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Influence of hydrodynamic features in the transport and fate of hazard contaminants within touristic ports. Case study: Torre a Mare (Italy)

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Abstract

The environmental quality of Torre a Mare port (Italy) was assessed evaluating on one side, the chemical concentration of nine metals and metalloids within bottom sediments and on the other one, by exploring the impact of hydrodynamic conditions in contaminant's transport within the most polluted basins. The investigated port was selected as case study because it resulted much more polluted than it was expected based on the touristic port activities and related stressors loading on it. In order to determine the origin and fate of contaminants in the port basin, 2D numerical simulations were carried out by MIKE21 software. The hydrodynamic module (HD) based on a rectangular grid was initially used to characterize the flow field into two domains that cover the inner and offshore harbor area. Then, advection–dispersion (AD) and water quality (WQ) modules were coupled in order to simulate the simultaneous processes of transport and dispersion of hypothetical pollutant sources. The dissolved/suspended sediment particulates (DSS) were selected as contaminant tracers. The comparative analysis between simulation responses and the real metal contaminant distribution showed high agreement, suggesting that contaminants mainly come from outside port and tend to accumulate in the inner basin. In fact, hydrodynamic circulations cause

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inflowing streams toward the harbor entrance and the particular port morphology hampers the exit of fine sediments from the inner basin, enhancing thus the accumulation of sediment-associated contaminants within the port area. The study confirms that the quality of touristic port areas strongly depends on both pollution sources located within and outside the port domain and it is controlled mainly by the hydrodynamic-driven processes.

Keywords: Environmental science, Hydrology

1. Introduction

Identification of contaminant sources is of fundamental importance for the hazard assessment protocols of port areas, which are continuously subjected to increased anthropogenic pressures that dramatically affect their quality. Port sediments are the matrix of most concern since they act as sink for all pollutants introduced in the port basin by point and diffuse sources. (Del Valls et al., 1998, 2004; Macken et al., 2008; Souza et al., 2016). Determining cause-effect relationships resulting from mixtures of chemical pollutants within sediments is impossible using separate observational components (e.g. chemical based only or ecologically based only). At this proposal, integrated approaches has proven to be a correct methodology for the sediment quality assessment. Pioneering studies on Triad Sediment Quality (SQT) approach, based on three main Levels of Evidence (LoE), chemical contamination, toxicity and biological data, were introduced by Chapman (1989) and further developed (Chapman, 2000, 2002; 2001; Long et al., 1998a, b, 2006). Indeed, the application of Weight of Evidence (WoE) approach based on multiple Level of Evidence was recently recognized as the most effective tool to determine possible adverse impact triggered by contaminated sediments (Piva et al., 2011; Mali et al., 2016; Regoli et al., 2014; Benedetti et al., 2014). Nevertheless, besides of chemical, biological, ecological and toxicological LoEs, evaluation of other factors and parameters become still necessary to reach a reasonable understanding of all pollution sources and to assess comprehensively the contamination trend of the bottom sediments. (Mali et al., 2016; 2017a).

The manner in which this multiple information are included in the assessment procedure, substantially affects the quality responses on pollution source identification and definitively the environmental managing protocols to undertake for port remediation (Grifoll et al., 2010; Mali et al., 2017b).

The main pollutants loading on a touristic port are the activities occurring within inner basins (*e.g.* yachting, maintenance and repair practices, docking maneuvers, etc.) and those related to external pollution sources (*e.g.* dumping of sewage contiguous waters and some seasonally entertainment and recreational activities occurring nearby the port area). Being sediments the last destination of contaminants, they constitute an efficient means for water-quality assessment,

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thanks to their tendency to accumulate contaminants in concentration higher than those observed in the water column. Therefore, the geo-bio-hydro-chemical features of sediments can be used to deduce sources of pollution and natural weathering trends (Viguri et al., 2007; Reis et al., 2009; Cossa et al., 2014; Mali et al., 2015; 2017c).

In order to identify the potential sources of contaminants and especially their spatial distribution within the port sediments, it is necessary to get insight into the port morphology and hydrodynamic conditions occurring both inside and offshore port area, being them factors influencing the transport of sediments, especially the finest ones, which are the main vehicles for contaminant dispersion.

In our group, previous studies have been carried out for spatial distribution assessment within touristic ports located alongside the southern Adriatic coast of the Apulia region (Italy) (Mali et al., 2015; 2016; 2017a, b, c), confirming that port activities seriously affect the quality of port aquatorium.

The aim of the present study is to investigate on the influence of hydrodynamic features in the transport and fate of hazard contaminants within a peculiar touristic port, Torre a Mare port, which resulted much more polluted than it was expected based on port activities and industrial stressors loading on it. In order to define the origin of pollution sources and to determine the pathways of contaminants before reaching and settling the inner port basins, 2D hydrodynamic simulation model was performed considering two domains covering the inner and offshore/outer harbor area. The dissolved/suspended sediment (DSS) particulates were selected as contaminant tracers for the hydrodynamic simulation and the modelling responses were compared to the real distribution pattern of nine metals and metalloids in order to validate the obtained results.

2. Materials and methods

2.1. Geographical, morphological and environmental setting

Port of Torre a Mare (TM) is located at the Southern Adriatic Sea on Italian coast. Regarding the geomorphological and geochemical features, the sediments of the study area are characterized by the presence of calcarenitic limestones and by sands as in the case of most of the Adriatic coasts. Port sediments contain both marine-derived carbonates and terrigenous fractions. This highly heterogeneous composition is dictated by several provenances and complex transport processes. The main sediment contribution comes from Ofanto River, one of the most important rivers flowing in the southern track of Adriatic coast. Sediments driven by North-Adriatic currents flowing southward coasts constitute other important inputs. In addition, complex mixing processes are also promoted by the presence of an inner anticyclonic current, which dominates the coastal area facing the harbor

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(Zavatarelli and Pinardi, 2003). Finally, a wide temporary watercourse's network affects the coast, but its contribution to the sediments composition is slightly influent, due to its seasonal regime.

TM port is considered a touristic port dealing with several port activities such as fishery, bathing and yachting as well as maintenance and repair activities considered the principal environmental stressors to the quality of the harbor basins. The impact of such anthropogenic pressure can be often observed in summer with the increasing of the fishery and yachting activities due to seasonal tourism demand. An important impact to the quality of the coastal area might be attributable to tourism firms operating alongside the coast for their unauthorized discharges.

2.2. Sampling

Six sampling sites were chosen in the Torre a Mare port in different basins as showed in Fig. 1. For each of the 6 sites, the sediment core samples were taken from the surface (0–0.5 m) and subsurface (0.5–1.5 m) layers of bottom sediments, for a total of 11 samples. The sampling campaign was carried out on 7th of May 2010. In order to obtain undisturbed samples, vibro-corer PF1, equipped with a liner was utilized and GPS system was exploited for correct positioning of sampling cores. Several aliquots of wet-sediment samples were stored in cleaned plastic bags at −20 °C. During the transport in the laboratory for further analyses, the sediments were conserved at 4 °C following procedures indicated in national guidelines.

