamic characteristics of the port, and to test a double monitoring system for turbidity control.

**Materials and methods** In the dredging operation of the Port of Genoa, we positioned a couple of fixed monitoring systems operating 24/7, consisting each of a conductivity–temperature–depth probe and two acoustic Doppler current profilers (ADCP), near the two port entrances to monitor turbidity and currents. To make the monitoring strategy more efficient, to periodically control the data transmitted by the fixed stations and to ensure coverage of those areas not covered by the fixed monitoring system, a vessel equipped with a vertical ADCP and a conductivity–temperature–depth probe with a turbidimeter periodically followed the dredger during its daily operations.

**Results and discussion** Using the data acquired during the pre-dredging and dredging phases, we considered turbidity and suspended solids variations caused by the dredging operation to study the evolution of the plume. The trailing suction hopper dredge (TSHD) plume extended from the surface throughout the entire water column at a distance of 50 m, with higher turbidity close to the bottom. At a distance of 200 m, the plume was much reduced. Instead, at a distance of 50 m, the turbidity produced by the backhoe was lower than that measured around the TSHD, while at a distance of 100 m the plume was reduced with only noticeable values near the bottom. Finally, we compared the turbidity data of the dredging with the background conditions near the *Posidonia oceanica* meadow present near the port.

**Conclusions** The data presented in this paper indicate that the choice of a combined monitoring system can be a good practical solution for reaching two different objectives: (a) to follow the evolution and movement of the turbid plume, and ensure that it does not flow out of the port, contaminating the surrounding area or damaging nearby coastal habitats or the *Posidonia oceanica* meadows; and (b) to study the differences between the turbid plumes created by two dredging tools (backhoe and TSHD) under different wind-wave conditions.

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## 1 Introduction

The estimate of the total suspended solids (TSS) is the first technique for determining the impact of such activities as port dredging, beach and coastline stabilisation, river navigation and drain construction on the surrounding

environment. The acquisition of real-time TSS data can be of strategic importance for making rapid decisions for protecting the environment (Bishop and Dammann 1996). The potential negative effects of the resuspension of bottom sediments on sensitive marine environments, including their benthic populations, fish nurseries (Nairn et al. 2004; Ogle 2005) and phanerogamic marine meadows (e.g. *Posidonia oceanica* and *Zostera marina* meadows; Erfemeijer and Lewis 2006), and adjacent areas of major economic interest such as beaches and recreational areas (Je et al. 2007; Wu et al. 2007), are cited as justification for restrictions on dredging projects or the adoption of precautionary operational measures (e.g. silt curtains—LaSalle et al. 1991; Wilber and Clarke 2001; Clarke et al. 2005).

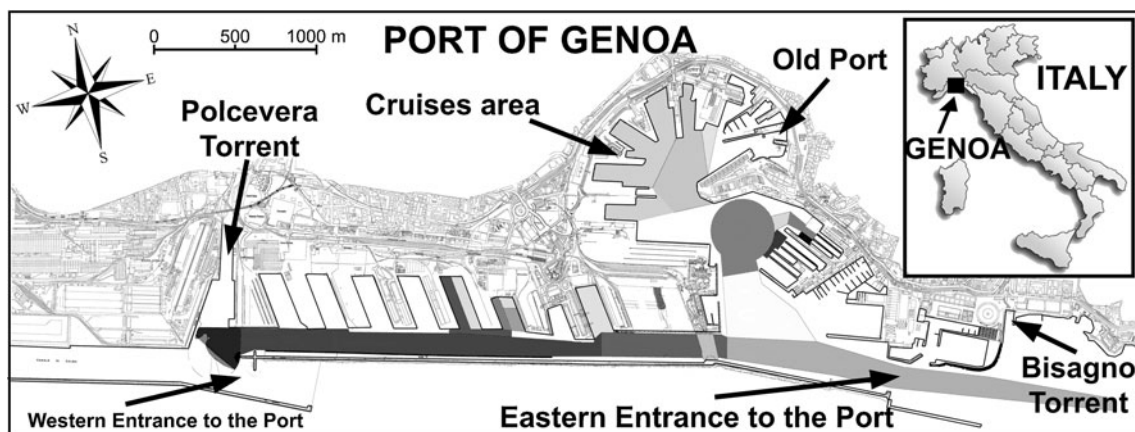
The Port of Genoa, Italy (Fig. 1), situated in the northernmost part of the Ligurian Sea (north-western Mediterranean Sea), is one of the most important ports in the Mediterranean Sea. In 2010, it handled 1.8 MTeu of containers. The port lies in a coastal region of major environmental and economic interest near numerous beaches, marine parks (the Marine Protected Area of Portofino and the Cetacean Sanctuary of the Mediterranean Sea) and a *P. oceanica* meadow. *P. oceanica* is an endemic species of seagrass intolerant of any activity that changes the sedimentary regime when the change is greater than the natural variation. However, it is likely to survive increased turbidity events for short time periods (Borum et al. 2004; Erfemeijer and Lewis 2006). *P. oceanica* is recognised as a ‘priority habitat’ by Directive 92/43/EEC, a Site of Community Importance (SCI) in the ‘Natura 2000 Sites’, a habitat of great importance (Guillen et al. 1994; EuroSION 2004; Terrados and Borum 2004; EEA 2005; Boudouresque et al. 2006), and is protected by national and international regulations (Borum et al. 2004).

The port has been undergoing dredging operations since July 2009. Dredging areas include areas outside the eastern entrance to the port (see Fig. 1), which are not far (0.5 nautical

miles, nm) from the sensitive sites described above. In accord with the conservative management approach of the Ligurian and Italian Governments, designed to minimise the impact from turbidity caused by dredging activities in the port, it was necessary to create an effective and precautionary monitoring system to ensure that a turbid plume did not escape from the dredging area and reach the sensitive zones, thereby damaging them.

We chose a monitoring system that combined two different methodologies and purposes: a remote-controlled fixed monitoring system functioning continuously at the two port entrances; and periodic on-site mobile monitoring (initially daily) aboard a fully-equipped monitoring vessel, to check the local dynamics of the turbid plume and try to understand and determine its behaviour, and to monitor the plume in the areas outside the port. A combined monitoring system was also chosen because two torrents (rivers) empty near the two port entrances, and it was necessary to conduct mobile monitoring to discriminate between the high turbidity due to the dredging (recorded by the fixed stations) and that due to the periodic floods of the torrents.

The instrument we considered most suited for checking the turbid plume, due to its widespread documented use in this field (Bishop and Dammann 1996; Bufkin and Rivero 1996; Reine et al. 2002; HR Wallingford Ltd and Dredging Research Ltd 2003; Hoitink and Hoekstra 2005; Defendi et al. 2010), was the acoustic Doppler current profiler (ADCP). This instrument measures the acoustic backscatter (BS) intensity of particles suspended in water, in addition to current magnitude and direction. To have a correspondence between the echo intensity and concentrations of suspended material, signal calibration is required using in situ samples and other concentration estimates. The main advantage of using an ADCP is that it measures currents and indirectly estimates the turbidity with a high degree of spatial resolution throughout most of the water column (Holdaway et al. 1999; Hill et al. 2003; Gartner 2004). Therefore, the acoustic



**Fig. 1** Map of the Port of Genoa: the grey areas indicate the areas to be dredged

monitoring can be used, coupled with optical instruments, as a surrogate for measuring the suspended sediment concentration so as to provide valuable real-time data to characterise the extent and dynamics of any suspended sediment plumes (Chanson et al. 2008).

