The Civitavecchia Coastal Environment Monitoring System (C-CEMS): a new tool to analyse the conflicts between coastal pressures and sensitivity areas

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Abstract

The understanding of the coastal environment is fundamental for efficiently and effectively facing the pollution phenomena, as expected by Marine Strategy Framework Directive, and for limiting the conflicts between anthropic activities and sensitivity areas, as stated by Maritime Spatial Planning. To address this, the Laboratory of Experimental Oceanology and Marine Ecology developed a multi-platform observing network that has been in operation since 2005 in the coastal marine area of Civitavecchia, where multiple uses and high ecological values closely coexist. The Civitavecchia Coastal Environment Monitoring System (C-CEMS), implemented in the current configuration, includes various components allowing to analyse the coastal conflicts by an ecosystem based approach. The long-term observations acquired by the fixed stations are integrated with in-situ data collected for the analysis of the physical, chemical and biological parameters of the water column, sea bottom and pollution sources detected along the coast. The in-situ data, integrated with satellite observations (e.g. temperature, chlorophyll-a and TSM), are used to feed and validate the numerical models, which allow the analysis and forecasting of the dynamics of pollutants dispersion under different conditions. To test the capabilities of C-CEMS, two case studies are reported in this work: 1) the analysis of fecal bacteria dispersion for bathing water quality assessment and; 2)

the evaluation of the effects of the dredged activities on *Posidonia* meadows, which make up most of the two sites of community importance located along the Civitavecchia coastal zone. The simulations results are combined with the presence of bathing areas and *Posidonia oceanica* distribution in order to solve the conflicts between coastal uses (in terms of stress produced by anthropic activities) and sensitivity areas.

1 Introduction

Coastal ecosystems are characterized by the spatial and temporal coexistence of multiple uses connected to many human activities such as aquaculture, energy production, maritime transport, tourism, and fishery. The overlap of such activities and their objectives has the ability to create user-user and user-environment conflicts (Douvere, 2008) that result in increasingly undesirable effects such as loss and destruction of habitat, pollution, climate change, over-fishing, and cumulative threats to the oceans and human health as a whole.

The Integrated Marine Policy (IMP) has faced this issue by the adoption of the Maritime Spatial Planning Directive (MSP, 2014/89/EU) whose main purpose is to promote the sustainable management of uses and conflicts in coastal areas through an ecosystem-based approach. MSP strategy allows to minimize the impacts on sensitivity areas, also enabling the achievement of the Good Environmental Status (GES) by 2020, requested by Marine Strategy Framework Directive (MSFD 2008/56/EC). In the last years a big effort was made by the scientific community to provide new approaches for the analysis of GES descriptors like the study of eutrophication (descriptor 5) through satellite ocean color data (Cristina et al., 2015) and the assessment of sea-floor integrity (descriptor 6) by SAR imagery (Pieralice et al., 2014). Important results were also obtained by the analysis of both commercial fishes and foodweb (descriptors 3 and 4), to assess the environmental status of European seas (Jayasinghe et al., 2015), and the levels of major contaminants (descriptors 8 and 9) and their pollution effects on aquatic biota (Tornero and Ribera d'Alcalà, 2014).

In keeping with the holistic nature of the MSFD, the achievement and the maintenance of marine ecological standards need the support of monitoring networks which use L-TER observations and integrate multi-disciplinary datasets, fundamental to forecast specific events (Schofield et al., 2002). However, a recent study by Crise et al. (2015) revealed gaps of data in the Mediterranean region (South European Seas), highlighting the scarcity, dispersion and heterogeneity of coastal waters datasets. It is accordingly necessary to develop monitoring systems in the southern European coastal areas capable of collecting both high-resolution and long-term data and building multi-disciplinary datasets. Recent advances in communication and sensor technology have led to the development of worldwide multi-platform networks that provide a significant amount of data on different spatial and temporal scales for the study of oceanographic processes and marine ecosystem monitoring (Glasgow et al., 2004; Hart and Martinez, 2006; Kroger et al., 2009). These monitoring tools are especially suited for coastal systems (i.e., Chesapeake Bay Observing System, CBOS; Li, 2005; Long-term Ecosystem Observatory, LEO-15; Schofield et al., 2002) characterized by high spatial and time variability and affected by strong conflicts between human uses and ecosystem conservation. In this context, the Laboratory of Experimental Oceanology and Marine Ecology developed a multi-platform observing network which operates since 2005 in the coastal marine area of Civitavecchia (Italy, Tyrrhenian Sea, Western Mediterranean Sea), critically interested by the presence of many conflicts.

This paper presents the C-CEMS as a tool to support the management of conflicts between anthropic uses and sensitivity areas. We focused on: (1) the functioning of C-CEMS and its components (Section 3); (2) its capabilities in reproducing the dispersion of fecal bacteria for bathing water quality assessment and of dredged fine sediments to evaluate the effects on *Posidonia oceanica* meadows present in the Sites of Community Importance (SCI) (Section 4); (3) the resulting analysis of "urban discharge - bathing area" and "dredging - SCI" conflicts (Section 5).

2 Study area

The study area is located along the north-east Tyrrhenian coast (Western Mediterranean sea) (Fig. 1A). The circulation of the Tyrrhenian basin is affected by mesoscale and seasonal variability (Hopkins, 1988; Pinardi and Navarra, 1993; Vetrano et al. 2010). The presence of a cyclonic gyre with a very pronounced barotropic component suggests that the wind play likely a major role as a forcing agent (Pierini and Simioli, 1998). Like most of the Italian coast, the north-east Tyrrhenian one counts many tourist and industrial areas primarily used for maritime transport and energy production, involving an intense exploitation of marine resources. Nevertheless, it houses several biodiversity hotspots and marine protected areas for the conservation of priority habitats and species.