Fig. 1. Map of study area and sampling sites within TM port.

http://dx.doi.org/10.1016/j.heliyon.2017.e00494

2.3. Analytical methods

Once in laboratory, sediments were defrosted, dried at 40 °C for 48 h and sieved with a ASTM sieves-set, for determining the granulometric fractions percentage, according Shepard classification (Shepard, 1954). The granulometric separation procedures follow Romano and Gabellini, 2001 method.

The determination of trace metal concentrations was made using inductively coupled plasma mass spectrometry (ICP/MS X Series Thermo Fisher Scientific) after sample mineralization by total acid digestion (HCl, HNO_3 and HF) (Pellegrini and Lucarotti, 2001). In order to avoid grain size effect, the fraction < 63 µm dried at 105 °C was used for the metal and metalloids determination. The results are expressed on the dry weight basis. The detection limits (LODs) were calculated from three replicates of procedural blanks (Table 1).

The certified reference material for Marine Sediment NIST 2702 (Inorganics in Marine Sediment) was used to check the accuracy and repeatability of the method (n = 3). Satisfactory recoveries at range from 80 to 100% for all elements were obtained.

Total organic Carbon (TOC) was determined by dry combustion at high temperatures by using a Perkin–Elmer 240B CHN Elemental Analyzer. The TOC values were calculated as difference of the total carbon (TC) determined before and after removing of carbonates (TIC) by reaction with hydrochloric acid, according to the formula TOC = TC-TIC, (Nieuwenhuize et al., 1994).

2.4. Spatial interpolation

In order to demonstrate spatial distribution patterns of heavy metals within sediment layers, the 3DField Software Package was utilized for converting concentration data into contour maps and surface plots. The kriging interpolation technique utilized by the programme is Universal kriging able to predict unknown values from data observed at known locations. This method uses a variogram to express spatial variation, and minimizes the error of predicted values, which are estimated by spatial distribution (Oliver and Webster, 1990). In a geostatistics context, kriging can be defined as a generalized linear regression technique used with a variogram model for spatial data interpolation. It is assumed that kriging provides statistically optimal and unbiased prediction (Ramanitharan et al., 2005; Gredilla et al., 2014).

Table 1. Detection limits (LOD, in mg·Kg^{-1}) of the analytical method applied.

	Al	As	Cd	Cr	Cu	Fe	Ni	Pb	V	Zn
LOD (mg.Kg^{-1})	0.4	0.05	0.001	0.001	0.001	0.015	0.001	0.01	0.001	0.3

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2.5. Numerical analysis

The details of the hydrodynamic patterns can provide a large frame of "quality state" of a port basin and could perform pollution source identification. In this paragraph, a practical application of a mathematical model on the TM port area is briefly illustrated.

An integrated and distributed MIKE 21 Flow Model was used to evaluate the current circulation condition, which was tested in previous works, some of them close to the investigated area (Malcangio et al., 2008; Damiani et al., 2009). The software package is designed in a modular structure and applicable to simulations of hydraulics, water quality and sediment transport in free-surface water bodies (DHI Water & Environment, 2009). In this research, the hydrodynamic (HD) module was initially used to simulate the hydrodynamics in the port area. HD equations are solved using the mass conservation and the RANS (the so-called Reynolds-Averaged Navier-Stokes) equations such as:

$$\begin{cases} \dfrac{\partial u_j}{\partial x_j} = 0 \\ \dfrac{\partial u_i}{\partial t} + \dfrac{\partial u_j u_i}{\partial x_j} = -\dfrac{\partial p}{\partial x_i} - \dfrac{\partial}{\partial x_j}\left(\tau_{ij} - \rho\overline{u'_i u'_j}\right) \end{cases} \tag{1}$$

where all variables are time averaged, u_i represents the velocities in the x_i coordinate directions, p is the fluid pressure, ρ the constant density, τ_{ij} the viscous stress defined as:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{2}$$

with μ the dynamic viscosity and $\overline{\rho u'_i u'_j}$ the Reynolds stress tensor that cannot be expressed exactly as a function of the mean flow variables and must be related to known quantities using a turbulence model. The HD model solves the equations (1), together with the conservation equations for salinity and temperature by means of the Explicit Finite Difference Method, with the Courant-Friedrichs-Lewy stability condition. The closure problem is solved in the turbulence module through the Boussinesq eddy viscosity concept, relating the Reynolds stresses to the mean velocity field. A constant value of 0.5 m^2s^{-1} for the eddy viscosity was set for the entire computational domain, which was tested in previous works (e.g. Damiani et al., 2009; Malcangio and Mossa, 2010).

Then, to reproduce the spreading of possible dissolved/suspended substances (DSS) subjected to advection and dispersion processes, two environmental modules, Advection-Dispersion (AD) and Water Quality (WQ), were implemented. The DSS was selected as the best tracer of contaminants, due to the well-known ability of finest sediments to be the main carriers for contaminant transport.

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In particular, the WQ module was carried out to explore on potential pollution sources located outside the port area and to investigate on contaminant pathways before reaching and settling in the inner part of the port. The AD equations are solved by the model using accurate finite volume schemes that ensure the mass conservation. It is possible to include the effects of the current density by activating the feedback option module between AD and HD, through which the density gradients become a forcing of the HD module. The transport equation for a component concentration C is formulated as:

$$\frac{\partial C}{\partial t} + \frac{\partial u_i C}{\partial x_i} = \frac{\partial}{\partial x_i}\left(D_i \frac{\partial C}{\partial x_i}\right) + SS \tag{3}$$

where *Di* is the dispersion coefficient in the i-direction and *SS* a source-sink term that can be defined as a discharge (in $m^3/s/m^2$). The dispersion coefficients were assumed to vary proportionally to the local current vector, i.e. there are separate dispersions in the longitudinal and transverse directions. To achieve the previously mentioned objective, two different simulations were carried out. With the first simulation, it was assumed the presence of a hypothetical conservative pollutant/tracer with concentration equal to 100% in the whole area of the largest domain external to the port and in the initial instant of simulation. Vice-versa, the second simulation considered the presence of the same component with the same instantaneous concentration (100%), but this time in the inner part of the harbour area.

The WQ environmental module was then coupled to the AD module in order to simulate the simultaneous processes of transport and dispersion. The system solves the process equations using a rational extrapolation method in an integrated two-steps procedure with the AD module. The aim of this module application was to analyse the spreading of a punctual pollution source of a conservative component that could come from outside port area. Since we suppose that the major pollutants determined within the TM port might come from outside port area, in the simulated model, we located the punctual pollution source at the entrance of the TM port with a constant contaminant concentration of 100%.

