



Research paper

On the impact of sediment plumes generated by offshore platform removal in the Adriatic Sea

Sher Shah ^{*}, Gianluca Zitti, Lorenzo Melito, Maurizio Brocchini

Department of Civil and Building Engineering, and Architecture (DICEA), Università Politecnica delle Marche, via Brecce Bianche 12, Ancona, 60131, AN, Italy

ARTICLE INFO

Keywords:

Decommissioning
Sediment transport
Hazard assessment
Numerical modelling
CORMIX
Turbidity plumes

ABSTRACT

The Adriatic Sea is rich in offshore platforms that have reached the end of their life. Their complete removal, however, can result in significant impact on the surrounding environment, as these are often located near the coast or in proximity to protected areas. We here provide a simple and physics-based methodology to estimate the length scale of the potential impact of sediment plumes ("impact distance") generated by the excavation and suspension of sediments during the operations of total platform removal. A thorough parametric analysis was performed using numerical simulations with the mixing-diffusion model CORMIX, testing varying sediment discharges and environmental conditions (water depth, ambient velocity, and distance from the coast). Input data largely come from in-situ observations, while unavailable data has been integrated using acknowledged databases (e.g. EU Copernicus Marine Service). Using a precautionary approach, predictive relationships were established for the impact distances in the Adriatic Sea, leading to a simple and representative index suitable for the implementation in a decision support system for the removal of offshore platforms. Further, simulations revealed rapid near-field dilution (53.8–67.1% within minutes) transitioning to far-field dispersion (99.96–100% dilution within 2.5–25 km), driven by ambient currents. For the Adriatic area, impact distances are transient and range between 0.1 and 14.6 km in direction sub-parallel to the coastline, with negligible hazards beyond 10 km. The implementation of the results in a decision system will support regulators in prioritizing mitigation, balancing ecological, economic and social constraints during decommissioning.

1. Introduction

Offshore oil and gas platforms could be either be fully or partially removed upon reaching the end of their operational lifespan (Colaleo et al., 2022, Grandi et al., 2017, Ministero dello sviluppo Economico, 2019). Decision on their decommissioning involves many environmental, economic and social issues, that must be taken into account. As a specific situation, the complete removal of an offshore platform in Italian waters involves the removal of subsea structures at different level below the sea bottom up to 3 meters below the mudline, implying the dredging of a significant amount of sediment in the surroundings of the platform. This poses significant environmental challenges, particularly regarding the hazard connected to the suspension and transport of fine sediments into the marine environment. To minimize this hazard, an Environmental Impact Assessment is necessary to ensure safe execution, while preserving the health of marine ecosystem, maritime navigation, and corporate financial responsibilities (Ministero dello sviluppo Economico, 2019). The spreading of the sediment put into suspension

during the decommissioning activities is one of the most relevant aspects in the definition of such hazard, even if general indications or safety thresholds for its impact have not been evaluated to date. The aim of this work is to develop a global index representative of the sediment suspension impact, suitable for being implemented in a Decision Support System (DSS) for the decommissioning of offshore platforms. In particular, based on a large set of simulations representative of the Adriatic-Sea environment, we develop a predictive function for impact distances, based on a reduced set of input information, for its use in the preliminary analyses for decommissioning. In fact, at the stage of DSS use, much information (type of removal, sediment analysis, weather condition) is not available. This calls for a general, simple, and precautionary approach.

Decommissioning is generally perceived as a one-time operation with limited impact; however, the induced sediment resuspension can lead to increased turbidity and degraded water quality, with harmful effects on aquatic organisms (Cordes et al., 2016, Chwan et al., 2007, MacIntosh et al., 2022, Melbourne-Thomas et al., 2021). Turbidity can

^{*} Corresponding author.

E-mail address: sher.shah@pm.univpm.it (S. Shah).

reduce light penetration, affecting photosynthesis and benthic vegetation, and may also provoke negative public response (Shao et al., 2015). The turbidity plume, in general, can spread for several kilometers under the effect of marine currents, potentially reaching ecological hotspots (MacIntosh et al., 2022, Melbourne-Thomas et al., 2021, Shao et al., 2015, Programmatic Environmental Impact Statement for Oil and Gas Decommissioning Activities On the Pacific Outer Continental Shelf, 2022). The fine suspended particles usually have slow settling velocities and can remain in suspension for a long time; they can be therefore transported at considerable distances from the platform location, further degrading water quality far away from the platform (Chwan et al., 2007).

Previous studies have employed remote sensing and field-based methods to investigate sediment plumes from dredging activities, though methodological constraints often limit the spatial and temporal resolution. For instance, a recent research application along the south coast of Korea combined Geostationary Ocean Color Imager (GOCI) satellite imagery and vessel-based water column profiling, revealing post-dredging plume dispersing up to 39 km far from the source. However, this approach faced challenges: GOCI data are highly sensitive to the cloud cover, and both satellite and vessel measurements were restricted to 8 discrete sampling points at 1-hour intervals, limiting the ability to capture the continuous evolution of the plume (Seo et al., 2018). Similarly, a study in the eastern English Channel used Differential Global Positioning System (DGPS) to map turbid plume from dredger overflow, identifying fine sediment deposits up to 6.5 km from the source (Duclos et al., 2013). Yet, critical gaps persisted here as well; near-seabed data coverage was limited, not covering bottom 10% of the water depth, measurements were intermittent rather than continuous, and a 4-meter blind zone above the seabed precluded observation of the benthic plume dynamics. These studies collectively underscore the persistent limitation of conventional methods in resolving fine-scale spatiotemporal variability, particularly near the seabed and during plume evolution. Further, a simple monitoring approach is not consistent with the preliminary and quick application of a DSS before the occurrence of the possible removal.

Dredged sediments also represent an environmental concern, potentially impacting the habitat value surrounding the platform. The Adriatic Sea has acted as a sink for a variety of suspended and sediment-bound chemicals, primarily originating from industrial, agricultural, and urban activities along its coast and major discharging rivers, such as the Po River. Common sediment-bound chemicals such as chromium, lead, and mercury (Jack et al., 2020, Tankere and Statham, 1996) are frequently adsorbed onto sediments, leading to long-term risks as these chemicals become bioavailable, entering the food chain and posing potential risks to human health (Simpson and Batley, 2016). Alternatively, they can settle on the seabed, creating long-term reservoirs that may transfer chemicals into the water column (Cordes et al., 2016). Hence, a prediction of sediment dispersion is essential for sustainable offshore platform decommissioning, particularly in sensitive ecological zones.

The purpose of this work is to provide a method for a quick, first-order evaluation of the maximum impact distance representative of the impact due to a sediment plume generated by a complete removal of offshore platforms. The methodology will provide the limits of the spatial and time influence for sediment plumes connected to decommissioning activities of platforms in the Adriatic Sea. This objective is tackled through the definition of a set of configurations, considering several possible environmental and operational conditions, based on a significant set of offshore platforms settled in the Adriatic Sea. The issue of sediment mobilization connected to human activities has been tackled by Italian environmental guidelines (Lisi et al., 2017), which suggest a characterization of hydrodynamic conditions around the platforms with devoted circulation models. However, the preliminary application of the DSS motivates us to propose a quicker, more direct and somewhat complementary approach. A parametric study has been preferred to

specific analysis of each platform, with the ultimate goal of obtaining a sufficiently large set of results to be extended to any other platform which is (or may be) located in the Adriatic Sea. Once defined the specific choice of removal type, a more accurate analysis of the local hydro-morphodynamics can be performed by, e.g., using available circulation models.

The mixing zone model CORMIX and its subsystems have been used to evaluate sediment suspension for each different configuration of the parametric study. The CORMIX system has also been employed to run iterative simulations of suspended sediment plumes to identify the optimal discharge angle showing that a range of $30^\circ - 105^\circ$ minimizes sediment dispersion during dredging operations (Purnama et al., 2016). The general behavior predicted by CORMIX is consistent with the findings of the present study; however, prior analyses were limited to sediment deposition patterns obtained directly from the model post-processor. In contrast, the present work further processes these outputs to quantify the travel distance of suspended sediments carrying specific concentrations of associated chemicals.

The dispersion plumes generated by platform removal are analyzed, with a specific focus on fine sediment dynamics, as they represent the worst-case scenario for potential chemicals mobilization and dispersion. Threshold concentrations for heavy metals prevalent in the region are used to estimate the length scale of the plume influence. An analytical approach has then been used to describe the sediment plume behavior and dispersion distances, developing predictive functions.

The proposed methodology and its results have been implemented in the DSS built by the Università Politecnica delle Marche team for potential offshore decommissioning activities to be carried out in the Adriatic Sea.

Details on the case study, the parametric setting and the methodology for the estimation of impact distances are given in Section 2. Section 3 reports on the main results of the numerical campaign, describing the physical characteristics of the sediment plume, while in Section 4 the main results, such as the plume dilution time and the impact distances, are discussed, proposing predictive functions involving the platform features and environmental characterization. A concluding section summarizes the results and their applications.

2. Methods

The parametric analysis is based on a set of numerical simulations performed by CORMIX, in which possible environmental and operational conditions for the removal of a significant set of offshore platforms in the Adriatic Sea are tested. The following subsections describe the main assumptions of the analysis, about the geographical setting, the platforms features, the Adriatic Sea hydrodynamics and the characterization of the excavation process. As for the description of the Adriatic sea platforms, a partial characterization is available on a dedicated ministerial website (Ministero dell'ambiente e della sicurezza energetica); other specific information regarding platform engineering, the sedimentological characterization and the technical aspects of removal operations, are based on indication provided by one of the operators in the Adriatic Sea.

