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Sediment transport modifications induced by submerged artificial reef systems: a case study for the Gulf of Venice

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Key words: Adriatic Sea, Numerical Modelling, Artificial Reefs, Coastal Circulation, Tegnùe

Abstract

The shallow, gently sloping, sandy-silty seabed of the Venetian coast (Italy) is studded by a number of outcropping rocky systems of different size encouraging the development of peculiar zoobenthic biocenoses with considerably higher biodiversity indexes compared to neighbouring areas. In order to protect and enhance the growth of settling communities, artificial monolithic reefs were deployed close to the most important formations, providing further nesting sites and mechanical hindrance to illegal trawl fishing.

In this framework, a multi-step and multi-scale numerical modelling activity was carried out to predict the perturbations induced by the presence of artificial structures on sediment transport over the outcroppings and their implications on turbidity and water quality. After having characterized wave and current circulation climate at the sub-basin scale over a reference year, a set of small scale simulations was carried out to describe the effects of a single monolith under different geometries and hydrodynamic forcings, encompassing the conditions likely occurring at the study sites. A dedicated tool was then developed to compose the information contained in the small-scale database into realistic deployment configurations, and applied in four protected outcroppings identified as test sites. With reference to these cases, under current meteomarine climate the application highlighted a small and localised increase in suspended sediment concentration, suggesting that the implemented deployment strategy is not likely to produce harmful effects on turbidity close to the outcroppings.

In a broader context, the activity is oriented at the tuning of a flexible instrument for supporting the decision-making process in benthic environments of outstanding environmental relevance, especially in the Integrated Coastal Zone Management or Maritime Spatial Planning applications. The dissemination of sub-basin scale modelling results via the THREDDS Data Server, together with an user-friendly software for composing single-monolith runs and a graphical interface for exploring the available data, significantly improves the quantitative information collection and sharing among scientists, stakeholders and policy-makers.

INTRODUCTION

The western coast of the Northern Adriatic (NA) Sea (Italy) is generally characterized by a sandy-silty bed, gently sloping down to approximately 50 m below the mean sea level (Sclavo et al. 2013). The morphological smoothness of the sea bottom is occasionally interrupted by the presence of rocky formations of different size (Newton & Stefanon 1975, Conti et al. 2002), called *Tegnùe* (grasps, in the local language) by local fishermen after their capability of trapping and tangling fish nets, which represent spots of outstanding biodiversity and ecological importance (Casellato et al. 2007). The rocky formations, whose exact number is currently unknown but estimated at above 1000 units (Casellato & Stefanon 2008), are generally scattered nearly parallel to the coast and most of them lie within 25 km offshore, at a depth between 10 and 40

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m. Their dimensions are strongly variable, ranging from a few to some thousand square metres in areal extent, and protruding from the sea bottom up to four metres. For encouraging sealife settlement and preventing illegal trawl fishing in these environments, the Veneto Regional Government decided to deploy modular artificial reef systems in the surroundings of the largest formations. The modules consist of permeable monolithic concrete structures with openings and cavities of different size acting as potential nesting niches for different fish species, and have overall characteristic dimension around 1 m^3. In order to control and prevent perturbations in the water quality potentially induced by the deployment of submerged structures, a numerical modelling tool was necessary to assess the impact of different spatial configurations on sediment transport and turbidity. In particular, the requirement was to provide an instrument capable of merging the information about wave and ocean dynamics at the sub-basin scale with hydrodynamic and sediment transport processes at a spatial scale smaller than the size of the structure. In addition, the approach had to be general enough to deal with different possible geometric and hydrodynamic conditions and to allow the exploration of a large number of deployment options at an acceptable computational cost.

To this aim, a set of small-scale simulations investigating the effect of a single monolithic structure in a simplified geometric configuration was run under different combination of external forcings, whose quantification was based on the results of sub-basin scale characterization of ocean circulation, wave climate and sediment dynamics. This made it possible to populate a database encompassing the possible conditions occurring in the NA Sea: the formulation of a criterion for composing this information in a realistic spatial configuration allowed to estimate a Suspended Sediment Concentration (SSC) increase in real systems under the analised conditions.

More generally, the development of a tool for understanding the interactions between human structures and bottom sediment dynamics in shallow basins can be of primary importance across the whole Northern Adriatic coastal zone, with applications ranging from the design of conservation and repopulation interventions to appropriate management of aquaculture sites, particularly active in this area (Rampazzo et al. 2013).

FROM SUB BASIN-SCALE MODELLING TO SINGLE MONOLITH SCALE SIMULATIONS

Modelling wave and ocean dynamics in the Northern Adriatic Sea

Characterization of the hydrodynamic climate on the Venetian coastal zone (Fig. 1) was obtained over one year of reef deployment and good observational data availability (from September 2010 to August 2011) via high-resolution, two-way coupled (i.e. mutually interacting) wave-current-sediment transport numerical modelling. More specifically, this simulation was implemented within the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modelling system (Warner et al. 2010) with ocean circulation computed via ROMS (Regional Ocean Modeling System, Haidvogel et al. 2008) and wave propagation reproduced by SWAN (Simulating Waves Nearshore, Booji et al. 1999) with the simulation period chosen in such a way as to allow the production of inter-seasonal statistics validated by a sound observational database.

With reference to the semi-enclosed Adriatic basin, the increasing suitability of integrated numerical tools for both preliminary investigations and effective littoral management and planning has been shown by successful recent implementations of COAWST. Carniel et al. (2011) and Ciavola et al. (2012) described coastal processes in the Bevano river region, an area of the NW Adriatic Sea characterized by a microtidal regime and low wave energy, by a high-resolution implementation of the coupled wave-currents-sediment transport COAWST system. Benetazzo et al. (2013) studied the effect of Wave-Current Interaction (WCI) phenomena on ocean circulation and wave dynamics in the NA Sea (Italy), implementing the system on a parent grid (with horizontal resolution of 2.0 km) covering the whole basin and a one-way nested child grid resolving the northern area (Gulf of Venice) at a resolution of 0.5 km. On the same line of thought, Sclavo et al. (2013) analyzed the effect of WCI in sediment dynamics, highlighting the importance of coupling in sediment and tracers transport in shallow basins and coastal environments.

In accordance with Benetazzo et al. (2013) and Sclavo et al. (2013), the COAWST run carried out in this work was performed on two nested regular grids. The parent domain encloses the whole Adriatic Sea, discretized at 2 km horizontal resolution, whereas a child grid allows a more resolved insight on the

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northern sub-basin with a 0.5 km grid step. Riverine water and sediment discharges in the Adriatic Sea are estimated according to Raicich (1994), Harris et al. (2008), and Bever et al. (2009). Five astronomic tidal constraints, obtained from the Oregon State University (OSU) model, are defined at the south-eastern open boundary of the domain. Atmospheric forcings are given by COSMO-I7, the Italian implementation of the model developed by the Consortium for Small Scale Modeling (COSMO, Steppeler et al. 2003) whose outputs, provided every 1 hour at 7 km resolution, were linearly interpolated on the COAWST grid. Further details on the present COAWST implementation in the NA Sea can be found in Benetazzo et al. (2013).