In particular this study is focused on coastal zone between Marina di Tarquinia and Macchia Tonda in the northern Latium region of Italy(Fig. 1B) including Civitavecchia city, where all the above mentioned uses could produce potential conflicts. The Civitavecchia harbor is one of the largest in Europe in terms of cruise and ferry traffic; it represents a fundamental point of commercial exchange in Europe. Thanks to the new Port Regulating Plan, the Port of Civitavecchia has increased its commercial traffic and cruise passenger flow. The Interministerial Committee for Economic Planning (CIPE) approved the final project for the 'strengthening of Civitavecchia harbor hub – first parcel functional interventions: Cristoforo Colombo embankment extension, ferries and services docks realization'. All of these operations involve the handling of significant quantities of sediments; the impacts of dredging on the adjacent natural ecosystems can be varied and difficult to predict (Nayar et al., 2007; Windom, 1976; Cheung and Wong, 1993; Lohrer and Wetz, 2003; Zimmerman et al., 2003). In conflict with the port activities, the study area hosts four SCIs. They are characterized by the presence of habitats (*Posidonia oceanica* meadows and reefs of rocky substrates and biogenic concretions) and species (*Pinna nobilis* and *Corallium rubrum*) enclosed in the attachment 1 and 2 of the European Union (EU) directive 92/43/CEE.

Moreover, the promotion of underwater natural beauty, touristic exploitation connected to the increased cruise traffic and the realization of suitable bathing facilities have led to a drastic increase in the population density in Civitavecchia during the summer. Many services are now available for recreation thanks to the several beach licenses granted for food, bathing, mooring of private vessels, and sport activities. An updated list of the Latium Region Office counts 72 beach licences released in 2014 to the municipal districts of Santa Marinella and Civitavecchia. However, this urban development was not associated with an upgrade of the wastewater treatment plant, which often caused the discharge of untreated water into the bathing areas. Along the coast, between Civitavecchia harbor and the Punta del Pecoraro bathing areas, four discharge points have been identified as shown in Fig. 1C in conflicts with the recreational use of the coastal zone. These discharge points present high concentrations of pathogenic bacteria that have been potentially affected by fecal contamination episodes.

3 Components of the C-CEMS

C-CEMS is a multi-platform observing system implemented in 2005 to face the coastal conflicts by an ecosystem-based approach. Accordingly to the Copernicus program, C-CEMS provides a monitoring service for the marine environment through multi-source data including in-situ and remote sensing observations. In addition, C-CEMS integrates this information within mathematical models that allow to simulate specific events and forecast potential impacts with a high spatial and temporal resolution, necessary to analyse the conflicts in coastal areas (Bonamano et al., 2015b).

As shown in Fig. 2, C-CEMS components interact between them to assess the coastal pressures analysing the dispersion of pollutant substances coming from the anthropic activities located along the Civitavecchia coastal area. Data provided by fixed stations, in-situ surveys, and remote sensing play a crucial role being used as input (I = input in Fig. 2) and for the validation (V = validation in Fig. 2) of the numerical models. They give a fundamental contribution in C-CEMS allowing to forecast the dispersion of pollutant substances within the sensitivity areas represented mainly by marine protected areas and zones designated for recreational uses (bathing, diving, watersports, fishing, etc.). To analyse the potential conflicts between the pressures on both marine coastal environment and human health, the results of the pollutants dispersion, obtained under different weather conditions, are overlapped with the thematic maps of the sensitivity areas.

Since marine coastal ecosystems have been acknowledged as providing the most benefits among all terrestrial and marine ecosystems (Costanza et al., 1997), the appointment of an economic value to these natural resources is essential for correct planning of marine coastal areas. Nevertheless the economic impact on the natural capital in terms of losses of ecosystem goods and services has not been evaluated in this work.

The block diagram (Fig. 2) shows all of the components of the C-CEMS that are outlined in the following paragraphs.

Fixed stations: The capacity of time series data collection is fundamental to improve the ability to control and forecast spatial and temporal variations in a marine environment. To this end, different fixed stations were installed along the Civitavecchia coast to acquire physical, chemical, and biological data, as shown in Fig.1. In particular, a weather station (WS) acquires every 10 min wind speed, wind direction, air temperature, air pressure, humidity and solar radiation. The wind speed and direction represent the main forcing of the hydrodynamic model while the solar radiation data are used as input in the water quality model. Two buoys (WB1 offshore, WB2 nearshore) measure every 30 min wave statistical parameters (significant height, peak period, and mean direction). The wave model is fed with WB1 data and then validated with the wave height data collected by WB2. An Acoustic Doppler Profiler, ADP (WCS), deployed in a Barnacle seafloor platform, acquires both current (with an acquisition rate of 20 min) and wave height and direction (at intervals of 3 h). The current velocity components are employed for the validation of the hydrodynamic model. Three water quality fixed stations, one buoy (WQB) outside the Civitavecchia harbor and two coastal stations (WQS1 and WQS2), make it possible to acquire every 20 min sub-superficial sea temperature, conductivity (salinity, density), pH, dissolved oxygen, fluorescence of chlorophylla, and turbidity. In order to validate the satellite ocean color data, chlorophyll-a (Chla) and total suspended matter (TSM) data acquired by WQB were calibrated with the concentrations obtained by the water samples analyses. The physical and biological parameters of the WQS1 and WQS2, as well as those acquired by satellite observations, are used as initial conditions of the water quality model.

WQB and WQS data are processed following the SeaDataNet parameter quality control procedures: daily validated datasets are produced in order to monitor in near real time the water quality, and Edios xml files are provided for monthly time series and stored following ISO 19139 and ISO 19115 formats provided for metadata.

In-situ surveys: A spatial extension of the observatory system is provided by in-situ collected data. The sampling strategy is conceived with the scope and context of the project objectives in order to select the most appropriate and efficient sampling approach. The field surveys typically include periodic and ad-hoc activities. The firsts concern the acquisition of the physical, chemical and biological variables of the water column performed by multiparameter probes and sea water samples. Data acquired during periodic surveys are used to validate and integrate the satellite observations in order to give the spatial distributions of the seawater parameters as the initial conditions of the water quality model. The ad-hoc samplings are carried out in order to define the nature and composition of the sea bottom and to analyse the indicators of pollution near the human activities outputs. These data feed the water quality model for the estimate of the bottom shear stress, as well as the dispersion and/or the decay of pollutants in the nearshore coastal waters .