The investigation domain was mainly focused on the port basin (Fig. 2b) embedding also the outer coastal area (Fig. 2a), in which the maximum sea depth is approximately 12 m. The utility of large computational domains in coastal models has been demonstrated by previous research (e.g. Westerink et al., 1995) and mostly resides in allowing accurate specification of boundary conditions. Even more so in this case study, since the sea surface elevation was derived from the measurements undertaken at the station of Bari by the National Mareographic Network (RMN), distant about 44 km from the target port area. A further reason to consider also a larger domain consists in aiming to understand the interaction between the inner part of the port system with the surrounding environment.

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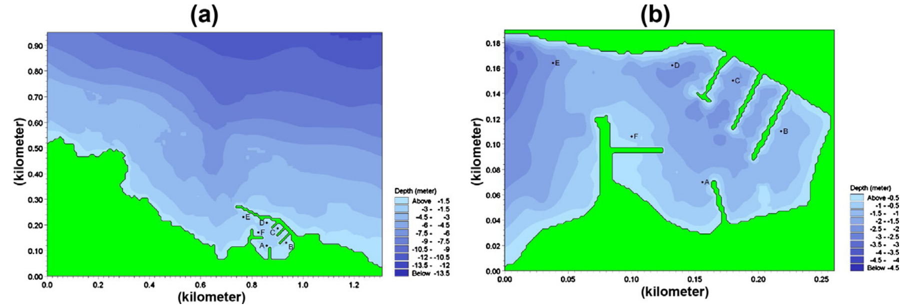

Fig. 2. Applied (a) large model domain, (b) small model domain, and bathymetry. Letters refer to sampling sites.

The bathymetry data were modeled using a rectangular grid with horizontal cell size of 10 m in both North and East directions for the enlarged domain (Fig. 2a), while the TM port was reproduced using a rectangular grid with 2 m spacing (Fig. 2b).

Verification study for the independence of the numerical results from the grid resolution was performed following the quantitative methodology and procedures proposed in literature (e.g. Wilson et al., 2001; Stern et al., 2006; Xing and Stern, 2010), only for the restricted domain of the port. For this purpose, two new simulations on a coarser and a finer mesh were carried out, with a grid refinement ratio $r_{12} = r_{23} = r = 2$, where the subscripts 1, 2 and 3 represent the fine (Fig. 3a), medium (Fig. 2b) and coarse (Fig. 3b) grids, respectively. If the solutions for the three grids are S_1, S_2, and S_3, respectively, the convergence of the solution is defined by

$$R = \frac{(S_2 - S_1)}{(S_3 - S_2)} \tag{4}$$

When $0 < R < 1$ monotonic convergence is achieved and the factor of safety method was used to estimate grid uncertainties. Exactly, to estimate how

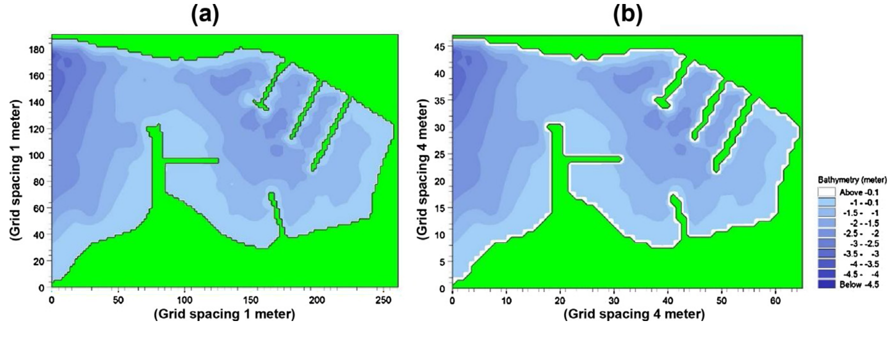

Fig. 3. (a) Fine grid, (b) Coarse grid, of the small model domain, with bathymetry.

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asymptotic the solutions are and thus the reliability of the error estimate, the observed order of accuracy *p* is calculated using Roache (1998) expression:

$$p = \frac{-\ln(R)}{\ln(r)} \tag{5}$$

which is valid only if the refinement factors between the three grids are equal. The solutions are expected to be in the asymptotic range when the observed order of accuracy is near the formal order of accuracy. The grid verification study showed R = 0.23, with an average p = 2.1. To get an error estimate on the numerical solution, the most modern form of Grid Convergence Index (GCI) derived by Roache (1998) and defined by

$$GCI = FS\frac{(S_2 - S_1)}{r^p - 1} \tag{6}$$

was calculated for the medium and fine mesh solutions, with FS the factor of safety. The GCI converted the estimate of the error in the numerical solution into an error of uncertainty band (Veluri et al., 2009). In the present case study the GCI resulted to be about 0.5%, considering the value of FS = 1.25, which is suggested by Roache (1998) for convergence studies with a minimum of three grids.

An additional assessment of the grid quality was done by inspecting the one-dimensional power spectra, as suggested by Cavar and Meyer (2012). As known in literature, the inertial subrange, that is the short wave number subrange of the equilibrium range which is not affected by viscosity, can be described by the Kolmogorov's K−5/3 power law, with K the wave number (Frisch, 1995). If the computational domain is well discretized, this inertial subrange can be identified by the abovementioned law in the velocity power spectra. Fig. 3 shows the power spectra that was calculated based on time series at frequency f = 0.8 kHz and consisting of 16384 samples, obtained by simulation with 2 m spacing grid and at a point located at the entrance of the harbor. Same analysis was carried out for other two points, outside and inside the port, obtaining same results as in Fig. 4. Exactly, the decay in the one-dimensional power spectrum with a slope of −5/3 can be

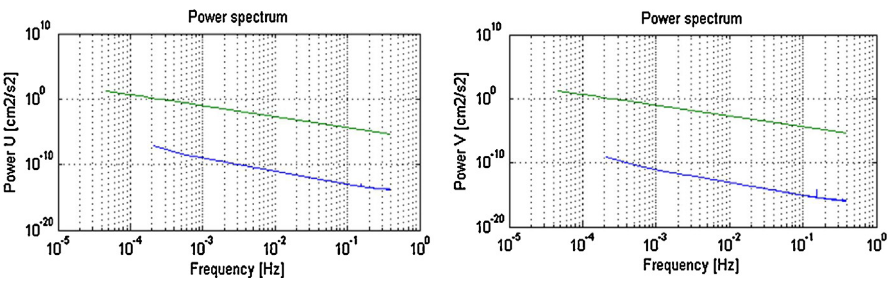

Fig. 4. Power spectrum densities of horizontal velocity components (U) (left), (V) (right). The green line above in both graphs represents the slope of −5/3.

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observed in Fig. 4 for both the averaged-in- depth U and V velocity components on the E and N direction, respectively. This result confirmed that effective simulation filtering occurs in the inertial subrange region, which is one of the basic demands for a well resolved calculation (Cavar and Meyer, 2012). Then, it can be stated that selection of the 2 m spacing grid is suitable for this study.