Small-scale simulations

Based on statistical analysis of the results of the NA Sea sub-basin modelling, a set of small scale simulations was performed with the DHI MIKE3 FM modelling suite (DHI 2011) on simplified spatial domains. For each considered geometric and hydrodynamic model set up, a "disturbed" configuration characterized by a cubic block with 0.80 m side was analyzed and compared to the corresponding undisturbed (no monolith) condition, for a total of 36 couples of simulations.

The simulations were carried out using the MIKE 3 FM modelling suite, implemented on a 120 × 40 m rectangular domain discretised in triangular cells ranging from 0.15 to 4.00 m side, progressively coarsening while moving away from the block located on the longitudinal axis at a 20.00 m distance from the upstream boundary. This distance was considered to be sufficient for dissipating boundary-generated perturbations. Vertical discretization was performed following a hybrid approach, relying on terrain-following sigma coordinates in the surface level for an accurate description of the water surface elevation, whereas underlying levels have been discretised in the vertical (z) coordinates for better resolution of the bathymetric discontinuity induced by the presence of a submerged structure. Level thickness ranges from 0.15 m in the vicinity of the bottom, up to 3 to 5 m close to the surface, depending on the considered bottom depth.

MIKE 3 FM provides a Finite Volume solution to 3-D Navier-Stokes and a sediment transport equation (advection and dispersion in a three-dimensional flow field) and provides the conditions forcing the transport of different classes of suspended sediments (DHI 2011). The MIKE 3 FM *MudTransport* module accepts either cohesive or non-cohesive sediments, but under the assumption that the bottom sediment mixture is dominated by granular material; all sediment classes were represented in this work with a granular behaviour (Van Ledden et al. 2004). In the considered processes, the key factor is the net erosion rate S_s, which is governed by the local hydrodynamics as well as by sediment properties, and is computed as the difference between erosional and depositional fluxes, expressed in our implementation as:

$$S_S = E\left(\frac{\tau_*}{\tau_{ce}} - 1\right) - Cw_S \qquad (1)$$

where E represents an erosion coefficient, τ_{ce} is the critical erosion bottom stress following an incipient motion approach and τ_* is the maximum between bottom stress and critical erosion stress (Partheniades 1965). C and w_s represent suspended sediment concentration and settling velocity respectively.

In the present study, E has been used to characterize the bottom erodibility and to parametrize the subgrid hydrodynamic processes; the latter enhancing the sediment resuspension phenomena close to the submerged obstacle (Nichols & Hirt 1973; Zhao et al. 2010). To this aim, this parameter was firstly estimated at 5.50E-05 kg m^{-2} s^{-1} based on experimental studies by Wang et al. (2011), and linearly increased up to 1.26E-03 kg m^{-2} s^{-1} within 0.80 m from the upstream edges. This correction allowed to reproduce the scouring patterns observed by Zhao et al. (2012) around a submerged cubic block hit by an orthogonal subcritical current.

Critical erosion bottom stress τ_{ce} has been computed for each granulometric class following the Shields theory (Shields 1936), assuming sediment density equal to 2650 kg m^{-3}. Settling velocity w_s has been calculated for each considered grain size, based on the Newton-Stokes theory (Coulson and Richardson 1955), as a result of an equilibrium between weight of a spherical particle, buoyancy and drag force. Table 1 summarizes the values computed for these parameters for each considered grain size.

Initial and boundary conditions have been selected as to be the most similar to the undisturbed condition. With reference to hydrodynamics, the initial velocity was uniform and equal to the vertically averaged value, while the steady logarithmic profile was defined at the upstream boundary and the steady

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Table 1

Critical shear stress and settling velocities for different grain sizes

d **(µm)**	τ_{cr} **(N m^{-2})**	w_s **(m s^{-1})**
20	2.05E-02	3.56E-04
60	6.14E-02	3.10E-03
100	1.02E-01	8.00E-03

undisturbed (equal to the mean sea level) water surface was imposed at the downstream end of the domain. The suspended sediment concentration was consistently zero at the initial time and the system was progressively fed from the upstream boundary with a sediment supply given by the SSC value corresponding to the hydrodynamic conditions following Eq. 1. This is equivalent to imposing the equilibrium concentration (Armanini & Di Silvio 1988, Stive & Wang 1998), namely the value of SSC corresponding to the zero net vertical flux condition, in a simple uniform flow configuration, and provides an estimate of the reference conditions for a system unperturbed by submerged structures. Depth-averaged equilibrium concentrations related to different conditions are summarized in Table 2.

The 3-D, steady-state SSC fields resulting from each single-block simulation were then compared with undisturbed fields, calculated by dedicated modelling runs. In particular, a database was created containing the SSC increase $\Delta C = C_B - C_U$ (where C_B and C_U are the SSC values, respectively, in the presence and absence of the submerged block in the local reference system) for each configuration due to the presence of the block. In order to extend the study to realistic systems, the effects of single blocks were thus combined following the conservative superimposition approach under the approximation of uniform bathymetry. More specifically, for a given submerged structure distribution, the overall SSC increase ΔC_{tot} was given by the sum of contributions of each block, computed in the global reference system and set to zero negative (sheltering) contributions for the sake of precaution, i.e.:

$$\Delta C_{tot} = \sum_{i=1}^{n} \Delta C_i^{+} \qquad (2)$$

The concentration increase ΔC_i^{+} for the generic *i*-th block is obtained in the global reference system by interpolating the positive local SSC increase field rotated accordingly with the environmental circulation direction affecting the blocks (assumed equal for all structures) on a regular grid with a 1 m horizontal step.

The analysis considered the following real systems within the coastal zone enclosed by a dashed line in Fig. 2:

1. *Tegnùa Ancora*: Located 18 m below mean sea level, surrounded by 31 blocks.
2. *Tegnùa Ancora Del Pelle*: Located 19 m below mean sea level, surrounded by 33 blocks.
3. *Tegnùa Doppia Mamo*: Located 19 m below mean sea level, surrounded by 36 blocks.
4. *Tegnùa dei Pesi*: Located 24 m below mean sea level, surrounded by 30 blocks.