Satellite observations: Remote sensing data are essential to provide synoptic and extensive maps of biological and physical properties of the oceans (Schofield et al., 2002). Few studies, among which Cristina et al. (2015), demonstrated the usefulness of remote sensing to support the MSFD, using MEdium Resolution Imaging Spectrometer (MERIS) sensor products. Similarly we exploited both ocean color from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and thermal infrared color from the Advanced Very High

Resolution Radiometer (AVHRR) to obtain daily Chla, TSM and sea surface temperature (SST) data. Such sensors data were chosen for their availability both in the region of interest and in the period of C-CEMS data acquisition.

Regarding the AVHRR data, they are downloaded from the NOAA website as a Local Area Coverage (LAC) dataset, at a resolution of 1.1 km. These data are processed using ENVI software, which computes SST images in degrees Celsius, using AVHRR bands 3, 4, and 5 and applying the Multi-Channel Sea Surface Temperature (MCSST) algorithms (Pichel et al., 2001).

Regarding the MODIS data, we download from the NASA website and process by the SeaDAS image analysis package that is freely distributed to users by NASA. The processing begins with a Level-1A file containing top of the atmosphere (TOA) radiance values recorded by the satellite radiometer. The second step is the Level-2 processing which takes the TOA radiance intensities in the Level-1A file and performs atmospheric corrections to derive a Level-2 file of normalized water leaving radiances (nLw), Chla concentration, geophysical parameters and quality control flags. A third step takes the geophysical data contained in the Level-2 file and maps it from the raw satellite perspective to a cylindrical coordinate system. To estimate Chla concentration, MedOC3 bio-optical algorithm is applied (Santoleri et al., 2008, Qin et al., 2007), while TSM estimation is derived from the 645 normalized water-leaving radiance (645 nLw) by applying the MUMM NIR atmospheric correction (Ruddick et al., 2006; Ondrusek et al., 2012).

Finally Chla and TSM data collected by WQB and periodic in-situ surveys are used to validate the algorithms used for remote sensing data. We are working on the implementation of a local algorithm specifically developed in the area of interest (CASE II waters) in order to reach a better quantification of Chla and TSM concentrations along the study area (Cui et al., 2014). Accordingly with the Copernicus vision, the future development of this module considers to integrate EO data coming from the Optical High-Resolution Sentinel sensors (Drusch et al., 2012), in order to increase the spatial resolution for a more accurate analysis of coastal dynamic processes.

Numerical models: Mathematical models play a key role in the C-CEMS by making it possible to analyse coastal processes at high spatial and temporal resolution. In this context, the entire datasets collected by fixed stations, satellite observations, and in-situ samplings were employed as input conditions and as a validation of the numerical simulations. The mathematical models used in C-CEMS included the DELFT3D package, specifically DELFT3D-FLOW (Lesser et al., 2004) to calculate marine currents velocity, SWAN (Booij et al., 1999) to simulate the wave propagation toward the coast, and DELFT3D-WAQ (Van Gils et al., 1993; Los et al., 2004) to reproduce the dispersion of conservative and non-conservative substances. The governing equations of these models are described in detail in Lesser et al. (2004) and Bonamano et al. (2015a).

The DELFT3D-FLOW model domain is rectangular and covers 70 km of coastal area with the Civitavecchia port located at the center. We applied Neumann boundary conditions on the cross-shore boundaries in combination with a water-level boundary on the seaward side, which is necessary to ensure that the solution of the mathematical boundary value problem is well-posed. Since small errors may occur near the boundaries, we positioned the study area away from the side of the model domain. The hydrodynamic equations are solved on a finite difference curvilinear grid with approximately 39,000 elements. In order to limit computational requirements, we applied a different resolution in the model domain extending from 15 × 15 m in the Civitavecchia harbor area to 300 × 300 m near the seaward boundary. We subdivided the water column in the vertical direction into 10 sigma layers with a uniform thickness to ensure sufficient resolution in the near-coastal zone.

Since dynamical processes occurring in coastal areas are modulated by wind and wave conditions (we neglect tidal forcing because it does not exceed 0.40 m over the simulation periods), we obtained the hydrodynamic field by coupling the DELFT3D-FLOW with SWAN that uses the same computational grid. Wind data collected by WS were used to feed DELFT3D-FLOW, and the wave parameters acquired by WB1 (offshore wave buoy) were employed to generate the JONSWAP wave spectra (Hasselmann et al., 1980) as boundary conditions of the SWAN model.

To resolve the turbulent scale of motion, the values of horizontal background eddy viscosity and diffusivity were both set equal to 1 m^2s^{-1} (Briere et al., 2011), and the k-ε turbulence closure model was taken into account (Launder and Spalding, 1974). To assign the spatial patterns of physical and biological parameters as initial conditions of DELFT3D-WAQ, the satellite observations in the offshore zone and the WQS measures in the nearshore one were used respectively. These data are integrated in the water quality model applying the DINEOF technique (Beckers et al., 2006; Volpe et al., 2012) that reconstructs the missing data along the coast and in the areas affected by clouds.

Since the pollutants dispersion represents the C-CEMS results, the capability of the observation system in reproducing the output of coastal pressures has been evaluated comparing the model results with sea currents (WQB) and wave (WB2) data.

The performance of the hydrodynamic models (DELFT3D-FLOW and SWAN) was evaluated using the Relative Mean Absolute Error (RMAE) and the associated qualitative ranking (excellent, good, reasonable, and poor) (Van Rijn et al., 2003).

The marine currents resulting from the coupling between DELFT3D-FLOW and SWAN were compared with in-situ measurements collected by WCS from 13–18 January 2015. The velocity magnitude was reproduced with a 'good' accuracy since the RMAE value was less than 0.2. The long-shore and cross-shore components of the marine currents exhibited a higher RMAE: 0.28 and 0.3, respectively. The validation of current speed, cross-shore, and along-shore components is shown in Fig. 3.

We evaluated the performance of the SWAN model using data acquired by the WB2. We calculated the RMAE both for the entire dataset and for three wave direction intervals: 139–198°N (1st interval), 198–257°N (2nd interval), and 257–316°N (3rd interval). Considering the entire dataset, the wave height has been accurately simulated (RMAE<0.1), but the model error changes significantly on the basis of the wave direction: the RMAE is higher between 139°N and 198°N (0.26; reasonable agreement) and lower in the 2nd and 3rd intervals (<0.01; excellent agreement), as reported in Fig. 4.