All simulations were performed considering a period of three months before the sampling campaign day (10th May), in order to recreate time-correctly the hydrodynamic conditions occurring within the port basin. It is well known that the circulation studies are strongly influenced by the selected forcing introduced in the system. It is generally assumed that the forcing functions that play an important role in water circulation dynamics are three: wind action, astronomical tide and wave action. For this study, for the enlarged domain model (Fig. 2a) the water level and the wind frequency registered during the abovementioned period by the mareographic station in Bari were considered as boundary conditions and as forcing function, respectively, constant in space. Subsequently, the output of this model, in terms of water level, was used as boundary condition input for the smaller domain confined to the TM port basin (Fig. 2b).

3. Results and discussion

3.1. Sediment features

The sediments of Torre a Mare port were composed by sand and fine grain size fractions in the range of 70.10% and 28.60% respectively. Nevertheless, differences in the grain size distribution were noticed when samples are divided in two groups, those coming from the inner basins and those located at the entrance of the port (Fig. 5). The amount of fine fraction resulted higher (ranging from 17% to 62%) in the inner sites while those of the sites located at the entrance of the port own a fine grain size fraction that range from 3 to 10%.

Several factors could influence the distribution of fine-grained sediment in the marine system, the most important being sediment transportation and sedimentary process (Suthers and Rissik, 2009; Tavakoly Sany et al., 2011; 2014).

The accumulation of finest sediments in the port could be facilitated by the presence of structures for protection against waves and marine currents (*i.e.* artificial headlands and breakwaters) and by all facilities employed to minimize the hydrodynamic energy inside the port area (Hancock et al., 2001). It seems that the peculiar morphology of TM port promotes a silting process. Indeed, winds coming from North-West and North and sometimes rainfall events, facilitated by the port morphology, convey the sediments spilled from nearby land canals toward the access channel of the port.

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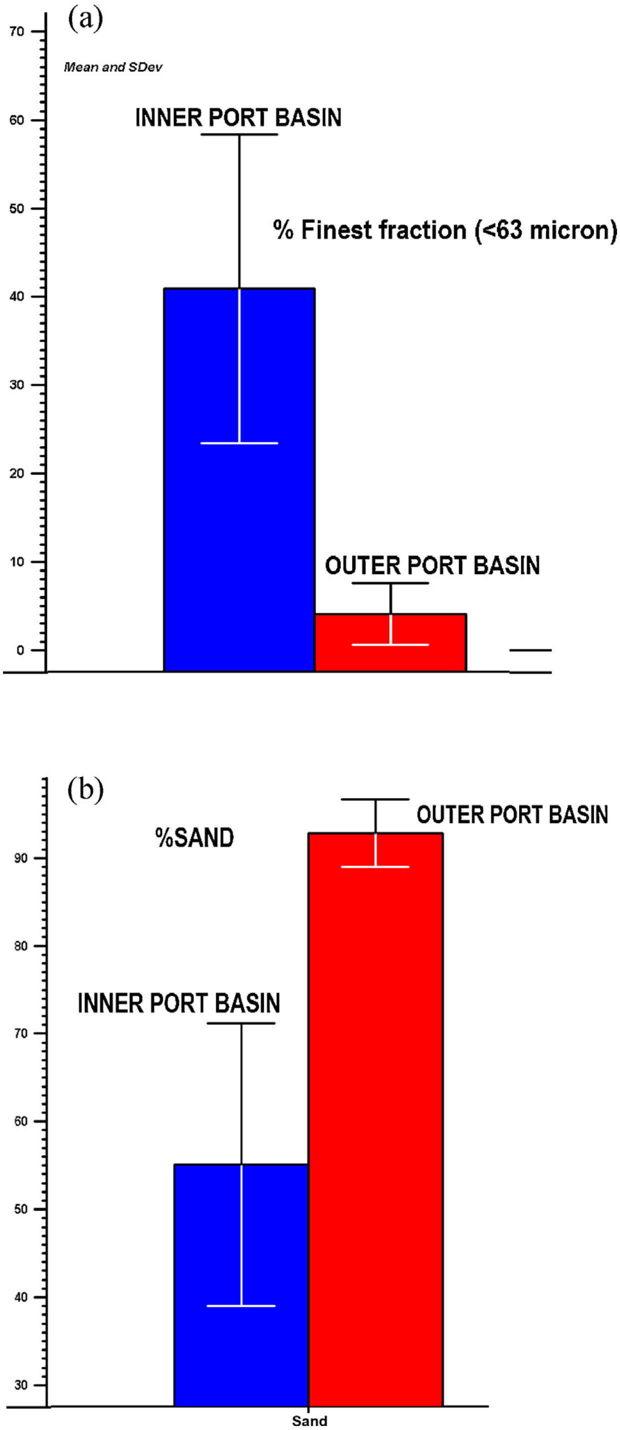

Fig. 5. Distribution (%$_w$) of (a) finest sediments and (b) sandy fractions (b) (expressed in %) within inner and outer port basins. The height of histograms represent the mean values, while the whiskers represent the mean±STD.

http://dx.doi.org/10.1016/j.heliyon.2017.e00494

3.2. Contaminant patterns

Table 2 shows the statistical concentration data (minimum and maximum concentrations and standard deviations, STD) for metals within the six sampling points. The metal distribution pattern, considering the whole database, was in the following order of concentrations: Zn > Cu > Pb > V > Ni > As > Cr > Hg > Cd, which differs substantially from both the upper crust concentrations (Turekian and Wedepohl, 1961) and the crustal average shale abundances (Wedepohl, 1995). We can notice that As, Cd, Hg, Pb, Cu exceed both upper crust concentration and crustal average abundances. Furthermore, the data are compared to Sediment Quality Guidelines defined by Long et al., Effects Range Low (ER_L) usually utilized as threshold above which the probability of toxicity could show an abrupt increase (Long et al., 1995). The maximum concentration of As, Ni, Pb and Cu exceed the ER_L values (reported in bold in Table 2).

As well as for granulometric distribution, marked differences are also revealed between the concentrations of heavy metals in the sampling sites located in the inner basin with respect to those located in the entrance of the port (Fig. 6), being higher in the inner port basin with respect to the outer one.

It is well known that fine particle sediments tend to concentrate contaminants (Salomon and Fôrstner, 1984; Horowitz, 1991), therefore the transport and fate of heavy metals are always associated with fine sediment dynamics. The morphology of the port structure probably facilitates the accumulation of silty sediments in the inner basin and consequently high levels of heavy metal concentration could be there registered (Villaescusa-Celaya et al., 2000; Palanques et al., 1995). To

Table 2. Metal concentrations (mg/kg ds) reported as mean, minimum, maximum and standard deviations in TM port. The data are compared to upper crust concentrations (Turekian and Wedepohl, 1961), to crustal average shale abundances (Wedepohl, 1995) and to Sediment Quality Guideline ERL (Effect Range Level) defined by Long et al. (1995). The bold characters indicated those metals (As, Ni, Pb and Cu) that have exceeded the ERL threshold in their maximum values.