Table 2

Depth-averaged equilibrium suspended sediment concentration (kg m^{-3}) with reference to different water depth (*H*) and current velocity (*v*), in the absence of submerged structures

	***d*=20 µm**			***d*=60 µm**			***d*=100 µm**		
***v* (m s^{-1})**	*H=10 m*	*H=15 m*	*H=20 m*	*H=10 m*	*H=15 m*	*H=20 m*	*H=10 m*	*H=15 m*	*H=20 m*
0.10	0	0	0	0	0	0	0	0	0
0.20	3.53E-01	3.14E-01	2.89E-01	1.70E-03	2.00E-04	0	0	0	0
0.30	9.88E-01	9.88E-01	8.43E-01	2.60E-02	2.27E-02	2.05E-02	3.30E-03	2.50E-03	2.00E-03
0.40	1.88E+00	1.72E+00	1.62E+00	6.01E-02	5.41E-02	5.03E-02	1.12E-02	9.80E-03	8.90E-03

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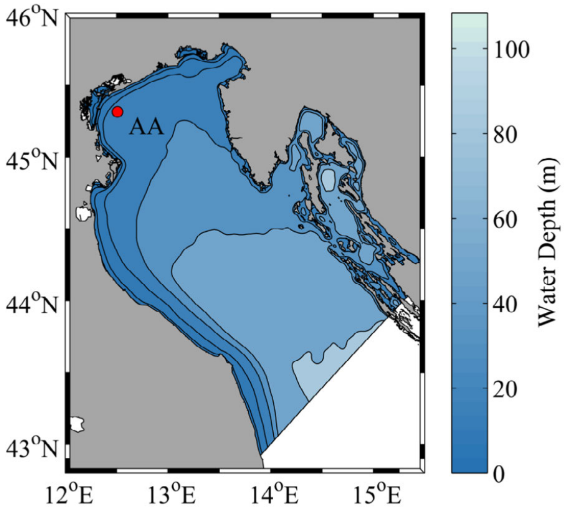

Fig. 1. Northern Adriatic Sea. High resolution computational domain and position of the Acqua Alta oceanographic tower (red dot), from Benetazzo et al. (2013)

RESULTS – CIRCULATION IN THE GULF OF VENICE AND SEDIMENT RESUSPENSION ON THE TEGNÙE AREA

Ocean circulation and waves in the Gulf of Venice

The results of the large scale modelling were validated against satellite data (Jason-1, NASA\CNES; Jason-2, NASA\CNES\EUMETSAT\NOAA, and Envisat, ESA) and observations collected at the CNR-ISMAR *Acqua Alta* oceanographic tower, located 8 miles off the Venetian coast (45°18'83" N, 12°30'53", a red dot in Fig. 1). Statistical indicators for the quality of the results, such as a linear regression slope (*P*), bias (*B*), root mean square difference (*RMSD*) and correlation coefficient (*CC*) have been computed with reference to the entire 1-year period and summarized in Table 3. As validation quantities, we considered wind velocity 10 metres above mean sea level (U_{10}), significant wave height

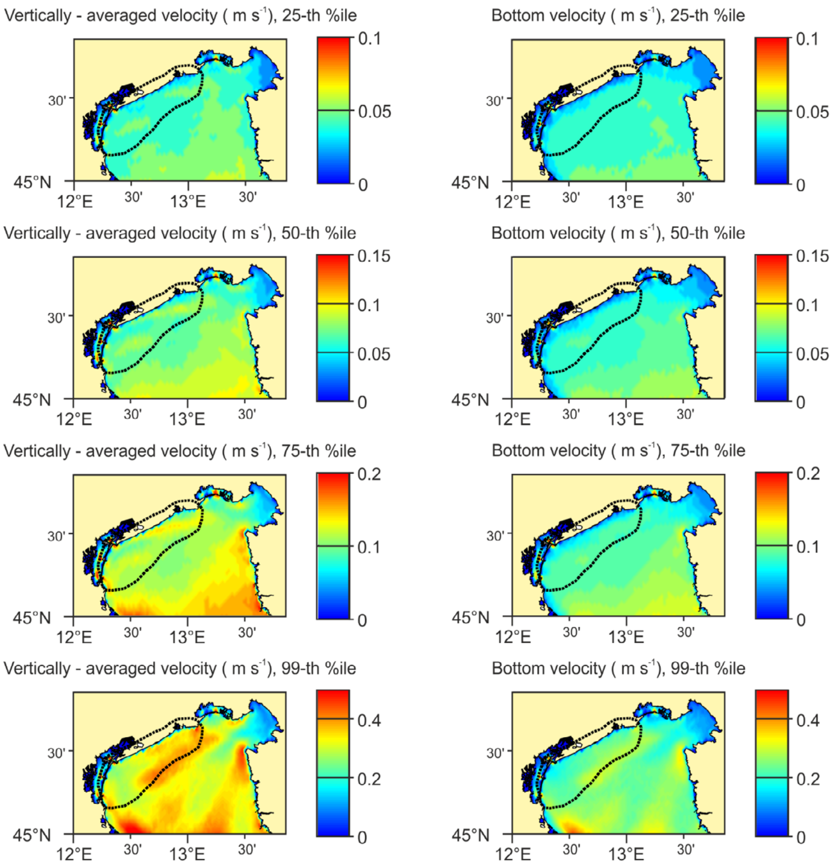

Fig. 2. Vertically-averaged (left column) and near-bottom (right column) current velocity in the Northern Adriatic Sea. Dashed line encloses the Tegnùe area.

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Table 3

Statistical indicators used for the model's validation against data from the Acqua Alta tower (AA) and satellite (Sat), with reference to the period September 2010 – August 2011

Variable	*P*	*B*	*RMSD*	*CC*
U_{10}-*AA*	0.90	-0.18 ms^{-1}	2.12 ms^{-1}	0.77
U_{10}-Sat	0.98	0.07 ms^{-1}	1.82 ms^{-1}	0.72
H_s-*AA*	0.89	-0.01 m	0.20 m	0.90
H_s-Sat	0.94	-0.02 m	0.26 m	0.81
T_{m02}-*AA*	0.92	-0.14 s	0.52 s	0.80

Variables:
wind velocity 10 metres above the mean sea level (U_{10}),
significant wave height (H_s),
mean wave period (T_{m02}).

(H_s) and mean wave period (T_{m02}), finding a good correspondence between modelling results and observations.

In accordance with the previous studies (Cavaleri et al. 1989, Bignami et al. 2007, Dykes et al. 2009), the NA Sea climatology has been found to be characterized by frequent wave-generating storms, dominated by Bora from North-East and Sirocco from South-East, giving rise to peculiar cyclonic circulation patterns (Carniel et al. 2009), see Fig. 3. Details about thermohaline features and coupled wave, ocean and sediment dynamics in the NA Sea can be found in recent works by Russo et al. (2012), Benetazzo et al. (2013) and Sclavo et al. (2013). In our paper, we focus on current statistics in the Gulf of Venice (Fig. 2), with particular attention to the coastal area where most of the outcroppings are located.