2.1. Geographical setting and spatial assumptions

The Adriatic Sea, shown in Fig. 1a, has an approximate length of 800 km in the NW to SE direction, and a width of 200 km in the NE to SW direction. It is an epicontinental semi-enclosed sea located between the Apennine and Balkan peninsulas, establishing a unique subregion inside the Mediterranean Sea area. The bathymetric analysis reveals that the Northern Adriatic is characterized by a small longitudinal topographic gradient corresponding to a slope $i = 3.5 \times 10^{-4}$, while the central Adriatic shelf presents a substantially steeper maximum gradient, corresponding to a slope $i = 8.7 \times 10^{-3}$ (Petrinec et al., 2012, Spagnoli

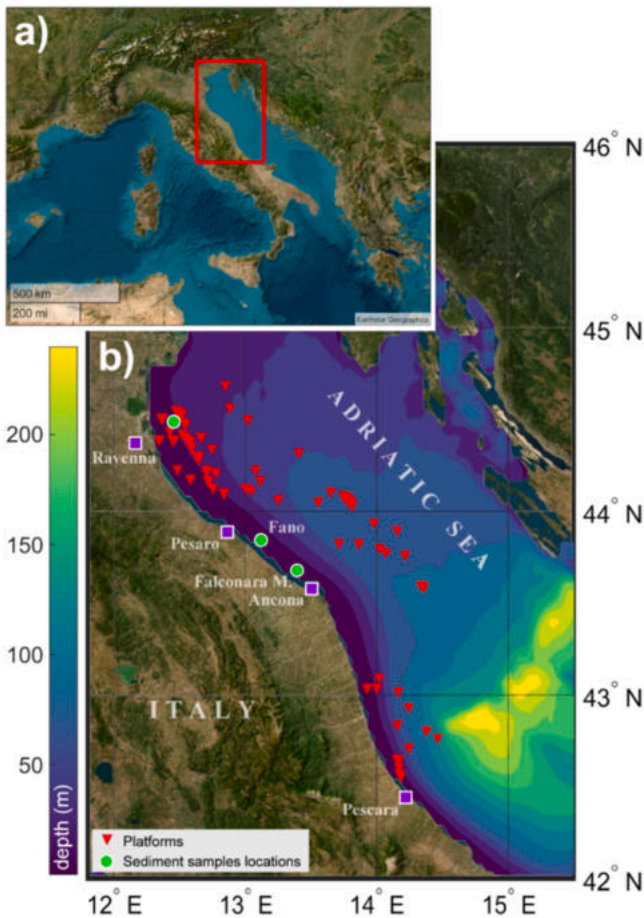


Fig. 1. a) Map of Italy. The red box shows the study area, where the analyzed platforms are located; b) bathymetry of the northern and central Adriatic Sea. The locations of the platforms are shown with red triangles. The locations of sediment sampling are shown with green dots.

et al., 2021, Vilibić and Supić, 2004). The Adriatic shelf, characterized by progressively deeper waters, gradually increases in slope along the coast from the Po delta (few meters water depth) to the area offshore Gargano with the cross-shore slope varying in the range between 0 and 8.7×10^{-3} (Foglini et al., 2012).

Our analysis makes use of a set of 97 platforms located across the northern and central sections of the Adriatic Sea. The platform locations are shown in Fig. 1b. They are installed at a distance from the coastline d_{coast} that ranges between 2 and 65 km, at water depths in the range $h = 8.5 - 117$ m (Ministero dell'ambiente e della sicurezza energetica). Platforms clustering has been performed based on d_{coast} and h . For nearshore platforms ($d_{coast} < 12$ km), the water depth ranges between 8.5 and 20 m; we thus considered varying parametrically d_{coast} over the following discrete values 2, 4, 6, 8, 10, and 12 km, and h over depths 8, 12, 16, 20 m. On the other hand, for the platforms farther from the coast ($d_{coast} > 12$ km), the water depth is in the range 17–117 m; hence we assumed a representative distance d_{coast} equal to 15 km and a set of depths $h = 15, 30, 45, 60, 75, 90, 105$, and 120 m. For platforms farther than 15 km, d_{coast} was not subject to variation since for such a large distance we did not expect the nearshore slope to significantly affect the dynamics of the plume.

Consistently with the requirements of the numerical model that would be employed for the simulated scenarios (i.e. CORMIX), the cross-section of the Adriatic Sea – i.e. the domain for modeling all plume-connected dynamics occurring therein – is approximated with a bilinear section partially bounded by the Italian coast. In line with the general bathymetry of the Adriatic Sea (Foglini et al., 2012), the

nearshore and shelf slopes are evaluated for each platform using its water depth and distance from the coast. The nearshore slope of the seabed was approximated by a constant value $i_{nearshore} = 5.3 \times 10^{-3}$ up to a distance $d_{nearshore} = 1500$ m from the coast, where the water depth assumes a representative value $h_{nearshore} = 8$ m. Beyond the nearshore zone, the Adriatic shelf is assumed to begin; the average shelf slope is then determined by a linear approximation as $i_{shelf} = (h - h_{nearshore}) / (d_{coast} - d_{nearshore})$. Hence, the shelf slope varies across platforms, as it is meant to take into account the possible influence of the local shelf on the dynamics of each platform plume. The schematic of the partially bound section and of the variables used above will be further clarified in *Model setup*, Section 2.3.1, and in Fig. 4.

2.1.1. Sediment characterization

The impact distances of suspended sediment plumes are clearly dependent on the mobilized sediment, in terms of sediment classes and respective fractions. Previous studies on spatial characterization of sediment distributions in the Adriatic Sea have shown clay-dominated deposits (45–70% of clay) in the northern/central Adriatic Sea (Vdović and Juracić, 1993). On the other hand, the south Adriatic pit is dominated by coarser sediment, with only 36–40% of clay content (Petrinec et al., 2012). The reference granulometry adopted for the characterization of sediment in this study is based on three collected sediment samples provided by the operator (Dec.O.Platt, 2024). The approximate locations of the sediment samples are shown by green dots in Fig. 1b. The finest sampled granulometry shows a composition of fine sediment (clay/fine silt) down to 3 m depth. Since the fine sediment fraction is the easiest to mobilize and the slowest to settle, it is assumed as the representative clay-dominant sediment mixture and attributed to all platforms. The characterization of the prototype sediment is summarized in Table 1.

2.1.2. Metocean conditions

Sea currents are the dominant force for the spreading of the turbidity plume. An analysis of the typical current conditions in the Adriatic Sea is, therefore, crucial for the definition of *ma Reanalysis* (Escudier et al., 2020) has been selected for this purpose.

A gridded data set of 3D daily currents spanning five years (2016–2020) and covering the northern and central parts of Adriatic Sea (latitude $42^{\circ}.1458$ N – $45^{\circ}.2292$ N; longitude 12° E – $15^{\circ}.9167$ E) has been statistically analyzed to estimate representative values for current flow velocities. In particular, the 95th percentile and mean direction of depth-averaged (U_{avg}) flow velocities have been evaluated at each grid node closest to the considered platforms.

This analysis revealed two distinct functional distributions for both current intensity and direction at the platforms. In relation to directional roses of depth-averaged currents, we identified *narrow roses*, for platforms whose ambient currents are generally more intense and exhibit a clear directionality, and *spread roses*, for platforms whose ambient current is generally milder and does not show a dominant direction. Examples of current roses for two narrow locations and two spread locations are given in Fig. 2. Whereas narrow roses are typical of locations closer to the Italian shore, where the global circulation usually follows the direction of the bathymetric contours and is directed south to south-east (red diamonds in Fig. 2), spread roses are mainly present at offshore

Table 1

Physical characteristics of the sediment taken as reference for the parametric analysis.

Characteristic	Symbol	Value	Units
Granulometry	-	clay 47.5% + silt 52.5%	-
Bulk density	ρ_{bulk}	1669	kg/m ³
Bulk dry density	$\rho_{bulk,dry}$	1033	kg/m ³
Grain specific gravity	G	2.65	-
Angle of internal friction	i	33°	degrees

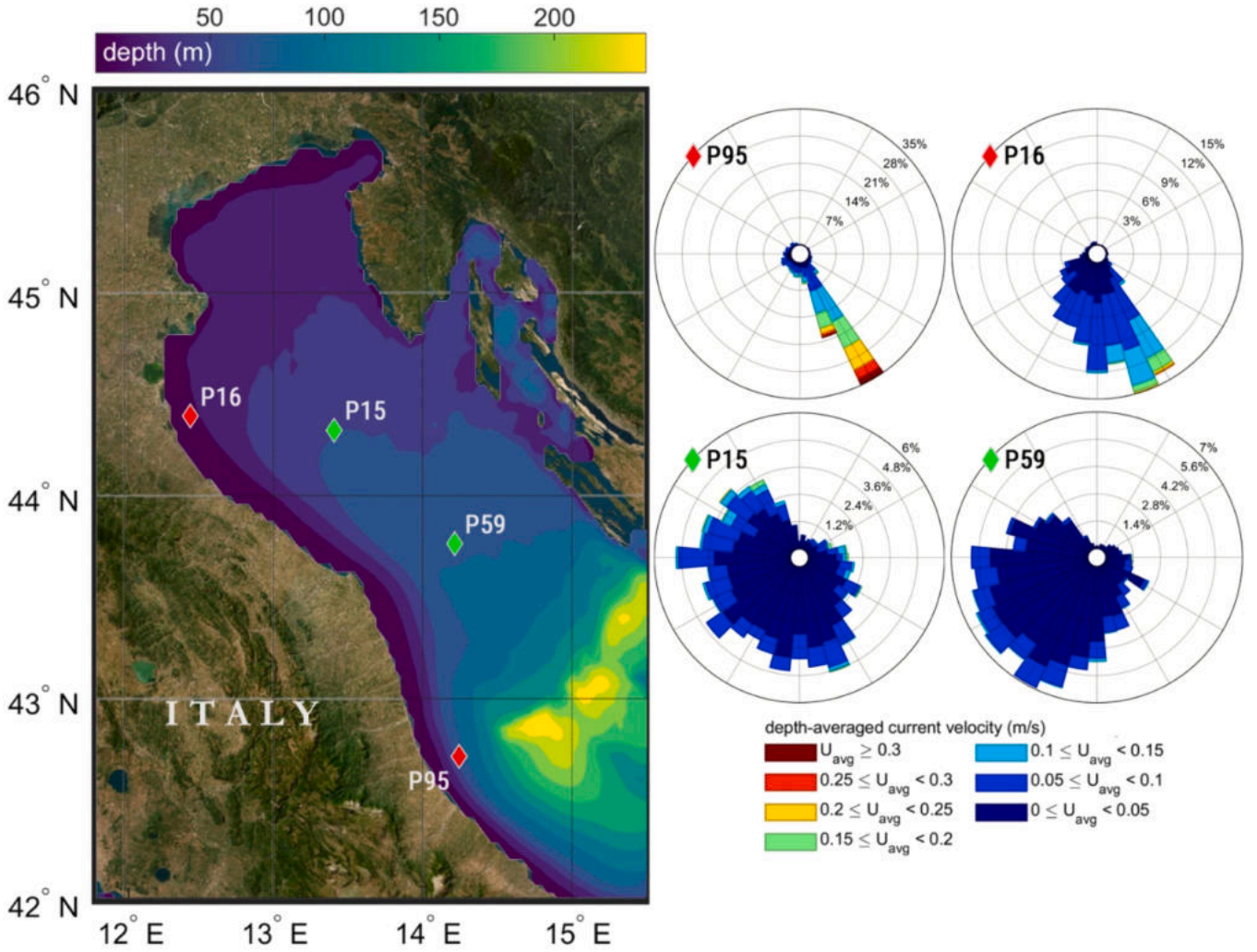


Fig. 2. Examples of platforms exhibiting narrow (red diamonds) and spread current roses (green diamonds), as resulting from analysis of Copernicus depth-averaged currents U_{avg} over the period 2016–2020.

locations and at larger depths (green diamonds in Fig. 2).