	As	*Cd*	*Cr*	*Hg*	*Ni*	*Pb*	*Cu*	*V*	*Zn*
Mean	7.64	0.19	3.52	0.10	16.35	23.58	32.14	22.72	47.03
Min	5.81	0.05	0.05	0.05	10.83	5.41	3.73	12.05	11.58
Max	**9.77**	0.48	15.50	0.15	**21.31**	**49.05**	**74.05**	34.36	86.90
STD	1.33	0.15	5.35	0.04	4.04	15.98	26.89	7.84	30.32
Crustal average abudances	2	0.1	35	0.06	18.6	17	14.3	52	53
Upper Crost Concentrations	1.7	0.1	126	0.04	56	14.8	25	65	98
ER_L	8.2	1.20	81	0.15	20.9	46.7	34	-	150

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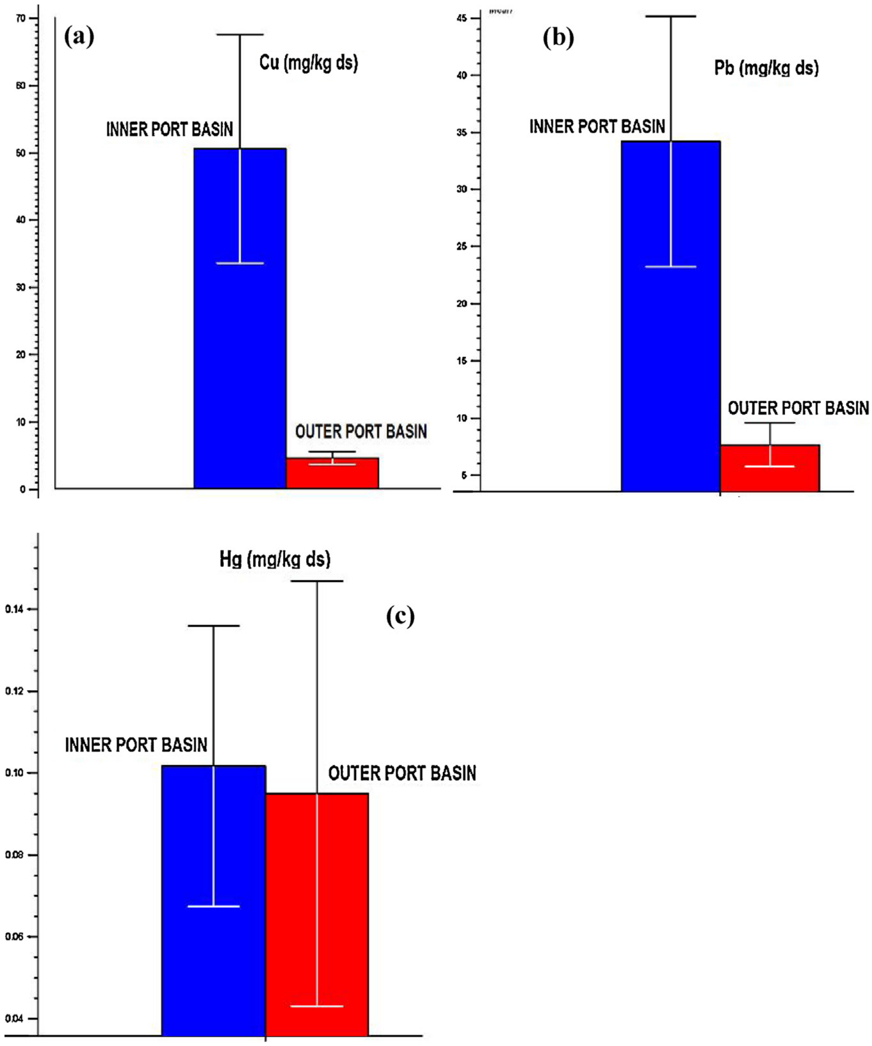

Fig. 6. Average concentration (mg/kg ds) of (a) Cu, (b) Pb and (c) Hg in the inner and outer port basins. The height of histograms represent the mean values, while the whiskers represent the mean±STD.

confirm this hypothesis, the simulation model of hydrodynamics within TM port was performed and the results obtained were compared to the real field data.

3.3. Mathematical model results

3.3.1. Impact of hydrodynamic currents in metal distribution

Fig. 7 shows the distribution of the currents averaged in about three months of simulation, *i.e.* from the 1st February 2010 till the 7th May 2010, being the last date coinciding with the sampling day. It is worth noting that the effect of the coastline, including the port structure, dominates the circulation in the domain, showing strong deviations to the main direction (North-West) imparted by the

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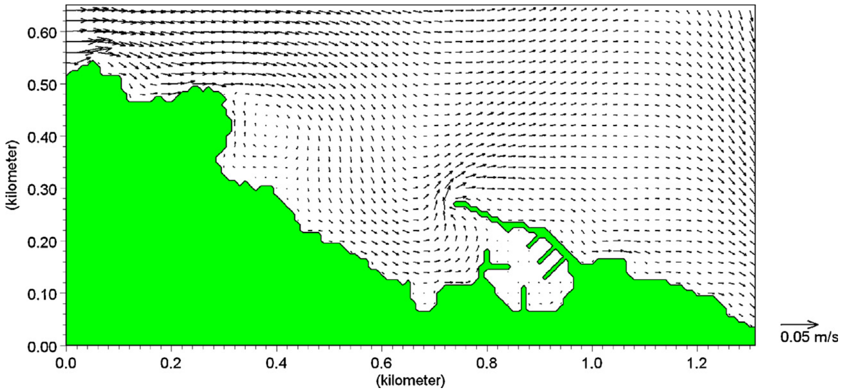

Fig. 7. Distribution of time-averaged current speed vectors in the large domain.

forcing functions imposed in the model, *i.e*. the wind stress and the boundary conditions. In fact, it is recognizable the formation of a cyclonic vortex nearby the harbour that disturbs the tendency of the current to follow the dominant flow promoting a partial inflowing current towards the entrance of the port, where the circulation is very low.

The same considerations arise from the results in Fig. 8, which instead shows the hydrodynamic circulation obtained from the model regarding the final instant of simulation, which coincides with the day when the sampling of sediments was performed. In this case, despite that the dominant current from northwest is more marked, it is evident that currents enter in the harbour area. The main result is that the TM port environmental situation is not so much dependent on what takes place within the port, but qualitatively it seems that it is heavily influenced by what occurs outside, and then transported by the main currents towards the inner port area.

