Answers to the interactive comment by anonymous referee #1

The answers to the interactive comments by anonymous referee #1 to the manuscript *"Impact of naval traffic on the sediment transport of the Port of Genoa – a modelling study"* follow. They have been shared with the co-authors of the manuscript. The numbering follows that of the referee's comments.

1. The comment does not require specific answers;
2. The comment does not require specific answers;
3. Answers are given within those to comments 4 to 7;
4. We agree that we introduced the three layer model without a thorough explanation of this choice, probably giving for granted the fact that a three layer bed model is more complex and potentially accurate than a one or two layer model, thus allowing intrinsically to represent the real physical processes in a more realistic way.
   The degree of consolidation of the bottom sediment is time and depth dependent. The surface layer - which directly contributes to the injection of material into the water column - is consequently much less consolidated than the lower layers, since there is no matter above it and since it is composed by freshly deposited sediment due to the continuous rework it is subject to. This is even enhanced in a port environment where the bottom is continuously influenced by the propellers' induced jets acting several times per day. To account for this a multilayer bottom model would be recommended. In fact, a single layer bed representation would imply an overestimation of the bed erodibility (soft mud, thus easily reworked), resulting in unrealistic further overestimations of sediment erosion and concentration along the water column. However, we considered that a bed composed by only two layers would also not be appropriate because it would have not allowed to account for a gradual transition from unconsolidated to consolidated material, causing an unrealistic abrupt passage between erodible and stable bed. This induced us to consider an intermediate layer allowing for a smoother transition. We will argument better these concepts in the revised version of the article.
   For what concerns the computational effort, the time needed for a single hydrodynamic simulation is approximately 8 hours for a parallel 20-core simulation using 2.4 Ghz processors, while the time needed for a single simulation of the sediment transport model is approximately 20 minutes with the same computational configuration. For potential operational purposes the hydrodynamic model could be run once in offline mode since the vessels trajectories to and from the same docks are very similar to each other. Then, for every new passage the sediment transport model could be run again in operational model (the short simulation time allows for it) and the bottom change kept up-to-date constantly, according to the actual vessels' passages;
5. As stated in the manuscript, since the shape of the wet basins is similar for all the simulated docks, also the hydro and sediment transport dynamics is similar for all the simulations, provided that the vessels are performing similar maneuvers (all docking operations are conceptually similar to each other, and so are all the undocking operations). This is the reason why only two docks were chosen for the presentation of the results, albeit particularly representative. However, we agree that the results of the bed evolution can be shown for each simulation providing benefit to the manuscript and reliability to the final results. Thus, for the sake of completeness and in order to

guarantee a better traceability of results we agree with the referee comment, and we will produce all the 24 maps of total bed change. Nevertheless, we think that introducing so many images in the manuscript would negatively impact the fluency of the reading, so we propose to add the missing results as supplementary material, or at the most as an additional appendix using a matrix of plots, as suggested;

6. We believe that the action to comment number 5 will fulfill also the requests of the present comment;
7. Same answer as number 6;
8. We agree that the title as is might not fully represent the focus of the paper. We will accordingly change it in the revised version referring to the novel proposed methodology and to the erosion/deposition concept, which is the final objective of the article more than sediment transport in general;
9. We agree that we used the expression sediment transport in a way that might be too large (and maybe not fully proper). The abstract should better reflect that the focus of the article is the reproduction of bed erosion and deposition, functional to an optimized management of the ports albeit relevant space was given to the description and interpretation of hydrodynamics and consequent transport of sediment. In the final version we will change the abstract in order to better reflect these concepts, as suggested by the referee;
10. We will proceed with a deep language revision in order to make it more direct, concise and concrete. Long sentences will be divided into a few shorter ones and redundant concepts will be eliminated;
11. Suggestions on the fluency of the language will be followed, the formal mistakes on citations will be corrected and the overall conclusions will be supported to the greatest extent possible. The sentence in lines 553-555 will be revised;
12. Wrong format of citations of formulae will be corrected;
13. The addressed objectives will be clarified in the abstract and better appointed in the introduction. The “Results” section will be changed into “Results and Discussion”, since much discussion is performed here, as the referee appointed;
14. The comment does not require specific answers;
15. The comment does not require specific answers.

Answers to the interactive comment by anonymous referee #2

The answers to the interactive comments by anonymous referee #2 to the manuscript *"Impact of naval traffic on the sediment transport of the Port of Genoa – a modelling study"* follow. They have been shared with the co-authors of the manuscript.

- **Comment on Line 42:** we have acknowledged the suggested article, but moved the citation in the beginning of the introduction;
- **Comment on line 72:** we added some considerations on the regularity of the most important lines in Section 4.1, when presenting the naval traffic analysis;
- **Comment on line 84:** information on the dimension and mean depth of the basin were added in section "3.1 – Bathymetry";
- **Comment on Line 89:** we added one sentence regarding the interest of Port Authority to the passenger area only;
- **Comments on lines 101, 135:** a short introductory paragraph to the simplification assumption of constant bathymetry as initial bottom condition was introduced at the end of section "2 – Methods". A comprehensive explanation was additionally given in the section "Results and Discussion";
- **Comment on line 153**: such shallow zones (5.0m-7.5m) are actually present only in the eastern boundary of the port. These are marginal areas for our study, rather far from the focus. Moreover, the hydrodynamic model uses sigma coordinates implemented over 10 equally spaced layers. The resulting layer thickness for 5 meter bathymetry would be 50 cm, which we believe would be acceptable for our purposes. Additionally, during the sensitivity study to the grid resolution we also investigated configurations with 20 vertical layers (see section 4.1.1) and explained the issue of increased vertical levels versus computational requirements. We didn't think an insertion in the manuscript was needed for this comment.
- **Comment on line 181:** we are not fully sure we understand the comment. We had the names of the vessels from the schedule provided by the Port Managers. From marinetraffic.com we got the information on the length, width, draught and tonnage of the single vessels. Then, for each dock we calculated the mean of these parameters weighted on the number of annual passages. From these mean parameters we calculated the mean propellers diameters (through empirical formulas). We finally associated to each dock the corresponding representative ship (whose characteristics are those given by the weighted means of the real ones, as explained above). However, to make things more simple we have removed the sentence and replaced it as follows : "The vessels' characteristics necessary to the modelling activity (i.e. length, width, tonnage, draught and typical routes within the port) where deducted from the available information on the web."
- No historical data (year 2017) were required since the vessels' names for the period of interest were given by the Port Managers.
- **Comment on line 197:** no actions needed;
- **Comment on line 250: y**es, This is what we have done in this study. It is not very straight forward since for each time-step of the model we have to define the position of the propellers, and since the propeller is represented through approximately 30 sources and 30 sinks (see description below). We have done this through an ad-hoc offline Matlab code which

automatizes the creation of the model set-ups accounting for the positions of the propellers at any time-step. The images of Figure 8 are an example of propeller in different positions at different instants. We believe no action is needed for this comment.

- **Comment on line 268:** brief clarification added in the text;
- **Comment on line 308:** no action needed;
- **Comment to line 313:** clarification on the confinement of the jet was added as well as the citation proposed;
- **Comment on Figure 8:** no actions needed;
- **Comment on line 464:** comment acknowledged; the caption was rewritten;
- **Comment on figure 10:** we increased the size of the label axis and clarified the legend;
- **Comment to figure 11:** we acknowledged the comment;
- **Comment to line 487:** acknowledging the referee's comment and suggestion we have added a comprehensive explanatory paragraph on this issue in the section "Results and Discussion" (from line552 to line 570);
- **Comment to line 517**: yes, it is correct indeed. As explained in the additional paragraph (see comment above) of section "Results and Discussion" we believe our assumption is acceptable and does not compromise the results of the study;
- Comment to line 584: we have added […] "and vessel drafts".

~~Impact~~Effects of naval traffic on ~~the~~ sediment ~~transport of the Port of Genoa~~ erosion and accumulation in ports: a ~~modelling study~~new model-based methodology

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Abstract

The action of ~~propellers ~~propeller-induced jets on the seabed of ports can ~~be responsible of~~cause erosion and the deposition of sediment around the port basin, potentially ~~inducing important variations of~~significantly impacting on the bottom topography ~~in~~over the medium ~~to~~and long time~~ scales. Such~~. If such dynamics are constantly repeated for long periods~~ can result in ~~, a drastic reduction ~~of~~in ships’ clearance ~~– in the case of~~can result through accretion~~–~~, or ~~might be a threat for~~it can threaten the stability and duration of ~~the ~~structures ~~– in the case of~~through erosion. These sediment~~-~~related processes ~~are sources of problems for the ~~present port managing authorities with problems, both ~~for the safety ~~in terms of navigation safety and ~~for~~in the optimization of ~~the ~~management and maintenance activities of the ports’ bottom and infrastructures.

~~In the present work we study the ~~In this study, which is based on integrated numerical modeling, we examine the hydrodynamics and the related bottom sediment erosion and ~~sediment transport~~accumulation patterns induced by the action of ~~the ~~vessel propellers ~~of naval traffic ~~in the passenger ~~Port~~port of Genoa (Italy~~) by means of integrated numerical modeling and we propose a novel~~). The proposed new methodology ~~and~~offers aa state-of-the-art ~~modeling ~~science-based ~~tools useful~~tool that can be used to optimize and efficiently plan ~~the ports managing activities~~port management and ~~the of~~seabed maintenance~~ of ports seabed~~.

1 - Introduction

~~Operational~~The operational activities of harbors and ports are ~~tightly~~closely related to the local bathymetry, which must be ~~as~~sufficiently deep~~ as~~ to guarantee the regular passage, maneuvering and berthing of ships. ~~On the contrary, ships~~However, ship clearance is often so limited that it threatens the safety of in-port navigation~~ might be at risk~~, and ships may even hit the ~~sea bed~~seabed in extreme cases. This is therefore a source of ~~high ~~criticalities~~, not only for safety sake, but also for the consequent rise of problems related to an efficient ~~ that often result in management and maintenance efficiency problems in terms of the bottom and ~~of the port~~a port’s infrastructure in general~~.~~ (Mujal-Colilles et al., 2016; Castells-Sanabra et al., 2020).

~~Ships’~~The action of a ship’s main propellers means that traffic ~~inside~~in ports is responsible for ~~the generation of~~generating intense current jets~~ produced by the action of the main propellers~~, as ~~sketched~~noted in Figure 1~~. Such~~ .Figure 1 The high velocities induce shear stresses on the sea bottom, which can possibly result in sediment resuspension~~,~~ when ~~exceeding~~they exceed the critical stress point for erosion (Van Rijn, 2007, Soulsby et al., 1994~~,~~; Grant and Madsen, 1979). Before depositing back onto the sea floor~~,~~ the re-suspended sediment ~~might~~may be ~~widely~~ transported widely around the basin by the combined ~~effecte~~effects of natural currents~~,~~ such as those induced by tides, winds or density gradients, and ~~vessels’ ~~by vessel-related currents, such as those ~~directly ~~induced by the propellers or

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again by the movement and displacement of the ships. Therefore, theThe continuous traffic in and out ports couldcan thus result in the displacement of a great amounthuge volume of seabed material, which can, in turn, then induce importantsignificant variations ofin the bathymetry in theover medium to long time scales. The result of these variations is the possibleThe formation of erosional or depositional trends forin specific areas of port basins can potentially result from these variations.

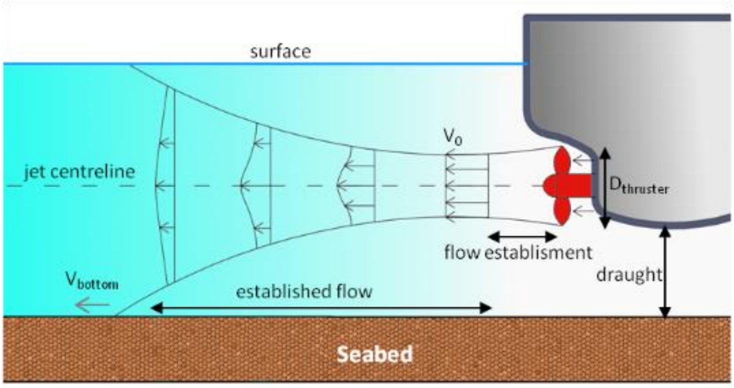

Figure 1 - Example of propeller induced jet of a moving ship (main propulsion without rudder)

These processes can have direct impact on the operability of ports and on safety depths for navigation (Mujal-Colilles et al., 2016, Castells et al., 2018). If such dynamics are particularly relevantpronounced and fastrapid (bottom accretion of thean order of tens of centimeters per year, or even higher) they induce), the port authorities tomust undergo dredging operations for the maintenance of the seabed in order, to fully recover the required clearance and operationalensure the conditions necessary for undisturbed ships motion, maneuvering and berthingdocking/undocking operations.

The majorityMost of the published literature and studies about the effects of ships' propellers on port sediments and structures is experimental., , and is mainly conducted in laboratories with the use of using physical models (Castells Mujal-Colilles et al. 2018), while port authorities suffer from the lack of; Yuksel et al. 2019). Few practical instruments are available to for port authorities that can provide robust and scientifically based studiesanalyses and predictions of the describedrelevant processes. Such tools would allow for an aware planning ofcan enable them to plan specific actions aimed at the maintenance ofmaintaining the seabed. This would, and thus help toboth guarantee the continuity in theof operational activities of ports on one side, and tooptimize the optimizationuse of the involved economic resources on the other side. In fact, the need of unplanned. Unplanned maintenance activities usually

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The integrated numerical modeling of hydrodynamics and sediment transport may representrepresents an important aid to Port Authoritiesport authorities, and more broadly to port managers and operators. It could be used to, as suggested by Mujal-Colilles (2018). This can reproduce and thus provide a better understandunderstanding of the seabed sediment dynamics induced by ships' propellers on theover short, medium and long- time scales and so provide the needed, thus establishing what tools inare required to ensure the perspective of an efficient operational maintenance of the seabed. Such tools can be used in delayed mode in order to reproduce the major sediment processes in the past - as it is the present case - or even in forecast mode through the implementation of real time operational services.

So far, the issue of propeller'sPropeller induced jet has beenjets have mainly been studied through empirical approaches, usually relying either on the German method (MarCorm WG, 2015, Grabe, et al. 2015, Abromeit et al., 2010,), or on the Dutch method (CIRIA et al., using2007). In such approaches, empirical formulas are introduced in order to estimate the propeller wash on the sea bed in terms of induced velocities and resulting induced shear stresses, dependingbased on specific characteristics of the ships and ports of interest, such as the propeller's bathymetry, propeller typology, diameter, and rotation rate, and ship's draught. The most common approaches are the German method (MarCorm WG, 2015; Grabe, et al., 2015; Abromeit et al., 2010,) and the Dutch method (CIRIA et al., 2007). The resulting induced velocities are usually only considered only locally for, to inform the technical design of mooring structures and for considerations on the protection of a port's infrastructures in general. Besides theinfrastructure. Although various assumptions are introduced in thethrough empirical formulas, such an approach is punctualthese approaches are limited and doesdo not provide the full picture offully consider the three--dimensional evolution of the induced jet throughout the water column at any distance from the propeller, inor at any location of the port. The tool isThese tools are therefore not suitable for athe comprehensive management of the ports in a broader way.

The present work showsWe conduct a pilot study of the hydrodynamics and seabed evolution induced by ships' propellers in the passenger area of the Port of Genoa (Figure 2Figure 2), where the naval traffic involves mainly passenger vessels (ferries and cruise ships, generally self-propelled) and wherein which the resulting sediment dynamics (in terms of erosion/deposition rates) is are particularly relevantsignificant: estimated in the order of several tens of centimeters per year (direct communication fromas directly estimated and communicated by the Port Operators and via an analysis of bathymetric surveys at different time). The proposed approach is based on fully). In this study, we propose that the integrated high--resolution numerical modeling of three-dimensional hydrodynamics

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and sediment transport~~.~~ can be a robust and science-based tool for the optimization and efficient planning of port management and maintenance activities. We propose a new methodology that can be used in a delayed mode, and can thus reproduce the historical major sediment processes over time, as in this study, or in a prediction mode through the potential implementation of real-time operational services.