In order to characterize all current flow regimes with the least possible number of parameters, two values of (depth-averaged, 95th percentile) representative current velocities $U_{avg,95\%}$ have been adopted: (a) a maximum velocity of 0.26 m/s, meant to encompass maximum current flows for all narrow roses, and (b) a threshold velocity of 0.11 m/s to more adequately represent all spread roses, whose $U_{avg,95\%}$ is globally smaller. Such values have been therefore used as ambient velocities for the simulations campaign.

2.2. Excavation characterization

According to guidelines of the Italian Ministry of economic development, the decommissioning of an offshore platform requires a complete removal of support structures, consisting in cylindrical legs, down to 3 meters below the mudline. To define a realistic scenario, the excavation depth for leg removal is thus assumed as 3.5 m. To evaluate the amount of local sediment excavated around each foundation leg, the excavation volume is estimated as that of a truncated cone with a side slope equal to an angle of internal friction of 33° (see Table 1) and with bottom excavation radius equal to 1 m. The latter value is consistent with the leg radius, which ranges between 0.5 and 0.75 m. Consequently, the volume excavated for each platform leg is here estimated as 200 m³. Since Adriatic Sea platforms usually have a variable number of legs n_{leg} ranging from 1 to 12, the estimated excavation volume V_{exc}

varies from 200 m³ to 2400 m³ across all platforms. The total dry sediment mass put into suspension during the whole excavation process (evaluated considering the bulk dry sediment density $\rho_{bulk,dry}$ given in Table 1), varies from 2.0×10^5 kg to 2.5×10^6 kg.

However, the dry sediment mass cannot be directly given as input to a CORMIX simulation; values of the effluent flow rate $Q_{effluent}$ (in m³/s; i. e. the volumetric amount of excavated mixture output by the excavation), and estimated excavation time T_{exc} (in hours) must be provided instead, in order to obtain post-process information on the amount of sediment mobilized and the impact distances due to platform excavation. These quantities are evaluated on the basis of the operational excavation rate Q_{exc} (in m³/s), which depends on the device used for the excavation and its efficiency. According to the technical data of a prototype excavation tool, we assumed realistic device excavation rates in the range $Q_{exc} = 0.1 - 0.2$ m³/s, depending on operational variability. To calculate the effluent flow rate $Q_{effluent}$ that must be provided as input to CORMIX, we use the following relation:

$$Q_{effluent} = \frac{q_{sed}}{\varphi_{sed} \rho_{sed,wet}} \quad (1)$$

where $q_{sed} = Q_{exc} C_{sed} \frac{\varphi_{sed,rest}}{\varphi_{sed}}$ is the sediment mass discharge at the outflow (in kg/s) and $C_{sed} = \frac{\varphi_{sed}}{\rho_{sed,wet}}$ is the sediment concentration in the effluent mixture (in kg/m³). C_{sed} is, in general, not known *a priori*, as it is influenced by the excavation process, which may dilute the

mixture by entraining the surrounding water (thus changing the phase fraction of sediment in the effluent mixture φ_{sed} with respect to the condition at rest $\varphi_{sed,rest}$). In other words, the same sediment mass discharge q_{sed} can in principle be provided by a reduced value of the sediment bulk density of the effluent ($\rho_{sed,wet}$) by increasing the effluent flow rate $Q_{effluent}$ (see Eq. 1).

To evaluate the influence of the effluent dilution on plume dimensions, a preliminary set of three sensitivity simulations has been defined. The three tests, labeled C-1 to C-3, are characterized by different sediment phase fractions in the outflow effluent mixture φ_{sed} . A summary of the simulations' parameters is provided in Table 2. These tests aimed at identifying the worst-case condition by assessing which sediment phase fraction leads to the largest impact distance. In all simulations, the same ambient and sediment features were assumed, as well as a constant nominal excavation flow rate $Q_{exc} = 0.11 \text{ m}^3/\text{s}$ and a phase fraction of local sediment prior to excavation $\varphi_{sed,rest} = 0.38$. The three different values of assumed $\varphi_{sed} = 0.21, 0.25$ and 0.38 represent different levels of effluent dilution during the excavation process. The case with $\varphi_{sed} = \varphi_{sed,rest} = 0.38$ represents a state of virtually no dilution of the sediment-water mixture with respect to the condition prior to excavation. The three values of φ_{sed} result in different values of effluent sediment concentration ($C_{sed} = 571, 680$ and 1033 kg/m^3 respectively) and effluent flow rate ($Q_{effluent} = 0.2, 0.17$ and $0.11 \text{ m}^3/\text{s}$ respectively). The effect of effluent dilution is assessed by comparing the maximum downstream distance reached by representative levels of sediment concentration (250, 50, and 10 kg/m^3). A summary of the simulated conditions and the resulting impact distances is also given in Table 2.

As expected, the results show an increase of the impact distance for increasing C_{sed} : the largest distance is obtained when the effluent sediment concentration corresponds to the bulk dry density ($\rho_{bulk,dry} = 1033 \text{ kg/m}^3$), which means that the worst scenario occurs when no dilution during the excavation. For this reason, the condition of no dilution is considered for the rest of the analysis. The corresponding effluent rate, according to Eq. (1) for $\varphi_{sed} = \varphi_{sed,rest}$, is therefore equal to the operational excavation rate Q_{exc} .

According to the typical excavation efficiency of excavation devices, which is in the range 102–204 kg/s, three sediment mass discharges q_{sed} were selected for the final parametric analysis: 100, 150 and 200 kg/s , yielding corresponding values of $Q_{effluent} = 0.097, 0.145$, and $0.194 \text{ m}^3/\text{s}$ to be provided as input for CORMIX.

Table 2

Reference sediment concentration lengths as a function of effluent sediment fraction φ_{sed} , evaluated from three CORMIX sensitivity simulations.

Parameter	Symbol	Unit	C-1	C-2	C-3
Excavation flowrate	Q_{exc}	m^3/s	0.11	0.11	0.11
Sediment fraction at rest	$\varphi_{sed,rest}$	-	0.38	0.38	0.38
Sediment mass discharge	q_{sed}	kg/s	114.8	114.8	114.8
Sediment bulk density	$\rho_{sed,wet}$	kg/m^3	2720	2720	2720
Ambient density	ρ_w	kg/m^3	1025	1025	1025
Ambient velocity	U	m/s	0.26	0.26	0.26
Near-shore slope	$i_{nearshore}$	-	0.15	0.15	0.15
Far-shore slope	i_{shelf}	-	0	0	0
Vertical angle	θ_0	$^\circ$	90	90	90
Distance to coast	d_{coast}	m	15000	15000	15000
Port diameter	-	m	1.5	1.5	1.5
Port height above bottom	-	m	0.5	0.5	0.5
Sediment fraction	φ_{sed}	-	0.21	0.25	0.38
Effluent discharge	$Q_{effluent}$	m^3/s	0.2	0.17	0.11
Effluent sediment concentration	C_{sed}	kg/m^3	571	680	1033
Effluent density	$\rho_{effluent}$	kg/m^3	1381	1449	1669
Length for 250 kg/mc	-	m	4.1	6.1	127.2
Length for 50 kg/mc	-	m	425.5	470.3	545
Length for 10 kg/mc	-	m	1097.1	1149	1202

Knowing the excavation volume V_{exc} and the operational excavation rate Q_{exc} , total excavation times can be estimated as $T_{exc} = V_{exc}/Q_{exc}$, yielding values between 0.3 and 7 hours for the complete excavation of up to 12 platform legs. The number of legs n_{leg} is not taken as a variable for the analysis, since the deposited mass and the deposition thickness – which will be used for the evaluation of the impact distances – are linearly dependent with the excavation time. Hence, it is sufficient to evaluate deposition maps for a single leg. The excavation time per leg $T_{exc,1}$ is thus needed as an input parameter for the definition of sediment deposition maps in CORMIX. Given that the excavation volume for one leg is 200 m^3 , the three values of $Q_{effluent}$ yield one-leg excavation times $T_{exc,1} = 0.559, 0.383$, and 0.287 hours, respectively.

2.3. Modeling campaign

The behavior of sediment plumes connected to decommissioning activities in the Adriatic Sea is evaluated using the CORMIX model, version v12.0 GTS (Doneker et al., 1990, Jirka et al., 1996). Developed with support from the U.S. Environmental Protection Agency (USEPA), CORMIX is a mixing zone model for the prediction of the dispersion of wastewaters, sediment discharges and brine into receiving water bodies (Doneker et al., 1990, Jirka et al., 1996, CORMIX USER MANUAL 1988).

In the present work, the subsystem of CORMIX for single port discharges has been used in conjunction with a hydrodynamic module for the modeling on negatively buoyant plumes. CORMIX predicts the geometry and dilution of sediment plumes in both the near-field (the region of the water body where initial plume characteristics influence its trajectory and mixing properties) and the far-field (where plume trajectory and mixing are conversely dominated by buoyancy spreading and passive diffusion). CORMIX uses the terminal properties of the near-field (plume width, velocity, concentration) as the initial conditions for the far-field module. CORMIX adopts sequential simulation modules for each distinct flow process and spatial region, by employing a hydrodynamic flow classification based on physical parameters and length-scale principles to assess mixing processes, such as momentum flux and buoyancy from boundary interactions (Purnama et al., 2015). CORMIX also allows for up to three-layer ambient density profiles and sloping bathymetries. As for model outputs, CORMIX is able to predict the mass and thickness of deposited sediments by calculating the plume's mass flux for each sediment class while accounting for particle settling, in order to estimate seabed loading under mass conservation principles. For dense, non-stratified plumes near the seabed, it is assumed that sediments settle immediately upon leaving the plume. In the near field, plume jet dynamics influence the separation and settling of particles.

The sediment deposition is quantified as a mass loading per unit area (in kg/m^2), which can be converted to deposition thickness using the following equation (adapted from (CorPlot User Manual, 2020, Nedwed, 2004).

$$T = M_{solid} \left(\frac{1}{\rho_{bulk,dry}} + \frac{W_w \alpha}{\rho_w (100 - W_w \alpha)} \right) \quad (2)$$

where T is the thickness (m) of the deposited sediment, M_{solid} is the seabed loading (in kg/m^2), $\rho_{bulk,dry}$ is the density of the discharged solids (in kg/m^3), and ρ_w is the ambient sea water density (in kg/m^3). W_w is the percentual weight of water in the excavated solids, calculated as $W_w = (100 M_{water}) / (M_{solid} + \alpha M_{water})$, where M_{water} is the mass of water, and $\alpha = 1 + S / (1000 - S)$, S being the water salinity.