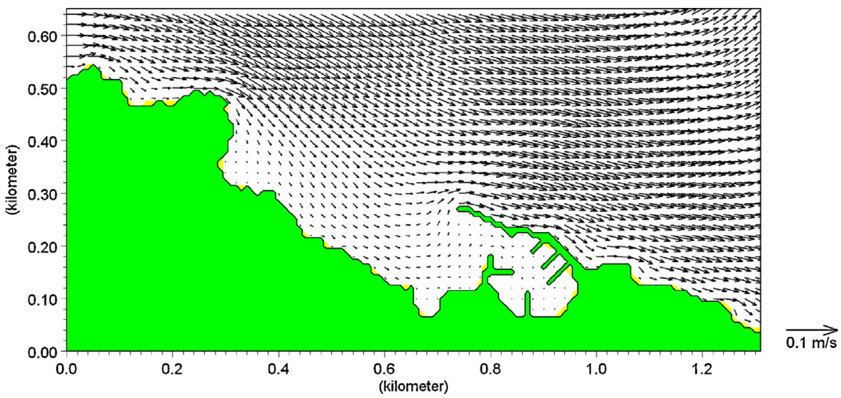

Fig. 8. Distribution of current speed vectors in the large domain on the day of sampling (*i.e.* the final time step).

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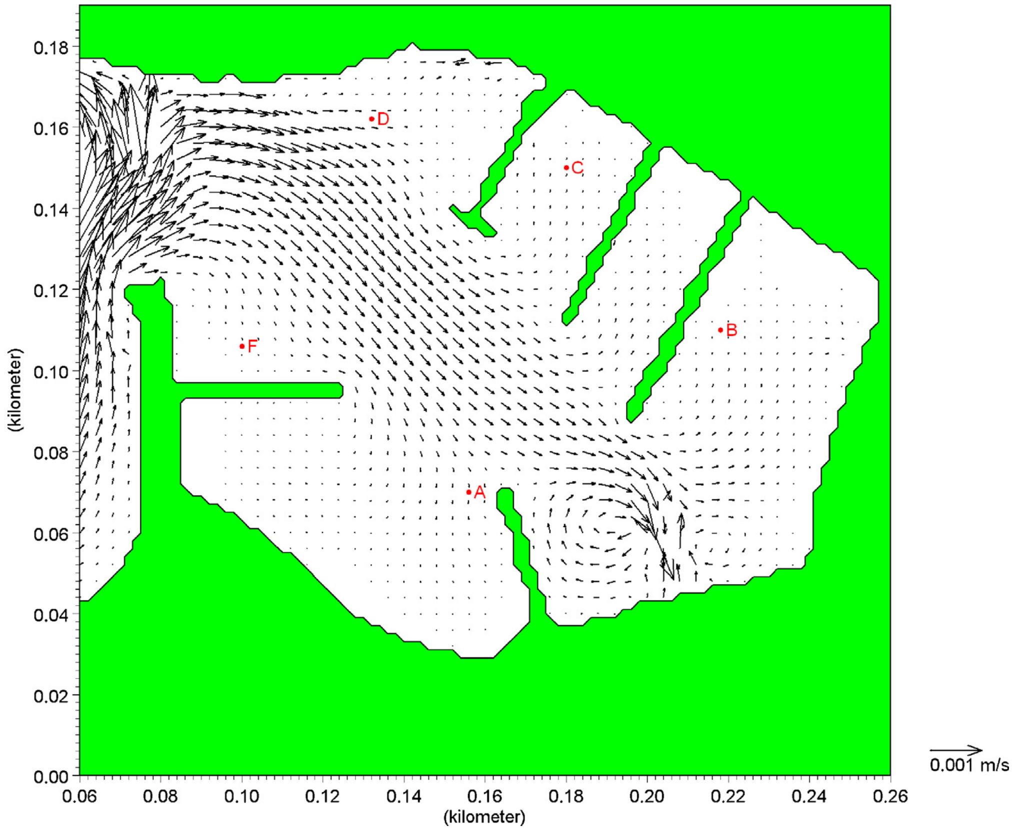

Fig. 9. Distribution of time-averaged current speed vectors in the small domain.

To better clarify the abovementioned aspect, a further hydrodynamic simulation was carried out considering a smaller domain restricted to the port area. The distribution of the time-averaged flow field is illustrated in Fig. 9. In this case, the inflowing currents, averaged in the period of investigation, are strongly evident, with a stronger effect in the central part of the port, while the lateral ones, divided by the various moles, have weaker currents and therefore present stagnation points. It is evident that the simulated hydrodynamics of the TM port definitely favors the entry of any external pollutants, thus leading to the need for a careful monitoring of the external environmental situation to ensure a satisfactory level of quality within the port.

3.3.2. Impact of water quality in metal distribution

A further important support activity for the marine monitoring of the TM harbor is represented by the study of the quality of inner waters of the port basin, aimed at estimating the possible causes of pollution and water recirculation conditions.

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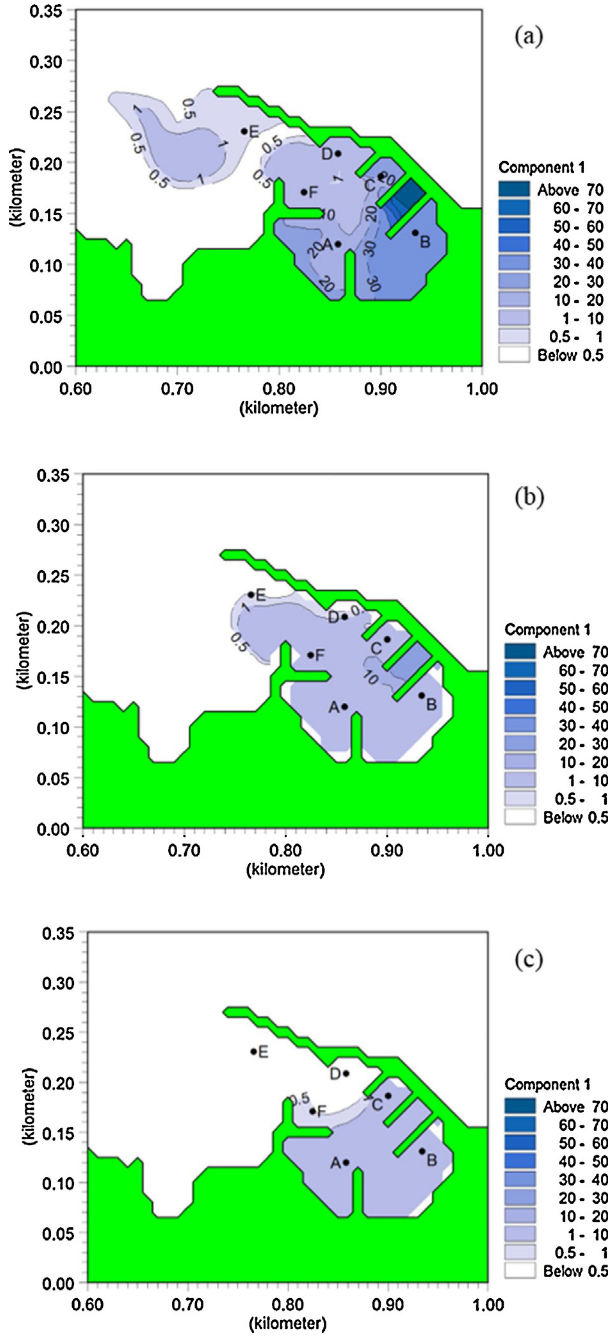

Fig. 10. Concentration distribution (in %) of a tracer within the port in the large domain (a) after one month, (b) after two months, (c) at the end, of the simulation.