Most of the surveyed formations lie at a depth between 10 and 25 m and are subject to small current velocities, being a semi-permanent value (namely the value that is not exceeded for half of the considered period, or the 50th percentile), generally smaller than 0.10 m s^{-1}, and maximum values around 0.40 m s^{-1}, only in a few cases above 0.50 m s^{-1}. Current velocities are mostly parallel to the coast (Fig. 4), reaching the maximum values on either NE or SW directions.

Sediment resuspension induced by submerged structures

In order to account for significant hydrodynamic conditions taking place in the system with different occurrence frequencies and discussed in Sec. 3.1, combinations of the following constraints were used in the runs:

- Vertically averaged current velocity: 0.10, 0.20, 0.30, 0.40 m s^{-1};
- Bottom depth: 10, 15, 20 m;
- Bottom grain size: 0.020, 0.060, 0.100 mm.

These values were selected based on the grain size distribution described by previously published studies (Goff et al. 2006, Harris et al. 2008, Bever et al. 2009) and collected in the framework of the Regional Project *Indagine preliminare sulle caratteristiche dei sedimenti superficiali della fascia costiera veneta, attraverso un nuovo approccio interpretativo (in Italian)* with reference to the NA Sea.

The results of single-block simulations show that

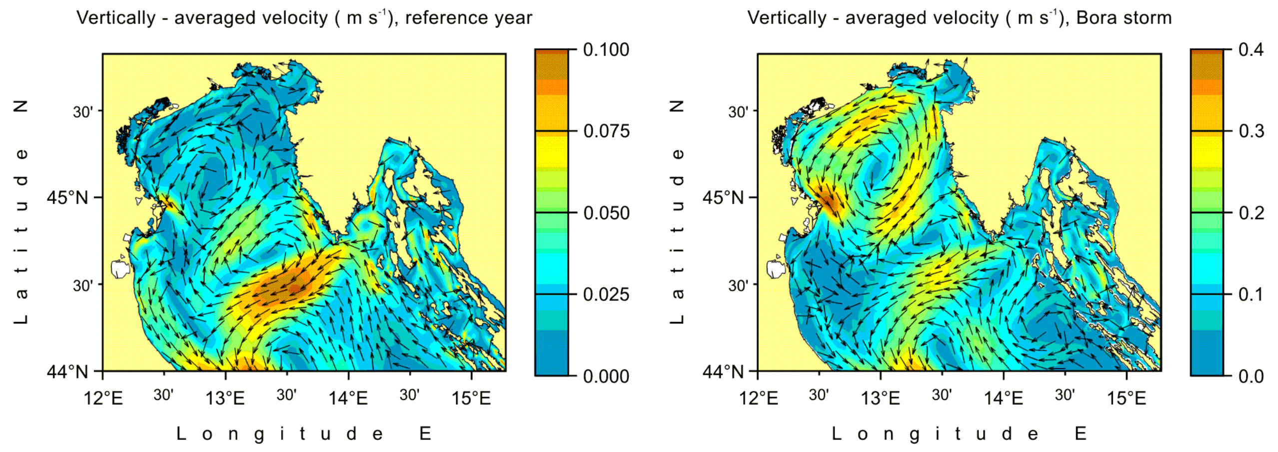

Fig. 3. Vertically-averaged mean circulation in the Northern Adriatic Sea over one year (left panel) and during the Bora storm (Feb, 28 – Mar, 04, right panel)

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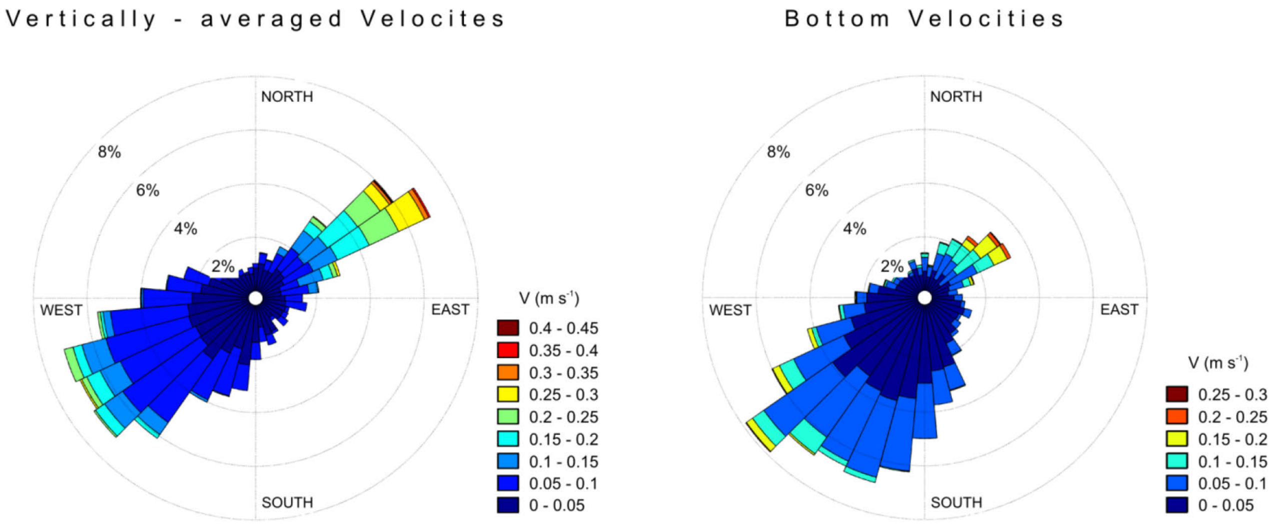

Fig. 4. Vertically-averaged (left panel) and near-bottom (right panel) modelled current roses in the Tegnùe area

the dynamics of suspended sediment transport follow approximately the same pattern in all the explored cases. However, this result is not surprising as considering that the flow is always strongly sub-critical, it allows a description of the phenomenon that can be helpful in assessing the more general cases.