The ~~manuscript~~remainder of this paper is organized as follows: in Sect. 2 we introduce ~~the adopted~~our methodology, ~~while~~and the data available for the study are presented in Sect. 3. Sect. 4 describes the numerical models used~~. The~~, and the results of the numerical simulations are presented ~~in Sect. 5~~ and discussed in Sect. ~~6, which offers some~~5. Finally, the summary and conclusions ~~as well~~of the work are given in Sect. 6.

2 – Methods

The study is based on the latest versions of the hydrodynamic and mud transport models MIKE 3 FM (DHI, 2017~~)~~), which ~~will be~~are described in detail in Sect. 3 and in APPENDICES A1 and A2.

~~In order to resolve in a realistic way the propellers induced jet, a~~ A very high resolution was ~~adopted~~used in the numerical model to realistically reproduce the propeller induced jet, both in the vertical and in the horizontal~~:~~, at approximately 1-2 meters and 5 meters, respectively. ~~This, together~~Together with ~~the use of~~ a non-hydrostatic version of the hydrodynamic model~~ allowed to reproduce very accurately~~, this enables the processes and ~~the main~~dominant patterns of the current field generated by the ships propellers during the navigation and maneuvering inside the port to be reproduced very accurately.

As shown in Figure 2Figure 2, 12 docks have been included in the study (marked with orange or red lines indicating ferry or cruise vessels, respectively). ~~Only passenger ships were studied. The turning basins where~~The Port Authority mainly focused on passenger vessels as they considered their effect on the seabed to be greater than other types of vessels that have much less frequent passage. Moreover, passenger ships are in general self-propelled, while other vessel types are often driven by tugboats. We therefore only simulated passenger ships.

The turning basins in which arriving vessels undergo maneuvers for berthing are represented in Figure 2 ~~with~~Figure 2 by the white~~-~~dashed circles marked ~~as~~ *a* and *b*. Circle *a* refers to vessels berthing at docks T5 to T11, while circle *b* refers to vessels ~~to~~for docks T1 to T3. Finally, the turning area for vessels arriving ~~to~~at docks D.L., 1012 and 1003 is at the entrance of the port and is not simulated in this study~~ since~~, as it is out of ~~the~~our area of interest.

The general methodology ~~adopted is organized in different~~can be separated into the following phases~~, as follows:~~.

1. *Assessment of the naval traffic during a typical year*. This ~~was~~phase is fundamental~~ to understand~~, as it identifies the typical dynamics of the naval traffic in the different sectors of the port and ~~to identify~~ the

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characteristics of the ships that ~~most impact~~have the greatest effect on the hydrodynamics and sediment re-suspension ~~from~~on the bottom~~, such as~~. These include the size of the ships, the related draught, the dimension of the propellers and their typical rotation rates. The results of the analysis, which ~~will be detailed~~are discussed in detail in Sect. 4.1, ~~led~~ also ~~to the definition of one most~~enabled representative synthetic ~~vessel~~vessels for each berth of the port to be defined.

2. *Implementation of a high-resolution 3D hydrodynamic model of the port of Genoa*. ~~The~~This numerical hydrodynamic model ~~that we implemented took into account the~~considered ship routes, both entering and exiting the port, as ~~analyzed within~~established through the previous vessel traffic analysis phase. As ~~it will be~~ detailed in Sect. 4.1, 24 ~~different~~ simulations of the hydrodynamic model have been implemented, one for each dock and route considered (docking and undocking). The resulting 24 ~~different~~ scenarios ~~have been~~were then simulated separately. This ~~allowed~~enabled us to analyze the effect of each vessel's passage on the induced hydrodynamics ~~in~~of the basin. ~~The single~~Each hydrodynamic ~~contributions were~~contribution was then used to drive the sediment transport model. ~~The present~~This approach ~~won't therefore~~does not consider potential simultaneous interactions amongst hydrodynamic patterns generated by different propellers, ~~assuming~~as we assume that ~~very close passages of different~~ vessels are unlikely to ~~happen~~pass each other very closely.

3. *Implementation of a coupled sediment transport model*. Based on the available data, a numerical model of sediment resuspension and transport for fine-grained and cohesive material was then implemented. The model was ~~coupled to~~combined with the hydrodynamics resulting from the 24 different vessels scenarios. ~~As with the hydrodynamic component, the~~The simulations of the sediment model were ~~carried out~~conducted separately for the hydrodynamic component.

4. *~~Gathering of~~Collating the ~~separate~~ results and the overall analysis*. The effects of the passage of the single vessels on the bottom sediment ~~have been summed up to each other~~were then combined in terms of the erosion/deposition ~~according to~~ resulting from the overall number of passages over the analyzed one-year period of time ~~previously analyzed.~~. This ~~led~~enabled us to provide aggregated information on the ~~resulting~~ annual sediment dynamics.

~~A~~We then conducted a semi-quantitative calibration/validation of the modeling results ~~was possible~~ through ~~the~~a comparison of the seabed evolution reproduced ~~with~~using the integrated modeling system and the ~~differential~~various bathymetric maps derived from ~~different~~ surveys of the port topography at approximately one year ~~interval~~intervals.

The proposed approach assumes that each hydrodynamic and sediment transport simulation uses the same bathymetry as the initial bottom condition. Although this assumption may have implications, as we explain in the results section, it does not compromise the main conclusions of the study.

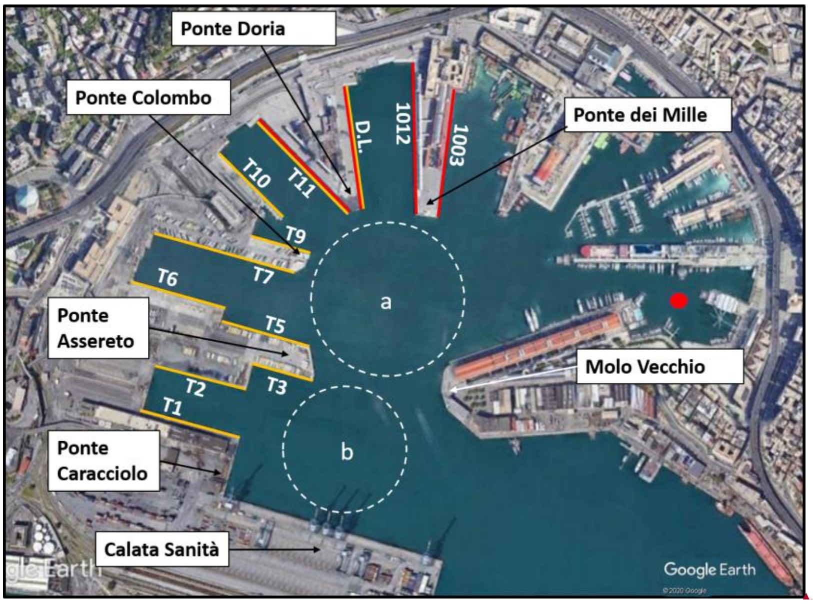

Figure 2 - Passenger port of Genoa. The colored lines along the docks refer to the typology of the operating ships: red lines indicate cruise vessels while orange lines indicate ferries. The names of the docks (in white) are next to the colored lines are. The red dot represents the location of the station where sediment samples with physical information on the grains are available (see Sect. 4.2). The white dashed circles marked as *a* and *b* represent the turning areas for vessels berthing to docks T5 to T11 and to T1 to T3

3 – Available data and information

~~The most relevant~~ Most of the data necessary for ~~the implementation of the work~~this project were provided by the Port Authority of Genoa and Stazioni Marittime SpA, ~~which cover the role of Port Authority and~~the main ~~Port Operator~~port operator in the ~~target~~ area~~, respectively~~.

3.1 – Bathymetry

Several bathymetry surveys of the ~~different~~ sectors of the port were available at ~~different~~various resolutions~~ in the domain of interest.~~. The dataset used for the simulations was ~~the result of the~~ obtained by merging ~~of~~ the latest available surveys (March-June 2018) ~~in~~of the inner sectors of the port, delivered on a regular grid of ~~5~~five meters of resolution. Figure 3Figure 3 shows the ~~latest available observed~~merged bathymetry ~~of~~for the entire port (left panel) and for a

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zoom focused on detail of the Ponte Colombo and the surrounding basin. AThe main area of interest for the study (from the line between Calatà Sanità and Molo Vecchio to the end of the Port, see Figure 2) measures approximately 0.60 km^2 and has an average depth of approximately 13 meters. The bathymetry is in general heterogeneous. The wet basins are approximately 10-11 meters deep, while areas shallower than 10 meters are present only in the eastern part of the basin, where yachts and non-commercial vessels operate. A deep natural pit is clearly visible a few tens of meters off the right edge of *Ponte Colombo* and *Ponte Assereto* (see Figure 2) a deep natural pit in the bathymetry is clearly visible, reaching, extending approximately 22 meters below the water surface. This area has often been used in the past by theThe Port Authority has regarded this area as a preferred site for dumping the sediment resulting from recurringregular maintenance dredging operations of the seabed, in those sectors where depositional trends are large enough to reduce vessels clearance and to impact onaffect the safety of navigation inside the port. Moreover, the same This depressed area is largelyalso used as a turning area by the passenger ferries heading to docks T5, T6, T7 and T9, which cover approximately the 50% of the entire naval traffic ofin the basin (see Sect. 4.1): during). During their manoeuvres over this pit the turning ferries produce intense turbulence, which may reach the newly dumped material resulting from the dredging operations. This material is still rather loose and can consequently subject to be easily re-suspended and transported again around the port basin, nullifying the results ofthus making the dredging operations ineffective.

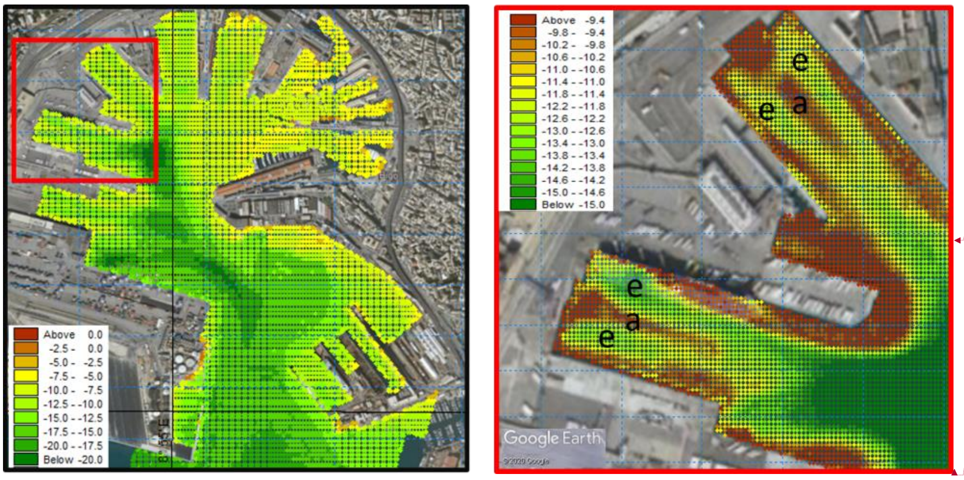

Figure 3 - Bathymetry of the port of Genoa. Entire Passenger Port (left panel) and zoom on *Ponte Colombo* and the surrounding basins (from T5 to T11, right panel)

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Additionally, theThe bathymetry presented in the right panel of Figure 3 shows a Figure 3 follows the pattern of erosion and accumulation common to the majority of the wet basins confined amongst the differentamong docks. Here, the propellersThe propeller activity when vessels leave or approach the berth induces areas of erosion, identified withby channels of deepened bathymetry (referred to with an “*e*” in the right panel of Figure 3, where colours areFigure 3, and coloured yellow-green) and areas of accumulation identified with tongues of shallower bathymetry (referred to with andenoted by “*a*” in the right panel of Figure 3, where colours areFigure 3, and coloured brown).

It is important to underline that anotherAnother survey covering approximately the same area as that of Figure 3 wasFigure 3 is available for the period May-June 2017. TheBy comparing the topographical information resulting from the difference of such topographies, integrated with the available of the two and integrating the information on dredging activities operated during the same period allowed, we were able to reconstruct fromin a semi-quantitative point of viewfashion the sediment dynamics occurredoccurring during this time window of approximately one year. SuchThis information was then used in the process of calibration/validation ofprocess for the numerical model of sediment erosion and transport, as detailed in Sect. 5.

3.2 – Sediment data

InformationThe availability of information on the sediment textures in the sea is usually poorly available. In this case we hadlimited. We were able to access to the MArine Coastal Information sySTEm (MACISTE; http://www.apge.macisteweb.com) implemented by the Department of Science of Earth, Environment and Life (DISTAV) of the University of Genova, where the results of several chemical and physical sediment surveys are stored and are accessible. Unfortunately, albeitalthough the chemical information is comprehensive, information on the grain size is rather poor for what concerns the inner area of the port. is incomplete. The red dot of Figure 2Figure 2 represents the only location inside the basin where the information on the texture composition and grain size was available. These characteristics are necessary for the sediment transport model, and they were used in the simulations for the entire domain of the numerical model (see Sect. 4.2).

3.3 – Naval traffic

YearIn terms of naval traffic, 2017 was considered as a typical year from the point of view of the naval traffic in agreement withby the Port Authority of Genoa and with Stazioni Marittime SpA. to be a typical year. The traffic wasdata were available on a daily basis and it included the information on the docks of arrival/departure and the namenames of the vessels involved vessels. The entire year was considered, in order to account for the typical

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seasonality of the traffic concentration, much more relevantwhich is particularly significant for passenger vessels in the period from the end of spring to the beginning of fall.

For extra information on the The characteristics of the vessels, such as required for the modelling activity (i.e.,. length, width, tonnage, draught and typical routes inside the port during arrivals and departures we referred to the) were obtained from information available through public web page https://www.marinetraffic.com. sources. The outcomeoutcomes of the analysis will beare presented in Sect. 4.1.

4 – The numerical models

The non-hydrostatic version of the MIKE 3 HD flow model (DHI, 2017) was used to simulate the propeller induced three-dimensional current along the port basin. The resulting hydrodynamic field was coupled with the sediment transport module MIKE 3 MT (DHI, 2019), suitable for fine-grained and cohesive material.,, in order to drive the erosion, advection-dispersion and deposition of fine sediment along the water column.

4.1 – The hydrodynamic model

The MIKE 3 FM flow model is an ocean circulation model suitable for different applications within oceanographic, coastal and estuarine environments at global.,, regional and coastal scales. It is based on the numerical solution of the Navier-Stokes equations for an incompressible fluid in the three dimensions (momentum and continuity equations), based on the advection-diffusion of potential temperature and salinity and on the pressure equation, which in the present non-hydrostatic version is split into a hydrostatic and a non-hydrostatic componentcomponents. The closure of the model is guaranteedobtained by the choice of a turbulence closure formulation with differentvarious possible options amongstwithin a constant value, and a logarithmic law scheme or a k-ε scheme, which is the one used in the present implementation. The surface is free to move and it can be solved using a sigma coordinate (as it is the caseused in the presetpresent study) or a combined sigma-zed approach. The spatial discretization of the governing equations of the model follows a cell-centeredcentred finite volume method. In the presentour implementation of the model we used the barotropic density mode, and thus temperature, salinity and consequently density arewere constant in time and space during the simulations.