The ADCP was supported by a conductivity–temperature–depth (CTD) probe combined with a turbidimeter in both the fixed and the mobile monitoring systems. Water samples were collected to determine the TSS for the calibration of the turbidimeter.

In this paper, we present and analyse the data obtained, and also present the experimental strategy for monitoring the turbid plume generated by dredging operations in the Port of Genoa.

## 2 Materials and methods

### 2.1 Application site

The dredging of the Port of Genoa began in July 2009, using a number of grabs (clamshells and orange peel grabs), a backhoe (a mechanical dredger with a number of buckets of capacity 9.5–16 m<sup>3</sup> used to remove coarse materials and boulders) and, at different times, three trailing suction hopper dredgers (TSHDs; self-propelled vessels, equipped with a hopper and a dredge installation to load and unload itself, used to remove fine material) with different internal capabilities (970, 1,300 and 4,500 m<sup>3</sup>). While excavation, hoisting and slewing to the sediment barge with grabs and backhoes create a turbid plume that expands in the direction of the current, TSHDs can generate turbidity in various ways. Examples include overflow from the hopper or from the bottom door, disturbance around the draghead, and scouring of the sea bed caused by the main propellers and bow thrusters (HR Wallingford Ltd and Dredging Research Ltd 2003). Furthermore, as the TSHD passes over the plume, some material may be entrained from the top of the plume by the propeller wake and redistributed back towards the surface while the bulk of the released sediment will remain in the lower part of the water column.

### 2.2 Remote monitoring system: fixed stations

To monitor the currents entering and exiting the Port of Genoa and the suspended sediments at the port entrances, it was decided to position fixed instruments, including a Teledyne RDI 300-kHz horizontal-ADCP (H-ADCP) with a three-beam head; this instrument can measure current profiles and the intensity of the echo along a theoretical horizontal line of about 300 m (Bradley 1999; RD

Instruments 2007, 2008a; Nihei and Kimuzo 2008) along the port's protective breakwater near the entrances. To cover the 230-m-wide eastern entrance to the Port—the nearest to the swimming facilities and *P. oceanica* meadow—an H-ADCP was mounted on the inner side of the breakwater, near the entrance, to measure the horizontal velocity profile at a fixed depth (7.5 m). This depth was partially chosen because of the geometric form of the instrument beam (instrument measuring cone angle of 1.7° at the exit of each transducer of the H-ADCP) and partially because during the preliminary hydrodynamic characterisation of the port it was noted that the greatest velocities and intensities of the out-bound current were around this depth. The size and the maximum number of bins of the H-ADCP were set at 4 m and 40, respectively, to cover more than 70% of the entrance to the Port. The distance covered (about 160 m) was considered sufficient to monitor the outbound water masses generated and pushed along the breakwater, where the H-ADCP was positioned, by winds coming from the N–NW (Capello et al. 2010).

As an H-ADCP cannot measure the current velocity and the intensity distribution of the echo in the vertical water column, we also employed a vertical ADCP (V-ADCP, Teledyne RDI 1200-kHz; RD Instruments 2008b). The V-ADCP bin size was set to 0.5 m, and the instrument was mounted at the end of a 'Z-shaped' stainless steel structure (3 m from the breakwater) to avoid the beam interacting with the submerged part of the breakwater before reaching the bottom (beam angle 20°).

The two current meters, coupled with a CTD probe fitted with a turbidimeter to measure the nepheloid layers, enabled us to obtain a panoramic view of what was happening along the most important 160 m of the entrance channel during the dredging operations. The equipment was powered by solar panels, and the instrument checks and the transfer of data were managed by a switchboard linked to a remote computer by GSM. The data, registered every 15 min, were sent to the remote computer through a data-checking and early-warning programme, and finally uploaded to a dedicated database ([www.apge.macisteweb.com](http://www.apge.macisteweb.com)).

The data were analysed constantly with software capable of identifying increases in turbidity related to particular conditions of the outgoing current and therefore potentially harmful to sensitive nearby areas. The current and turbidity values imposed on the management programme were finalised due both to the physical–dynamic data acquired during seven oceanographic campaigns—conducted in the port under different meteorological conditions before the beginning of the dredging operations—and to a sedimentation experiment carried out in the port (Capello et al. 2008, 2010). These values corresponded to the maximum values of current magnitude and turbidity recorded during these seven campaigns.

In the event of an outbound easterly current (in the direction of the nearby *P. oceanica* meadow) with a velocity greater than  $20 \text{ cm s}^{-1}$  being detected at the same time as an increasing turbid plume greater than 30 formazine turbidity units (FTU) and lasting longer than 15 min, the software would send a short message (SMS) to the researchers involved in the monitoring operation informing them of the possibility that these limits may be exceeded.

Several strategies were followed to resolve the problem of fouling. The aluminium body of the H-ADCP was varnished with a Cu-based anti-fouling paint. The PVC body of the V-ADCP did not require anti-fouling treatment but was covered with a plastic sheet to facilitate ordinary cleaning. The V- and H-ADCP transducers were protected with a thin layer of zinc-oxide cream ( $\text{ZnO}_{\text{min}} > 15\%$ ); the optical window of the turbidimeter was kept clean with a built-in anti-fouling wiper (Hydro Wiper®; Zebra-Tech Ltd). The same precautions were carried out on the equipment at the western entrance to the port.

### 2.3 Portable monitoring system

A Teledyne RDI 600-kHz Workhorse® over-the-side-mounted V-ADCP with bottom-track function, using a 316L stainless-steel bracket, was used to collect current velocity, direction and BS data. RDI software ‘WinRiver® II’ running on a laptop computer was used to collect and display the data. This software determines and records current velocity and direction in predetermined vertical bins along each transect surveyed. The direction and speed of the vessel and the current velocity in three directional axes at selected collection data ranges, the depth of the bottom, and the surface water temperatures were recorded. An internal fluxgate compass allowed the instrument to correct the ADCP current velocity and direction regardless of vessel speed or orientation. Navigation data received from an external global positioning system (GPS) were also collected and used in the data post-processing.

The hydrological data were collected using a CTD probe equipped with a number of auxiliary sensors, including a turbidimeter and a dissolved-oxygen sensor. Before the beginning of the dredging, all the probes were factory adjusted to obtain comparable results.