When the flow hits the upstream face of the submerged obstacle, local three-dimensional flow features develop in the proximity of the structure, giving rise to sediment resuspension (parameterised, at the sub-grid scale, by the Erosion Coefficient E, see Sec. 2.2), while vortex-averaged flow is parted on either direction (Fig. 5). In particular, flow

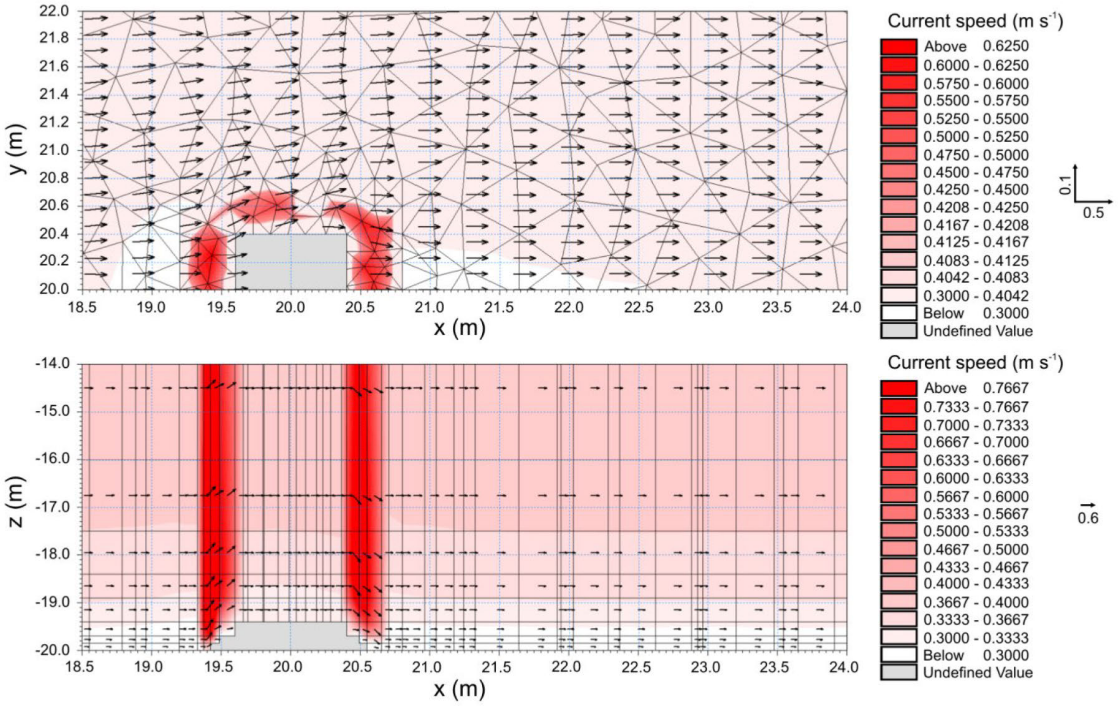

Fig. 5. Modelled circulation close to a block: plan view (0.6 m above the sea bottom, upper panel) and the longitudinal profile along the block axis (lower panel)

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components surrounding the block on its side contribute to a cross-flow dispersion of the suspended matter, whereas the flow overtopping the block rises the sediment plume above the block and throughout the water column, whence it is transported downstream by the mean current generating a net depositional flux supplying the sediments to the bottom layer. By contrast, the flow diversion induced by the structure attenuates the downstream bottom stress, hampering the sediment stirring and protecting the bottom from erosion.

SSC increase along the longitudinal axis of the domain (Fig. 6) is thus the result of the competing actions of sediment resuspension from the upstream face of the structure and its advective downstream transport, opposed by the bottom sheltering effect exerted by the structure itself. Depending on the relative weight of these processes, compared to the background undisturbed transport regime, the net perturbation can display different positive (increase) values (up to 17 g m^{-3} along the longitudinal axis of the domain, locally increasing by one order of magnitude in the very correspondence of the upstream corners) as well as slightly negative values immediately behind the block and occasionally some metres downstream.

The combined effects of multiple monolyths deployed in real systems have been explored with reference to different current velocities and bottom compositions. In particular, besides analising the single-grain configurations related to each considered sediment class, a site-specific sediment class (referred as NA) has been defined with the composition summarized in Table 4. Values for the relative

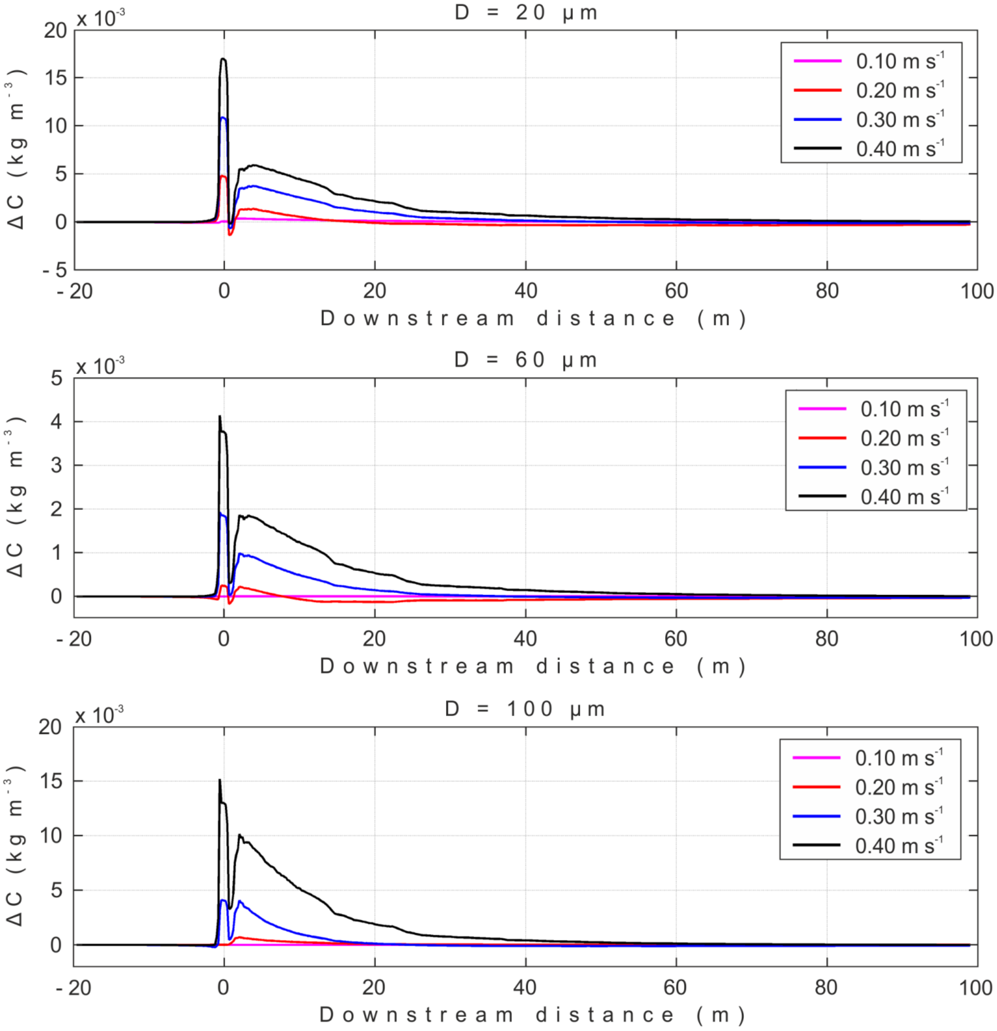

Fig. 6. Longitudinal profiles of SSC increase induced by a submerged obstacle

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Table 4

Bottom grain size composition

Sediment class	1	2	3
D_i(μm)	20	60	100
β_i	0.785	0.065	0.150

fraction β_i of each class in the mixture have been assumed based on surveys performed in the Venetian littoral (Boldrin, pers. comm.)