4 C-CEMS Applications

To test the capabilities of C-CEMS in defining the areas mainly affected by pollutants dispersion, we considered two case studies which concern the potential effects produced by untreated wastewater discharge and dredging activities (coastal pressures) on bathing areas and SCIs (sensitivity areas), respectively. For both cases two scenarios with different weather conditions are considered: one reproduces a low wind intensity and low wave height (low condition, LC), and the other simulates a strong high wind speed and high wave height (high condition, HC).

4.1 Bacterial dispersion in bathing areas

The presence of pathogenic bacteria in seawater may cause several illnesses including skin infections and dangerous gastrointestinal diseases (Cabelli et al., 1982; Cheung et al., 1990; Calderon et al., 1991; McBride et al., 1998; Haile et al., 1999; Colford et al., 2007).

The probability of human infection depends on the exposure time and the concentration of the bacterial load in bathing areas. These parameters are linked to the presence of untreated wastewater discharge in the study area and the local hydrodynamical (currents and waves) and environmental (salinity, temperature, and solar radiation) conditions. Among the bacteria that can damage the health of bathers, *Escherichia coli*, a Gram-negative enteric bacteria present in the feces of humans and warm-blooded animals, is considered to be an indicator of water quality. Although the pathogenic bacteria are neglected by MSFD, microbes are relevant to several GES descriptors, notably Descriptor 1 (D1, Biological Diversity), Descriptor 4 (D4, Foodwebs), Descriptors 5 (D5, Eutrophication), Descriptor 8 (Contaminants) (Caruso, 2014). However, controlling water quality in bathing waters is required by national (d.lgs 116/2008) and community environmental directives (2006/7/CE).

Under the umbrella of C-CEMS to provide fecal pollution monitoring, in-situ water samplings were performed weekly during the summer 2012 at the discharge points indicated in Fig. 1C to analyse the abundance of *E. coli* according to standard culture methods (APAT CNR, 2003).

To define the zones mainly affected by the dispersion of pathogenic bacteria in the Civitavecchia bathing area, we used the Microbiological Potential Risk Area (MPRA), defined as the area over which the *E. coli* concentration is greater or equal to 1% of the concentration measured at a discharge point (Bonamano et al., 2015a). The dispersion of *E. coli* has been simulated by DELFT3D-WAQ using the mean bacterial concentration measured during the summer at the discharge points. The model shows a good performance of reproducing the bacterial load concentration near the discharge points (Zappalà et al., 2015). The LC and HC simulations that last two days were set to occur on August weekends when the beaches are characterized by a larger number of bathers. The distribution of bacterial concentration calculated by DELFT3D-WAQ over the study area depends on the hydrodynamic field obtained from coupling between DELFT3D-FLOW and SWAN and on the decay rate proposed by Thoe et al. (2010). It was calculated using the salinity acquired by

WQS1, WQS2 and WQB, the surface solar radiation measured by WS, TSM and SST obtained by the integration between satellite observations and WQS stations data.

The *E. coli* concentration calculated near the discharge points was high when low marine currents (LC) were present, as reported in Fig. 5A. In particular, the area around the PI18 point exhibited maximum values of pathogenic bacteria because of the slow dilution of contaminated waters in that area. During intense weather conditions (HC), the *E. coli* concentration near the discharge points was lower than that calculated in the LC simulation. However, the *E. coli* concentration was distributed over a more extended area, as reported in Fig. 5B. In both simulations, the dispersion of *E. coli* did not affect the bathing area located to the south of the study area.

4.2 Dredged sediments dispersion on *Posidonia oceanica* meadows

As previously reported, the port of Civitavecchia has been subjected to extensive dredging between 1 November 2012 and 31 January 2013. During the first phase of the project, the dredging of the channel to access the port of Civitavecchia was conducted by deepening the seabed to a depth of -17 m above mean sea level over an area of approximately 31,000 m^2. In the ferry dock area, the seabed reaches a depth of -10 m over an area of approximately 123,650 m^2 and -15 m over an area of approximately 51,900 m^2. The total dredging volume was approximately 918,000 m^3.

Studying sediment resuspension caused by these dredging activities is critical because of its role in the dispersion of particulate matter in the adjacent marine environment in both the sediment and water (Van den Berg et al., 2001). Within MSFD, turbidity due to fine sediment dispersion is an indicator reported in Descriptor 1 (D1, Biological biodiversity), Descriptor 5 (D5, Eutrophication) and Descriptor 7 (Hydrographical condition). In this work, we considered two out of the four SCIs coded as IT60000005 (434.47 ha) and IT60000006 (745.86 ha) localized in the north and the south of the Civitavecchia harbor, as shown in Fig. 1B. Since *Posidonia oceanica* makes up most of the SCIs, we focused on studying the effects of dredging activities on the status of the seagrass. Dredging-induced suspended sediment transport and deposition may have direct and indirect impacts on this seagrass such as reducing the underwater light penetration and producing the burial of the shoot apical meristems, respectively. The survival of the plant can be compromised if the light availability is less than 3–8% of SI (Erftemeijer and Lewis, 2006) or if low-light conditions persist for more than 24 months (Gordon et al., 1994). The survival rates of *Posidonia oceanica* can also be reduced if the sedimentation rate exceeds 5 cm per year (Manzanera et al., 1995).

The health status of *Posidonia oceanica* meadows located in the two SCIs has been evaluated by shoot density descriptor. This parameter was acquired by scuba-divers in the late Spring of 2013 in correspondence of 14 stations (3 in IT6000005 and 11 in IT6000006) following the method reported in Buia et al. (2003). The thematic map is obtained spatially interpolating the data collected in the two areas.