In order to analyze the water volume change within the basin, the dispersion model AD was carried out. This model is based on the simulation of the dispersion process of a tracer, hypothesized to occupy the whole harbor basin area with an initial concentration of 100%. Fig. 10 shows a zoom of the resulting dispersion of the conservative component, while in the remaining part of the enlarged domain a

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concentration near to zero was observed. It thus follows that a hypothetical pollutant within the port remains confined in its inner basin, due to the hydrodynamic conditions previously discussed. Furthermore, the same Fig. 10 shows how the concentrations remain quite high in correspondence of the two inner parallel piers, amounting to 65% of the initial quantity after a month, and between 5% and 10% after three months.

A further simulation was carried out in the small domain, considering a 100% initial concentration of the same type of conservative component above-mentioned, but this time concentrated outside of the port. The numerical results are reported in Fig. 11, after one month (Fig. 11a), two months (Fig. 11b) and at

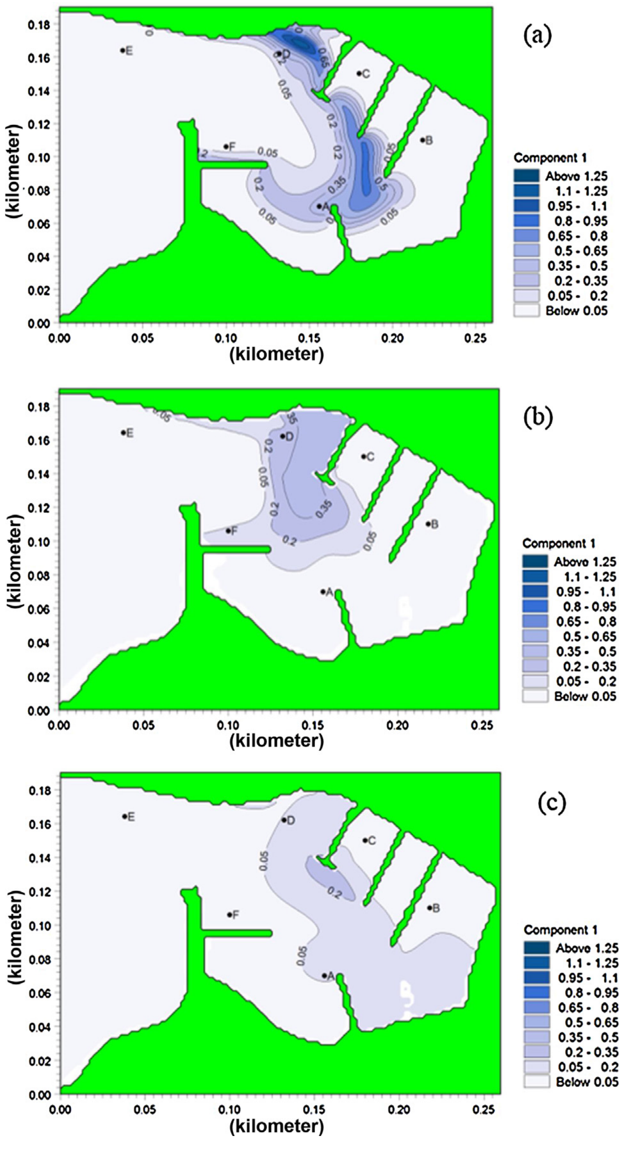

Fig. 11. Concentration distribution (in %) of a tracer outside the port in the small domain (a) after one month, (b) after two months, (c) at the end, of the simulation.

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the end of the simulation (Fig. 11c). Fig. 11 again shows how the circulation currents convey the tracer towards inside of the port, even though in this case the concentrations are intensely reduced already after a month, reaching 0.35% of the initial concentration at the end of the three months (Fig. 11c).

3.3.3. Comparison of simulation responses to real metal distribution

In order to facilitate the comparison of simulation responses with real field measurement and to demonstrate graphically the spatial distribution patterns of metals within TM sediment, a kriging interpolation technique was utilized. The kriging maps of the concentration distribution of metals exceeding the ERL threshold (As, Pb, Cu and Ni), determined within the surficial sediment layer (50 cm), are reported in the Fig. 12a-d.

By comparing the metal maps of Fig. 12 to the simulation of DSS pattern reported in Fig. 9, it can be noticed that the real distribution of metal pollutants results consistent with the software responses. As well as for the contaminant tracer (DSS), the concentration of metals are very high in the inner port area limited by the parallel piers. The same considerations arise analyzing the pattern distribution of fine fraction (Fig. 12e). As previously reported, the finest sediments are the main carriers of contaminants that are preferentially absorbed onto fine fraction (with size diameter less than 63 μm). They can be transported by marine drifts over long distances due to the bottom shear stresses induced by currents (Mali et al., 2017a, b, c), following thus the current trajectory. When the inflowing currents enter the port basin, transportation and redistribution of finest sediment occur and consequently the associated-contaminants are introduced in the inner port area. Then, the low hydrodynamic conditions established within the inner port allow a gradually settling of the finest particles (Alyazichi et al., 2015) and humper their exit from the port.

As an additional validation of the model responses, near the shoreline and in the mouth of the port, a very high percentage of sand is observed. It can be supposed that these areas have high tidal and current activity, which promotes resuspension phenomena and transports the fine and very fine particles into deeper and inner port basin (Alyazichi et al., 2015). The hypothesis presented and the model responses are also supported by the gradual silting process verified in the TM port.