SSC C_{NA} in the presence of NA bottom sediment mixture is given as a sum of SSC C_i for each class weighted by its relative fraction in the bottom layer β_i:

$$C_{NA} = \sum_{i=1}^{3} \beta_i C_i \qquad (3)$$

Figures 7-10 summarize the results of the analysis performed in the rocky systems. Left panels show the system topology (black squares mark the position of submerged blocks and green polygons delineate the limits of the outcroppings) and the SSC increase field at the bottom level in the critical case of the finest sediment grain size and the strongest current speed. Right panels focus on the zones of the outcropping rocks most affected by the SSC increase for different velocities and bottom compositions.

A comparison of the results shown in Figures 7-10 against the background undisturbed SSC values reported in Table 2 shows that structure-induced increases are almost negligible for vertically-averaged current velocities smaller than 0.2 m s^{-1}, namely up to the highest percentiles of the frequency distribution. Moreover, even in the case of the strongest current speed, the relative increase has the order of magnitude of a few percent units, indicating that the investigated configurations are not apparently perturbative for the water turbidity in zones of valuable environmental quality.

DISCUSSION

The strategy underlying the present work consisted in characterising the sediment transport close to a submerged structure by constructing a thorough database of simple cases, representative of the local climate conditions, which can then be combined to infer the information about more complex systems.

The flexible mesh discretization used in the single-monolyth cases allowed to increase the model resolution in the vicinity of the block even to reproduce the realistic vortex-averaged flow fields around the submerged obstacle (Nichols & Hirt 1973, Zhao et al. 2010). Thus, whilst the sub-grid three-dimensional vortexes responsible for local scouring and sediment resuspension required a dedicated tuning of the erosion coefficient for being properly taken into account, the suspended sediment pathways should not be significantly affected by this approximation.

The superimposition approach adopted to represent the effect of multiple structures is equivalent to neglect both the sheltering effect of the blocks and the possible second-order increases in SSC given by hydrodynamic interactions between two or more neighbouring blocks. Although a quantitative investigation of this point may be of interest for a more precise definition of the limitations of this approach, this possible underestimation can occur when the following conditions are simultaneously fulfilled:

- the distance between the structures is smaller than the length scale of the hydrodynamic disturbance, namely of the order of a few meters, which is a typical deployment spacing;
- the interacting structures are not deployed parallel to the current direction, so no sheltering effect can take place.

On the other hand, this method systematically neglects the sheltering effect of blocks in the downstream area, both in terms of bottom stress and sediment resuspension (Fig. 6), and of hydrodynamic disturbance on the sheltered blocks. Hence, as long as the objective of the study is to verify whether the defined reference values for the water quality (and in particular for turbidity) are not exceeded, the proposed method appears conservative in most cases of practical use.

In principle, taking into account only the inorganic sediment fraction as a proxy of turbidity may result in partial description of the transport dynamics, completely neglecting the possible contribution coming from biological material. In fact, biological activity provides negligible biomass compared to inorganic sediment resuspended during significant storms, which mostly occur during winter (Boldrin, personal communication). Hence, focusing on inorganic sediment does not appear as a major

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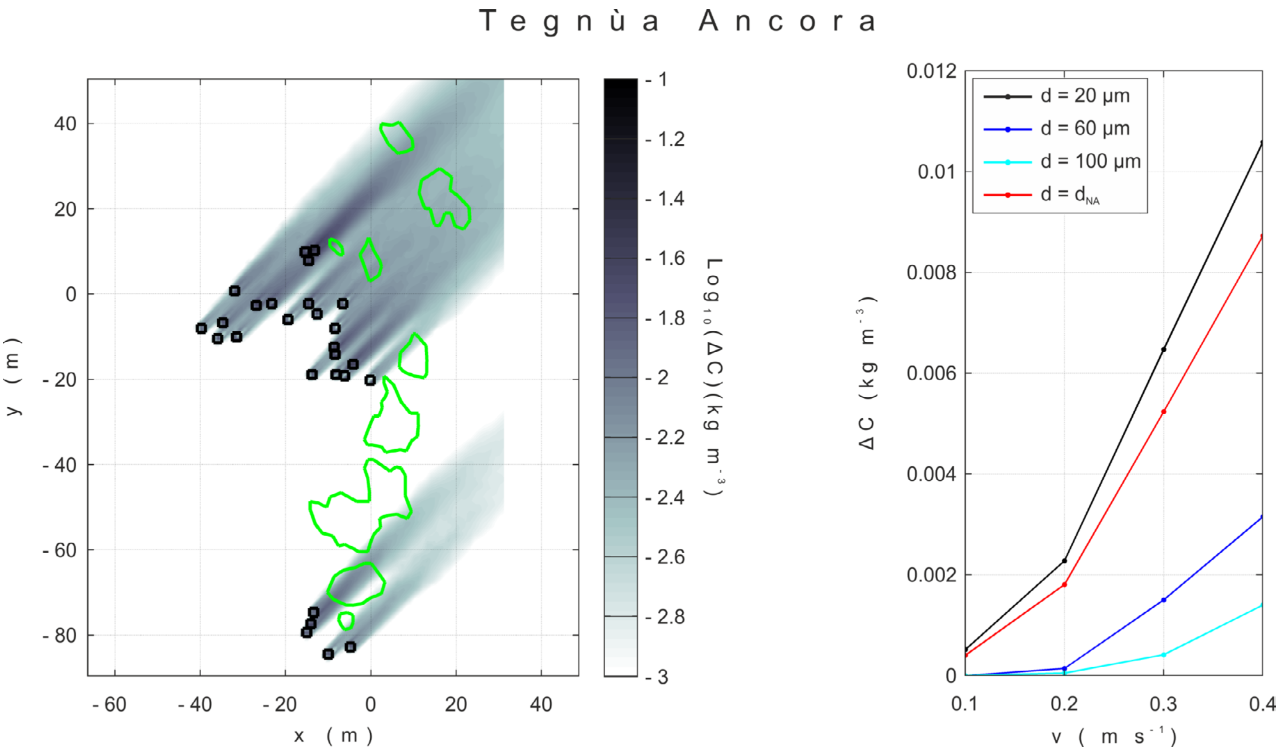

Fig. 7. Tegnùa Ancora. Worst-case (d=20 μm and v=0.4 m s^{-1}) SSC increase plume (left panel) and maximum SSC increase on the outcroppings for different average velocity and bottom composition (right panel)