The domain of the present implementation of the model is presented in the upper panels of Figure 4.Figure 4. The images show two examples of computational grids used for the simulations. In these casesHere, the docks are T1 (left panel) and T10 (right panel) during inbound operations. The grids are a combination of unstructured triangular and quadrilateral cells with horizontal resolutionresolutions varying from 30 meters in the furthest areas from the ship

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Formattato: Tipo di carattere: Times New Roman, 10 pt, Inglese (Regno Unito) trajectory~~,~~ to 5 meters approximately within the closest area to the ~~ships~~ships' propellers. The mesh is rectangular in ~~those~~ areas where the ships are moving straight ahead and the 5 meter resolution covers a corridor of approximately 50 meters of width. In the manoeuvring areas, the mesh becomes unstructured and the resolution is again 5 meters. The red lines in the middle of the ~~5~~ five-meter resolution corridors of the upper panels represent the routes followed by the ships inside the port. The lower panels of the figure are snapshots taken from the web service ~~https://www.marinetraffic.com showing~~https://www.marinetraffic.com, which show the actual routes of the vessels birthing in the ~~same~~ docks ~~as~~in the upper panels (T1 and T10) as recorded by the AIS system mounted on the ships. As shown in Figure 4Figure 4 the reconstructed trajectories of the ships in the model are realistic and fully representative of the real ~~ones~~trajectories.

Table 1 Table 1 shows the results of the traffic analysis within the Port of Genoa for ~~year~~ 2017 conducted ~~on~~using the daily traffic data provided by Stazioni Marittime SpA~~ on a daily basis.~~. The ~~average lengths, widths~~annual traffic is generally regular, and ~~draughts of the ships were evaluated calculating~~its frequency varies from basin to basin and depends on the season. Generally, the ~~mean~~busiest docks are T5, T6 and T7, accounting for almost 50% of the ~~single quantities weighted on~~total traffic. They follow an approximately daily frequency all year round, whereas the ~~number of~~wet basins towards the end of the port, which mainly serve cruise vessels, show an evident seasonality, probably related to the Mediterranean cruise season (few and irregular passages ~~occurring per year.~~ from January to May, then regular and in a much increased frequency from June to October/November).

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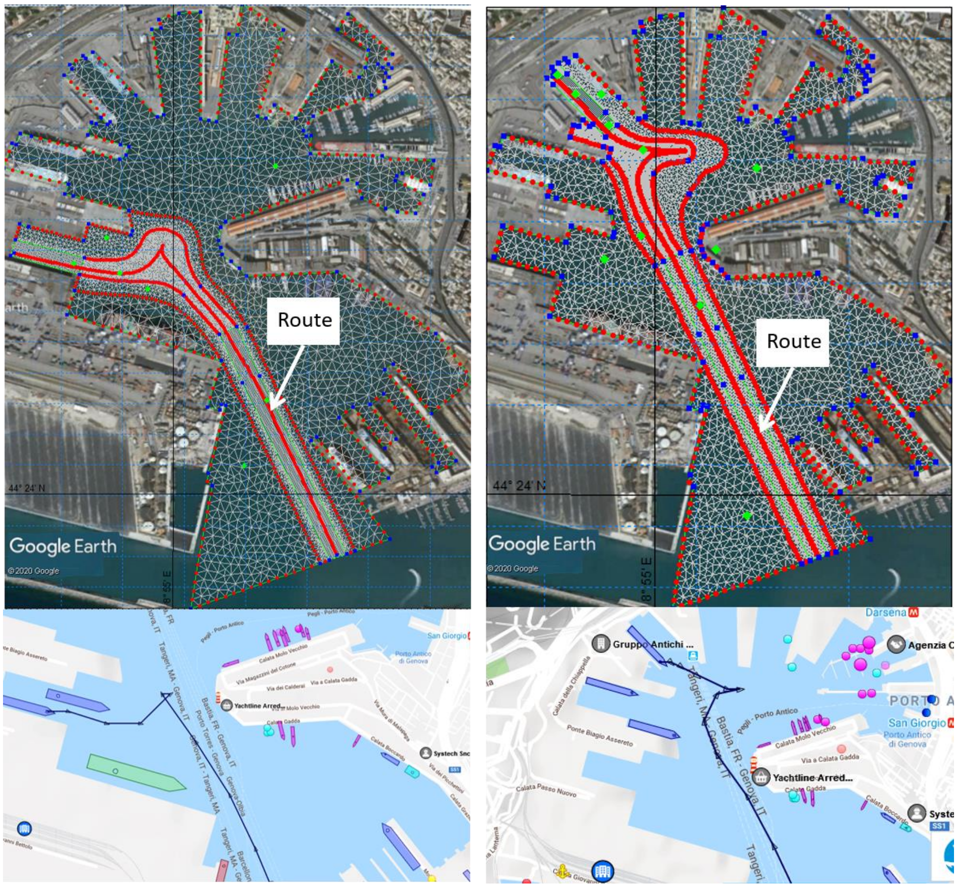

Figure 4 - Model domain and computational grids for docking routes of T1 (left panel) and T10 (right panel) docks. In the lower panels the corresponding actual routes are shown

Table 1 - Analysis of ship traffic in the port of Genoa for year 2017 and main characteristics of the ship representative of each dock. The ship's length, width, draught and propeller's diameter values are expressed in meters

Dock	**Number of Berthing**	**% Berthing**	**Average Length [m]**	**Average Width [m]**	**Average Draught [m]**	**Average Diameter [m]**
1012	122	6.4%	318.41	37.86	8.33	5.80
1003	47	2.5%	276.20	30.07	7.45	5.20
D.L.	12	0.6%	290.86	32.02	7.82	5.40
T11	123	6.4%	213.23	31.67	7.16	5.20
T10	202	10.5%	181.88	26.44	6.46	4.70
T9	8	0.4%	152.96	24.81	5.91	4.40
T7	308	16.1%	214.27	26.45	6.85	4.90

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T6	291	15.2%	204.93	26.35	6.62	4.80
T5	351	18.3%	203.93	29.57	6.95	5.00
T3	87	4.5%	155.16	25.60	6.17	4.50
T2	202	10.5%	185.66	27.85	6.68	4.80
T1	164	8.6%	204.00	28.33	6.93	5.00
TOTALE	**1917**	100.0%	---	---	---	

In the vertical, the model is resolved over 10 sigma layers evenly distributed. sigma layers. The resulting layers depthlayer depths vary from approximately 1 meter in the berthing areas to approximately 2 meters in the pits and in the areas closer to the port's entrance.

4.1.1 - Propeller'sPropeller jet velocity

The propellerspropellers' maximum jet velocity was calculated through the guidance provided inbased on the Code of Practice of the Federal Waterways Engineering and Research Institute (Abromeit et al., 2010) and in the PIANC Report n. 180 (MarCom WG 180, 2015), basing ontaking the German approach. The relevant parameters for the calculations are those shown in Figure 1Figure 1. The maximum velocity V_0 after the jet contraction generated by the propeller is developed along the propeller'sits axis. For unducted propellers it is described by, we use Eq. (1a),) for the propeller ratio $J=0$ (ship not moving) or Eq. (1b) for $J\neq 0$ (moving ship).

$$V_0 = 1.60 f_n\, n_d D \sqrt{K_T} \qquad (1a)$$

$$V_{0j} = \frac{\sqrt{(J^2+2.55K_{Tj})}}{\sqrt{1.4\frac{P}{D}}} V_0 \qquad (1b)$$

where n_d [1/s] is the design rotation rate of the propeller,; f_n is the factor for the applicable propeller rotation rate (non--dimensional),); D is the propellerspropeller diameter [m],]; K_t or K_{tj} is the thrust coefficient of the propeller (non--dimensional) in the case of non-motion or motion of the ship, respectively; and P is the design pitch [m]. Typical values for fn are 0.7 - 0.8 during manoeuvring activities, while the P/D ratio can be assumed to be approximately equal to 0.7. K_t or K_{tj} can be estimated through Eq. (2a) and (2b), according to the state of motion of the ship:

$$K_t = 0.55\frac{P}{D} \qquad (2a)$$

$$K_{tj} = 0.55\frac{P}{D} - 0.46J \qquad (2b)$$

The propeller ratio J depends on a wake factor w varying, which varies from 0.20 to 0.45 (non-dimensional)), and on the velocity of the ship according to Eq. (3):

$$J = \frac{v_{s(1-w)}}{nD} \qquad (3)$$

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As proposed by Hamill (~~Hamill,~~ 1987) and further described by Wei-Haur Lam et al. (~~Lam et al.~~ 2005), the downstream propeller~~-~~-induced jet is divided into a zone of flow establishment (closer to the propeller) and a zone of established flow (further downstream). The resulting velocity V_0 used in the model to calculate the corresponding discharge and momentum sources is considered as the maximum velocity at the beginning of the zone of the established flow.

~~Having~~As we had no direct information ~~on~~about the size of the ship's propellers, ~~reference was made~~we referred to the specific literature~~ on this topic. In particular, for what concerns~~. For the propellers of the Ro-Ro ferries ~~which normally~~that typically serve docks T1, T2, T3, T5, T6, T7, T9, T10 and T11, we ~~relied on~~referred to the report n° 02 of the project "Mitigating and reversing the side-effects of environmental legislation on Ro-Ro shipping in Northern Europe" (Kristensen, 2016) implemented by the Technical University of Denmark (DTU) and HOK Marineconsult ApS. According to this study, the relationship between the draught and the diameter of the ferry's propeller is given by Eq. (4):

$$D_{prop} = 0.56 \times H_{draught} + 1.07 \tag{4}$$

where D_{prop} is the propeller's diameter [m], and $H_{draught}$ is the maximum draft of the ship [m]. ~~Such~~This relation is not valid for cruise ships~~ having usually bigger~~, as they typically have larger propellers. For this type of ~~ships, serving~~ship, which serve docks 1012, 1002 and~~, only~~ partially~~,~~ D.L. and T11, we ~~relied on direct communications from~~ directly referenced operators in the passenger ~~ships~~ship design sector, and double checked the information with the formulas ~~of~~from Eq. (4) and from Eq. (5), ~~this latter~~which is also valid for double propeller passenger ships. This qualitative analysis ~~brought to~~provided the diameters presented in ~~Table 1~~Table 1Table 1.

$$D_{prop} = 0.85 \times H_{draft} - 0.69 \tag{5}$$

~~In order to represent the propeller in a realistic way the~~ The water discharge was obtained by combining the diameter of the propeller and the intensity of the jet~~ is~~, which was discretized into a certain number of smaller discharges ~~respectively~~ associated ~~in the numerical model to different~~with various smaller sources of momentum~~.~~ in the numerical model. We thus realistically represented the propeller. The distribution of volume and momentum sources follows a ~~Guassian~~spatially Gaussian (normal) distribution with a discretization step of 0.5 meters and a constant rotation rate of the propeller.

Figure 5 Figure 5 shows the ~~representation of the~~ propeller's induced jet in the hydrodynamic model. The left panel represents the plan of Dock 1012, where a large cruise ship is departing. The solid line of the upper left panel is the location of the vertical transect shown in the upper right image, representing the jet velocity in the plane *xz*. The dashed line in the upper left panel represents the trajectory followed by the axis of the departing ship, and the associated jet's

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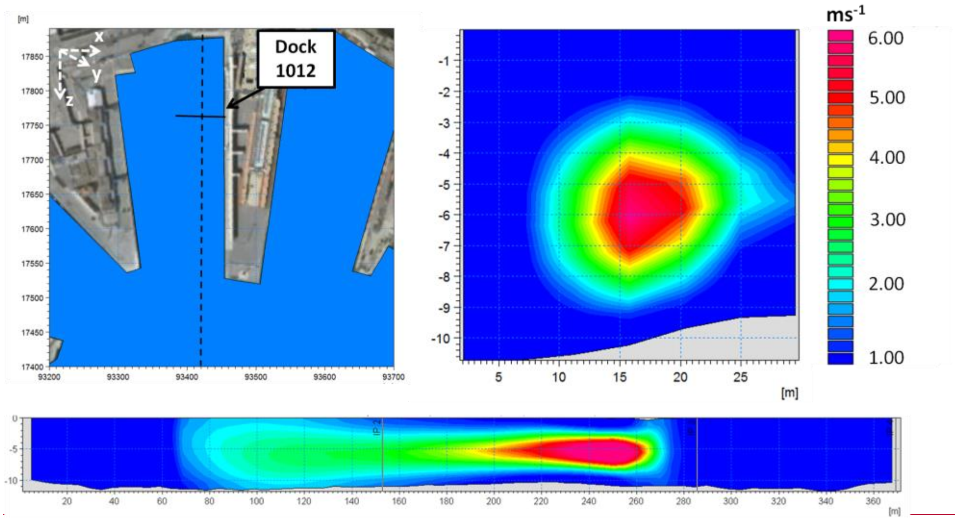
velocity in the *yz* plane is shown in the bottom panel. ~~Albeit~~Although the ~~non optimal~~ horizontal resolution is non-optimal in terms of ~~propellers~~propeller representation, the resulting jet appears extremely realistic both in ~~the~~ transverse and ~~in the~~ longitudinal directions.



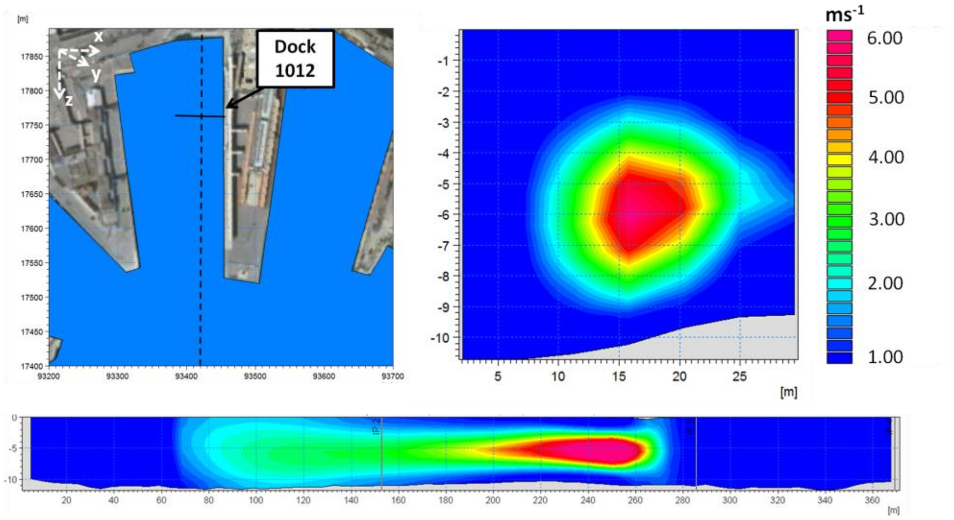


Figure 5 – Representation of the propeller-induced jet of the most representative ship departing from Dock 1012. Left: plan view; the dashed line represents the trajectory followed by the axis of the undocking ship, the solid line represents the position of the vertical transect shown in the upper right panel, showing the jet's induced

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velocity in the *xz* plane (propeller's plane). Lower panel: transect of velocity along the propellers axis (*yz* plane). Velocities are in ms^{-1}

~~In order to~~To preserve the water mass budget, we associated a sink to each source. Sinks are prescribed in terms of negative equivalent discharge (m^{3}s^{-1}) in the ~~adjacent~~ grid cell adjacent to ~~the one~~that hosting the source, in the direction of the ship motion (sinks precede corresponding sources).