The potential impacts due to dredging activities have been evaluated by DELFT3D-WAQ simulations assuming a continuous release of fine sediments (< 0.063 mm) in the northern zone of Civitavecchia harbor. The amount of material released during dredging was calculated using a formula from Hayes and Wu (2001) using a resuspension factor of 0.77%, which is typical of hydraulic dredges (Anchor Environmental, 2003). The percentage of fine sediment fraction is 8.87% and its density is 2650 kg m^{-3} according to sedimentological data collected in the area affected by the dredging works. Considering also that the time spent on dredging operations was approximately 3 months (from November 2012 until January 2013), we assumed a continuous release of 0.314 kg s^{-1}. TSM distribution, obtained by the integration between satellite observations and WQB data, was used as a proxy of spatial variation of fine sediment concentration in the study area to provide the initial conditions of DELFT3D-WAQ. The transport, deposition, and resuspension processes associated with the fine particles was reproduced taking into account a settling velocity of approximately 0.25 m day^{-1}, a critical shear for sedimentation of 0.005 N m^{-2}, and a critical shear for resuspension of 0.6 N m^{-2} (Alonso, 2010). The DELFT3D-WAQ simulations were run over the periods 26 November 2012 through 3 December 2012 (HC simulation) and 3–10 January 2013 (LC simulation). These time intervals included the dredging period.

Analogous to the analysis of bacterial dispersion, the fate of dredged sediments within the study area was evaluated over an area in which the suspended solid concentration was greater or equal to 1% of the value estimated at the source point. This area is referred to as the Dredging Potential Impact Area (DPIA). The results of the LC simulation, reported in Fig. 6A, revealed that the dredged suspended materials were transported into the southern zone of the study area achieving a maximum distance of approximately 2 km from dredging point. In the HC simulation reported in Fig. 6B, the dredged sediment dispersion moved toward the north with higher concentration in the nearshore zone. Although the sediment plume extends 20 km from the source, higher values of suspended solid concentration only affects the *Posidonia oceanica* meadow closer to the harbor (the southern part of SCI IT 6000005) (Bonamano et al., 2015b).

5 Discussions

C-CEMS was implemented in 2005 along the coast of Civitavecchia, which is a highly populated area characterized by the coexistence of industrial and human pressures with environmental resources and values. It integrates fixed stations, in-situ survey and satellite observations which ensure the availability of a large amount of data allowing the analysis of coastal conflicts by the detection of pollution phenomena. Moreover C-CEMS provides an ecosystem-based monitoring tool for the analysis and forecasting of the coastal conflicts thanks to the use of mathematical models. The validation of hydrodynamic models with sea currents (WCS) and wave (WB2) data, shows how C-CEMS is able to reproduce accurately the output of coastal pressures in terms of pollutants dispersion. DELFT3D-FLOW reproduces with good accuracy the velocity components of marine currents, while SWAN calculates the wave height in the nearshore area with an higher skill when the interval direction is 198-316 °N. On the contrary, when the wave direction ranges between 139 °N and 198 °N, the capacity of the model is more affected by the increase of diffraction processes due to the Civitavecchia harbor breakwater.

The application of C-CEMS to the two case studies examples allowed to define the MPRAs in bathing zones and the DPIAs on SCIs under different weather conditions (HC and LC). The overlap of the model results with the thematic maps of the sensitivity areas enabled the detection of the coastal areas interested by conflicts.

In the first case, the overlap of MPRAs calculated in LC and HC scenarios shows that most of the bathing areas are affected by high level of bacterial contamination (Fig. 7A). Maximum values of *E.coli* abundance were found near the PI18 and PP24 discharges because the dilution of the contaminated waters was inhibited by the presence of artificial barriers. These unfavorable conditions may cause possible risks to human health related to the contamination of potentially infectious microorganisms for bathers. As a result, the bathing facilities located within this zone are at risk of suffering significant economic losses. However the southern bathing area, where more bathers are found, is never affected by *E. coli* dispersion (Fig. 7A).

In the second case study, the simulation results differ among LC and HC scenarios (Fig. 7B). In the LC scenario, DPIA does not overlap the southern SCI (IT 6000006), even though the seagrass meadows are characterized by poorer health than in northern SCI. In HC, DPIA includes a restricted zone of *Posidonia oceanica* meadow (98.84 ha) in the northern SCI, closer to Civitavecchia harbor, characterized by high shoot density values (between 400 and 550 shoots m^{-2}). A previous study (Bonamano et al. 2015b) shows that after the dredging activities the shoot density values were slightly higher than before, highlighting how this conflicts does not produce a loss of environmental resources.

6 Conclusions

The main objective of C-CEMS is to provide an observation system for a rapid environmental assessment and to forecast the coastal dynamic processes at appropriate temporal and spatial resolutions. It can also contribute to the availability of marine observations and coastal data, increasing the knowledge about the environmental status of marine ecosystems. To make C-CEMS more effective, a flexible X-Band Radar System to continuously measure the sea-state (surface currents and wave field) in the near-shore zone (Serafino et al., 2012) has been recently integrated. Moreover, to improve the resolution of multi-spectral imagery in the study area, C-CEMS will be soon available to get data also from Sentinel-2 mission.

The final goal of this study was to use C-CEMS to address potential conflicts among the different human activities that persist on the coast using an ecosystem-based approach as requested by IMP for the EU.

C-CEMS allowed to define the output of human activities by the use of 'potentially-polluting zoning indicators' as MPRA and DPIA giving the potential impacts produced by pathogenic bacteria and dredged fine sediment on sensitivity areas. Such information overlapped with the characteristics of recreational coastal uses and marine ecosystems can be considered as the first step for the establishment of marine functional zoning scheme made by different types of zones with varying levels of limited uses (Douvere, 2008). The last step toward an adequate management and conservation of marine environment resources concerns the quantification of economic impacts related to the losses of ecosystem services and goods through the analysis of the present and future conflicts.