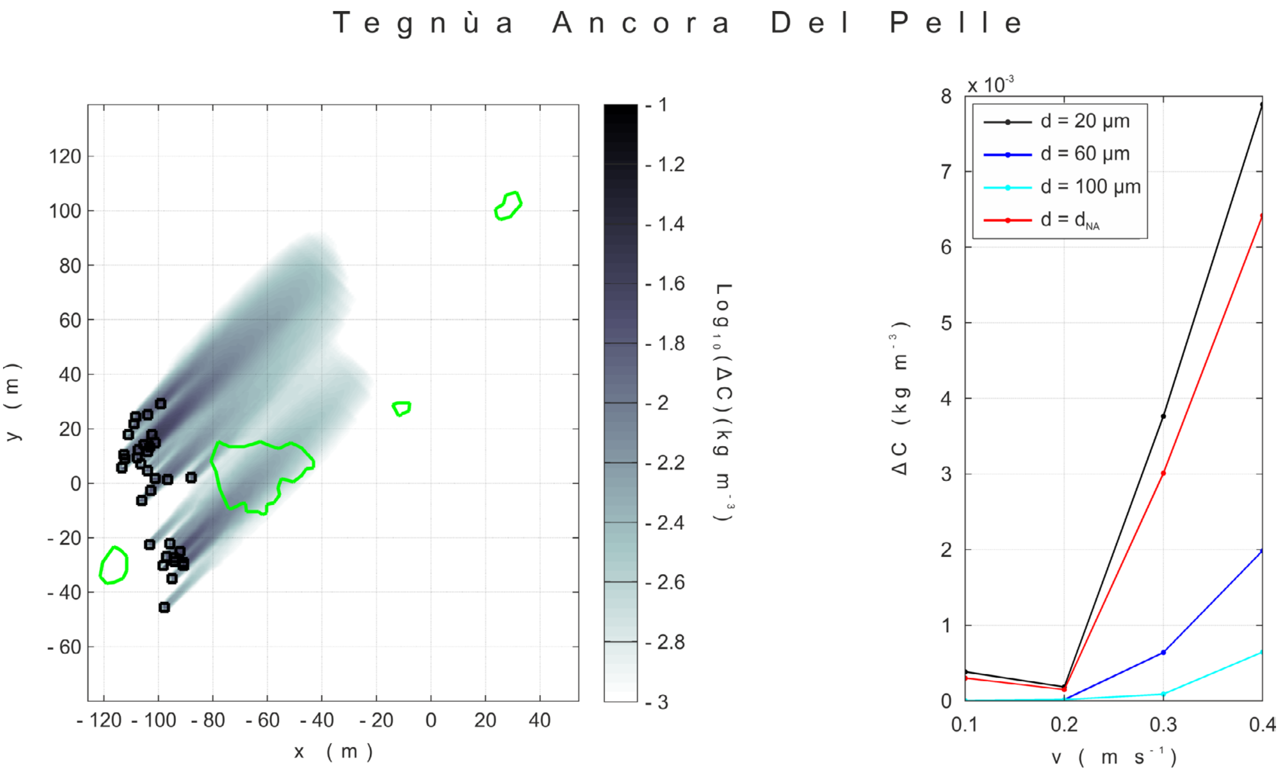

Fig. 8. Tegnùa Ancora Del Pelle. Worst-case (d=20 μm and v=0.4 m s^{-1}) SSC increase plume (left panel) and maximum SSC increase on the outcroppings for different average velocity and bottom composition (right panel)

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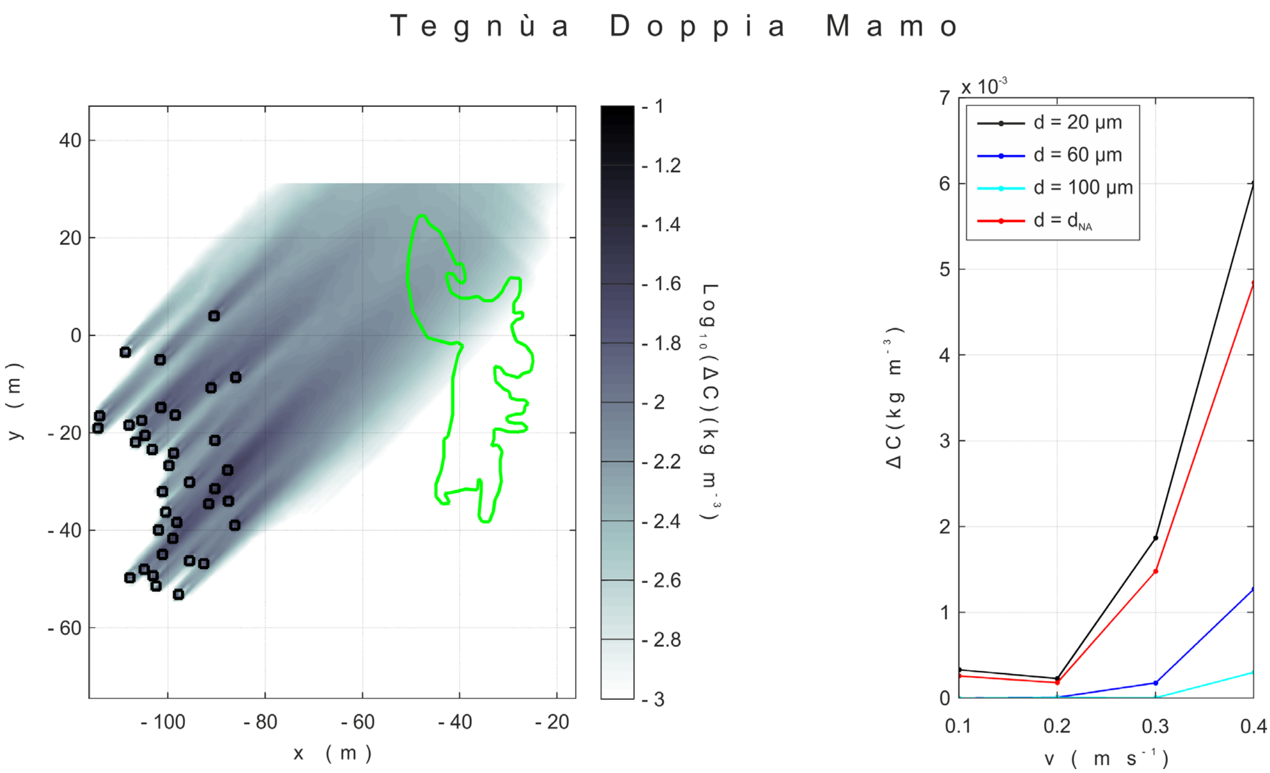
Tegnùa Doppia Mamo

Fig. 9. Tegnùa Doppia Mamo. Worst-case (d=20 µm and v=0.4 m s^{-1}) SSC increase plume (left panel) and maximum SSC increase on the outcroppings for different average velocity and bottom composition (right panel)