The choice of the vertical and horizontal ~~resolution~~resolutions of the hydrodynamic model ~~was~~were the result of a thorough sensitivity analysis ~~to~~of the grid's ~~cells dimension.~~cell dimensions. We assumed that the most appropriate resolution for the model ~~is the one that~~ allows the maximum (jet centreline) current produced by the combined discharge and momentum sources in the model to reach the input maximum velocity of V_0. For the sensitivity analysis, we considered a 4-meter diameter propeller with a rotation rate of ~~2~~two rounds per second (rps) at full power. According to Eq. (1b), ~~such a~~this configuration results in a V_0 of approximately 6 ms^{-1} at the depth of the propeller's axis once the jet is fully developed. ~~To this purpose, we~~We set up an experimental configuration domain~~,~~ 100 meters wide and 500 meters long. ~~The different~~ We tested horizontal resolutions ~~tested were~~of 20 m, 10 m, 5 m, 2 m and 1 m, while for the vertical we considered two configurations: 10 and 20 layers in a constant bathymetry of 20 meters. The input value of the jet current to the model was 6 ms^{-1}.

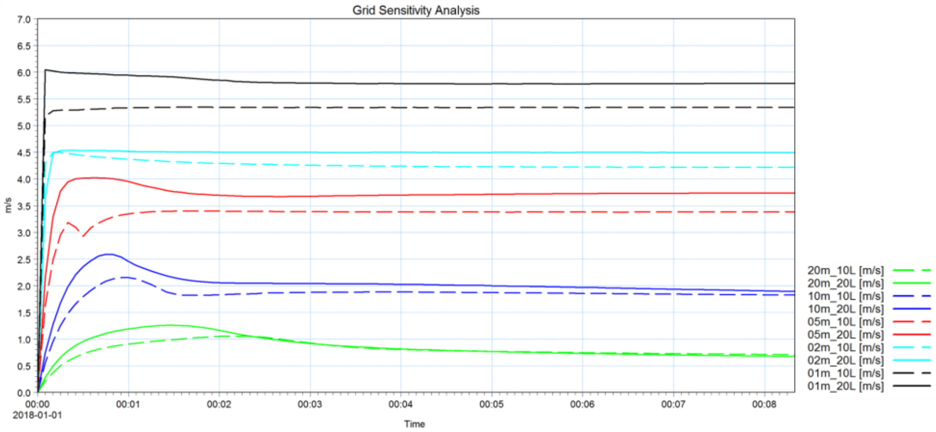

Figure 6 – Model grid sensitivity analysis to the cells dimension. The different colors correspond to the different horizontal resolution. Dashed lines indicate the configurations with 10 layers while solid lines indicate those with 20 layers

Figure 6 shows the sensitivity analysis ~~to~~of the grid resolution. The resulting velocity at the propeller's axis is proportional to the resolution, both in the vertical and ~~in~~ the horizontal: the higher the resolution, the higher the resulting velocity. The most appropriate grid ~~would be the one~~is that with a 1-meter resolution and 20 vertical layers,

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which is the only configuration of the model ~~which~~that allows the jet to reach the maximum speed imposed as the input. However, this configuration would require approximately ~~one~~1 year of computational time to run the 24 simulations implemented ~~for~~in this study in the same computational configurations, which is obviously unrealistic. We thus ~~looked for~~sought a compromise between acceptable computational demand and realistic resulting velocity. The final configuration ~~was the one with~~took 5 meters as the horizontal resolution and 10 vertical levels. ~~Since such~~As these resolutions ~~would~~did not allow for the complete development of the current speed, we introduced a correction to the input velocity of each simulated vessel by increasing it ~~of~~by the necessary amount to reach the empirically calculated V_0. This ~~implied~~involved considerable additional time for manual calibration.

4.1.2 – Forcing and boundary conditions

Due to the nature of the focal processes ~~of interest the~~, we only ~~forcing accounted~~account for ~~is~~the force of the ~~propeller~~propellers of the vessels. ~~In fact, the~~The jet induced by its motion is of ~~the~~an order of magnitude of several meters per second in the area surrounding ~~of~~ the blades~~,~~ and when unconstrained it has a length of influence of at least 40-50 times the propeller's diameter behind the ship (Verhei, 1983). This is also an important source of toe scouring in the presence of a quay wall (Hamill & Johnston 1999). Natural forcing such as wind, density gradients or tides are one to two orders of magnitude smaller ~~in this area,~~, and can thus ~~they can~~ be neglected without introducing errors that can potentially ~~impacting on~~affect sediment resuspension from the bottom. ~~On~~However, the ~~contrary,~~ Bernoulli wake ~~might~~may be responsible for currents of comparable intensity (Rapaglia et al., 2016), ~~albeit~~although smaller, and ~~it would be worth to be considered as~~ can be a forcing ~~of~~source in the system. ~~In this study, though~~Anyhow, we ~~neglected it~~ do not consider this due to technical complications and time ~~obligations. It will be interesting to include~~constraints. Including such a process in further developments and ~~to analyse the~~analysing its impact on the overall dynamics of ship -induced sediment transport~~. However, the satisfying~~ would be of interest. Our final results ~~of the present work suggest~~prove satisfactory, suggesting that the governing processes for these dynamics are associated ~~to propellers~~ more with propeller-induced currents ~~more~~ than ~~to~~with the motion of the ship itself, likely due to the limited speeds of vessels ~~speed~~ in this inner part of the harbour and to the relatively large volume of water available for each passing vessel.

The boundaries of the hydrodynamic domain are the docks ~~all~~ around the basin and the port entrance, which is the only open boundary. Here we imposed a Flather condition (~~Flather,~~ 1976) assuming constant zero velocities and levels. ~~Such a choice~~This allowed us to minimize the boundary effects, albeit with some interference between the flux and the boundary line ~~is present~~ (not shown). However, due to the distance between the open boundary line and the berthing areas, such effects do not influence the results of the study. A zero normal velocity was imposed along the closed boundaries.

4.2 – The sediment transport model

The hydrodynamic model was coupled with a sediment transport model – MIKE 3 MT FM - valid for fine-grained and cohesive sediment (diameter smaller than 63 µm, Lisi et al., 2017). This is the main type of sediment ~~is mostly present~~ in the port of Genoa and is particularly relevant ~~for the~~in terms of erosion, transport and further deposition, ~~since~~as its small particle dimension and light weight ~~favour relevant~~rapidly lead to its resuspension and advection around the basin.

The ~~governing~~ equations of the mud transport model are based on the advection and dispersion (AD) of the sediment concentration ~~of the sediment~~ along the water column and ~~they~~ are detailed in APPENDIX A2. The AD equation is solved using an explicit, third order finite difference scheme called ULTIMATE (Leonard, 1991).

The model ~~accounts for~~consists of two ~~compartments~~areas: a water and a seabed environment. The seabed is represented through a multi-bed layer and multi-fraction approach in which the ~~different~~ layers can exchange mass and only the top level is active, thus making it available for erosion. The different layers are defined ~~through~~by the ~~fractions~~proportions of sediment ~~they're composed of~~in their composition, the degree of consolidation of the sediment within each layer, and the thickness of the single layer. The ~~different~~ sediment ~~fractions~~proportions are described through their associated physical characteristics, and ~~they~~ are eroded and deposited proportionally to their concentration both in the bed texture and along the water column. ~~Within~~Flocculation processes occur in the water environment~~,~~ of the model ~~includes flocculation processes~~ when ~~exceeding~~ a certain ~~threshold of~~ concentration threshold is exceeded (here assumed to be equal to 0.01 gl^{-1}~~) and hindered~~), while at a threshold of 10 gl^{-1} settling is hindered, according to ~~Wintwerp (~~the definition of Winterwerp and ~~Van~~ Kesteren~~,~~ (2004~~) definition with a threshold of 10 gl-1.~~). The deposition of the sediment is based on a Teeter (~~Teeter,~~ 1996) profile and the threshold for deposition used was 0.07 Nm^{-2}. The sediment grain diameter is defined through the associated settling velocity, based on ~~Stokes~~Stokes' law. In the interface between the water and the bottom the sediment may be eroded ~~following the approach~~, as proposed by Partheniades (~~Partheniades,~~ 1965) for consolidated sediment or ~~that~~ by Parchure and Metha (~~Parchure and Metha,~~ 1985) for soft or unconsolidated sediment. In both cases the sediment is eroded and injected into the water column when the shear stress resulting from the current, the wave action or a combination of both exceeds a certain critical value. ~~In the present case waves were not considered since we are~~We do not consider waves as our focus is inside the port.

The specific equations and parameterizations referred to in the sediment model are summarized in APPENDIX A2.

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4.2.1 - Sediment characteristics

Three ~~different~~ sediment surveys were ~~carried out~~conducted between June 2009 and July 2010. Table 2 Table 2 presents the results of the surveys in terms of percentage and class of sediment per survey (last and central column,

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respectively). Given the nature of ~~the~~our study~~ we are interested in~~, our focus is on mud and fine sand, and thus ~~the part of the texture~~grains coarser than 2 mm ~~was~~were not ~~taken into consideration~~considered.

Table 2 - Sediment size data inside the port (see station identified with the red dot of Figure 2). Three different surveys were carried out between June 2009 and July 2010

Date of survey	Sediment Size	%
2009-06-15 16:00:00	Ø < 63 µm	82.4
2009-06-15 16:00:00	63µm < Ø < 2mm	16.2
2009-06-15 16:00:00	Ø > 2 mm	1.4
2009-07-15 16:00:00	Ø < 63 µm	89.2
2009-07-15 16:00:00	63µm < Ø < 2mm	9.1
2009-07-15 16:00:00	Ø > 2 mm	1.7
2010-07-28 09:00:00	Ø < 63 µm	78.2
2010-07-28 09:00:00	63µm < Ø < 2mm	17.7

We assumed that the ~~fraction~~proportions of the samples with Ø < 63 µm ~~was~~were composed ~~by~~of two grain sizes with diameters of 30 μm and 50 μm, respectively, while for the observed ~~component~~components with ~~diameter~~diameters in the range of 63μm to 2 mm we assumed ~~the diameter of~~ 100 μm ~~would~~to be representative.

The degree of consolidation of the seabed is both time- and depth-dependent. The upper layer, which mostly contributes to the flux of re-suspended sediments into the water column, is composed of freshly deposited sediment as it is subject to continuous reworking. The lower layers are more consolidated, and the degree of consolidation increases by depth. This vertical gradient in seabed properties is enhanced in a port environment as the upper layers are continuously influenced by the propeller induced jets several times per day, hence a multilayer modelling of the seabed is appropriate. Teisson (1992) and Sandford and Maa (2001) also took this approach. A single layer bed representation would imply an overestimation of the bed's erodibility (soft mud, thus easily reworked), resulting in unrealistic further overestimations of sediment erosion and concentration along the water column. Thus, a multilayer representation of the seabed is required to account for the ~~present study.~~

~~The~~ transition from unconsolidated to consolidated material. Amorim et al. (2010) used a two-layer approach to model the seabed with MIKE software, simulating the sediment transport in the navigation channel of the Port of Santos. However, as they suggested, a two-layer representation of the seabed may produce an unrealistically abrupt transition between erodible and hard bed layers, so to consider a gradual transition from freshly deposited to consolidated material, three ~~fractions chosen were distributed into three active bed layers.~~bed layers were defined here, representing the freshly deposited, slightly consolidated and fully consolidated sediments. The percentage of the fine ~~fractions amongst~~particles in the sediment texture ~~of sediment~~ was assumed to decrease proportionally to the depth of the layers. Thus, the first layer contained 80% of ~~fines (specifically~~ fine grains (50% of grains ~~with~~of Ø=30 μm and 30% ~~with~~of

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Ø=50 *μm*) and 20% of coarse (Ø=100*μm*), while the third layer contained 50% of coarse (Ø=100*μm*) and 50% of fines (specifically fine (20% of grains withof Ø=30 *μm* and 30% withof Ø=50 *μm*). In the mid layer, an even distribution was assumed among the three. The thicknesses of the three fractions. The thickness of the three layers isare 0.5 *mm*, 1 *mm* and 50 *mm* at the beginning of each scenario. The first layer is composed byof very soft mud sinceas it is the result of the newly deposited and finer mud. The other two layers are more consolidated and thicker, sinceas they are harder to beless easily eroded and they are shielded by the upper layers. The adopted description of the bottom withThe different layers and fractions of sediment allowedthat characterise the bottom enabled us to represent the port bed in a complex and comprehensive way, includingand include the different degreevarious degrees of consolidation of the layers and the resulting different responseresponses to shear stress solicitations.

A summary of the most relevantThe main characteristics of the layers and sediment fractionsproportions implemented in the sediment transport model isare presented in Table 3Table 3Table 3.

Finally, potential sediment input mightmay also potentially come from six minor streams inflowing inthat flow into the port area. TheyThese have very modest basins -of approximately 1 km^2 on the average—, and they have been ceiling-covered for long time, acting many years, so they now act more as sewage collectors than as natural streams. An estimate of theirTheir contribution to the sedimentary dynamics of the port of Genoa has been conductedestimated and the annual sediment supply to the port basin from each stream has been evaluated referring to , based on the method proposed by Ciccacci et al. (Ciccacci et al., (1989). The estimated sediment contribution of sediment resulted inwas only a few hundreds of cubic meters per year in the worst casescase, which corresponds to a contribution to the wet basins of a few millimetres of annual accumulated sediments insediment from the surrounding of the river inlet to the wet basins. Such amount. This level of solid matter has not been considered in the model sinceas the erosional and depositional processes induced by the propellers'propeller activity are higher by one or two orders of magnitude.

Table 3 – Summary of sediment characteristics as implemented in the mud transport model

Parameter	**Layer 1**	**Layer 2**	**Layer 3**
Layer thickness (mm)	0.5	1	50
Type of Mud	softSoft	hard	hard
Dry density of bed layer (kgm^{-3})	180	300	450
Parameter	**Fraction 1**	**Fraction 2**	**Fraction 3**
Φ (μm)	30	50	100
% of fraction in layer 1, 2, 3	50, 33, 20	30, 33, 30	20, 33, 50
W_s (mms^{-1})	0.7	2.2	8.8
τ_{ce} (Pa)	0.15	0.25	0.5
τ_{cd} (Pa)	0.07	0.07	0.07
C_{floc} (gl^{-1})	0.01	0.01	0.01
C_{hind} (gl^{-1})	10	10	10
ρ_s (kgm^{-3})	2650	2650	2650

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5 ~~–~~ Results and discussion

The ~~most representative~~main results of the hydrodynamic and sediment transport model are presented in this section. Due to the large number of simulations carried out, only those regarding two docks are shown. However, the current and sediment concentration results ~~not shown~~ corresponding to the other simulations are qualitatively similar ~~in terms of hydro and sediment dynamics. The results discussed are those of~~. We focus on the simulations of docks 1012 and T7. Dock 1012 is particularly important ~~since~~as it hosts the ~~biggest~~largest passenger vessels operating in the port, while dock T7 ~~is particularly relevant due to the~~has a high frequency of passages.