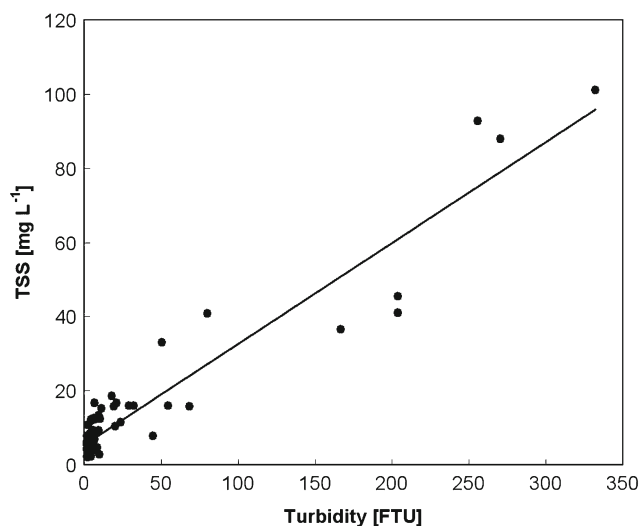
Water samples were collected with a Niskin bottle at different depths from the surface to the bottom and analysed using the gravimetric method. The depths at which the water samples were collected were selected to coincide with selected layers of high optical turbidity by following the turbidity profile on video during the descent of the CTD. Following Capello et al. (2009), the filters were weighed on a Sartorius balance (accuracy  $\pm 10 \mu\text{g}$ ). The TSS concentrations in the water samples (78 samples) were then matched to the turbidity data to calibrate the turbidity sensor response:

the linear regression of the data (turbidity vs. TSS; Fig. 2) yielded a good correlation ( $R^2=0.90$ ).

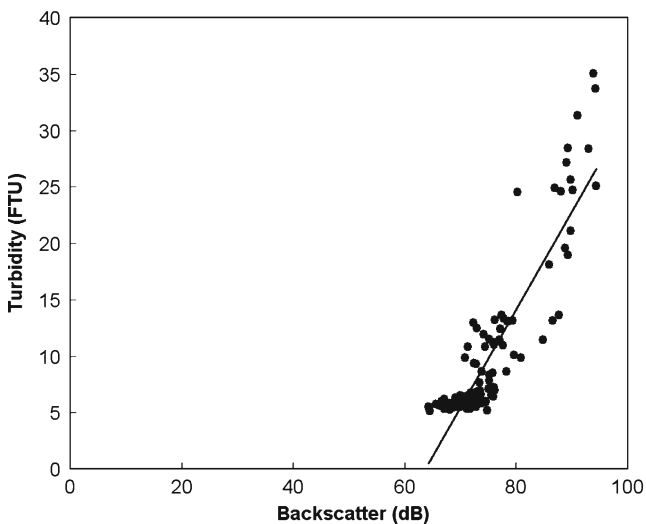
In the first 2 weeks of the dredging, the frequency of the monitoring activities with the portable system was daily, and after that was weekly. During the pre-dredging phase, the ADCP BS signal was calibrated and converted into TSS using DRL Sediview Software and Method (Capello et al. 2010). Because Sediview is a post-processing method that cannot give real-time results, and because the variations in echo intensity are comparable to those of the turbidity with a good approximation ( $R^2=0.80$ ; Fig. 3), during the monitoring of the dredging echo intensity was used both as a surrogate measure of the TSS and to identify and follow the turbid plume in real time.

## 3 Results

Given the large quantity of data acquired during the 19 months of work (July 2009–February 2011), we have presented only a few of the most representative situations that emerged during the monitoring, the different methods applied for data processing to better evaluate the response of the different instruments, and an overview of the values recorded during the dredging. We have not reported examples of the monitoring around the grabs as these were exclusively employed in the innermost sectors of the port basin—an area with low hydrodynamics—where the grabs generated a turbid plume that was too weak to reach the port entrances, thereby not posing any danger for the area surrounding the port. Contrary to what happens, for example, in the ports of northern Europe, it should be noted that the



**Fig. 2** Linear regression of turbidity vs. total suspended solids (TSS) data (78 samples) obtained with TSS sampled at the beginning of the dredging



**Fig. 3** Linear regression of backscatter (BS) vs. turbidity data

tide has low values inside the Port of Genoa, generally less than 30 cm, and its effect on the currents and sedimentary transport can be considered negligible.

### 3.1 Fixed station near the eastern entrance to the port

We have provided details for 2 days with different meteorological conditions on which current and turbidity measurements were carried out at the eastern entrance to the port.

#### 3.1.1 Data from 14.05.2010

On this day there was a gentle SE wind, calm sea and light rain. The backhoe was working near the breakwater, about 1,300 m from the eastern fixed station. The turbidimeter at the fixed station registered turbidity levels within the normal range (8–14 FTU) established during our preliminary campaign to characterise the area (Capello et al. 2010). In Fig. 4a, it is possible to see the typical dynamics of the current generated at the eastern entrance to the port by a SE wind. In this case, because of the rotation due to the configuration of the port basin, an outbound current ( $\rightarrow$ E) was generated near the breakwater, corresponding to the first 20 measuring cells of the H-ADCP (about 80 m). An inbound flux ( $\rightarrow$ W) was also generated in the central part of the entrance channel, corresponding to the second 20 measuring cells. Cell 20 highlighted a transition zone between the outbound and inbound currents. It is also possible to note that the outbound current (data monitored by the early-warning system) never exceeded the imposed limit value of  $20 \text{ cm s}^{-1}$ .