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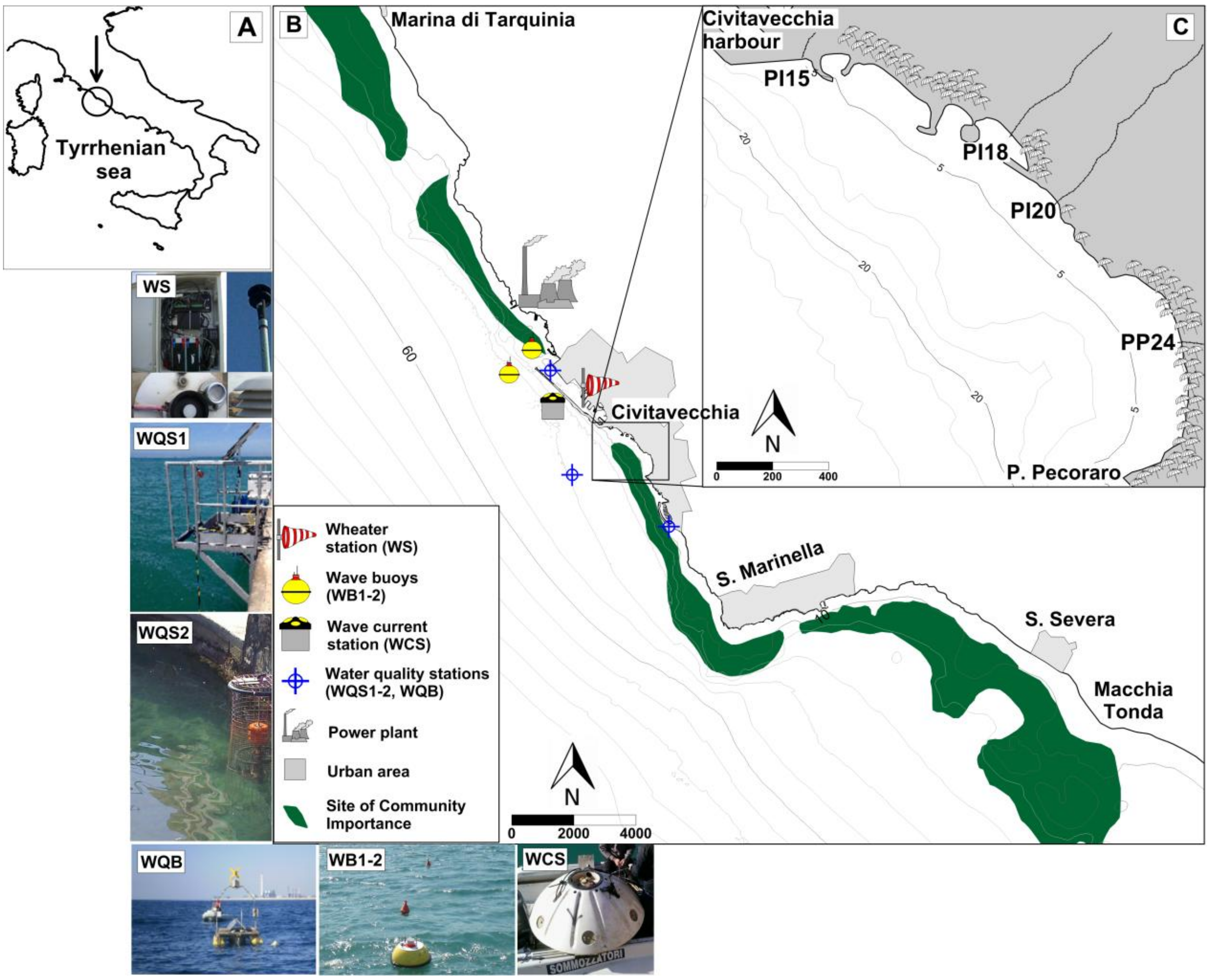

Figure 1. Location of the study area along the north-east Tyrrhenian coast of Italy (Western Mediterranean sea) (A). Zoom-in on the area of C-CEMS applications: the location of coastal uses, SCIs, and measurement stations indicated (B) and the Civitavecchia bathing areas with discharge points and bather density indicated (1 umbrella corresponds to 5 bathers) (C). The fixed station pictures are reported in the bottom-left corner of the figure.