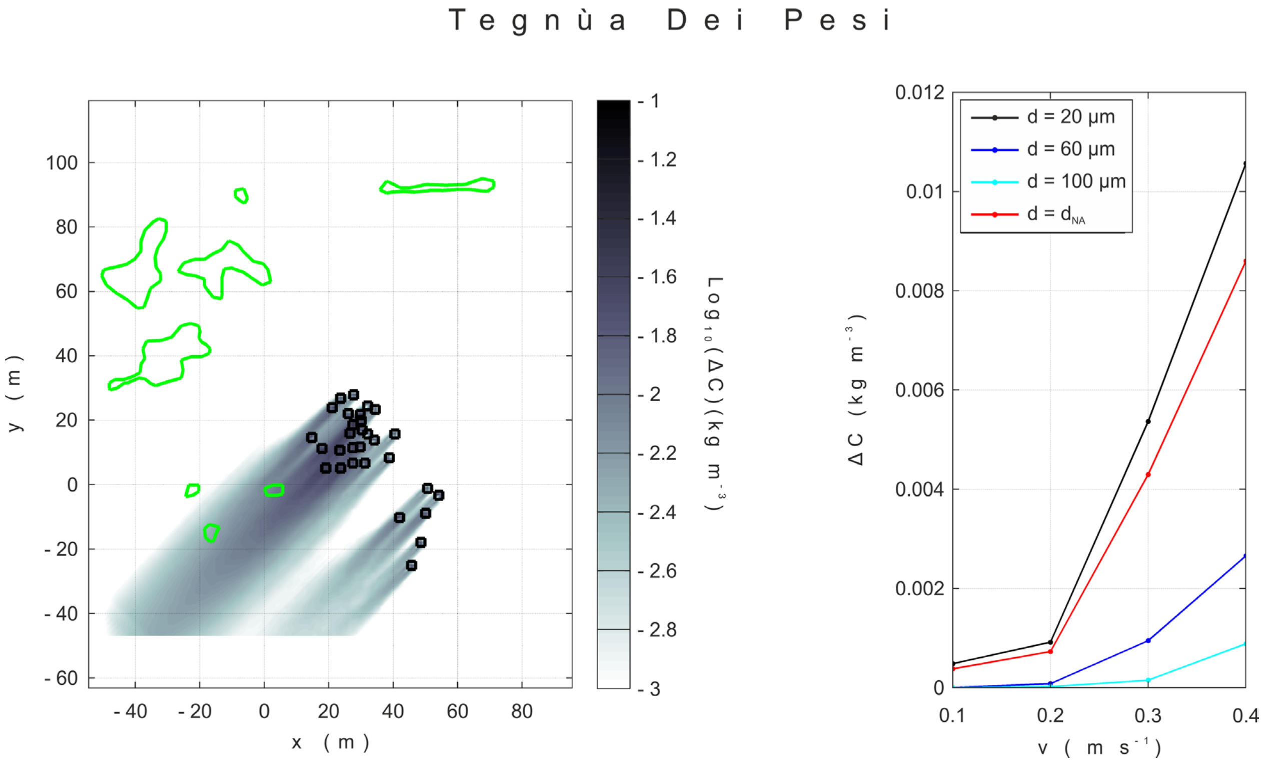
Tegnùa Dei Pesi

Fig. 10. Tegnùa Dei Pesi. Worst-case (d=20 µm and v=0.4 m s^{-1}) SSC increase plume (left panel) and maximum SSC increase on the outcroppings for different average velocity and bottom composition (right panel)

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limitation for the present approach; on the contrary, it may be a useful simplification when representing similar systems. In particular, considering the SSC increase fields in the case of uniform composition with the 20-μm grain size may provide a precautionary estimate compensating the uncertainties on the bottom composition and taking into account the possibility of a strong stirring event subsequent to a relevant deposition of fine material. Nevertheless, the representation provided in the present study refers to steady-state sediment transport processes in simplified, although realistic cases. A field monitoring study, together with the model-based exploration of the effect of unsteady flows and alternating depositional and erosional events, is therefore suggested for a better insight into the implications and limitations of the performed conceptualization and for improving the parameterization of sediment properties and sub-grid processes.

As a corollary of the modelling activity, a particular attention has been given to valorisation and dissemination of the results. In this direction, the climatological characterization of the Adriatic Sea was uploaded into a THREDDS Data Server (TDS, Signell et al. 2008; Bergamasco et al. 2012; http://tds.ve.ismar.cnr.it:8080/thredds/catalog.html) and made accessible to the Veneto Regional Administration via a protected connection. TDS is a free and supported tool for data distribution with no need for modifications, via standard web services, and their retrieval by data users via specific catalog brokering systems, with great advantages in terms of model data access and interoperability. An interactive tool for visualization of the available information concerning the surveyed rocky formations was also developed, with the possibility of further feeding the database with new modelling or observational data. In addition, the management of a single-block modelling run database and the analysis of real cases have been made easily reproducible by means of a graphical stand-alone application.

CONCLUSIONS – A DESIGN TOOL FOR THE DEPLOYMENT OF ARTIFICIAL REEF SYSTEMS

In the present study, we investigated the effect of submerged artificial reefs on local hydrodynamics and sediment transport under different conditions, evaluating their possible impacts on natural outcropping systems of special environmental relevance. The hydrodynamic analysis was carried out by state-of-the-art modelling tools at different scales, from sub-basin scale circulation (500 m horizontal resolution) to local flow field perturbations at the structure scale. With reference to NA Sea bottom composition and meteo-marine climate, we found that the impact of the considered structures are relatively small and rapidly dissipating within a length of some ten metres. Even in the most severe conditions, with maximum annual current velocity and the finest sediment grain size, the structure-induced relative increase in the suspended sediment transport over the rocky formations reaches up to a few percent units with respect to the undisturbed flow field.

Due to the presence of various, sometimes competing, marine and coastal activities taking place in the NA Sea (Santoro et al. 2013), the artificial reef deployment at this site is a typical case of multi-purpose intervention, potentially oriented to different applications such as resource conservation, aquaculture, diving tourism and research, and generating a number of direct and indirect use values (Whitmarsh et al. 2008). In the framework of progressive diffusion of multi-criterial and multi-disciplinary approaches to marine resource management, participation of aware stakeholders is a key for a successful decision-making process. To this aim, the diffusion of scientific results together with the tools adopted for their achievement helps to share and update the set of available quantitative information about the problem under examination. In fact, the whole modelling chain and the results' dissemination system set up in this work is preliminary to constitute a user-friendly tool for policy-makers, scientists and engineers dealing with the management of highly valuable benthic environments. By accessing the oceanographical information at different scales, characterising the reference environmental conditions and exploring a wide range of possible deployment solutions at a small computational cost, it is possible to provide an extensive physical characterization of the problem, setting the basis for further high-detailed analysis and decisional evaluations.

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