#### 3.1.2 Data from 06.12.2010

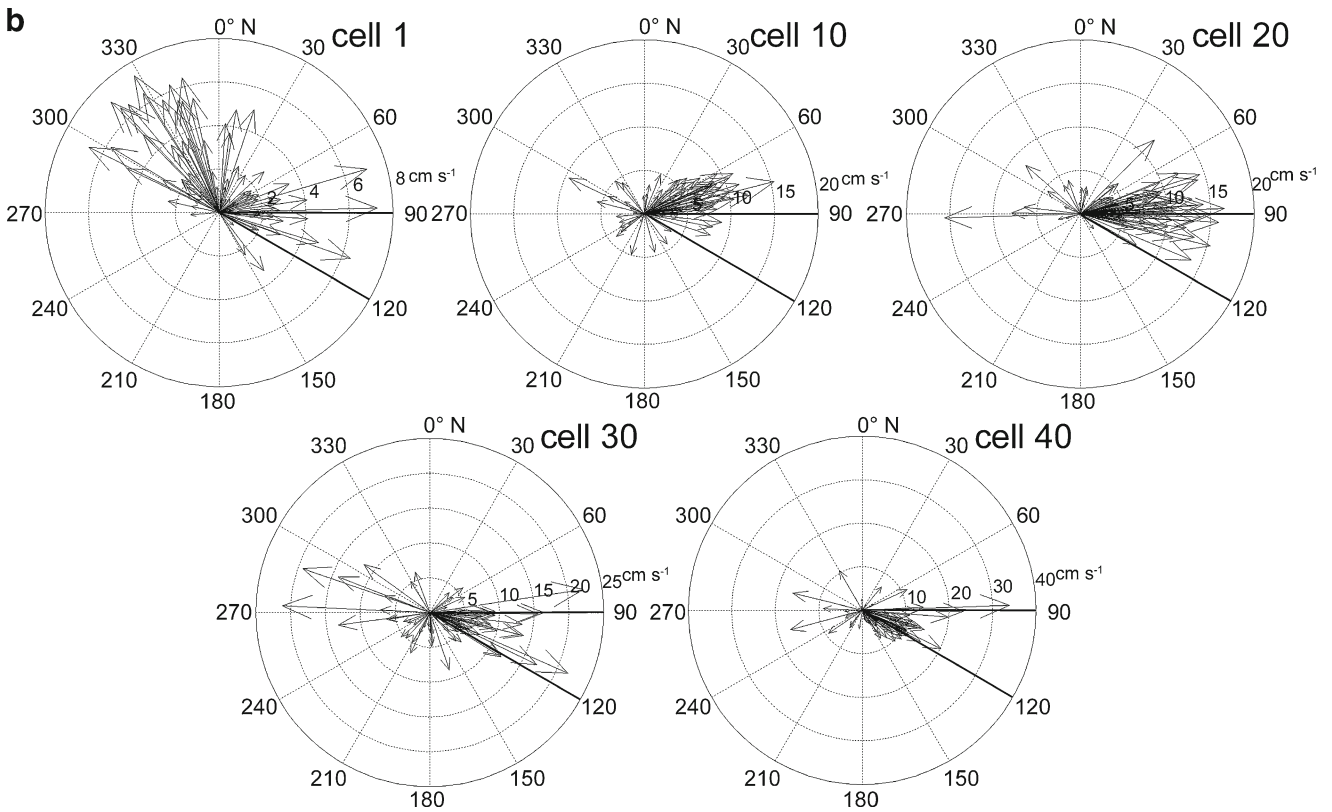
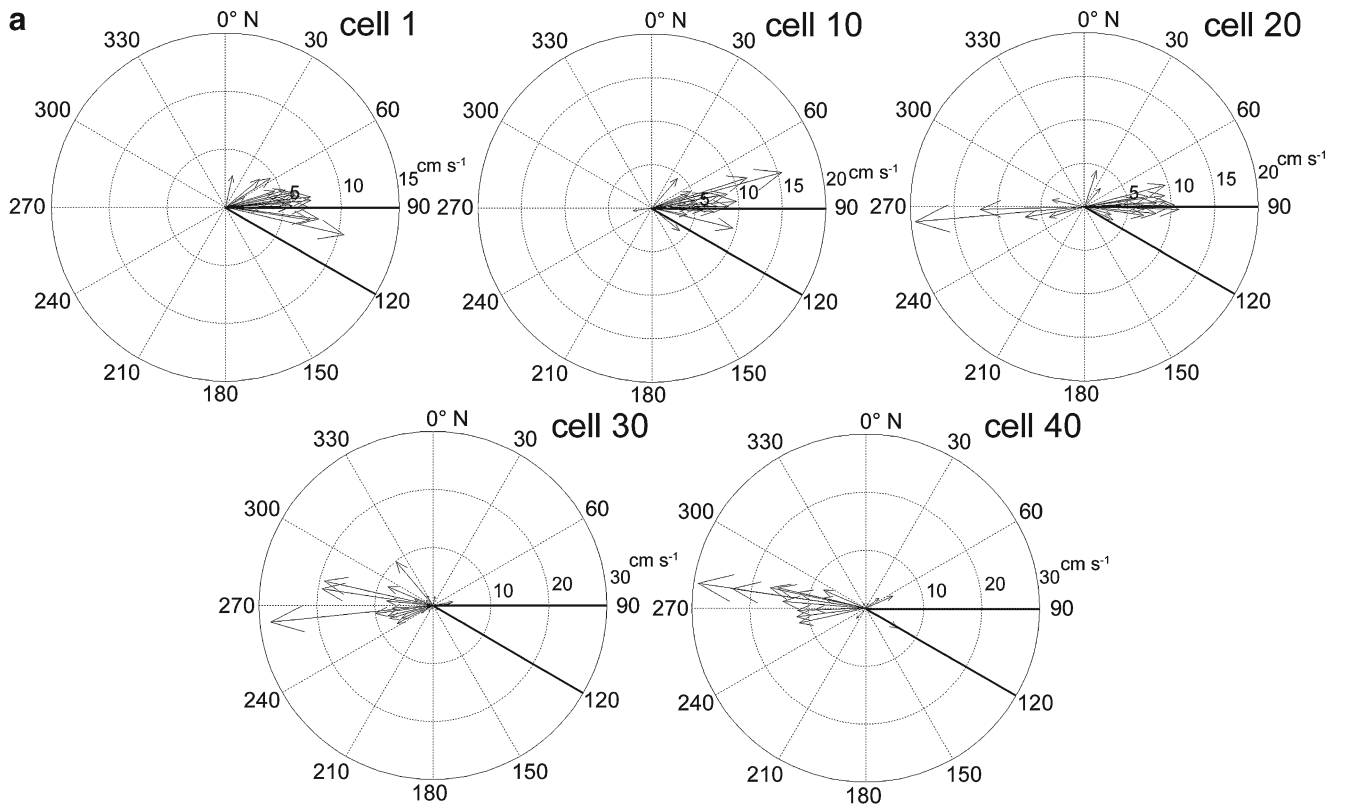
On this day, there was a strong wind from the N, choppy sea and rain. The TSHD was working in the eastern entrance channel near the breakwater, about 2,000 m from the eastern fixed station. The turbidimeter registered relatively high turbidity values (max. about 30 FTU), largely due to the sedimentary transport of the torrent that empties just outside the eastern port entrance. This situation is also highlighted by the first compass diagram in Fig. 4b, where it is possible to see that several current vectors tend to the NW and, therefore, the currents enter the port area, despite the northerly wind. In Fig. 4b, it is also possible to see the typical current dynamics generated at the eastern entrance by a northerly wind. In this case, an outbound current ( $\rightarrow$ E) is generated along the entire entrance channel; only in the first cell is it possible to see a notable variation in the current direction due to the creation of reflux waves near the breakwater by the northerly wind. It is also possible to note that the outbound current at the eastern port entrance (data monitored by the early-warning system) only very rarely exceeded the imposed limit of  $20 \text{ cm s}^{-1}$ ; the values above  $20 \text{ cm s}^{-1}$  registered in cells 30 and 40 were momentary and so did not trigger the early-warning system.

#### 3.1.3 Fixed station: general results

The turbidity values generally remained below the limit we had imposed (30 FTU) during the monitoring period. The values only approached and exceeded the limit in two situations: when the torrents were full and when the TSHD was in operation near the eastern port entrance. In the first case, the turbidity values were between 15 and 40 FTU. For example, turbidity measurements taken at the western fixed station, near the mouth of the Polcevera Torrent (see Fig. 1) over 25 continuous days in autumn 2010, revealed two high-turbidity events due to the action of the torrent that generated values of ca. 25–30 FTU (normal turbidity range is 1–7 FTU). In the second case, with the TSHD in operation near the eastern fixed station, the turbidity exceeded the limit value (maximum registered, about 80 FTU) during the mobile monitoring of the plume.

### 3.2 Mobile monitoring

Below we describe two examples of the monitoring around the TSHDs and backhoe, the approaches adopted to analyse the data during the post-processing, and the principal results obtained.