2.3.1. Parametric analysis

Following the consideration in the previous sections, a parametric analysis has been set up to evaluate the variation of potential impact distances of excavation processes in the Adriatic Sea, as a function of several possible environmental parameters (i.e. local water depth, distance from the coastline, ambient flow velocity) and technical, excavation-related parameters (i.e. total sediment mass discharge and

effluent flow rate). The parameters subject to variation, as well as their range of values, are reported in Table 3 according to the platform distance from the shoreline. A comprehensive list of platforms and their features is also given in the *Supplementary Material (Supplementary Material_platforms.xlsx)*.

Using the parameters reported in Table 3, the CORMIX model was set up as described in Section 2.3.2 to perform a total of 192 simulations. The full set of input parameters and corresponding results is provided in the *Supplementary Material (Supplementary_Material_Numerical_results.xlsx)*. These simulations provide a characterization of the plume and the important processes involved which will be illustrated in Section 3.1.

2.3.2. Model setup

Fig. 3 schematically summarizes the CORMIX setup and shows which parameters are fixed and which are varied, accordingly with ranges reported in Table 3, in the parametric analysis. The model configuration is defined through three main input groups: (i) effluent data, (ii) ambient data, and (iii) discharge data.

The *effluent data* specify the effluent characteristics, which consists of a mixture of water, fine silt, and clay as specified in Table 1. By prescribing the sediment concentration at the outflow ($C_{sed} = 1033 \text{ kg/m}^3$), the corresponding effluent density ($\rho_{effluent} = 1669 \text{ kg/m}^3$) is fixed. The varied parameter in this input section is the flow rate $Q_{effluent}$, set at 0.097, 0.145, and $0.194 \text{ m}^3/\text{s}$. These values ultimately represent different excavation efficiencies, as described in Section 2.2. The *ambient data* are used to characterize the receiving environment: i.e. water density, total water depth, nearshore depth, seabed slopes in the near-shore and far-field regions and the ambient velocity (U), with reference to the partially bounded cross-shore section illustrated in Fig. 4. The *discharge data*, finally, are used to characterize the features and location of the discharge outlet (i.e. the excavator device). The outlet is here modelled as a single-port discharge located 0.5 m above the seabed, with an outlet diameter of 1.5 m and a vertical release angle of 90° . The outlet distance from the shoreline is the only variable parameter in the parametric analysis.

Relevant outputs for our analysis are two-dimensional gridded maps of deposited mass $M(x,y)$ and deposition thickness $T(x,y)$ for the evaluation of excavation impacts. Such sediment maps, created through a specific post-processing subsection of CORMIX (CorPlot), are provided over a grid with resolution and extent specified by the user. It is worthwhile to mention that this grid is not used as a computational support for CORMIX, but only for post-processing purposes. In fact, CORMIX uses a semi-analytical, integral approach, rather than a numerical solution over a grid, to compute the main variables of the

dispersion process. The grids chosen for the output maps cover an area of $6 \times 2 \text{ km}$ downstream of the outlet location for simulations ID1 to ID96, while a larger grid of $15 \times 2 \text{ km}$ was used for simulations ID97 to ID192 to account for a larger ambient velocity. All grids have a horizontal resolution of $dx = dy = 10 \text{ m}$. The maps are obtained considering the excavation time related to one single leg only (see Section 2.2); for platforms with more than one leg, both sediment deposition and thickness maps are multiplied by n_{leg} thanks to the linearity of the problem.

CORMIX simulations give suspended sediment outputs for a steady-state *infinite* effluent flow, while deposited sediment maps are provided for *finite* effluent flow, since the effluent duration must be specified. The implicit infinite nature of suspended sediment transport limited us in using CORMIX outputs directly. Hence, specific procedures have been followed to evaluate impact distances for deposited sediment and suspended sediment through sediment maps. Such procedures are described in Section 2.4.

2.4. Evaluation of impact distances

The results from the numerical simulations were used to assess the potential impact of the sediment plume by combining the modelled dilution processes with a threshold of the sediment-bound contaminant content. Relevant chemicals, such as metals, are generally bound to fine particles, can travel distances significantly larger than coarser sediments; thus, the deposition mass loading and deposition thickness maps of fine sediment (diameter $< 0.004 \text{ mm}$) are used to assess the impact distances. With this approach, we are assuming, in a conservative way, that the bound chemicals are completely associated to the fine fraction of the sediment, and they do not dissociate from it during suspension. The analysis of the impact distance has considered both the impact of deposited material, and of the material placed in suspension.

2.4.1. Impact of deposited material

In the assumption that the fine sediment deposits on the seabed with the same bound chemicals proportion ϕ_p as the excavated material, the thickness map of the *deposited* sediment $T(x,y)$ can be used as reference for the evaluation of the impact distance of deposited material. This distance has been computed from the total deposited sediment thickness map of the respective CORMIX simulation by identifying the isoline corresponding to a threshold thickness of a single clay particle ($T_{threshold} = 0.004 \text{ mm}$). This threshold thickness is necessary because of the analytical hyperbolic decay solution evaluated by CORMIX. For this reason, instead of searching for a zero thickness we used a negligible thickness, corresponding to the size of the finest particle.

The maximum impact distance of deposited material has then been calculated in the direction of ambient flow ($d_{dep,x}$) and in the crossflow direction ($d_{dep,y}$) as the maximum distance at which the deposited material exceeds the thickness threshold. Top panel in Fig. 5 reports an explanatory sketch of the evaluation of $d_{dep,x}$.

2.4.2. Impact of material in suspension

CORMIX simulations provide direct *suspended* sediment results under steady-state conditions (i.e. assuming infinite effluent flow), which are not compatible with finite-time excavation processes. Therefore, such results cannot be used for the estimation of an impact distance for suspended material. Instead, a procedure was developed to estimate the maximum suspended sediment concentration from finite-time *deposited* sediment maps. The procedure is based on dividing the deposited sediment mass map $M(x,y)$ into sections, as shown by the sketch in bottom panel of Fig. 5. The maximum amount of sediment that can be suspended above the circular crown section highlighted in grey, associated with a distance d , is conservatively estimated as the entire mass deposited at a distance greater than d :

$$M_{outside}(d) = \int_{x^2+y^2 \geq d^2} M(x,y) \, dx \, dy \quad (3)$$

Table 3
Parameters used in the numerical campaign.

Fixed parameters					
Ambient density (kg/m^3)	Near-shore slope	Port diameter (m)	Port height above bottom (m)	Effluent sediment concentration (kg/m^3)	Effluent density (kg/m^3)
1025	0.153	1.5	0.5	1033	1669
Varied parameters					
Parameter	Unit	For $d < 12 \text{ km}$		For $d > 12 \text{ km}$	
Distance from coast (d_{coast})	km	2, 4, 6, 8, 10, 12		15	
Water depth (h)	m	8,12, 16, 20		15, 30,45, 60,75, 90, 105, 120	
Ambient flow velocity (U)	m/s	0.11, 0.26		0.11, 0.26	
Mass discharge (Q_{sed})	kg/s	100, 150, 200		100, 150, 200	
Effluent flowrate ($Q_{effluent}$)	m^3/s	0.097, 0.145, 0.194		0.097, 0.145, 0.194	
Excavation time per leg ($T_{exc,1}$)	hr	0.559, 0.383, 0.287		0.559, 0.383, 0.287	

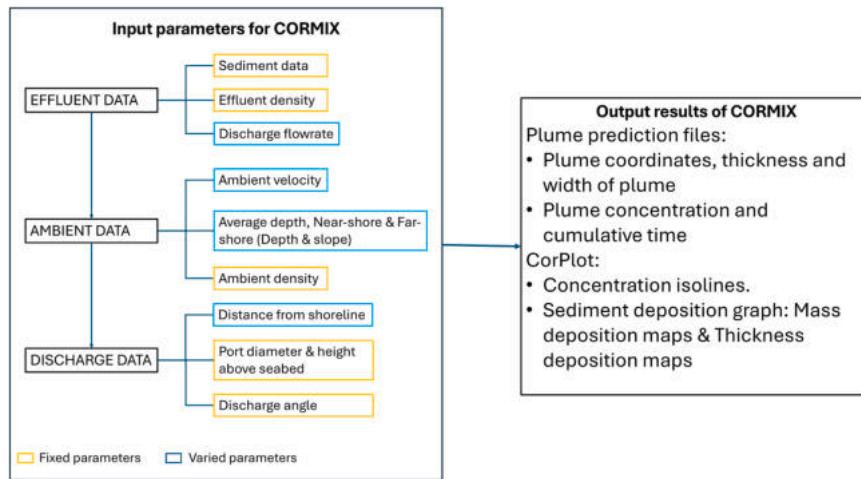


Fig. 3. A sketch of a CORMIX simulation.

Afterwards, the concentration of suspended sediment at distance d has been estimated as

$$c_s(d) = \frac{M_{outside}(d)}{V_{cyl}(d)} \quad (4)$$

where $V_{cyl} = \frac{\pi h_{plume}(d)}{4} dx(2d - dx)$ is the volume of the cylindrical crown section, being $h_{plume}(d)$ the plume height at distance d from the source. To avoid any divergence of the results, a lower limit has been assigned to the plume height: $h_{plume} > 1$ m. This limit corresponds to the typical size of the device commonly used for metal concentration sampling methods and considers that metal concentration samples are typically collected 1 meter above the seafloor (Cutter and Bruland, 2012). The use of the 90° circular crown section, with outer radius d and thickness equal to the map grid cell size dx , is corroborated by the results, showing that the sediment mass is transported in the direction of the ambient flow within a 90° angle region from the source location, as we will see in Section 3.2.

The concentration of suspended sediment-bound chemicals in water, c_p , has been estimated by multiplying the sediment concentration in water c_s , obtained with Eq. (4), by the content of bound chemicals φ_p :

$$c_p = \varphi_p c_s \quad (5)$$

The content of bound chemicals has been evaluated by assuming a fixed concentration in the sediment. The information has been extrapolated from technical reports on monitoring campaigns of chemical contents in sediment at predefined distances from each platform (50 to 500 meters); platform operators are legally required to execute such monitoring campaigns on a yearly basis. From said reports, chromium has repeatedly been found in potentially hazardous concentrations in the Adriatic Sea; this observation was confirmed by specific literature on this matter (Martinić et al., 1990). For the purpose of our study, we therefore assumed a chromium concentration $\varphi_p = 133$ mg/kg, as recorded in the Adriatic Sea between 2019 and 2021.

To evaluate the impact distance of the suspended sediment d_{susp} , the concentration of suspended sediment-bound chemicals c_p must be compared with a bound chemicals-concentration threshold $c_{p,lim}$, which is defined as:

$$c_{p,lim} = \frac{c_{p,lim,w}}{A} \quad (6)$$

where $c_{p,lim,w}$ is the limit value for the chemicals concentration in surface waters defined by the Italian Law 172/2015 (Il Presidente della Repubblica, 2015). Since the most hazardous scenario is connected to chromium content, its concentration threshold in surface water is used: $c_{p,lim,w} = 4$ mg/m³ (Cormix User Manual, 1988).