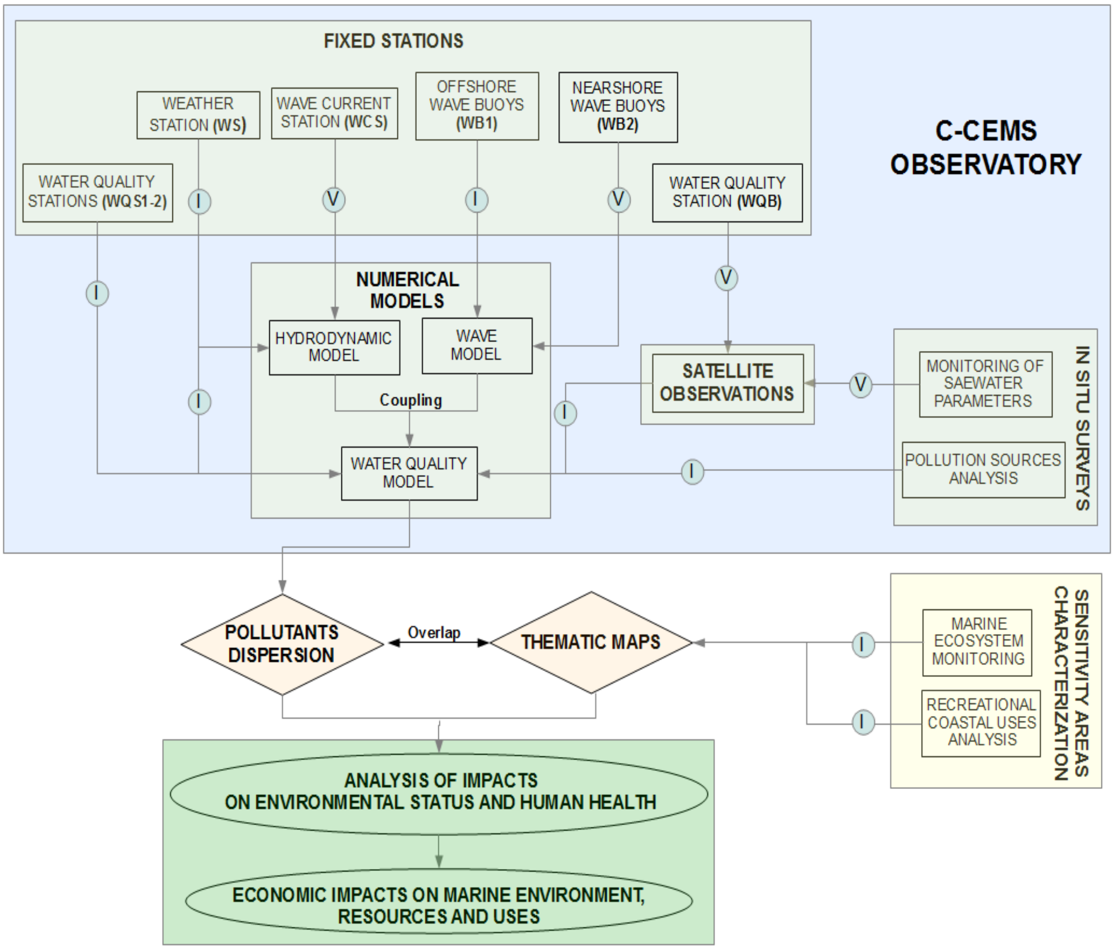

Figure 2. The functioning of C-CEMS for the analysis of the conflicts between coastal pressures and sensitivity areas. The C-CEMS components interact between them to transfer data (by input (I) and validation (V)) from the in-situ and satellite observations to numerical models in order to reach a temporal and spatial resolution enough to analyse the pollutants dispersion in coastal waters. The conflicts are evaluated overlapping the model results with the thematic maps of the sensitivity areas. The economic impact of the conflicts on the marine environment and human health is reported, even though it is not analysed in this work .

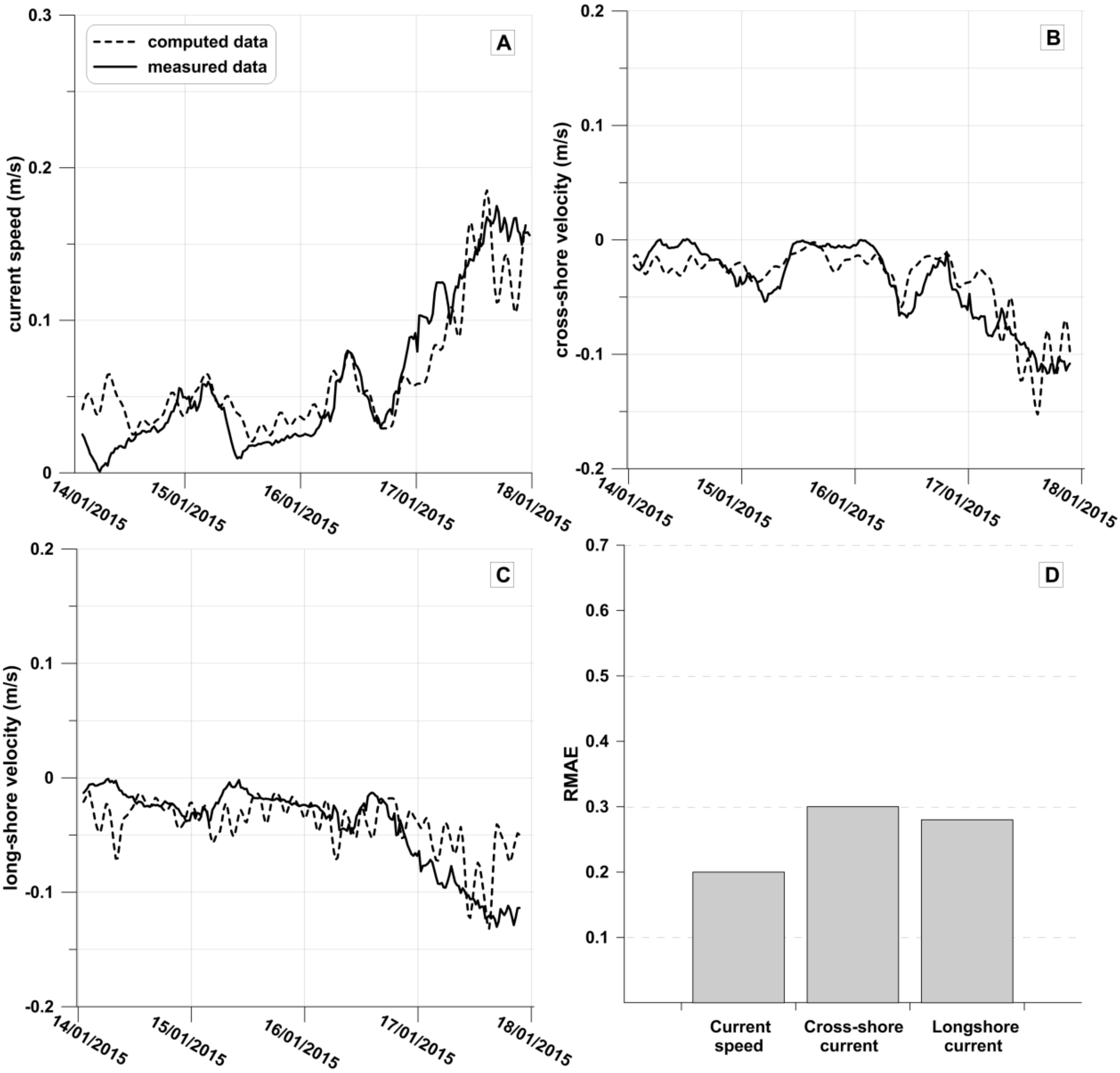

Figure 3. Validation of current speed (A), cross-shore (B), and along-shore (C) components. The solid and dotted lines represent the measured and computed time series, respectively. Statistics (RMAE) for current speed, cross-shore, and along-shore components are reported in panel D.