◀ **Fig. 4** Compass diagrams displaying the distribution of the current vectors over 24 h in five different representative cells (1, 10, 20, 30 and 40) as measured by the H-ADCP. The current direction and intensity are expressed in °N and centimetres per second, respectively; E–SE (90–120°N) corresponds to the outgoing flux. Current vector magnitude has a specific scale for each compass (**a** data from 14.05.2010; **b** data from 06.12.2010)

### 3.2.1 Monitoring around the TSHDs

Monitoring around the TSHD was carried out in calm conditions, with a gentle northerly wind while the dredge was operating along the breakwater.

We have reported an example of the good correlation ('Portable monitoring system') of the turbidity values with the BS values of the portable V-ADCP of the samples taken (Fig. 5). The turbidity and BS profiles have a very similar trend, highlighting a turbid plume only near the dredge and relatively low values in a range of 5–38 FTU with a maximum near the dredge, corresponding to 64–94 dB of backscatter.

Figure 6 shows that all the current vectors point towards the W–NW, and so the currents entered the port. The magnitude of the current, greater at the surface because of the wind, varied between 0 and 14 cm s<sup>-1</sup>.

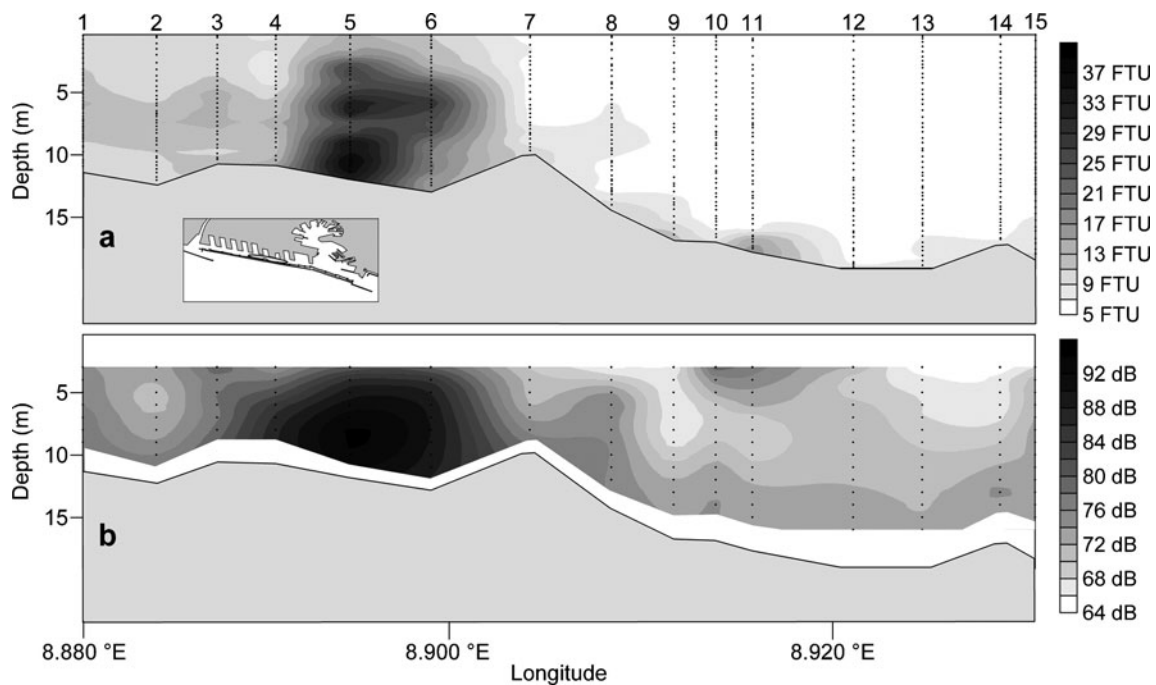
### 3.2.2 Monitoring around the backhoe

The monitoring of the backhoe operations occurred during calm seas with a gentle SE wind and cloudy sky. The

backhoe was working near the breakwater to remove the bottom boulders that had formed part of the ancient breakwater which was dismantled at the end of the 1930s. Near the backhoe, the currents flowed SW–NW in the entire water column and the turbid plume created by the movement of the bucket towards the sediment barge tended to remain inside the port. The turbidity values remained relatively low (maximum 17 FTU) due to the previous removal of the fine sediment fractions carried out by the TSHDs.

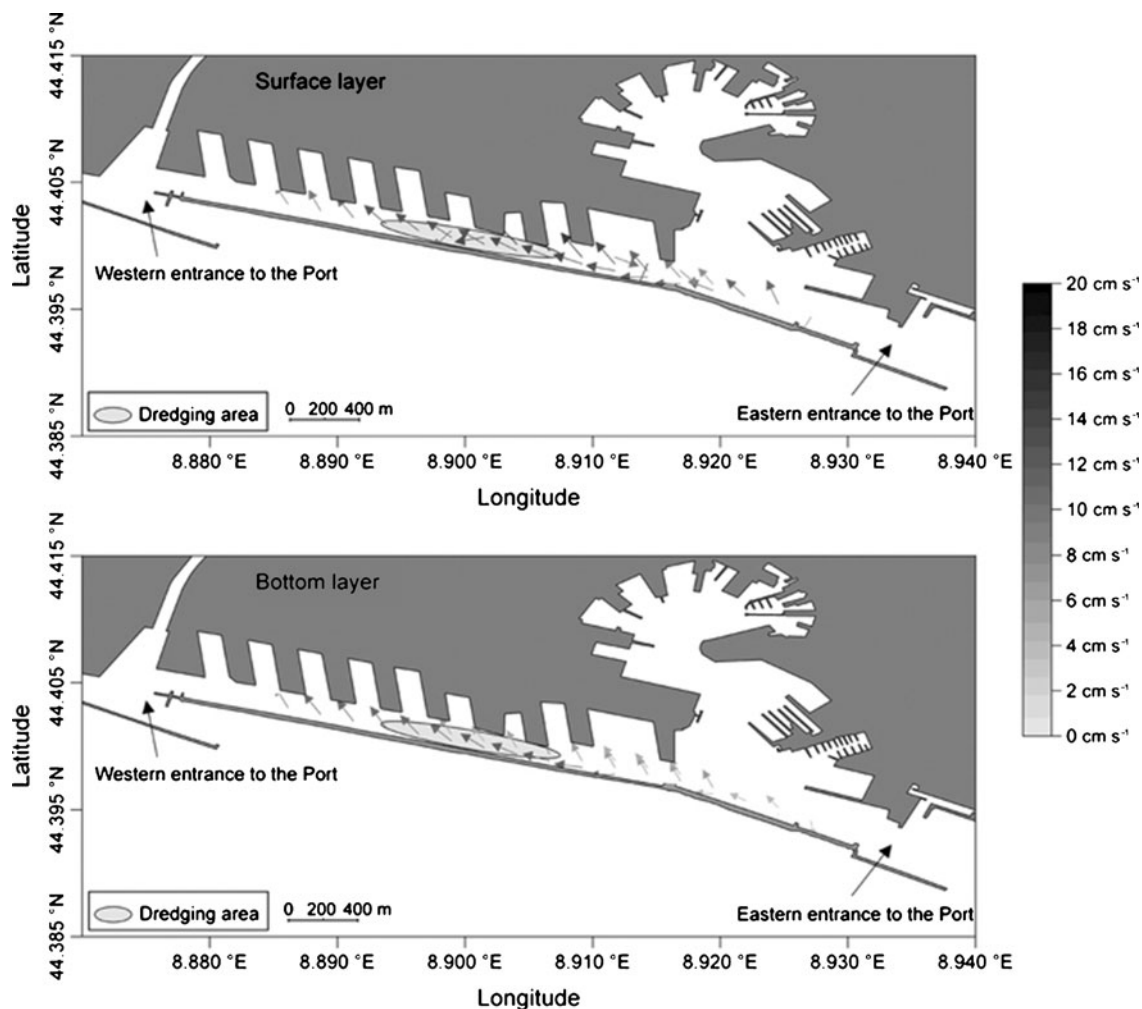
### 3.2.3 Mobile monitoring: general results