Assuming that the bound chemicals are associated to clay only, A is the ratio between the total sediment mass and the clay fraction mass. The sediment characterization reported in Table 1 yields

$$A = \frac{1}{0.475} \approx 2.11 \quad (7)$$

Eq. (5) and (6) allow for the definition of the concentration threshold for suspended sediment in water:

$$c_{s,lim} = \frac{c_{p,lim}}{\varphi_p} \quad (8)$$

which is compared with c_s as in Eq. (4) to obtain the impact distance of the suspended sediment d_{susp} . Considering the values reported above, the value of the chromium concentration in the fine sediment fraction is equal to $c_{s,lim} = 0.014$ kg/m³.

The suspended sediment distance d_{susp} has been calculated by finding a minimum distance (d) at which the concentration of suspended sediment c_s is less than the concentration threshold for suspended sediments in water ($c_{s,lim}$) as shown in top panel of Fig. 5.

The proposed approach assumed that the sediment-bound chemical content is the same over the whole excavated sediment, even if its measurements were performed in the upper soil layer only (top 10 cm). This results in a precautionary approach since most chemicals were found to come from water and are therefore localized in the surface layers. On the other hand, the method excludes the background chemicals content in water due to its negligible levels in the study area, as reported in the existing literature (Tankere and Statham, 1996, Middag et al., 2022).

3. Results

3.1. Plume characterization

For the sake of conciseness, results of the numerical campaign stemming from the combination of parameters given in Table 3 are illustrated and discussed for the reference simulation ID1 only¹, characterized by an effluent (excavation) flow rate of 0.097 m³/s, located 2 km from the coastline at a water depth of 8 m, in ambient flow velocity of 0.11 m/s. Its characterization is consistent with all simulations,

¹ All files related to the plume generation (plume height, cumulative travel time and sediment concentration at specific coordinates of the plume) and the parameters used for the CORMIX simulations can be obtained by specific request to the operator.

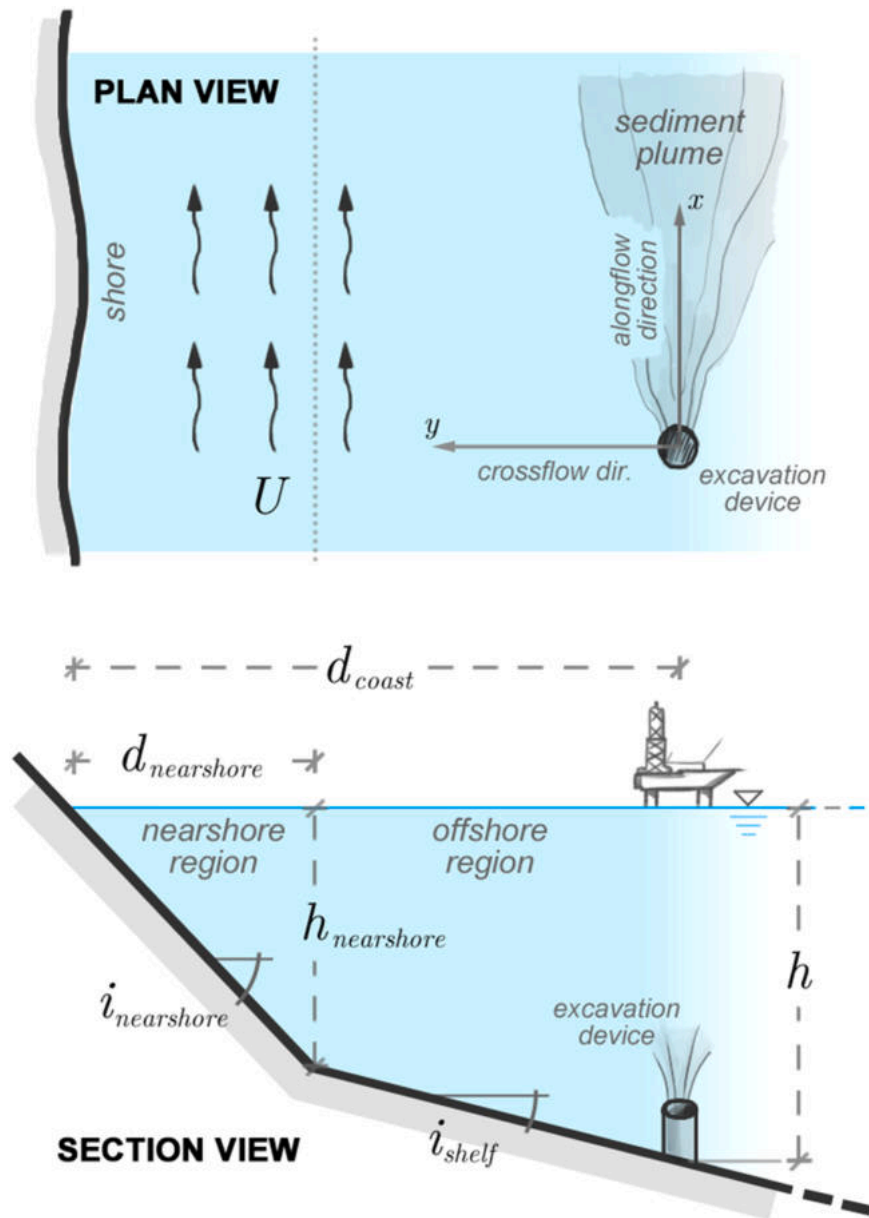


Fig. 4. Schematization of the cross-shore section for CORMIX simulations and relevant variables.

except for the quantitative values and few cases explicitly mentioned in the following. In fact, based on the length-scales classification implemented in CORMIX, all numerical simulations are dominated by a “strong negative buoyancy over the momentum”.

A side view of a typical modeled plume for simulation ID1 (Fig. 6) shows the dynamics of a dense, sediment-laden fluid ejected from the bed. In the immediate proximity of the excavation device ($x = 0$ m), the effluent is discharged vertically and rises a short distance (≈ 0.8 m for all tests). Initially, the discharge is driven by momentum and is propelled upwards as a jet. Buoyancy quickly overtakes the initial momentum and becomes the dominant force governing the following evolution as a plume. The jet-plume transition occurs very close to the source (0.0143 m for ID1 and < 0.15 m for all tests).

Upon interacting with the ambient water, the plume experiences near-vertical impingement driven by low ambient velocity and high-density contrast. The plume spreads upstream against the current up to a stagnation point, then moves downstream across the near-field, while its thickness decreases significantly at distances ranging between 6.3 and 47.3 m from the source. In this region, classified as LBI &

US (layer boundary impingement and upstream spreading; Fig. 6), the combined effects of plume impingement and upstream spreading lead to strong turbulent mixing, causing rapid dilution (down to 53.8% – 67.1% of initial effluent concentration) over short times (0.4 to 7.1 minutes) (Purnama et al., 2016).

Finally, the plume transitions to far-field dispersion (BAS region in Fig. 6) and spreads in both the along flow and crossflow directions, advected only by the ambient flow. This process induces further dilution as the plume height (h_{plume}) increases. Larger plume heights provide larger volumes for 3D turbulent mixing and increasing the overall dilution capacity (Jirka et al., 1996). Across all tests, plumes physically extended at distances between 2.5 and 25 km from their source, reaching complete dilution in 2.67 to 63.13 hours. For test ID1, 99.93% plume dilution is achieved just 25.1 hours after the beginning of excavation.

The spatial redistribution of the excavated sediments illustrated in Fig. 6 shows that most of the sediment mass (more than 90%) settles rapidly within a few hundred meters from the source, while the remaining fraction is advected by the ambient current and transported

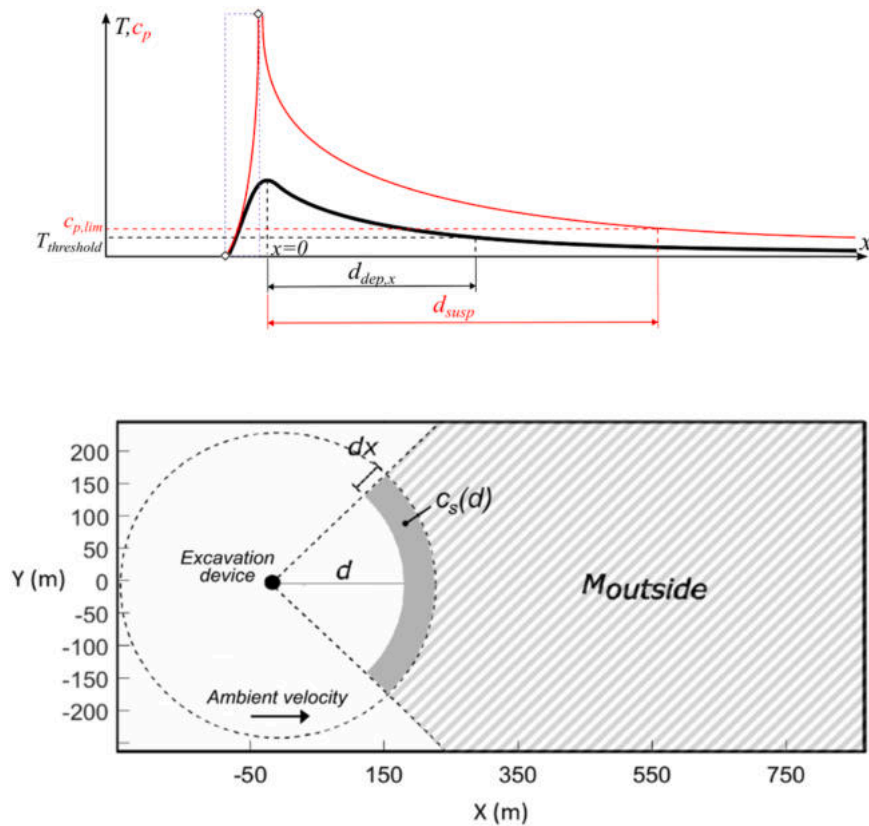


Fig. 5. Top panel: Sketch of the deposited mass thickness T (black line) and concentration of suspended sediment-bound chemicals in water c_p (red line) in the streamwise x direction, with identification for the respective threshold and impact distance evaluation. Bottom panel: 2D sketch of the deposited map domain for the estimation of suspended sediment concentration $c_s(d)$. The reference circular crown sector over which c_s is calculated is shown in grey. The region over which $M_{outside}$ is calculated is shown with the dashed grey region.