Figure 7 shows the ~~propeller's~~ propeller-generated current in the bottom layer and at the depth of the propeller's axis (upper right and left panels, respectively) and the resulting suspended sediment concentration in the same layers (corresponding lower panels) during the departure of a cruise vessel from dock 1012. The characteristics of ~~the~~a vessel representative of the traffic ~~of~~in the dock are ~~those of~~given in Table 1~~.~~Table 1. When departing, the engine ~~is operated~~operates close to full power, which we ~~assumed to result~~assume results in a rotation rate of ~~2~~two rounds per second (rps) for the propeller. This induces a maximum velocity at the depth of the propeller axis close to 9 ms^{-1}, which is damped to approximately 2 ms^{-1} on the bottom of the berthing basin along the vessel's route. ~~Such~~This intense jet is deflected to the left due to the head wall of the berthing basin, which constrains the flow and induces a cyclonic eddy~~,~~ that is well developed along the whole water column. The cone-like ~~envelop~~envelope of the jet in the vertical plane, as ~~sketched~~illustrated in the theoretical scheme of Figure 1 ~~is appreciable from~~Figure 1 can be observed in the upper panels of Figure 7, which refer to the same ~~instant~~example: the influence of the propeller on the bottom occurs several tens of meters behind the propeller's position, and the velocity at the bottom is ~~strongly~~much reduced. The induced eddy in the wet basin acts as a trap for the eroded sediment, which enters the cyclonic gyre (or anti-cyclonic in the case of departure from the opposite dock) and tends to deposit in the middle of the basin, where the fluxes progressively decrease. The position of the eye of the cyclone evolves parallel to the docks' longitudinal walls and induces the sediment trapped inside the gyre to sink along the longitudinal axis of the wet basin. Such dynamic occurs similarly for all the horseshoe-shaped wet basins, inducing accumulation along the central portions. The re-suspended sediment may reach very high concentrations ~~in the bottom layers,~~ of up to several hundreds of mgl^{-1}~~,~~ in the bottom layers, depending on the different specific characteristics of the sediment texture (~~mainly~~such as grain size, level of ~~compactation,~~ consolidation and availability to erosion) and of the vessel (~~mainly dimension~~such as dimensions of the propellers, rotation rate~~,~~ and draught).

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~~Different~~Various hydro and sediment dynamics occur during the inbound phase of vessels manoeuvring inside the port. ~~The majority~~Most of the manoeuvring operations (i.e~~.~~., when vessels rotate within a turning basin and proceed backwards to the docks) occur in the turning basins ~~delimited~~denoted by the dashed circles *a* and *b* ~~shown~~ in Figure 2~~.~~ ~~When~~Figure 2. The engines operate at high power when starting the manoeuvre, ~~engines operate~~ to ~~high power in order the~~ allow for the rotation of the ship. ~~Within these operations the~~The vessel's longitudinal axis then rapidly changes direction (~~order of~~from tens of seconds up to a few minutes) ~~spanning~~and can span wide angles ~~according to~~, depending on the specific manoeuvre ~~to be undertaken.~~. The ~~propellers~~propeller induced jet follows the same rotation along the horizontal plane, resulting in a fan-like distributed set of directions for the associated currents. Such operations are realistically represented by the model ~~in a realistic way,~~ as shown in Figure 8, which refers to the berthing of the vessel representative of dock T7. The currents shown in the figure are those associated ~~to~~with the propeller's axis during four different moments of the turning manoeuvre. Each panel refers to ~~a~~successive time ~~interval~~intervals of approximately 100 seconds ~~from the previous one. The~~. These successive instants are presented in the order of up-left, up-right, down-left and down-right~~, respectively.~~. In the lower-right panel the propeller has already changed rotation direction ~~of rotation~~ and the vessel is now proceeding backwards. The induced current jet is thus heading towards the centre of the port~~,~~ and pushing the sediment towards this area. ~~What simultaneously happens at the~~The simultaneous seabed activity is shown in Figure 9~~. Albeit~~Figure 9. Although the jet induced currents are very much weaker at the seabed than those at the depth of the propeller's axis, they are still ~~relevant~~significant and may reach intensities of up to 1 ms^{-1}, depending on the local bathymetry.

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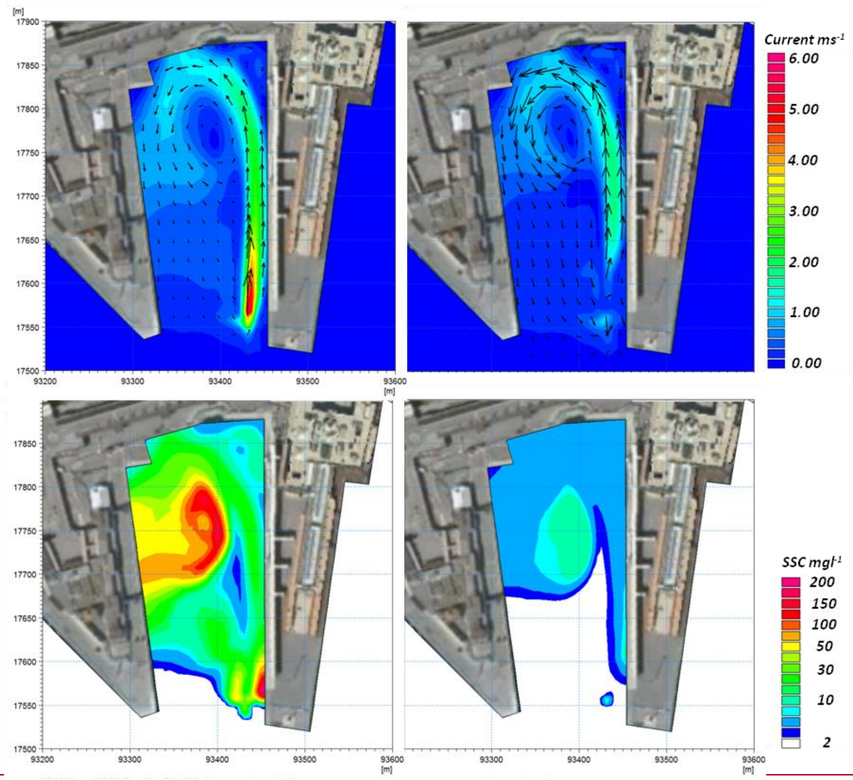
Current ms-1
6.00
5.00
4.00
3.00
2.00
1.00
0.00
SSC mgl-1
200
150
100
50
30
10
2
[m]
17900
17850
17800
17750
17700
17650
17600
17550
17500
93200
93300
93400
93500
93600

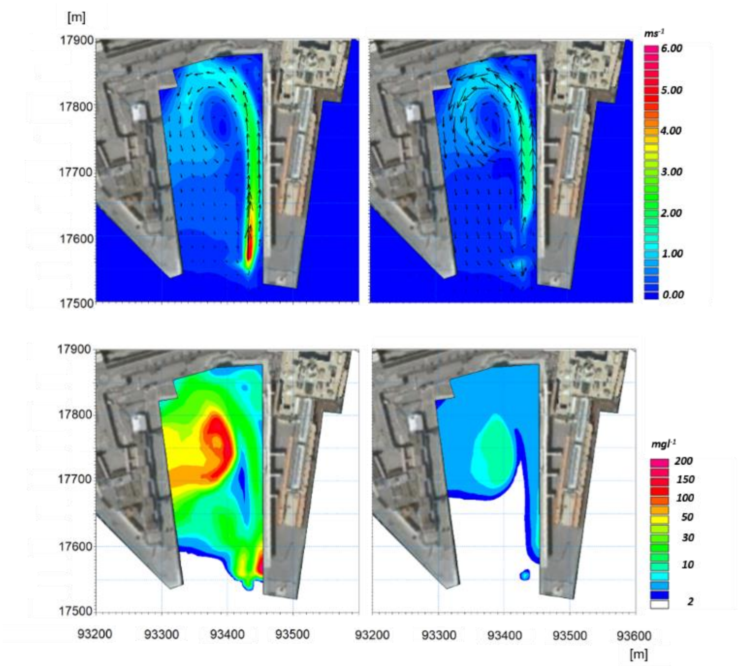

Figure 7 – Results of the numerical models. Upper panels: current intensity and direction in the bottom layer (right) and in the layer corresponding to the axis propeller. Lower panels: resulting suspended sediment concentration (SSC, mgl^{-1}) in the same layers as the upper panels. The images refer to the undocking of the cruise vessel representative of dock 1012.

The current distribution at the seabed is much more chaotic than at the propeller's axis depth. ~~It is to be noted that this~~This area of the port corresponds to the natural pit (which reaches approximately 22 meters below the surface in the deeper part~~, approximately) where~~) in which the material dredged from the accumulation areas is ~~normally~~often dumped during the sea bottom maintenance activities. The dashed line shown in the lower-right panels of Figure 8 and Figure 9 Figure 9 refers to the transect presented in ~~Figure 10, in the same instant (i.e.~~**Figure 10Figure 10** in the same instant (i.e. when the vessel has ended the manoeuvre in the circle *b* and is approaching dock T7 backwards).

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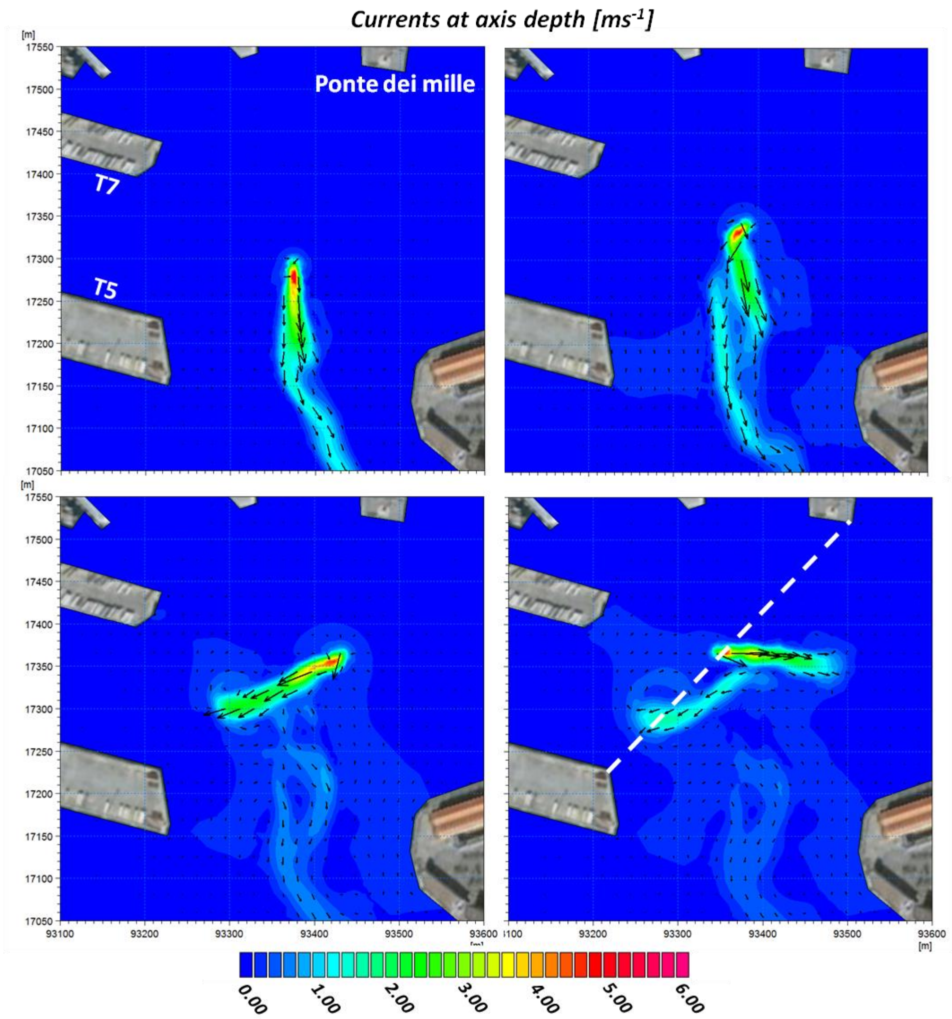
Currents at axis depth [ms-1]
Ponte dei mille
T7
T5
[m]
17550
17500
17450
17400
17350
17300
17250
17200
17150
17100
17050
93100
93200
93300
93400
93500
93600
0.00
1.00
2.00
3.00
4.00
5.00
6.00

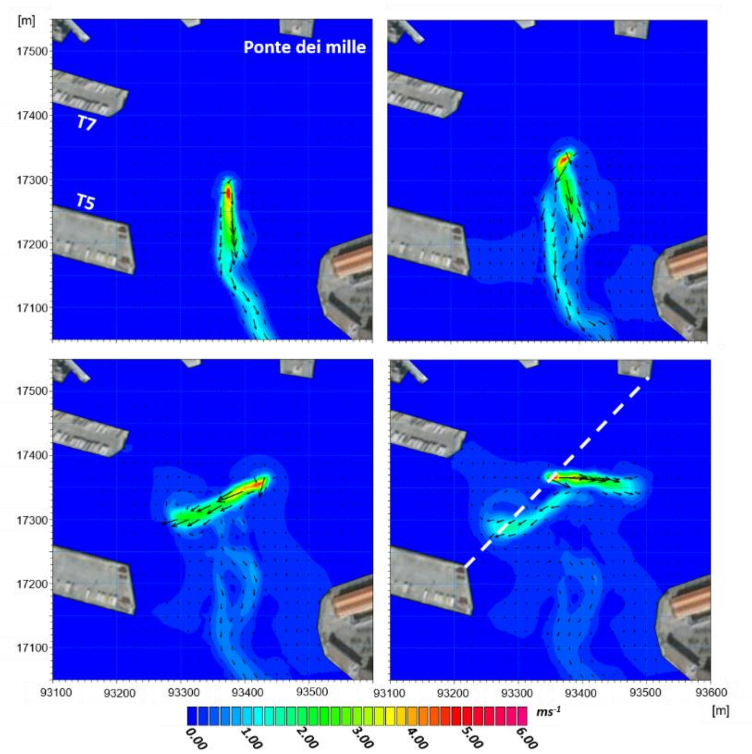

Figure 8 – Results of the hydrodynamic model at the depth of the propeller's axis. Each panel refers to a time interval of approximately 100 seconds from the previous one. The temporal order of the panels is up-left, up-right, down-left and down-right. The images refer to docking maneuvers of the Ro-Ro vessel representative of dock T7

A combined analysis of Figure 8, Figure 9Figure 9 and ~~Figure 10~~**Figure 10Figure 10** helps us understand the dynamics occurring in the turning basin *b* during the manoeuvres ~~to approach~~when approaching docks T5, T6 and T7~~.~~ ~~This is~~, and particularly ~~important in order to understand~~ the overall sediment dynamics of the entire port~~ since~~, as these three docks ~~operate~~account for approximately half of the entire passenger traffic. The ~~propeller's~~ propeller-induced velocities at the bottom of the natural pit during turning manoeuvres ~~is~~are variable and may exceed 1 ms^{-1}, which is a ~~relevant~~significant current intensity ~~able to~~that can entrain and move a large amount of sediment. The resulting re-suspended sediment concentration may reach ~~important~~ values~~,~~ exceeding 50-60 mgl^{-1}, as shown in the lower panel of ~~Figure 10.~~**Figure 10Figure 10**. Once re-suspended from the pit, the sediment is advected ~~around~~ by the jet~~-~~-induced

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complex field of currents of Figure 8 and Figure 9Figure 9. This area is ~~normally~~typically refilled with freshly dredged material resulting from the seabed maintenance activities, and thus the propeller's induced currents on the bottom have an enhanced ~~effect of~~ erosion effect on the unconsolidated material and ~~are able to~~can rapidly nullify the benefit of the dredging operations. ~~In this regard~~Thus, the results of the simulations suggest ~~to avoid to~~avoiding the use of the natural pit as a dumping area for the resulting material ~~of such activities~~, and ~~prove~~confirm that integrated modelling can be ~~a fundamental~~an effective tool for ~~the comprehension of~~simulating the processes and mechanisms related to sediment transport, and for ~~an~~the optimized planning of maintenance activities.