The turbidity values monitored by the mobile station at different distances from the TSHD (50, 100 and 200 m) and the backhoe (50 and 100 m) are summarised in Table 1. Generally, the highest values were found near the TSHD (Fig. 7) at a distance of 50 m in the upper layer and 100 m at the bottom. The lowest values were generated by the backhoe (Fig. 8), including a maximum of 37 FTU near the bottom 50 m from the dredge and 3 FTU in the entire water column 100 m from the dredge. The TSS values are reported in Table 2. The same quantity of material (1–22 FTU, 7–14 mg l<sup>-1</sup>), whether expressed in turbidity units or milligrams per litre, can be found 200 m from the TSHD and 100 m from the backhoe.



**Fig. 5** Profiles of the vertical distributions of turbidity (**a**) and the correlated V-ADCP backscatter (**b**) along the internal side of the breakwater. The points in the water column in (**a**) correspond to the samples of the CTD probe; in (**b**) they correspond to the V-ADCP

measuring cells. The two vertical scales (depths) are exaggerated. Map of the CTD stations, the ADCP transect and the location of the dredging area are shown in the *box*



**Fig. 6** Example of the dynamics along the internal side of the breakwater during the monitoring of the TSHD operations. The *arrows* indicate an inward current in both the surface and bottom layers (*above* and *below*, respectively), with intensity between 0 and 14 cm s<sup>-1</sup>

**4 Discussion**

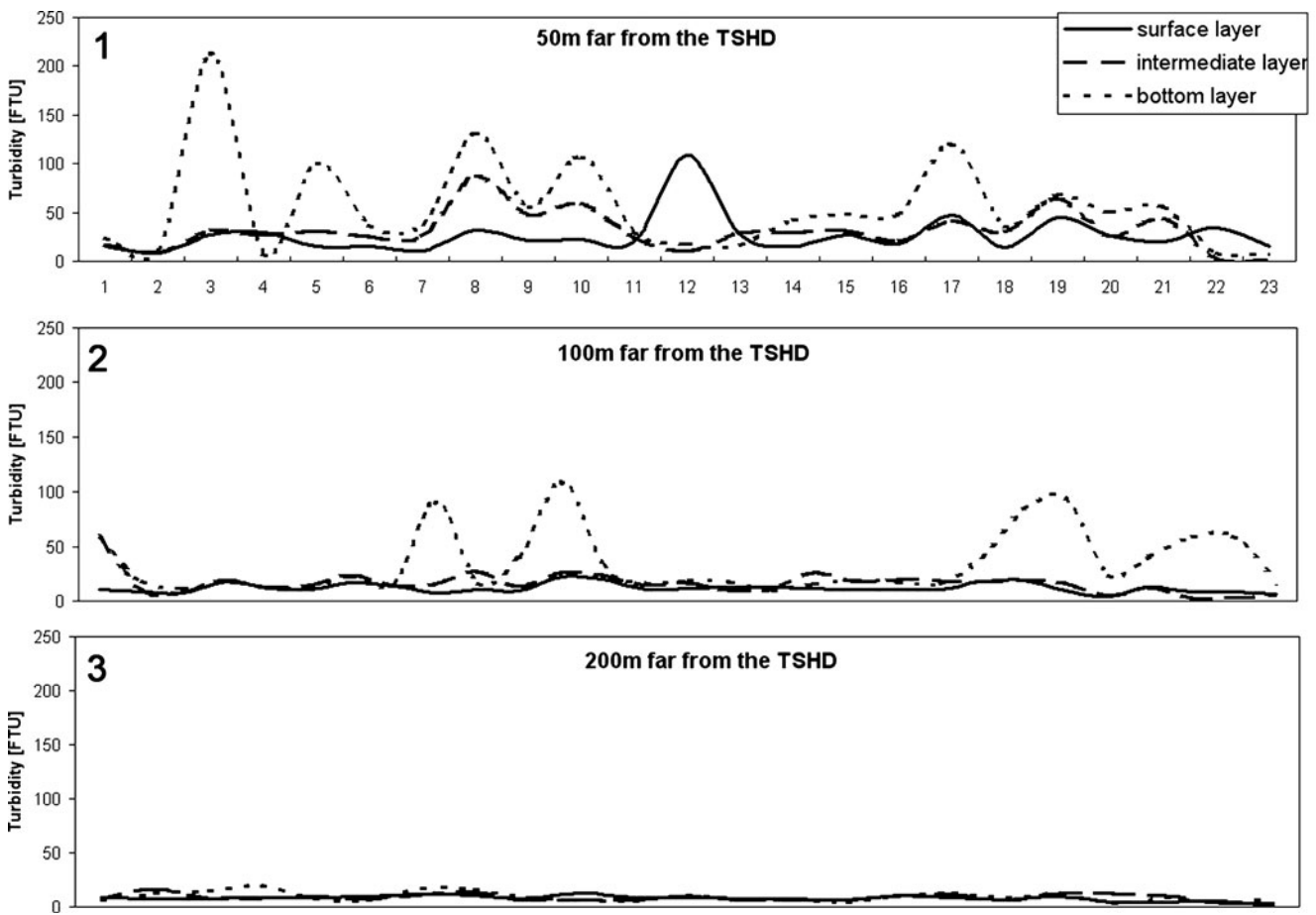
Dredging operations inside the port were monitored at the two fixed stations, which were installed to give due warning of the outflow of a turbid plume in the

direction of the *P. oceanica* meadow. Only in the event that the system registered turbidity levels above the limit (30 FTU) in concomitance with an outward current greater than the limit imposed (20 cm s<sup>-1</sup>) would the alarm be raised.