Finally, in order to verify the possibility that pollution of sediments within the port can somehow also connect to the external environmental situation of the harbor, a last simulation was conducted, considering the pollution source located at the center of the harbor mouth. At this proposal the WQ module was used, and the results at the final instant of simulation are shown in Fig. 13. It is clear that the highest concentrations of tracer are confined within the port, as observed

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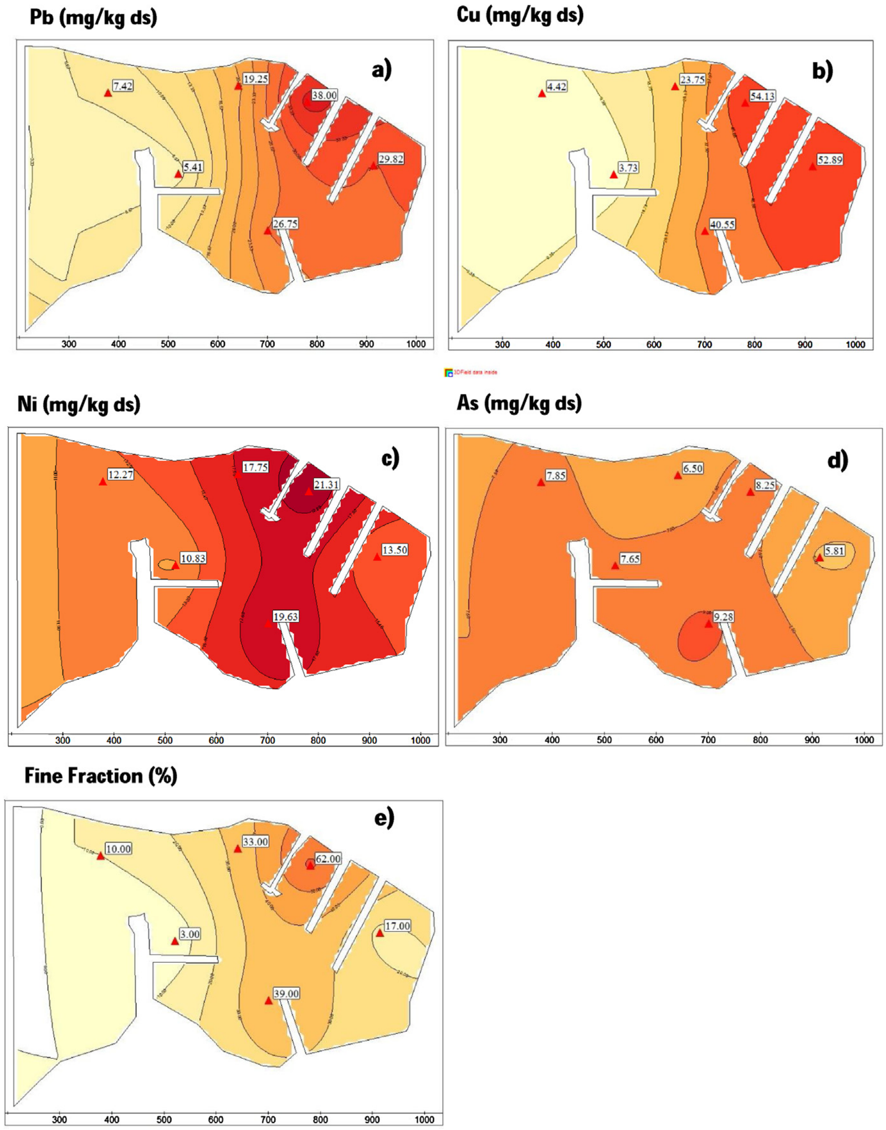

Fig. 12. Concentration patterns (mg/Kg^{-1} d.s.) of (a) Pb, (b) Cu, (c) Ni, (d) As, and (e) fine fraction (%$_w$). On each point-marker the maximum concentration within the sampling site is reported.

previously in Fig. 10. This result highlights once again that any polluting source that comes from the waters outside the harbor, invariably tends to access the port altering its quality. However, the abatement of the tracer, continuously placed in the water body through the point source, after three months of simulation is considerable, i.e. it is greater than 90%.

4. Conclusions

The hydrodynamic simulation performed within the high-polluted touristic port of Torre a Mare (Italy) demonstrated that port structure dominates the water currents,

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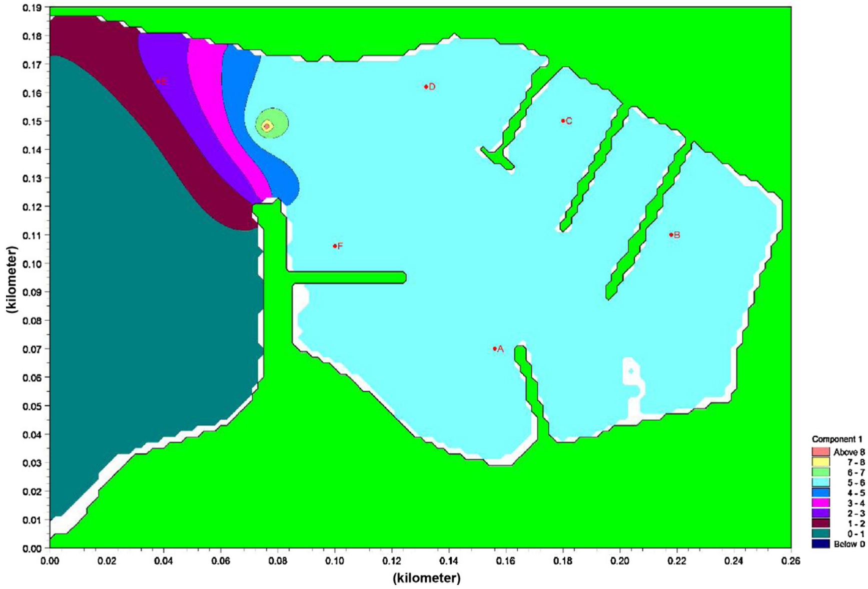

Fig. 13. Concentration distribution (in %) of a conservative component source within the port in the small domain on the day of sampling (i.e. the final time step).

promoting an inflowing stream inside port area, where the circulation is very low. Our computational study showed that dissolved sediment particles coming from outside, selected to simulate contaminant vehicles, are transported by marine currents inside the inner basin where they tend to accumulate. In addition, the phenomenon is strongly enhanced by the typical port morphology that hampers the tracer-exit from the inner area. Being all software responses in a very good agreement with the real distribution pattern of nine metals contaminants, we can safely state that hydrodynamic features of the port have an important role in fostering accumulation of sediment-associated contaminants. Thus, it can be concluded that the environmental state of the harbor area depends on pollution sources located both inside and outside the port domain. From the practical point of view, the authors wish to point out that:

1. identifying the trajectory of pollutants through specific studies is fundamental for decision-makers, especially in establishing clean up or remediation plans. Attributing contamination exclusively to activities carried out in the inner port basins could lead to inefficient land reclamation plans. Pollution outside port basin and the related hydrodynamic-driven processes should be preliminary evaluated.
2. the construction of ports should be also made after prior careful analysis of the morphology of the coastal and hydrodynamics of the coastal track. The port of Torre a Mare is a case example of a small touristic port that, for its improper morphology, accumulates high pollution from outside sources.

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Declarations

Author contribution statement

Matilda Mali: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Daniela Malcangio: Conceived and designed the experiments; Performed the experiments.

Maria Michela Dell'Anna: Performed the experiments.

Leonardo Damiani, Piero Mastrorilli: Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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