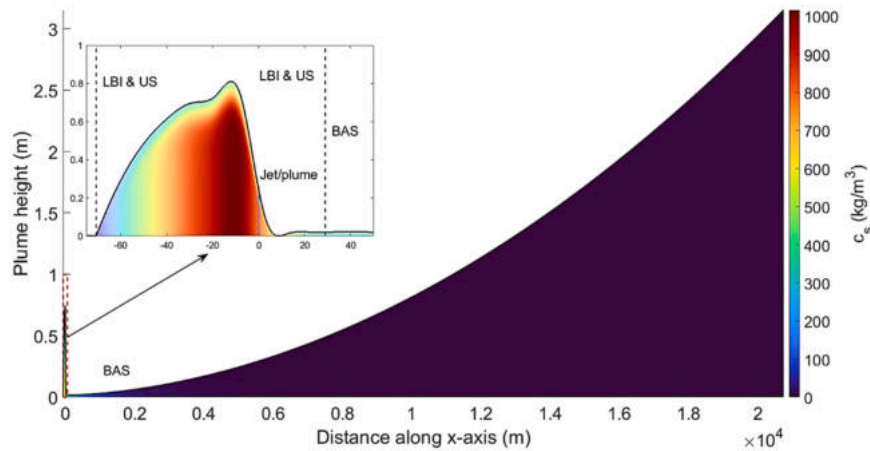


Fig. 6. Side view of the predicted plume development in the along flow direction for simulation ID1.

within a 90° sector downstream of the source.

Given that the mean flow current (either $U = 0.11$ or 0.26 m/s) is generally higher than the estimated plume outflow velocity ($V_{eff} = 0.0625$ m/s, yielded by $Q_{eff} = 0.11$ m³/s and an estimated outflow area of the excavation device of 1.76 m²), modelled plumes fall into the classification of passive plumes, for which plume dynamics are dominated by the ambient velocity in the far-field, and quick dilution is promoted by entrainment due to turbulence (Dankers, 2002, Purnama et al., 2014).

3.2. Impact distances

Fig. 7 illustrates the isolines of deposited fine sediment corresponding to a thickness of 0.004 mm for simulation ID1, as a function of the numbers of legs. They have been derived from the deposited thickness maps obtained as output of the respective CORMIX simulations (Section 2.4.1). Impact distances in the flow direction ($d_{dep,x}$) vary between 1410 and 2921 m, while in the crossflow direction ($d_{dep,y}$) they range from 240 to 410 m across all simulations. As expected, the deposited sediment impact distance increases with the number of excavated legs; however,

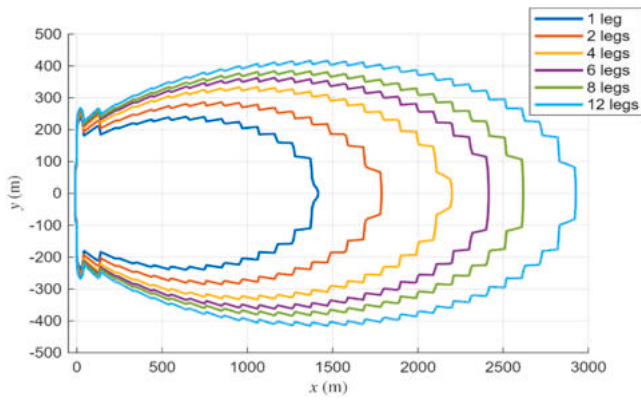


Fig. 7. Isolines of deposited fine sediments corresponding to deposited thickness of 0.004 mm as a function of platform legs for the evaluation of $d_{dep,x}$ and $d_{dep,y}$, for simulation ID1. The source (i.e. the excavation point) is at the origin of the coordinate system.

though the deposited thickness maps are linear with n_{leg} , the increase in the impact distance is not linear due to the deposition processes.

The *suspended* sediment impact distance d_{susp} is shown in Fig. 8 for the reference simulation ID1 as a function of platform legs. Again, d_{susp} increases nonlinearly with the number of legs (Fig. 8b) due to suspended sediment decay, reducing the concentration in a nonlinear fashion.

The values of the deposited and suspended impact distances, calculated for all the test simulations, are collected in the file

“Supplementary_Material_Impact_distances.xlsx”. Among all platforms, the maximum impact distance for the deposited sediments in the flow direction is $d_{dep,x} = 6.5$ km. In the crossflow direction, the maximum impact distance is $d_{dep,y} = 0.8$ km. The maximum impact distance for the suspended sediments is $d_{susp} = 14.6$ km.

4. Discussion

4.1. Plume dilution times

The simulation campaign allowed us to evaluate the behavior of sediment plumes across a wide variety of environmental and operational conditions. All plumes simulated in the parametric analysis display consistent behavior, characterized by a strong dilution (see Section 3.1): the cumulative time for complete dilution ranged between 2.67 and 63.13 hours from the start of the excavation process. However, a few tests (namely ID29, ID97, ID129, and ID161) displayed distinctly short dilution times (less than 10 hours) and relatively short total dilution distances (from 2.5 to 9 km). Such four tests, therefore, represent the lowest impact conditions and have been excluded from the final dataset for the definition of impact-distance predictive functions.

By comparing the range of dilution times (25 to 65 hours) with the range of excavation times (0.3 to 7 hours; see Section 2.2), it has been observed that the time scale for plume dilution is about one order of magnitude larger than the excavation operations, but still within the limit of a few days. We thus expect any plume impact, as well as the due control and containment actions, to be relevant only within a few days of excavation.

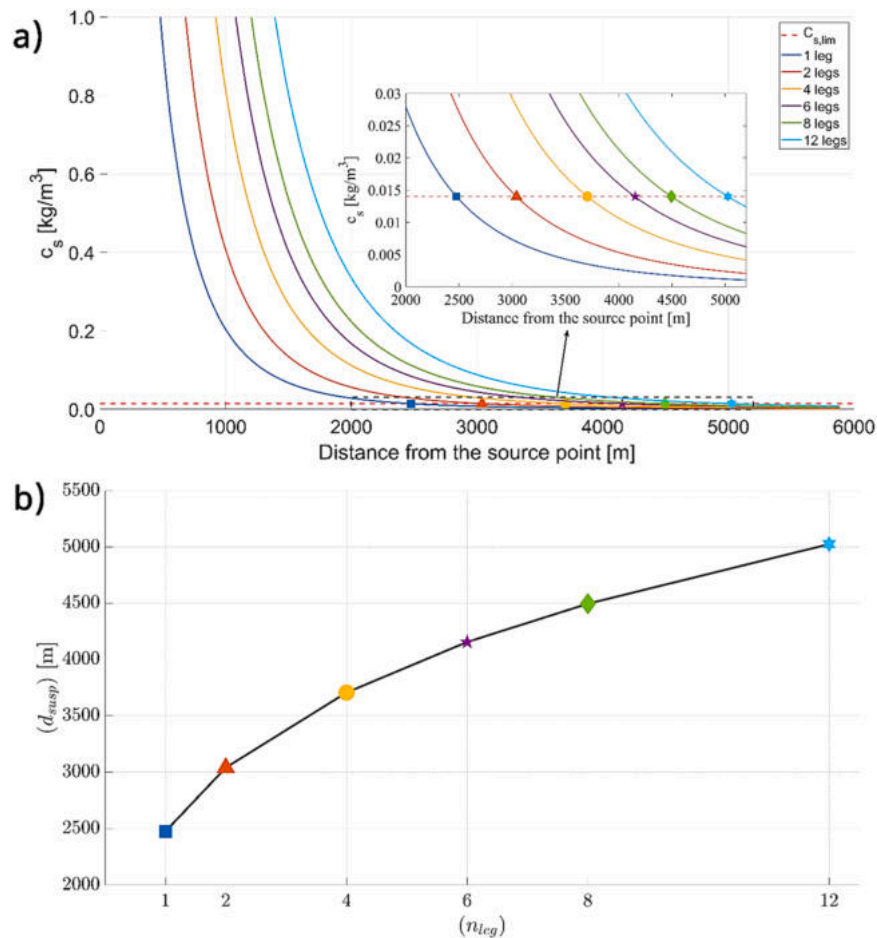


Fig. 8. a) comparison of the estimated concentration of suspended sediment $c_s(d)$ (colored lines) with the limit concentration $c_{s,lim}$ (horizontal dashed red line) for the evaluation of d_{susp} , for test ID1; b) suspended sediment impact distance as a function of the number of legs, for test ID1.

On intuitive grounds, plume transport times are highly influenced by the ambient velocity. Moreover, the tests characterized by a larger ambient velocity ($U = 0.26$ m/s) present faster dilution, in the order of 25.8 to 26.7 hours, likely due to increased turbulent mixing (see Section 3.1); by comparison, lower ambient velocities ($U = 0.11$ m/s) generally achieve full plume dilution in twice the time (52.5 to 63.13 hours).

4.2. Impact distances and their predictive functions

The impact distances of the deposited and suspended sediments for all platforms are used as a dataset to build practical predictive functions that allow users to have an informed estimate on impact distances due to platform decommissioning once environmental and technical parameters are known. To this end, a regression functional form has been developed based on the analytical solution for the concentration of a 2D diffusion-type problem (Fisher et al., 2013):

$$c \approx \frac{M_{sed}}{\sqrt{4\pi t D}} e^{-\frac{(x-Ut)^2}{4Dt}} \quad (9)$$

where M_{sed} is the total mass of excavated sediment, U is the ambient velocity, and D is the diffusion coefficient of the receiving ambient. In this formulation, the settling velocity is not considered because it depends on the sediment diameter, which has not been considered as a parameter.

Being the aim of our work to identify the impact distance associated with a specific concentration, from Eq. (9) the distance reached by a

specific concentration can be evaluated as $d = \left(U - 2 D \ln \left(\frac{4c^2 \pi D t}{M_{sed}^2} \right) \right) t$.

Its maximum value d_{max} , which can be linked to a maximum impact distance, is attained at $t = \frac{M_{sed}^2}{4c^2 \pi D} e^{-\frac{2D-U}{2D}}$ and it is equal to

$$d_{max} = \frac{M_{sed}^2}{2c^2 \pi} e^{-\frac{2D-U}{2D}} \quad (10)$$

To specify the general form of Eq. (10) in our study, we here replaced its variables with specific quantities object of the parametric analysis. The suspended mass is proportional to the number of legs ($M_{sed} \propto n_{leg}$; Section 2.2). The diffusion coefficient depends on both ambient velocity and water depth ($D \propto Uh$) but is also affected by the different processes described in Section 3.1. Therefore, a best-fitting approach has been used to develop a relationship that, using Eq. (10) as a physically sound base, would include all the significant parameters of our analysis: namely, the number of excavated legs, the sediment mass discharge, the ambient velocity, and the water depth. Therefore, the final form of the regression function d_{fit} has been obtained searching for a regression function consistent with Eq. (10), with a reduced number of coefficients, and capable of providing a satisfactory determination coefficient:

$$d_{fit} = \frac{K_0 q_{sed}^{K_q} n_{leg}^{K_n}}{\sqrt{Uh}} e^{-\frac{K_{Uh}}{Uh}} \quad (11)$$

Using Eq. (11), a nonlinear least-squares regression has been performed using the inputs of the parametrical analysis (h , U , q_{sed} and n_{leg}) as predictors of sediment transport behavior. The purpose is to find the values of the tuning parameters K_0 , K_q , K_n and K_{Uh} that yield the best fit for different impact distances ($d_{dep,x}$, $d_{dep,y}$ and d_{susp}) evaluated with the procedures described in Sections 2.4.1 and 2.4.2. Fitted relationships are then employed to inspect connections between key hydrodynamic and sediment transport variables.