**Table 1** Turbidity values measured around the TSHD and backhoe; while for the TSHD typical turbidity values of the port are reached at 200 m, for the backhoe these values are reached by 100 m

Distance (m)	Surface layer			Intermediate layer			Bottom layer		
	Range (FTU)	Mean (FTU)	Std dev	Range (FTU)	Mean (FTU)	Std dev	Range (FTU)	Mean (FTU)	Std dev
TSHD									
50	5–110	27	20	2–90	32	20	5–215	55	49
100	4–25	12	4	3–60	17	10	10–110	35	28
200	1–15	8	3	2–20	9	3	7–14	10	5
Backhoe									
50	5–15	10	3	5–30	15	7	4–37	17	12
100	3–10	7	2	3–11	7	3	3–22	10	6





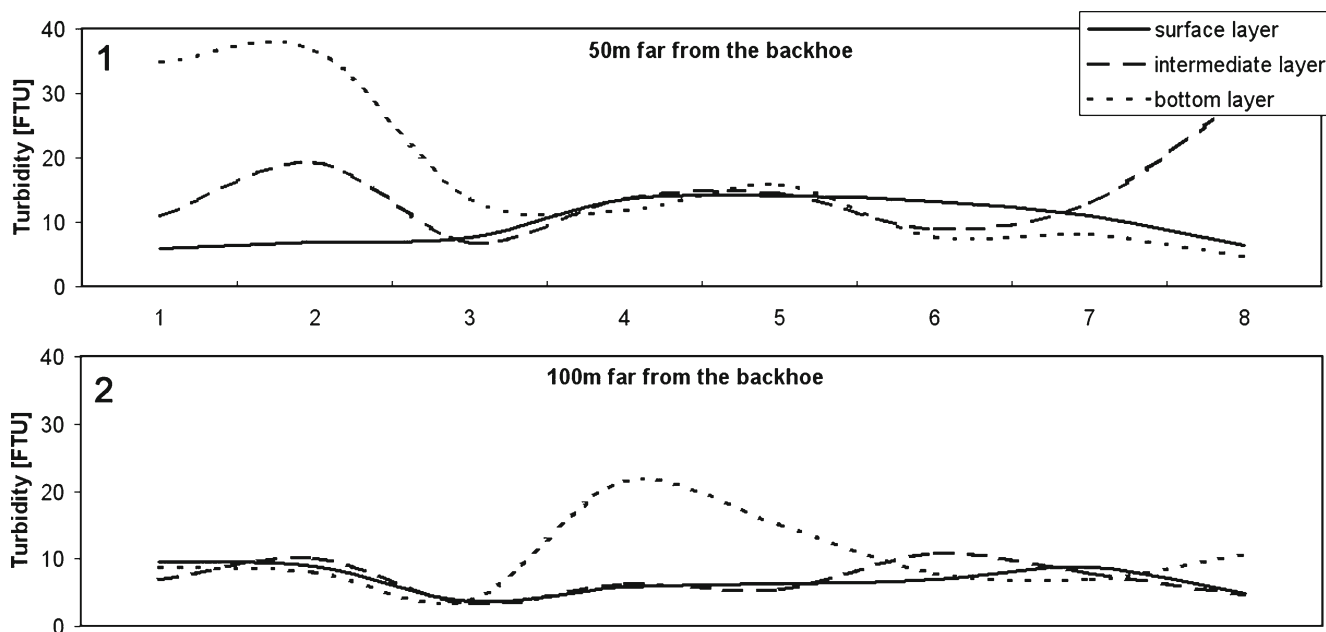
**Fig. 7** Turbidity values (y-axis) in the upper water layer (1 m below the surface; *solid line*), measured during the dredging in the intermediate layer (6 m below the surface; *broken line*) and in the bottom layer (1 m above the seafloor; *dotted line*), respectively, at 50 m (1), 100 m (2) and 200 m (3) from the TSHD. The x-axis only represents the sequence of the measurements

The two wind situations reported above (‘Data from 14.05.2010’ and ‘Data from 06.12.2010’) are typical of the Genoa area; the winds from the N–NE (0–30° N) and SE (135–150° N) are two of the most frequent winds in winter and summer, respectively (for details, see [www.idromare.it](http://www.idromare.it); [www.windfinder.com](http://www.windfinder.com)). Both winds cause eddies in the currents at the eastern port entrance, dividing the entrance canal into two with opposite current directions. In the case of SE winds, the currents on the southern side of the entrance flow outwards, while those on the northern side flow inwards. In the case of N winds, the currents in nearly the entire tract monitored by the H-ADCP flow outwards.

The turbidity data acquired near the TSHD by the mobile station during the monitoring programme (maximum 215 FTU near the seafloor) were higher than those obtained from the dredging simulation that involved the berthing operations of a ferry (Capello et al. 2010; 50–60 FTU maximum). However, the TSS values had an inverse trend, having values of about 80 mg l<sup>-1</sup> vs. 300 mg l<sup>-1</sup> (Capello et al. 2010). This difference may be due to various factors: (a) different sampling distances

from the point of perturbation (less than 50 m from the ferry during the pre-dredging experiment and never less than 50 m from the TSHD), (b) different sediment mobilisation mechanisms (resuspension of bottom sediments in the case of the ferry, disturbances caused by the draghead and overflow in the case of the TSHD) and (c) different material compositions sampled by the Niskin bottles for the calibration of the optic signal. In the last case, it should be noted that while the sediment collected around the ferry was composed of undisturbed small-medium bottom particles rich in iron oxides, the particulate material sampled near the dredge did not contain medium-large particles, only finer particles (i.e. silt and clay), because of the overflow (HR Wallingford Ltd and Dredging Research Ltd 2003). Only near the bottom around the draghead was there resuspension of uncohesive sediment. This was less than the overflow and difficult to sample because it lay under the dredge, and was not present or present only in small quantities at a distance of 50 m because it settled rapidly (HR Wallingford Ltd and Dredging Research Ltd 2003).

From the turbidity data analysed, it was possible to distinguish between the behaviour of a turbid plume generated by



**Fig. 8** Turbidity values ( $y$ -axis) in the upper water layer (1 m below the surface; *solid line*), measured during the dredging in the intermediate layer (6 m below the surface; *broken line*) and in the bottom layer

(1 m above the seafloor; *dotted line*), respectively, at 50 m (1) and 100 m (2) from the backhoe. The  $x$ -axis only represents the sequence of the measurements

a TSHD and a backhoe. At a distance of 50 m, the turbidity produced by the TSHD extended from the surface throughout the water column, due to the overflow, but with higher values close to the bottom. On the contrary, at a distance of 100 m, the values in the water column were reduced with high values only on the bottom due to resedimentation, and at a distance of 200 m the entire water column had relatively low values ( $<30$  FTU). Instead, at a distance of 50 m, the turbidity produced by the backhoe was generally lower than that measured around the TSHD and showed values higher than 30 FTU only near the bottom, while at a distance of 100 m the values in the water column were much reduced with only a few noticeable values near the bottom.