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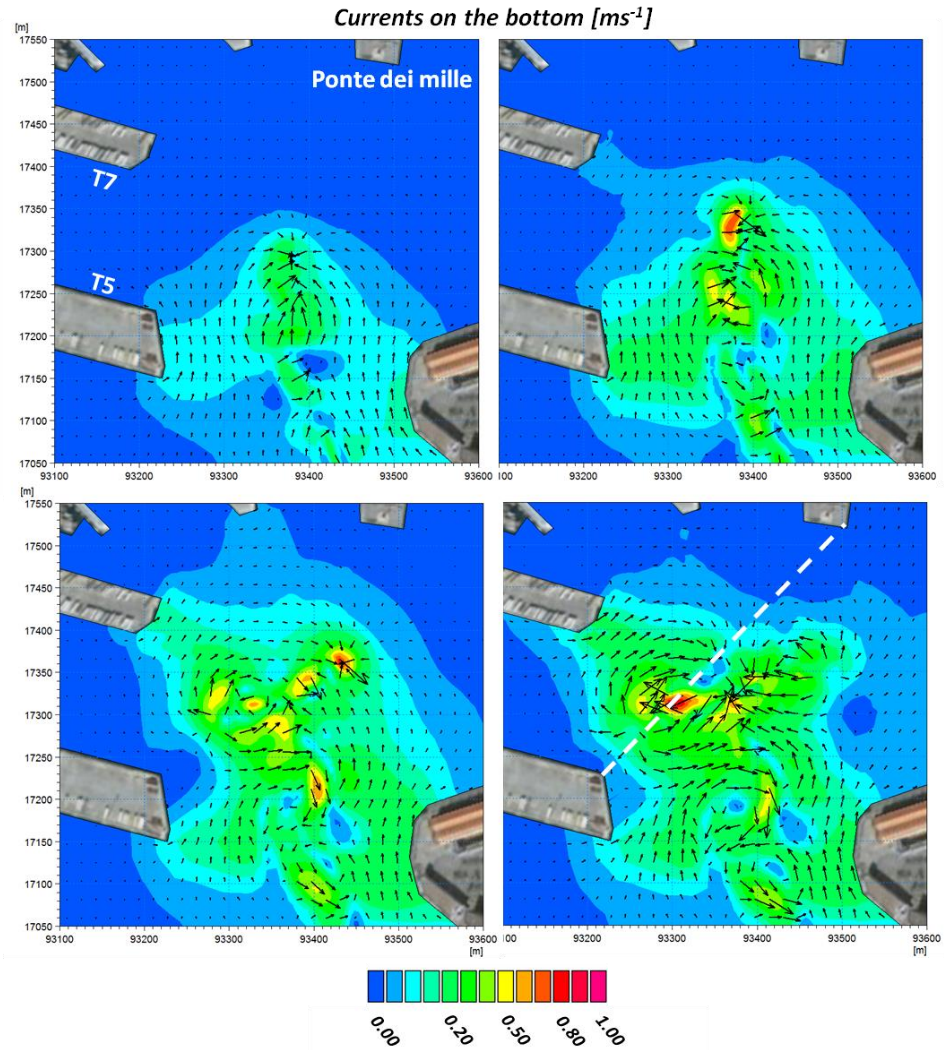

Currents on the bottom [ms-1]
Ponte dei mille
T7
T5
[m]
17550
17500
17450
17400
17350
17300
17250
17200
17150
17100
17050
93100
93200
93300
93400
93500
93600
0.00
0.20
0.50
0.80
1.00

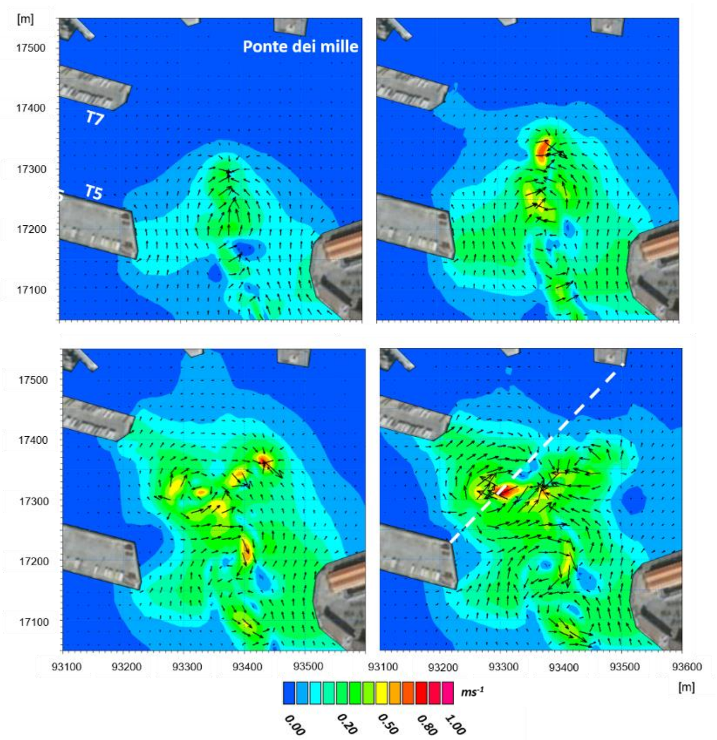

Figure 9 — Same as Figure 8 but for the bottom layer

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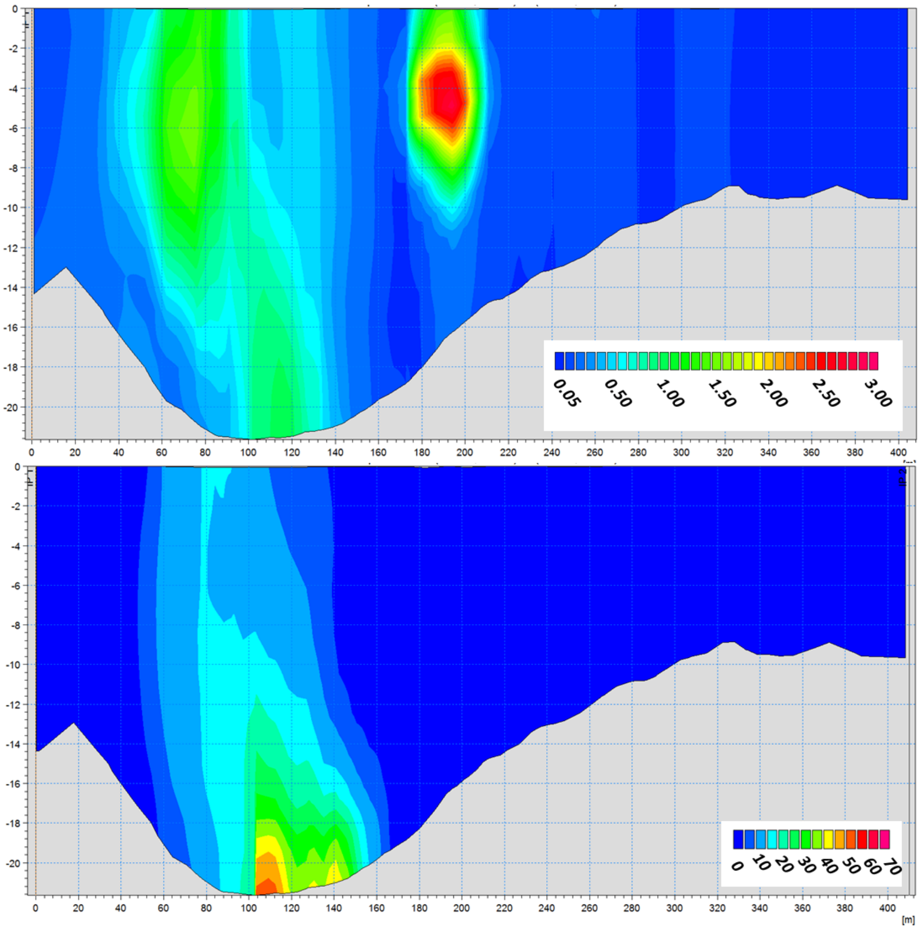

– Results of the hydrodynamic model in the bottom layer. Each panel refers to a time interval of approximately 100 seconds from the previous one. The temporal order of the panels is up-left, up-right, down-left and down-right. The images refer to docking maneuvers of the Ro-Ro vessel representative of dock T7

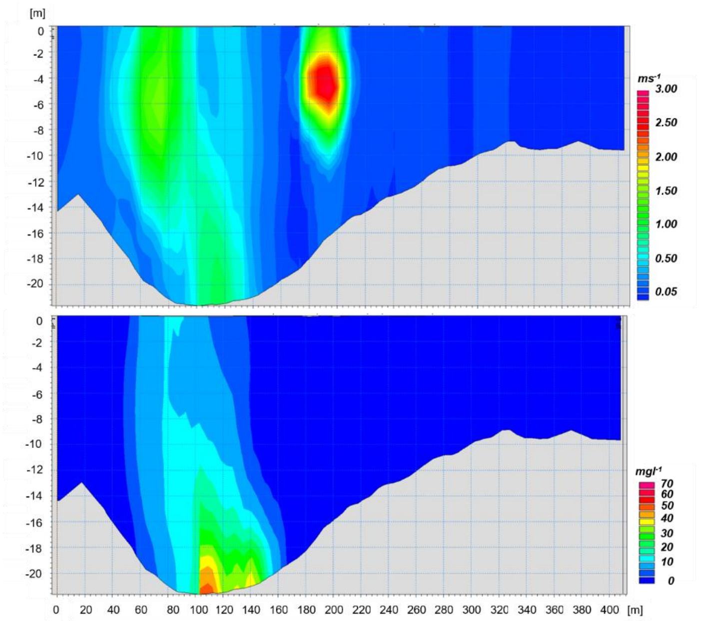

Figure 10 ~~-~~- Velocity intensity in ms^{-1} (upper panel) and sediment concentration in mgl^{-1} (lower panel) along the transect from the head of *Ponte Assereto* to the head of *Ponte dei Mille*

The impact on the bed thickness ~~due to~~of the naval traffic is ~~depicted~~illustrated in Figure 11Figure 11, which presents the erosion and deposition maps resulting from the simulations of one departure (left) and one arrival (right) of the representative passenger vessels of docks 1012 (up) and T7 (down). The blue ~~colors represent~~color represents areas of erosion, while the red ~~colors represent those of~~represents the accumulation of the sediment after an interval of time ~~sufficiently~~ long enough for the re-suspended sediment to completely settle~~ down. It is evident from the~~. The left panels of the figure show that during the vessel's departure a considerable amount of material tends to be eroded from the ~~basement~~bases of the docks and settles in the center of the mooring basins. This mechanism is clearly related to the vessel's departure (left panels) rather than ~~to the vessel's~~its arrival (right panels). The erosion underneath the vessel's keel along the ship's trajectory is ~~well~~ evident, both during departure and arrival~~., in agreement with~~, thus supporting previous experimental ~~literature~~ findings (Castells et al~~.~~., 2018). The order of magnitude of erosion and deposition of ~~one~~a single vessel's passage is of a few millimeters in the areas most influenced by the vessel's activity.

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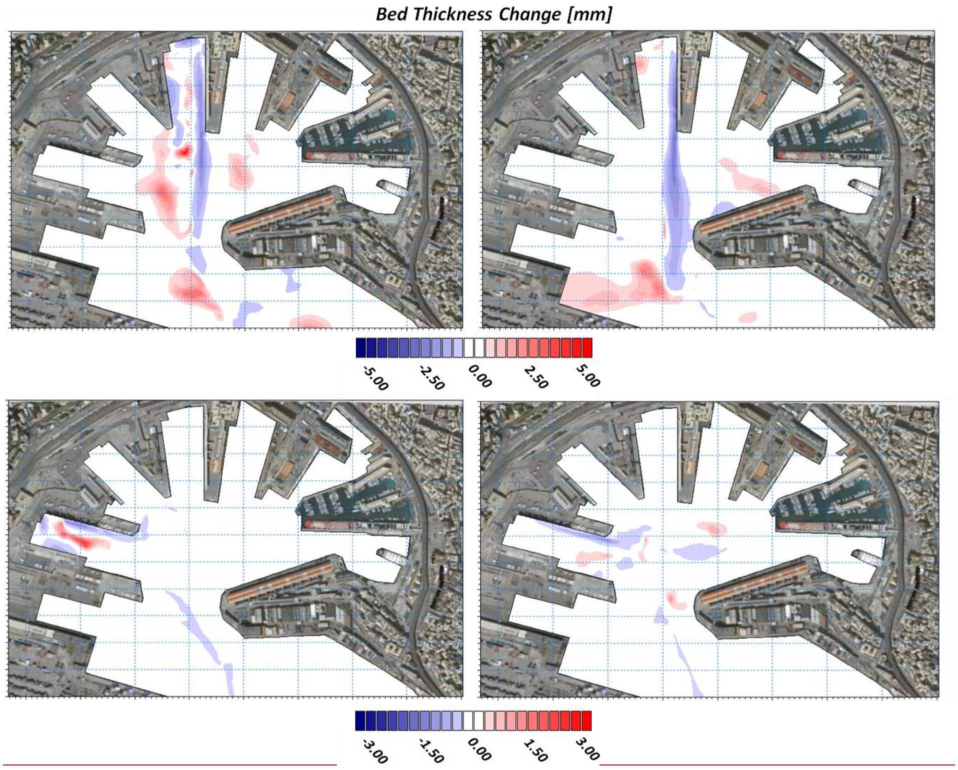
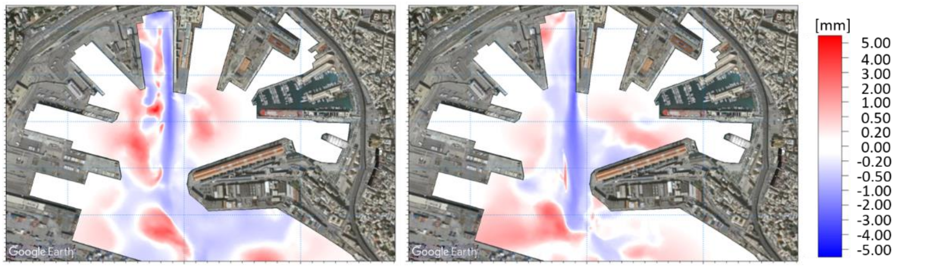

Bed Thickness Change [mm]
-5.00
-2.50
0.00
2.50
5.00
-3.00
-1.50
0.00
1.50
3.00


Google Earth
Google Earth
[mm]
5.00
4.00
3.00
2.00
1.00
0.50
0.20
0.00
-0.20
-0.50
-1.00
-2.00
-3.00
-4.00
-5.00

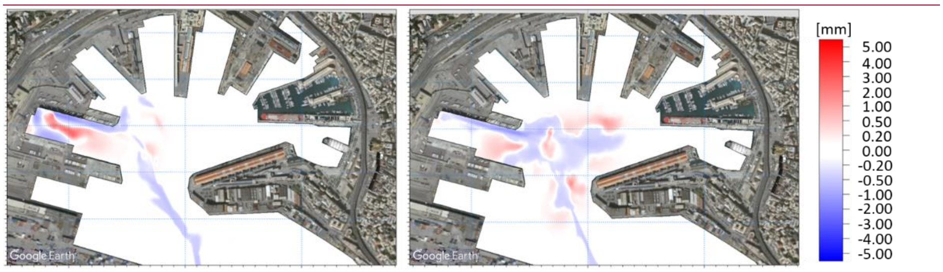

Google Earth
Google Earth
[mm]
5.00
4.00
3.00
2.00
1.00
0.50
0.20
0.00
-0.20
-0.50
-1.00
-2.00
-3.00
-4.00
-5.00

Figure 11 – Erosion and deposition maps resulting from one departure (left) and one arrival (right) of the representative passenger vessels of docks 1012 (up) and T7 (down)

Such impact ~~might~~can become a real threat ~~for~~to the continuity of ~~the operability of~~ operations in large and busy ports ~~like the Port of~~such as Genoa ~~in the~~over medium ~~and~~to long timescales. The few millimeters of accumulation and erosion ~~might~~can become several tens of centimeters after a few ~~thousands of~~thousand annual passages. ~~Relying~~For the sake of completeness, the results of the impact on the bed thickness due to the activity of the other vessels not shown here are presented in APPENDIX A3.