Prior to performing the regression, physically unrealistic configurations that could compromise the reliability of the fit were excluded from the dataset. In particular, all cases characterized by a shelf slope $i_{shelf} > 0.01$ within a short distance from the coast ($d_{coast} = 2$ km) were removed, as such conditions do not occur in the Adriatic Sea. In addition, regressions have been performed by splitting the dataset into two sub-sets according to the ambient velocity (either 0.11 or 0.26 m/s) and fitting

them separately. According to this criterion, the tests characterized by $U = 0.11$ m/s, $i_{shelf} = 0$ and $h = 8$ m have been excluded from the fitting data set; this choice was made out within a conservative approach, as they provided very low, non-significant impact distances (lower than 2 km). Moreover, these configurations are, again, not representative of the real set of platforms, since all platforms affected by a small ambient velocity are placed at water depths significantly larger than 8 m. Finally, the tests with $U = 0.26$ m/s, $i_{shelf} = 0$ and $h = 8$ m have been removed due to the fact that they are characterized by impact distances smaller than 6.7 km in case of d_{susp} , smaller than 1.2 km in case of $d_{dep,x}$, while $d_{dep,y}$ are in the range of 200 m.

The best fit coefficients for the two sub-sets are given in Table 4, while scatter plots comparing the predicted and simulated distances are presented in Fig. 9. The proposed correlations align with the outputs of the numerical tests with an error range of $\pm 40\%$.

The best fit coefficients were obtained by fitting the proposed functional form to the complete simulations set (unrealistic scenario excluded), and are, therefore, intended to be applied to any platform within the investigated parameter ranges (depth between 8 and 120 m, sediment discharge between 100 and 200 kg/s; platform legs between 1 and 12; and ambient current velocities in the order of 0.11 and 0.26 m/s). Analyzing the order of magnitude of the fit coefficients also suggests which processes and ambient features are the most influent in defining decommissioning impact. As an example, the free model coefficient K_0 for $d_{dep,x}$ is generally an order of magnitude larger than or comparable to those in d_{susp} , while 3 orders of magnitude larger than those in $d_{dep,y}$ (see Table 4). This indicates that, as common sense would suggest and regardless of the flow intensity, the immediate downstream region of any given platform is always the most susceptible to being impacted by decommissioning activities, especially through deposition of entrained sediment. Cross-stream deposition is conversely less dominant, although its relevance increases as the ambient velocity increases.

The values of the diffusion-related coefficient K_{Uh} being comparatively similar across the three impact distances for the same ambient velocity suggest that diffusive effects hold similar importance in plume dynamics, for either deposited or suspended sediments.

The leg number n_{leg} influences the global amount of excavated sediment and the excavation duration for a constant excavation efficiency, generally increasing the impact distances for deposited and suspended sediments, as hinted at by the relative fit coefficient K_n being always larger than 0. However, this relationship is nonlinear, as the coefficients are always smaller than unity ($K_n = 0.097$ to 0.656 across all scenarios), indicating that the “added impact” generated by the excavation of additional legs is reduced as the total number of legs is increased. This is particularly true for the increase in crossflow deposited sediment impact, since K_n involved in $d_{dep,y}$ is always the smallest.

Interestingly, it turns out that the sediment mass discharge (q_{sed}), representative of the excavation rate, is positively correlated with $d_{dep,y}$ and d_{susp} , but negatively correlated with $d_{dep,x}$; even more so when the ambient velocity is small ($K_q = -0.784$ for $U = 0.11$ m/s). We attribute this behaviour to the possibility that high sediment loads under weak currents promote faster settling due to increased particle interactions. Conversely, q_{sed} increases $d_{dep,y}$, suggesting that higher excavation rates generate wider lateral plumes, possibly through enhanced turbulent spreading. A similar but modest positive effect is observed for d_{susp} ($K_q = 0.148$ to 0.185), suggesting that suspension distances are driven more by hydrodynamics than by sediment input.

To support the interpretation of the regression results and quantify the relative influence of the input parameters, an analysis of predictor importance was performed using a Random Forest algorithm with an ensemble of 1000 decision trees (Breiman, 2001). The normalized contributions of single predictor variables to the impact distances (shown in Fig. 10) highlight the large influence of the ambient velocity U , particularly on the impact distances of deposited sediments. The number of platform legs, on the other hand, is determinant for

Table 4Functional fit relationship coefficients and best determination coefficients R^2 of the resulting fit.

	U = 0.11 m/s					U = 0.26 m/s				
	K_0	K_q	K_n	K_{Uh}	R^2	K_0	K_q	K_n	K_{Uh}	R^2
$d_{dep,x}$	58345.4	-0.784	0.656	1.482	0.919	16307.45	-0.134	0.547	3.872	0.934
$d_{dep,y}$	19.09	0.872	0.097	1.506	0.849	93.50	0.385	0.256	3.52	0.758
d_{susp}	6012.69	0.148	0.366	1.455	0.90	10563.15	0.185	0.385	3.63	0.899

suspended and downstream deposited sediment impacts. It is noted that, according to our model, the excavator mass discharge q_{sed} holds a non-negligible influence on cross-stream sediment impact; this behavior could be linked to the aforementioned increment of $d_{dep,y}$ with increasing q_{sed} . Ultimately, all such considerations would greatly benefit from validation against real data to reinforce or challenge their validity.

In general, we expect the impact of plumes generated by decommissioning in the Adriatic Sea to be low for most platforms. This assumption is corroborated by the moderate deposited sediment impact distances ($d_{dep,x} < 7$ km and $d_{dep,y} < 0.8$ km; see Fig. 9), coupled with near-complete dilution within 10 km from the source and dominant current directions almost always sub-parallel to shore, thus limiting possible interactions with the coast and related environments. In the following section we however evidence few cases of potential interaction.

4.3. Applicative example: most impactful platforms in the Adriatic Sea

Despite the generally low expected impact, the proposed predictive functions may help to identify possible interferences of decommissioning activities with areas of high environmental vulnerability in the Adriatic Sea. They can also serve as a quick and qualitative tool in the framework of a DSS requiring informed, scientifically sound estimations for suitable design and management of coastal operations. In fact, the decommissioning process has several different economic, social, safety, and environmental impacts, of which the sediment plume environmental impact assessments is only one aspect (Capobianco et al., 2022, Vidal et al., 2022, Vidal et al., 2022, EKE 2023, Henrion et al., 2015, Li and Hu, 2022, Na et al., 2017).

To qualitatively explore the application of predictive functions, we here apply the evaluation of impact distances to the configuration of some real platforms. Table 5 presents data for six platforms located in the Ravenna offshore area, for which we identified the chance of interaction with the shore due to their distance from the coastline being comparable to estimated impact distances (evaluated through the predictive function in Eq. (11), equipped with the respective fit coefficients given in Table 4 and provided with the relative input values for h , U , q_{sed} , and n_{leg}).

For the 12-leg (P88, P89) and 8-leg platforms (P11, P90), estimated d_{susp} are between 5 to 14 km and are potentially in range of the closest shoreline; however, dominant current directions in their proximity are consistently sub-parallel to the coastline, resulting in no expected coastal interaction even when d_{susp} exceeds the distance to shore. The 6-leg platform P17 shows similar impact distance ($d_{susp} \approx 11.7$ km), but slightly offshore-oriented typical currents there would imply limited environmental risk. Finally, the 4-leg platform P12, located 2 km from the coast, yields potentially harmful shoreline interaction thanks to comparable impact distances, both for suspended and deposited sediment; however, simulated impact distances remain short and the plume transports subparallel to the coast, making coastal effects unlikely. Overall, the evaluated platforms present negligible hazard to the coastline during decommissioning.

Up until now we have focused our attention on the general interaction of platform plumes with the shoreline; however, the Adriatic Sea hosts several marine and land protected areas which require particular attention due to their high environmental value. As they are generally

placed at substantial distances from offshore platforms, significant impacts from decommissioning activities are not expected to reach such areas. Nevertheless, we suggest coupling the use of predictive functions like the ones presented in this work with local specific studies targeted at the assessment of possible impact due to dredging or excavation activities near protected areas.

5. Conclusions

This study presented a parametric approach to assessing environmental impact of sediment plumes generated by the complete removal of offshore platforms in the Adriatic Sea. Using the CORMIX software, we simulated plume dispersion for a set of platforms under a wide range of environmental conditions (water depths, distance from coast, ambient velocity) and operational conditions (sediment discharge rates). Site-specific bathymetry, fine sediment granulometry and two cases of ambient velocity are assumed. The analysis focused on fine-clay sediments, adopting a precautionary assumption for both sediment-bound chemicals content (typical of the Adriatic Sea) and dilution thresholds, to evaluate impact distances for both deposited and suspended sediments mobilized by the excavation process. The dataset of modelled impact distances has been finally employed to generate best-fit predictive functions that could estimate platform impacts upon input of platform characteristics.

All simulated plumes are quickly dominated by buoyancy and experienced strong near-field dilution within minutes (Purnama et al., 2016). They then transitioned to far-field, ambient-driven dispersion with near-complete dilution within 25 km from the source across all simulated platforms. Plumes thickness remained low, minimizing water column impacts.

Expected impact distances are always lower than 7 km in the flow direction and 800 m in the crossflow direction, scaling nonlinearly with the number of platform legs to be excavated. Although suspended sediments posed the greatest threat, with suspended distances up to 14.6 km from the source, their expected impact on the mainland is minimized by the fact that dominant current directions are in most cases sub-parallel to the coastline. Decommissioning impacts related to sediment resuspension are transient and spatially constrained, with negligible hazards beyond 10 km for the platforms involved in this study thanks to strong dilution occurring within days from the start of excavation.

The proposed regression functions, validated within an error margin of $\pm 40\%$, offer a practical tool for regulators and operators to prioritize mitigation efforts, balancing economic, social, and ecological constraints. Targeted, more detailed assessments are, however, recommended for platforms near protected areas.

Although the results presented in the present work pertain to platforms located in the Adriatic Sea, the methodology for the derivation of predictive functions described in this manuscript can be of general interest to operators and researchers alike, required to deal with a quick yet scientifically sound evaluation of risks connected to platform decommissioning activities.