The turbidity values recorded around the TSHD were similar when it was working inside the port (monitored by the fixed station) and outside near the *P. oceanica* meadow (outside the monitoring of the fixed station). The turbidity levels near the *P. oceanica* meadow during the pre-dredging phase were 4–6 FTU, corresponding to 0.5–6.0  $\text{mg l}^{-1}$

(Capello et al. 2010) and 26–150  $\text{gm}^{-2} \text{day}^{-1}$ . These values are in agreement with those found in the meadow of the Golfo di Baratti (Tuscany, Italy; 2–6 FTU corresponding to 0.3–3.2  $\text{mg l}^{-1}$  and 40–390  $\text{gm}^{-2} \text{day}^{-1}$ ) and around the meadow of Loano (Liguria, Italy; 1–5 FTU corresponding to 1.8–4.5  $\text{mg l}^{-1}$  and 60–410  $\text{gm}^{-2} \text{day}^{-1}$ ), both monitored during the Interreg IIIC European Project ‘Beachmed-e’, sub-project EUDREP (Nicoletti et al. 2007a, b, 2008). Prolonged periods of high turbidity produced by the dredging activity, with values similar to those recorded near the dredge (about 2–215 FTU corresponding to 7–80  $\text{mg l}^{-1}$ ) would have had negative consequences for the *P. oceanica* meadow, as documented in other cases of dredging operations in or near/around seagrass areas (Erftemeijer and Lewis 2006).

There is very little literature on research into turbidity during dredging in other parts of the world. Instead, there are reports on the data acquired during monitoring and we have reported some datasets below for comparison with our findings. Assuming that the turbidity values are site specific and that their variations during dredging operations also depend on environmental factors beyond the dredging itself (e.g. tides, specific factors influencing the North Sea and the Atlantic and Pacific coasts of the USA, and fluvial supply, especially for many ports in northern Europe), and considering the background values, the data recorded around the TSHD at Genoa are comparable with those of other studies (Table 3). In the cited examples, only New Bedford Harbor (USA) showed background values (2.1 NTU and 5.7  $\text{mg l}^{-1}$ )

**Table 2** Total suspended solids (TSS;  $\text{mg l}^{-1}$ ) at increasing distance from the two dredges calculated by the correlation turbidity vs. TSS

Distance (m)	TSS ( $\text{mg l}^{-1}$ ) range	
	TSHD	Backhoe
50	7–80	8–20
100	7–45	7–14
200	7–14	–

**Table 3** Comparison of turbidity and TSS values measured by different authors in different situations during the monitoring of sediment treatment activities

Authors	Port	Dredges	Background turbidity and TSS	Dredging turbidity and TSS	$\Delta$ turbidity and TSS	Notes
This paper	Genoa (Italy)	TSHD	2–6 FTU 0.5–6 mg l <sup>-1</sup>	2–215 FTU 7–80 mg l <sup>-1</sup>	209 FTU 6.5–74 mg l <sup>-1</sup>	Plume absent at 200 m
Healy and Tian 1999	Pine Harbour Marina (New Zealand)	Dredge/barge	4.3 NTU 38 mg l <sup>-1</sup>	25–30 NTU 67–70 mg l <sup>-1</sup>	20–25 NTU 29–32 mg l <sup>-1</sup>	Plume present only close to the bottom at 250 m
Dragos 2009	New Bedford Harbor (USA)	Disposal of navigational dredged material inside silt curtain	2.1 NTU 5.7 mg l <sup>-1</sup>	>110 NTU >260 mg l <sup>-1</sup>	>108 NTU >254.3	–
Clarke et al. 2005	Redwood City (USA)	Knockdown barge	2–55 NTU 45 mg l <sup>-1</sup>	– 600 mg l <sup>-1</sup>	– 555 mg l <sup>-1</sup>	50–100 mg l <sup>-1</sup> after 13 min
Reine et al. 2002	Cape Fear River (USA)	Barge	– –	– 190 mg l <sup>-1</sup>	– –	60–80 mg l <sup>-1</sup> at 300 m

FTU formazine turbidity unit, NTU nepheloid turbidity unit, TSS total suspended solids,  $\Delta$  difference between dredging and background

similar to those found in Genoa, though it is located in a bay, at a river estuary. The other examples have higher background values, in terms of TSS; 38 and 45 mg l<sup>-1</sup> for the Pine Harbour Marina (New Zealand) and Redwood City (USA), respectively. During the dredging activities, the TSS values found in Genoa were lower than those recorded in New Bedford Harbor (>260 mg l<sup>-1</sup>) and were only similar to those reported by Healy and Tian (1999) for the dredging of the Pine Harbour Marina approach channel (67–70 mg l<sup>-1</sup>). In the other examples, the TSS values were much higher than those of Genoa, and a maximum in the case of Redwood City (located in a creek and with natural high background values of 45 mg l<sup>-1</sup>), where an increase of 555 mg l<sup>-1</sup> has been reported, partially due to the flooding of the creek. The typical background condition of the Port of Genoa, characterised by water masses relatively poor in TSS, makes the differences between turbidity and TSS dredging vs. background (the  $\Delta$  column in Table 3) particularly significant; this condition requires greater attention during environmental monitoring.

## 5 Conclusions

We have presented results for the two different monitoring systems used to follow the turbid plume generated by dredging and the other port operations in the Port of Genoa, and have described the different use of the results to estimate the transport of suspended sediments by the currents. The fixed monitoring system was installed in the Port of Genoa in July 2009 and operated until the beginning of February 2011,

when the dredging operations were temporarily suspended. The purpose of the system was to acquire and process data for uploading to an *ad hoc* database connected to an early-warning system that would avoid the need to employ a technician 24 h a day to check the enormous quantity of input data and advise the dredging company of any adverse situations.

Because of the configuration of the port basin and the dependence of the current dynamics on the wind–wave conditions, as revealed by our preliminary study of the area, it was concluded that a wind from the SE (the most frequent wind) or N would create outbound currents on the southern side of the entrance channel, as also demonstrated by the analysis of the data presented above. It was, therefore, decided to install a 300-kHz H-ADCP, even though it would not cover the entire eastern entrance, as it could provide more than adequate coverage of the critical currents.

The portable monitoring system enabled us to study the phenomena occurring at close quarters and better understand the evolutive dynamics of the turbid plume generated by dredging operations with different types of dredging tools (backhoe and TSHD) under different wind–wave conditions. These two dredging tools generate two different turbid plumes with different behaviours and diffusive tendencies. The mobile monitoring using a CTD probe with a turbidimeter and an ADCP for the continuous acquisition and visualisation of data in real time (bottom-track function) proved ideal for monitoring the extent and diffusion of the turbid plume in relation to the currents operating in real time. The choice of these two instruments enabled us to obtain results such as the direct visualisation of the turbid

plume that would not have been possible with other monitoring systems (e.g. the use of a CTD probe with turbidimeter on its own, sampling with a Niskin bottle and subsequent laboratory analysis).

The data indicate that the choice of a combined monitoring system, consisting of an automated fixed system and a mobile one, can be a good practical solution for reaching two different objectives that could not be reached with a single instrument: (a) to follow the turbid plume and ensure that it did not flow out of the port basin (objective of primary importance in the case of Port of Genoa), contaminating the surrounding area by dispersing contaminants found in the mobilised sediments or damaging nearby coastal habitats or *P. oceanica* meadows; and (b) to study the behaviour of the turbid plume created by different dredging tools (backhoe and TSHD) under different wind–wave conditions.

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