Based on the traffic analysis of Table 1Table 1 we projected each single naval passage to a one-year ~~period~~duration and superimposed the effects of erosion and deposition of ~~the~~ vessels that are representative of all of the passenger docks. We were thus able to reconstruct the annual port seabed evolution for the year of 2017. The effects of the single passages were weighted by the specific occurrences of ~~the~~that year ~~2017~~, thus obtaining 24 maps (one for each docking and one for each undocking), and the results ~~of the 24 maps~~ were integrated to obtain ~~the~~a final map. ~~To take into account the fact that~~

As the trajectories ~~to reach~~for reaching a dock (or ~~to depart~~departing from it) vary slightly ~~vary~~ from passage to passage, a Bartlett spatial filter was applied to the integrated results using the values of 4, 2 and 1 as weights. Figure 12Figure 12 presents the results of this analysis. In the left panel the results from the modeling system in terms of annual erosion (blue) and accumulation (red) are shown, while in the right panel the observed seabed evolution is shown. The observed map was reconstructed ~~through~~using the ~~results~~outcomes of two ~~different~~ bathymetric surveys carried out in the periods of May-June 2017 and March-June 2018. The difference ~~of~~in the bathymetries of the two surveys resulted in the evolution of the seabed during the approximate ~~period of~~ one~~-~~year period, except for dredging operations. We ~~used numbers in~~indicated the ~~maps to indicate~~ areas where the most ~~relevant~~significant dynamics ~~outlined by the study take~~took place on the maps using numbers.

~~It is to be noted that the~~The area between the ~~head~~heads of *Ponte dei Mille* and ~~the head~~ of *Molo Vecchio*, identified as 1, was dredged during the period October-December 2017, and approximately 15.000 m^3 of solid material ~~were~~was removed and dumped into the natural pit of the port, ~~here~~as indicated ~~with~~by the number 5. ~~Consequently~~Thus, what appears to be at first sight ~~from observations as~~ an area of erosion due to ~~the~~ vessel traffic - area 1 in the right panel of Figure 12Figure 12 - is actually an area of accumulation, ~~as it~~which is ~~also~~ confirmed by the fact that dredging operations were conducted. Similarly, the accumulation observed in area 5 (right panel of Figure 12Figure 12) is not the result of the induced action of the propellers, but ~~it is the result~~ of the accumulation of the sediment dumped after the maintenance dredging operations. The model results are in total agreement with these dynamics. As discussed

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above, the material re-suspended during vessels' maneuvers is likely pushed towards area 1 during the phase of the backward advancing of the vessels when approaching the docks. ~~On the contrary~~Conversely, area 5 is partially an area of erosion, as evidenced by the model. The freshly deposited material during dredging operations is thus ~~soon~~rapidly re-suspended.

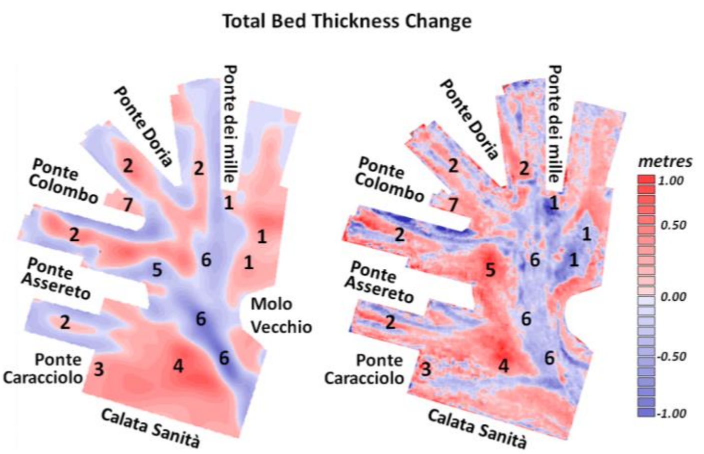

Figure 12 – Annual erosion and deposition map reconstructed on the basis of the hydrodynamic and sediment transport simulations for the year 2017

Area 1 accounts for approximately 30-40 cm of accumulated material per year, with local maxima of up to 50 cm. Similar values were estimated ~~against~~through years of managing experience by the personnel of Stazioni Marittime S.p.A (personal communication).

The central portions of the wet basins marked with number 2 in Figure 12Figure 12 are areas of deposition, mainly due to the phase of departure of the ships. Again, the model ~~is able to~~can well reproduce both the accumulation along the central parts of the basins, where it may reach 20 cm per year or even more, and the erosion along the walls of the docks. Here, the ~~propellers~~propellers' erosive action ~~might~~may result in ~~issues for the~~ stability ~~of~~problems for the docks, ~~especially~~particularly along ~~those~~the walls of dock 1012, where the biggest cruise vessels operate.

The erosion underneath the vessels' typical routes (i.e.~~.~~, from the entrance to approximately the center of the port) is also well represented by the model, and ~~it~~ is identified in the figure with the number 6. ~~Good agreement between the~~The model and the observations ~~is~~ also ~~evident~~ exhibit good agreement in the deposition area ~~identified with the~~ (number 7~~,~~), where a local gyre forms and entraps the suspended sediment. Finally, ~~also~~ areas 3 and 4 are also subject to deposition, and qualitative agreement between the model and the various bathymetric ~~differential survey~~surveys is

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evident from Figure 12Figure 12. The erosive print observed in the survey under these areas is most likely due to activities related to cargo vessels ~~when~~ approaching and departing from dock *Calata Sanità*. ~~This latter was~~These vessels were not ~~object~~the focus of ~~the~~our study, ~~which was intended only for passenger docks whereas~~and *Calata Sanità* only operates ~~only~~ container ships, and thus the model does not include the naval traffic here.

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In general~~., the comparison between,~~ the observed and the modeled annual evolution of the port seabed ~~shows a~~show very good agreement, ~~it proves~~which confirms the reliability and robustness of the hydrodynamic and sediment transport model and ~~it finally shows~~demonstrates the potential importance of an integrated modeling approach ~~to optimize~~in optimizing the management of ~~the~~ port activities.

The assumption of unvarying initial bathymetry conditions in the different scenarios deserves some additional consideration, as it undoubtedly introduces some inaccuracy into the results. This approach does not consider the real order of vessels' passages or the impact that the evolving seabed has on the hydrodynamics and sediment transport simulations. In particular, the variable clearance distance between the propeller's tip and the seabed due to the evolving erosion/deposition processes is not considered, although this will increase the differences over time. However, the complexity of the system requires the introduction of several approximations, such as the dimension and rotation rates of the propellers, the typology and distribution of the sediment, the layering of the sea bed, the shear stress for erosion and deposition, or the constant initial bathymetry. A solution for the bathymetry issue could be to implement the system in operational mode, and thus continually updating the initial bottom boundary conditions through the simulation iterations. However, this was not realistic in terms of computational effort, and was beyond the scope of the study, which was to identify areas of erosion and deposition in the port and to evaluate the order of magnitude of the corresponding evolution rates to support the port management. Nevertheless, if we consider the most significant variation of the seabed and the typical propeller induced bottom velocities, which are in the order of 50 cm (Figure 12) and 1-2 ms^{-1} (Figures 7, 9 and 10), respectively, the resulting bottom shear stresses are in the order of 2-4 Nm^{-2}. Such values are orders of magnitude larger than the typical critical shear stress for the deposition-erosion of freshly deposited fine sediments (in the order of 0.07-0.15 Nm^{-2}, respectively), suggesting that variations in the bottom shear stresses due to a change in the clearance distance of the propeller's tip of an order of 50 cm (a conservative estimate), would not have a significant impact on the mobility of the sediments. Consequently, such differences would not imply substantial variations in the erosional and depositional processes and patterns.

5 – Summary and Conclusions

The impact of naval traffic on the seabed of the ~~passengers Port~~passenger port of Genoa was investigated ~~by means of~~through numerical modeling. The combination of a very high resolution, non-hydrostatic, circulation model (MIKE 3

HD FM) with a sediment transport model (MIKE 3 MT FM), based on unstructured grids on the horizontal and on sigma levels on the vertical allowed, enabled us to reconstruct the annual evolution of the port seabed. The final results of the modeling, in terms of maps of erosion and deposition inside the basin, were qualitatively supported by observational evidence. TheOur approach followed was to simulate only one arrival and one departure from each dock of the port and to analyze the impact of a single naval passage on the seabed in terms of sediment concentration, motion and distribution.

FollowingFrom the traffic analysis in the port for a typical year (year 2017)), we could obtain the detailed situation of the number of arrivals and departures for each dock was available as a starting point for the study. ThroughBy superimposing the superimposition of the single effects of the trafficsingle vessels weighted for the annual number of passages of the most representative vessel operating on each dock the, an annual map of erosion/deposition was reconstructed and validated on a semi-quantitative basis versus differentialby comparison with various bathymetric surveys available for the same period.

In general.,, the simulations showed that the velocity intensities on the bottom induced by propeller's propeller-generated jets maycan reach almost 2 ms^{-1}, and mainly dependingdepend on the dimensiondimensions of the propellers, on the rotation rate and on the distance between the propeller and the bottom. Such velocities may reach up to 8-9 ms^{-1} at the propeller's axis depth, and penetrate horizontally through the water for long distances, up to at least 40-50 times the propeller's diameter. The bed shear stresses induced by these velocities, as well asand the propeller jet induced entrainment, mobilize and re-suspend highlarge amounts of the fine and less compacted sediments present inside the port. Fine fractionsproportions with smallerlower fall velocities tend to remain in suspension for longer periods of time, resulting in the creation of sediment plumes. Hong et al. (2016) have shown in their laboratory test results the dependency of the concentration profiles behind propeller jets to sediment grain size distribution, amongst other parameters.

The finalOur findings showed how relevant the significant these deposition rates mightcan be in a densely operated port, reaching values of several tens of centimeters per year in some localspecific areas.

The type ofOur approach we adopted was particularly useful not just because it allowedenabled us to minimize the computational time, but and also because it allowed to decompose the overall complex pictureview of sediment transport of the entire port into several simpler picturesviews. Consequently, we were able to analyze the analysis of the singlespecific hydro and sediment dynamics occurring for each dock and vessel was possible as well as the identification of the, and to identify specific routes responsible of the particular problems offor particularly serious erosion and accumulation, as historically reported by the managing authorities of the port operations and traffic. The range of current intensities induced by the propellerspropeller action was identified along the water column, and itthis can be further used as a ~~solid~~sound and ~~scientific~~ scientifically based benchmark value for potential defensive actions ~~for~~on the seabed and port structures ~~that might be undertaken in the future in order to preserve the port's~~ , to guarantee the ongoing full operability of the port.

The most ~~relevant~~significant mechanisms ~~regarding~~for the ~~port~~port's hydro and sediment dynamics ~~occurring~~that occur during ~~vessels~~vessel passages were identified and the ~~following~~subsequent analysis ~~allowed to understand~~identified how and why specific areas are subject to erosion and other areas are subject to deposition, and ~~to what~~the extent of these mechanisms ~~occur~~. In particular, the mechanism of ongoing erosion ~~ongoing~~ along the docks walls and ~~that~~ of deposition along the central portions of the mooring basins were identified and explained, ~~as well as~~along with the ongoing deposition process ~~constantly ongoing~~ in the area ~~confined~~ between the ~~head~~heads of *Ponte dei Mille* and ~~the head of~~ *Molo Vecchio*. ~~This last~~Identifying and reproducing this process for the port managers was particularly important ~~to reproduce and understand for the port managers since~~ as it occurs at a very ~~important~~significant rate~~,~~ of up to 40-50 cm per year in some ~~local~~ areas. Finally, the natural hole located off the heads of *Ponte Colombo* and *Ponte Assereto* was identified through the model as an area of erosion, ~~albeit its relevant~~although at significant depth. This is mainly due to the turning maneuvers carried out by vessels in this area ~~which~~, and partially corresponds to one of the turning basins of the port and ~~which~~ involves approximately ~~the~~ 50% of ~~the~~its entire traffic ~~of the port~~ (docks T5, T6 and T7). ~~Since such~~This location has ~~been~~ historically been used as a dumping site for the material resulting ~~material of~~from seabed maintenance dredging, ~~the~~but our study showed how unfit this area is for such purpose, ~~since~~as the freshly deposited sediment is soon re-suspended by the intense currents induced by the vessels turning operations.

The importance of this study ~~was~~is not only to ~~prove~~confirm how an integrated high resolution modeling ~~might be able to~~ can reproduce the most ~~relevant~~significant and complex mechanisms of hydrodynamics and sediment transport occurring inside ports ~~–~~, which was ~~however done~~ successfully ~~–~~achieved, but it ~~was~~ also ~~to suggest, once its reliability was proven,~~suggests that it can be used as a ~~fundamental~~ tool for ~~an optimized~~optimizing port management. ~~In fact, it~~It could be ~~used~~applied to ~~regulate~~regulating the naval traffic in ports ~~in order identify~~and thus identifying the most suitable schedule and routing in terms of sediment concentrations, bottom velocities, erosion ~~and~~, accumulation ~~. Or again it~~ and vessel drafts. It could also be used to identify the ~~biggest~~largest vessels that can potentially ~~operating~~operate in the docks ~~for the~~when planning ~~of the~~ future commercial traffic, or to study the impact of ~~the increasing~~ increased port traffic ~~of ports~~ on the seabed and on the ~~ports~~port's structures ~~, or finally for an awareness planning of the~~ . Finally, in recurring dredging operations ~~related to the~~, most busy ports must regularly face sediment accumulation problems ~~that the majority of densely operating ports must regularly face, most of the times without being correctly~~, and our tool can therefore inform awareness planning of such activities so the authorities are fully prepared.

Daily fully-operational implementations of similar integrated systems arecan also possible tobe set up, sinceas the daily schedule of the port is known. This would allow to continuously monitor enable the continuous monitoring of the evolution of the seabed and allow authorities to be constantly and fully aware of the potential criticalities tothey face.

An important process that Future research following on from this study should be included in the future developments of the present study isalso consider the effect on the sediment resuspension, advection and dispersion due to of the Bernoulli wake and itsin combination with the propeller's induced jets. on sediment resuspension, advection and dispersion. This mechanism was not includedconsidered in the present version of the system. The current intensities caused by vessels' generated waves during and after their passages are surelywill be smaller than those induced by propellers along their axisaxes, but they tend to penetrate along the water column and reach the bottom, thus carrying a significant amount of energy, and possibly re-suspending importanta substantial amount of solid material (Rapaglia et al.., 2011), probably enhancing thewhich is likely to enhance vertical mixing and maybe inducingmay induce the sediment to be suspended for longer periods and at higher depths.