5.1. Limitations and future directions

While this study provides a robust method to estimate platform decommissioning impacts under general environmental and geometric

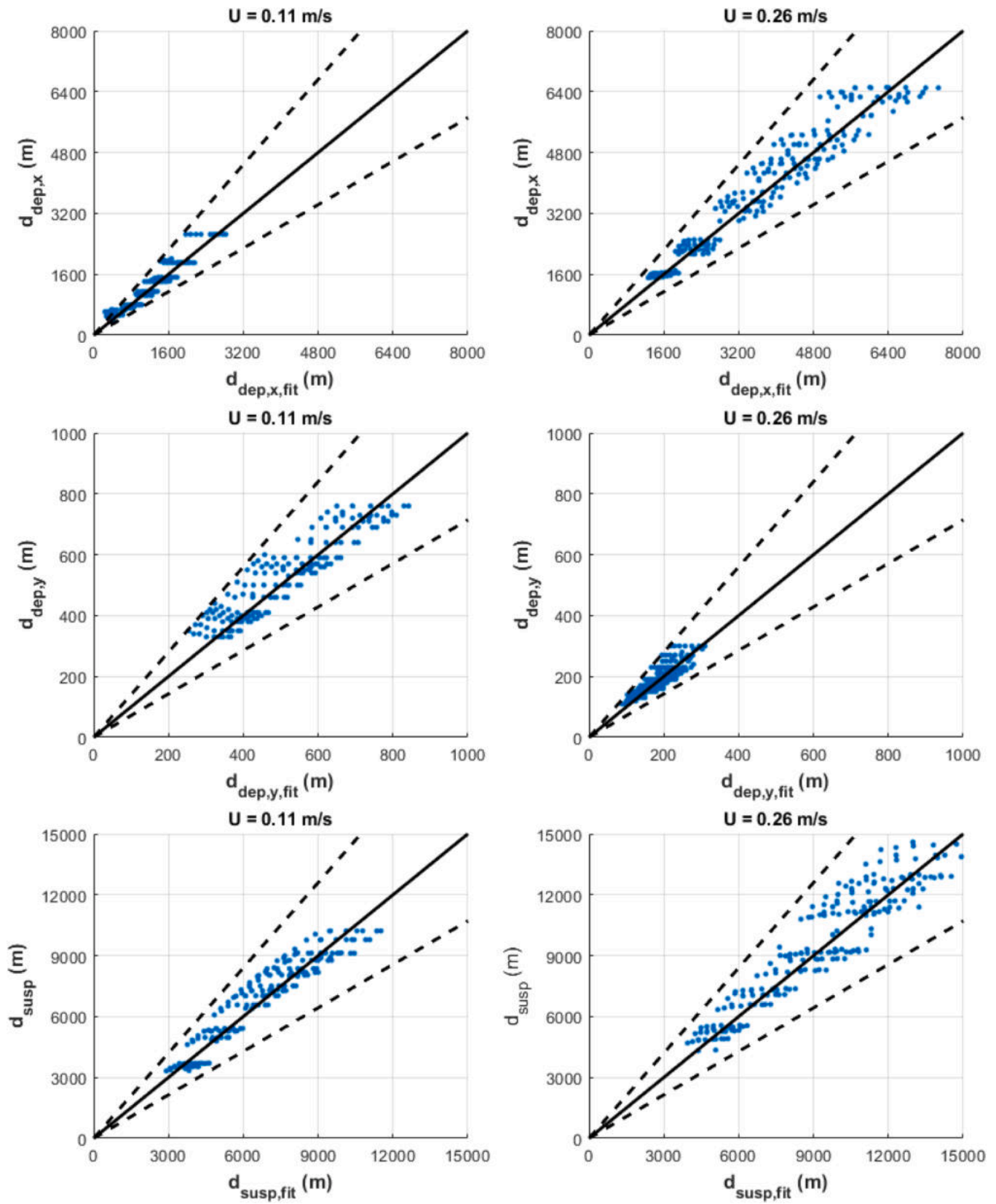


Fig. 9. Comparison of the numerical results with the predicted values obtained with the fit functions. Plots are given separately for different ambient velocities. The dashed lines represent the $\pm 40\%$ error range.

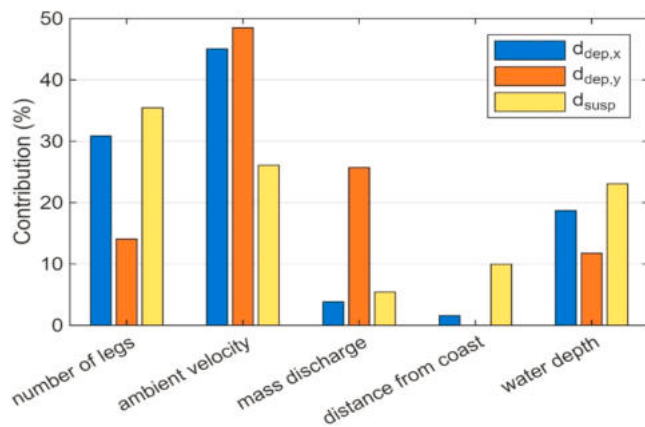


Fig. 10. Relative contribution of predictor variables on the definition of impact distances.

conditions, it is worthwhile to highlight some limitations and avenues of improvement. The hydrodynamic CORMIX model setup relies exclusively on steady ambient currents as forcing action and does not currently contemplate a coupled wave-current approach. However, surface boundary layers generated by waves are able to trap sediment, providing for a possibly relevant process of sediment motion, especially for near-surface sediment flows on continental shelves (Geyer et al., 2004). Also tide was seen to be an influential factor in defining plume properties in dredging activities (Spearman, 2015). Methods to include the potential effect of wave-related forcings on plume dynamics are therefore desirable, also in the framework of established dispersion models which currently lack such interaction.

Moreover, our methodology precautionarily assumes that heavy metals, such as chromium, remain entirely bound to the fine sediment fraction. This approach does not consider other biogeochemical processes which could influence contaminant bioavailability, such as desorption.

Finally, a key challenge highlighted by this study lies in the absence of monitoring of field data for sediment concentration during platform decommissioning. The complete removal of offshore platforms represents a prospective scenario that has not yet been implemented in the Adriatic Sea. Field monitoring campaigns targeted at collecting environmental data during actual decommissioning events are, therefore, highly recommended to provide high-resolution empirical data to validate and refine the predictive measures.

Acknowledgements

Part of the activities carried out within this research were funded by the third-party agreement with Eni S.p.A., within the project DECOPLAT “DECommissioning of Offshore PLATforms,” concerning a study aimed at the decommissioning of offshore mining platforms. The authors

would like to thank Giovanni Russo, Mauro Anzani and Carlos Henrique Friederichs, who helped to define the operating conditions of the excavation activities, by providing company-owned information regarding sedimentological characterization and removal operations.

List of symbols

Symbol	Description
h	Water depth
d_{coast}	Distance from coast
$i_{nearshore}$	Nearshore slope
i_{shelf}	Far-shore Slope
$h_{nearshore}$	Water depth at nearshore
$d_{nearshore}$	Distance from coast to nearshore
ρ_{bulk}	Bulk density
$\rho_{bulk,dry}$	Bulk dry density
G	Grain specific gravity
i	Angle of internal friction
U_{avg}	Depth average velocity
$U_{avg,95\%}$	depth-averaged velocity, 95 th percentile
n_{leg}	Number of legs
M_{sed}	Dry mass of excavated sediment
V_{exc}	Excavated volume
$Q_{effluent}$	Effluent flow rate
Q_{exc}	Excavation rate
T_{exc}	Excavation time
C_{sed}	Actual sediment concentration
$\phi_{sed,rest}$	Sediment fraction at rest
ϕ_{sed}	Sediment fraction
q_{sed}	Sediment mass discharge
$\rho_{sed,wet}$	Sediment bulk density
$\rho_{effluent}$	Effluent density
ρ_w	Ambient density
U	Ambient velocity
θ_0	Vertical angle
T	Deposition thickness
M_{solid}	Mass loading
M_{water}	Mass of water
W_w	percent weight of water in solids
S	Water salinity
dx, dy	Horizontal resolution of grid
$d_{dep,x}$	Maximum deposited impact distance in flow direction
$d_{dep,y}$	Maximum deposited impact distance in crossflow direction
$T_{threshold}$	Thickness threshold (equal to single clay particle)
ϕ_p	Sediment-bound chemicals fraction
$M(x,y)$	map of deposited sediment mass $M(x,y)$
$M_{outside}(d)$	sediment mass deposited beyond a given distance
$c_s(d)$	suspended sediment at the specific distance
V_{cyl}	volume of the cylindrical annulus
$h_{plume}(d)$	Plume height/thickness
c_p	Concentration of suspended sediment-bound chemicals
d_{susp}	Impact distance of suspended sediment
$c_{p,lim}$	sediment-bound chemicals concentration threshold
$c_{p,lim,w}$	sediment-bound chemicals concentration limit in surface waters
A	Ratio of Mass of total sediment to fine sediment (coefficient)
$c_{s,lim}$	Concentration limit for chromium
c	Concentration of 2D diffusion
D	Diffusion coefficient

(continued on next page)

Table 5
Platforms with potential interaction with the coastline.

Platforms	P88, P89	P11	P90	P17	P12
Reference simulation	ID 142	ID 65	ID 42	ID 183	ID 134
d_{coast} (km)	7 to 8	2	8	11	2
Number of legs	12	8	8	6	4
h (m)	12.5 to 13.5	8.5	13.5	15	19.5
U (m/s)	0.26	0.11	0.11	0.26	0.26
Dominant current direction	sub-parallel to the shore (193°.06 N).	sub-parallel to the shore (166°.07 N).	sub-parallel to the shore (193°.06 N).	slightly offshore (154°.7 N)	sub-parallel to the shore (176°.57 N)
$d_{dep,x}$ (km)	6	3.04	1.4	4	2.96
d_{susp} (km)	13.96	5.84	12.9	11.67	4.44
h_{plume} (m)	0.033	0.21	0.081	0.035	0.045
Potential interaction with the coastline	No plume hazard	No plume hazard	No plume hazard	No plume hazard	coastal interaction unlikely.

(continued)

Symbol	Description
d	Distance of specific concentration at time t
K_i	Model coefficient for prediction function
$d_{dep,x,fit}$	Predicted Impact distance of deposited sediment in flow direction
$d_{dep,y,fit}$	Predicted Impact distance of deposited sediment in crossflow direction
$d_{susp,fit}$	Predicted Impact distance of suspended sediment

CRediT authorship contribution statement

Sher Shah: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianluca Zitti:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Lorenzo Melito:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization. **Maurizio Brocchini:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The activities and results presented in this paper were funded by Eni S.p.A. under the Dec.O.Plat. project, which focuses on data analysis, reporting, and the development of a decision support system for the decommissioning of offshore platforms.

The funding provided did not influence the research activities or compromise professional integrity, and we confirm our complete independence from any external interests.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.apor.2026.105136](https://doi.org/10.1016/j.apor.2026.105136).

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