APPENDIX A1 – Hydrodynamic model governing equations

MIKE 3 Flow Model FM is based on the Navier-Stokes equations for an incompressible fluid under the assumptions of Boussinesq. The governing equations of the model are the equations of momentum (A1.1) and mass continuity (A1.2), the equations of heat and salinity transport (A1.3 and A1.4, respectively) and the equation of state (A1.5) based on the UNESCO formula of 1981 (UNESCO, 1981a). Considering a Cartesian coordinate system *(x,y,z)* we have:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \text{(A1.1)}$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-\frac{1}{\rho_0}\frac{\partial q}{\partial x}-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(\nu_t^v\frac{\partial u}{\partial z}\right) \qquad \text{(A1.2.1)}$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=fu-\frac{1}{\rho_0}\frac{\partial q}{\partial y}-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(\nu_t^v\frac{\partial v}{\partial z}\right) \qquad \text{(A1.2.2)}$$

$$\frac{\partial w}{\partial t}+\frac{\partial w^2}{\partial z}+\frac{\partial uw}{\partial x}+\frac{\partial wv}{\partial y}=-\frac{1}{\rho_0}\frac{\partial q}{\partial z}+F_w+\frac{\partial}{\partial z}\left(\nu_t^v\frac{\partial w}{\partial z}\right) \qquad \text{(A1.2.3)}$$

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z}=F_T+\frac{\partial}{\partial z}\left(D_{ts}^v\frac{\partial T}{\partial z}\right)+\hat{H} \qquad \text{(A1.3)}$$

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$$\frac{\partial S}{\partial t}+\frac{\partial uS}{\partial x}+\frac{\partial vS}{\partial y}+\frac{\partial wS}{\partial z}=F_s+\frac{\partial}{\partial z}\left(D_{ts}^{v}\frac{\partial S}{\partial z}\right) \qquad \text{(A1.4)}$$

$$\rho=\rho(S,T) \qquad \text{(A1.5)}$$

Since we used the barotropic density mode the only hydrodynamic equations used for the present work are A1.1 and A1.2. The symbols used in the governing equations of the model are presented in Table 4

Table 4 – Symbols used in the governing equations A1

x,y,z	Cartesian coordinate system
u,v,w	components of the field of velocity [ms^{-1}]
g	gravity acceleration [ms^{-2}]
ρ	water density [kgm^{-3}]
ρ_0	reference value for water density [kgm^{-3}]
q	non-hydrostatic pressure [Pa]
p_a	atmospheric pressure at the sea surface [Pa]
f	Coriolis parameter (non-dimensional)
ν_t^v	vertical eddy viscosity [m^2s^{-1}]
F_u, F_v, F_w	horizontal diffusivity
T	temperature [°C]
S	Salinity [PSU]
F_T, F_S	Horizontal diffusion terms for *T* and *S*
D_{ts}^v	vertical eddy diffusivity [m^2s^{-1}]
$\hat{H}$	Source term due to heat exchange with the atmosphere

APPENDIX A2 – Mud transport model governing equations and parameterizations

The sediment transport module is based on the advection dispersion equation for a passive tracer in an incompressible fluid. The tracer is the concentration *C* of sediment along the water column. The field velocity used for advection is the one calculated through the hydrodynamic set of equations of Appendix A1. The symbols used in the set of equations A2 are summarized in Table 5

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}(uC)++\frac{\partial}{\partial y}(vC)+\frac{\partial}{\partial z}[(w+w_s)C]=\frac{\partial}{\partial z}\left(D_C^{v}\frac{\partial C}{\partial z}\right)+F_C \qquad \text{(A2.1)}$$

The vertical bottom boundary condition for sediment flux is expressed as:

$$D_C^{v}\frac{\partial C}{\partial z}\bigg|_{z=-H}-w_sC=S \qquad \text{(A2.2)}$$

and the sediment flux *S* at the bottom is calculated through the approach of Krone (~~Krone,~~ 1962) for deposition (Eq. A2.3), through that of Partheniades (~~Partheniades,~~ 1965) for erosion of consolidated sediment (Eq. A2.4) and through that of Parchure and Metha (~~Parchure and Metha,~~ 1985) for erosion of soft or unconsolidated sediment (Eq. A2.5).

$$S_d = w_s c_b p_d \qquad \text{(A2.3)}$$

where

$$p_d = 1 - \frac{\tau_b}{\tau_{cd}} \quad \text{valid for } \tau_b < \tau_{cd} \qquad \text{(A2.3.1)}$$

$$S_{ec} = E\left(\frac{\tau_b}{\tau_{ce}} - 1\right)^n \quad \text{valid for } \tau_b \geq \tau_{ce} \text{ and hard bed} \qquad \text{(A2.4)}$$

$$S_{es} = E\, exp\left[\alpha(\tau_b - \tau_{ce})^{1/2}\right] \quad \text{valid for } \tau_b \geq \tau_{ce} \text{ and soft bed} \qquad \text{(A2.5)}$$

The settling velocity for sediment is calculated through the Stokes law (A2.6).

$$w_s = \frac{gd^2}{18}\left(\frac{\rho_s}{\rho_w} - 1\right) \qquad \text{(A2.~~5~~6)}$$

Table 5 – symbols used in the equations and parameterizations A2 of the sediment transport model

x,y,z	~~cartesian~~Cartesian coordinate system (same as Table 4)
u,v,w	components of the field of velocity (same as Table 4) [ms^{-1}]
C	sediment concentration [gmc^{-1}]
C_b	sediment concentration in the bottom layer [gmc^{-1}]
w_s	settling velocity [ms^{-1}]
D_C^v	vertical eddy diffusivity for C (same as for T and S) [m^{2}s^{-1}]
F_C	horizontal diffusion terms for C
H	water depth [m]
S_e	bottom sediment flux for erosion [kgm^{2}s^{-1}]
S_d	bottom sediment flux for deposition [kgm^{2}s^{-1}]
$S_{e,s}$	bottom sediment flux for erosion of soft bed [kgm^{2}s^{-1}]
$S_{e,c}$	bottom sediment flux for erosion of consolidated bed [kgm^{2}s^{-1}]
p_d	probability of deposition for the sediment [non dimensional]
τ_b	bottom shear stress [Nm^{-2}]
τ_{bd}	critical stress for deposition [Nm^{-2}]
τ_{ce}	critical stress for erosion [Nm^{-2}]
E	bottom erodibility [Nm^{-2}]
α	empirical coefficient [$m/\sqrt{N}$]
n	Power of erosion (empirical non-dimensional)
d	diameter of grains [m]
ρ_s	density of dried sediment [kgm^{-3}]
ρ_w	density of water[kgm^{-3}]
g	gravity acceleration [ms^{-2}]

APPENDIX A3 – Results of total bed change

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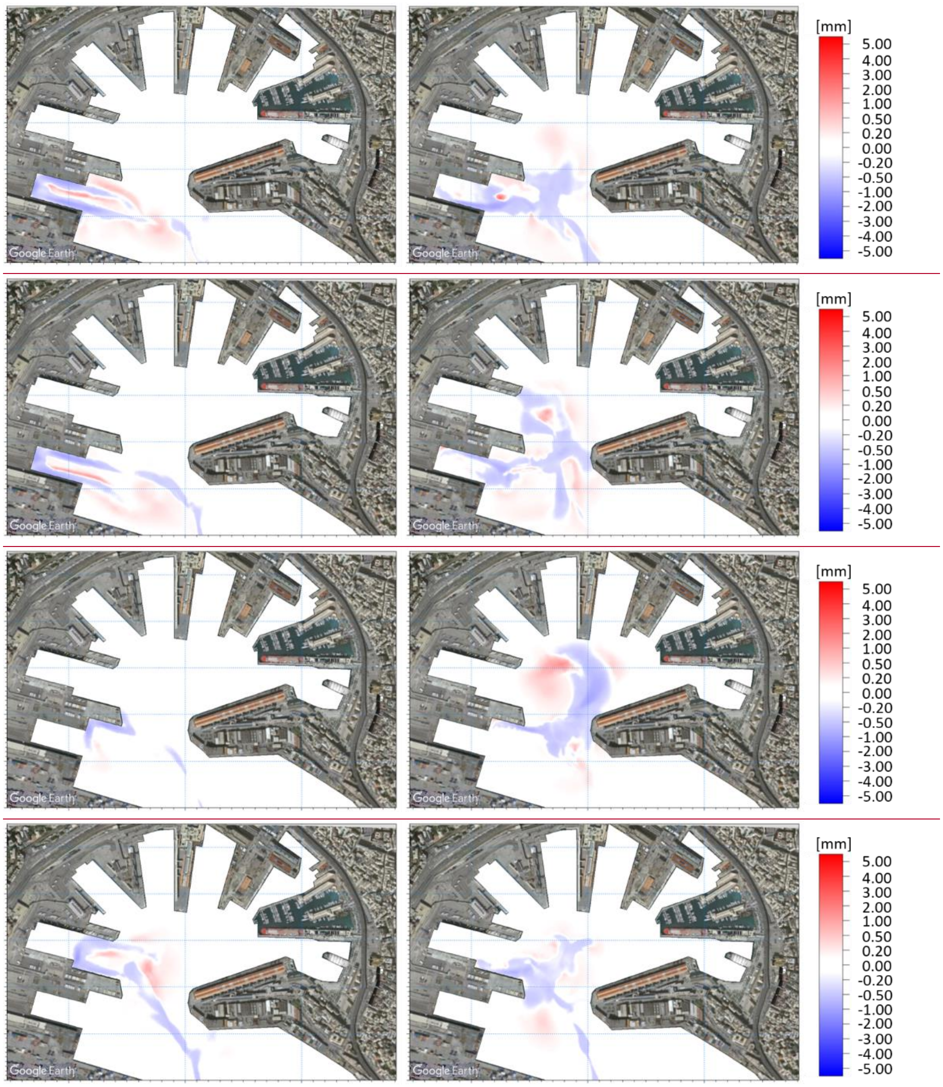
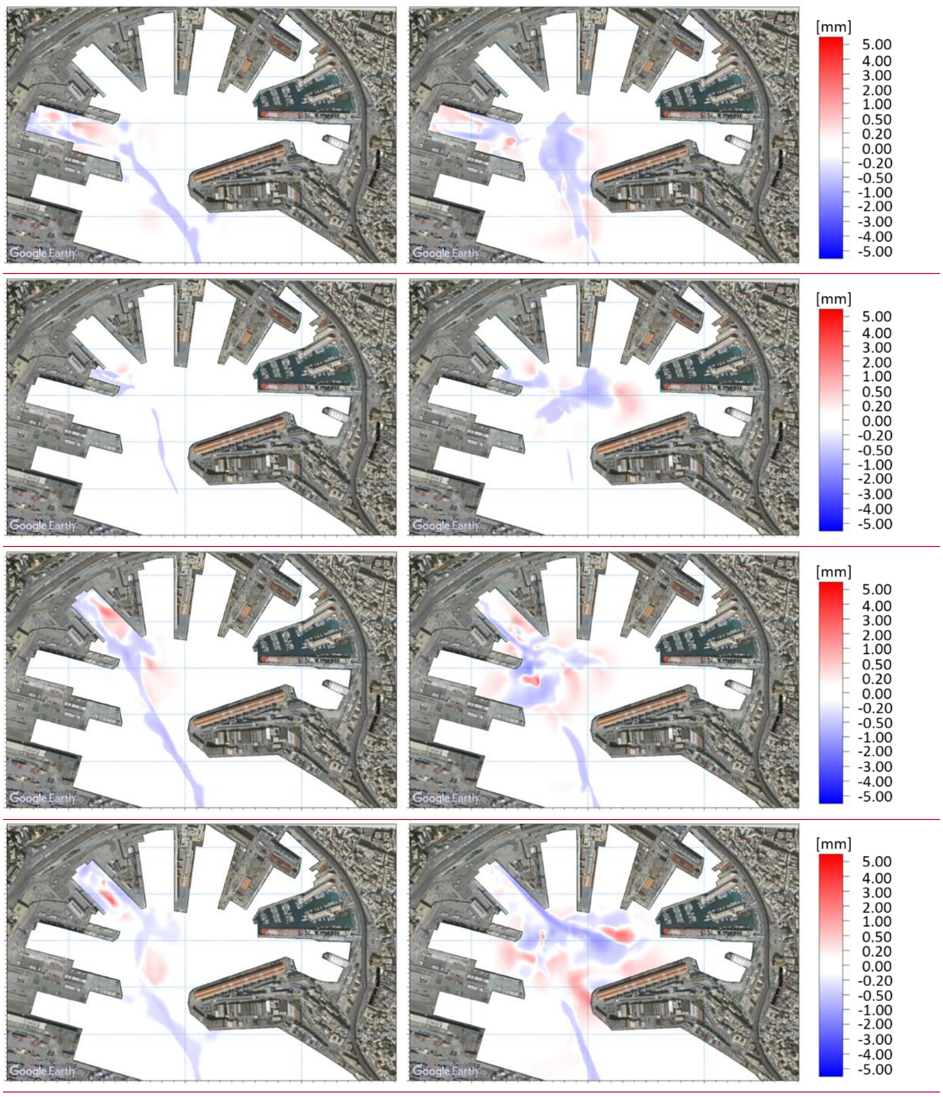
The following matrix of plots presents the results in terms of sediment erosion and accumulation for a single undocking (left) and docking (right) respectively for the scenarios of docks T1, T2, T3, T5, T6, T9, T10, T11, DL, 1003, (top to bottom).

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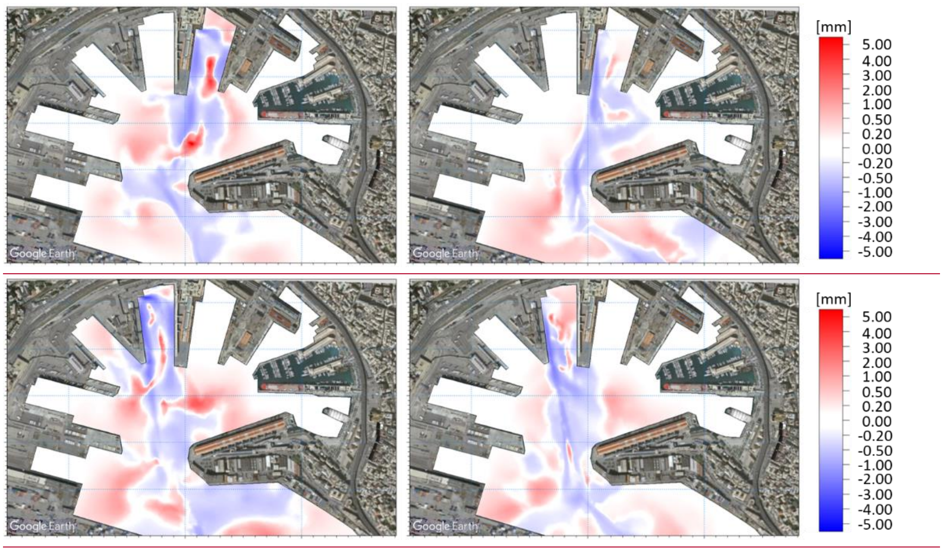

Data Availability

The modelling dataset including the simulations produced for the present study covers a volume wider than 2 TB. Such an amount of data raises an evident problem in order to make them available on data repositories. Consequently, the output of the simulations won't be directly available. However, the model set-up and all the files necessary for their reproduction will be made available in MIKE FM format upon request to the corresponding author.

Team list

Antonio Guarnieri (first and corresponding author), Sina Saremi (co-author), Andrea Pedroncini (co-author), Jakob H. Jensen (co-author), Silvia Torretta (co-author), Caterina Vincenzi (co-author), Marco Vaccari (co-author).

Author contributions:

Antonio Guarnieri implemented the numerical models and simulations, post-processed the raw output, analysed the results and wrote the manuscript;

Sina Saremi gave technical and scientific support during the implementation of the models, provided the code for the propellers modelization as input to MIKE and supported the writing and finalization of the manuscript;

Andrea Pedroncini first conceived the idea of the methodology adopted in the study, gave scientific support for the implementation of the models and feedback during the writing of the manuscript;

Jacob H. Jensen provided scientific support and advice regarding the driving mechanisms of naval induced sediment dynamics;

Silvia Torretta provided technical support for the model implementation and for the observed bathymetry analysis and reconstruction;

Caterina Vincenzi and Marco Vaccari provided bathymetry data, sediment data and information on dredging activities and general sediment related issues. They also favored the acquisition of the naval traffic data.

Competing interests:

Caterina Vincenzi and Marco Vaccari are employees of the Port Authority of Genova (Autorità di Sistema Portuale del Mar Ligure Occidentale), which commissioned and funded the present study to DHI, a private not-for-profit consultancy and research company in the field of water. Andrea Pedroncini, Silvia Torretta, Sina Saremi and Jakob H. Jensen are DHI employees. Antonio Guarnieri was DHI employee when the study was conducted; he is now employed at Istituto Nazionale di Geofisica e Vulcanologua (INGV).

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