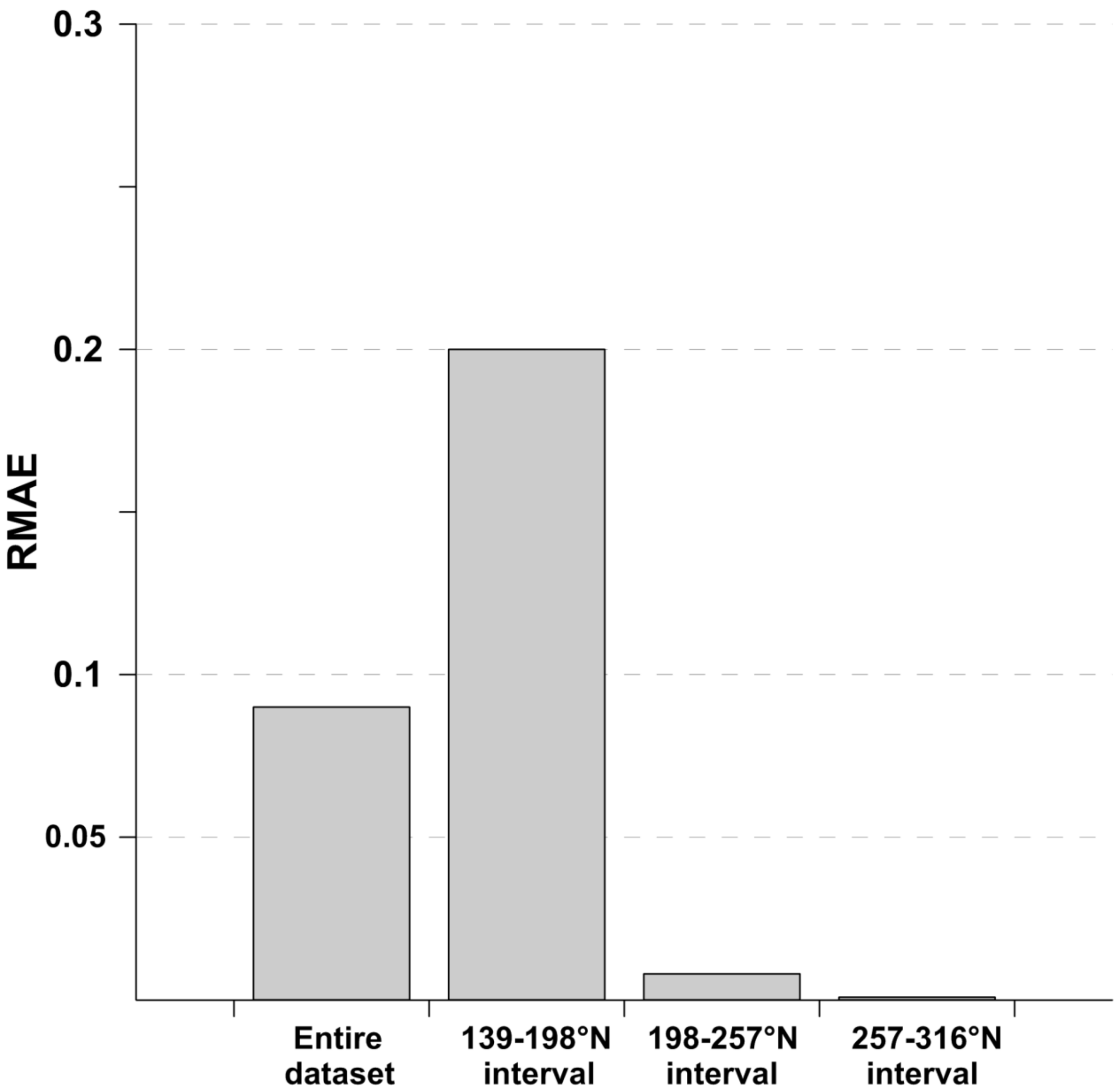

Figure 4. Validation of the SWAN model using RMAE values calculated both for the entire dataset and for three wave direction intervals.

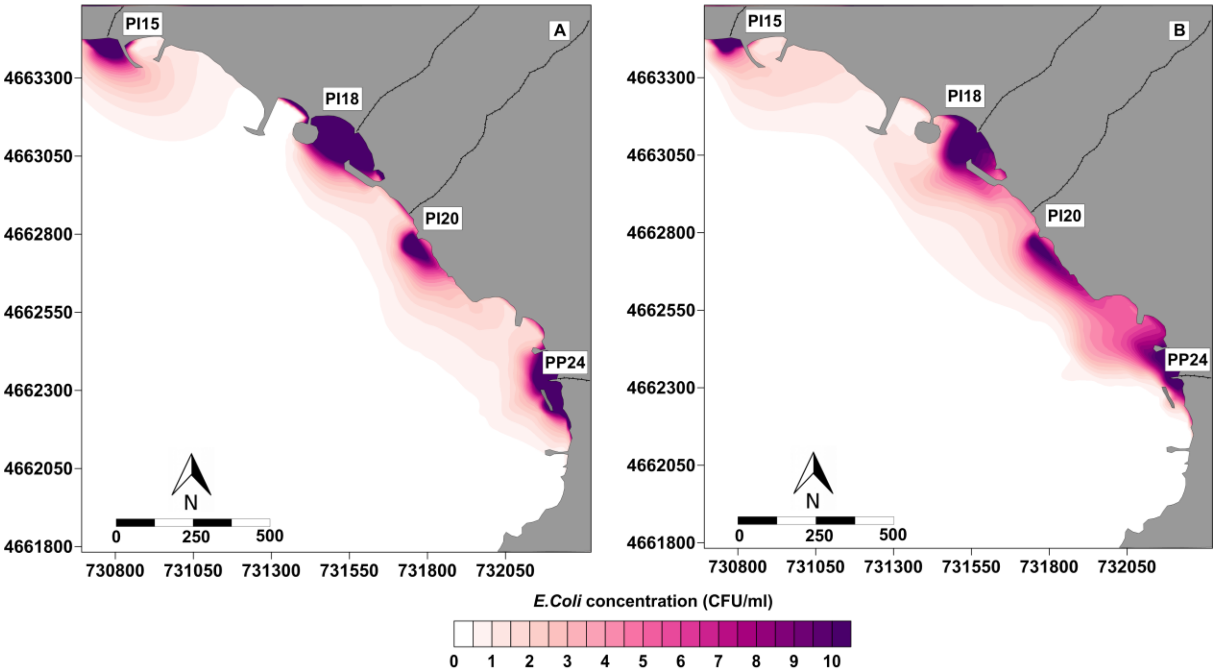

Figure 5. LC (A) and HC (B) simulations results of the bacterial dispersion in the Civitavecchia bathing areas. The distribution of *E. coli* concentration refers to the end of the simulation period.

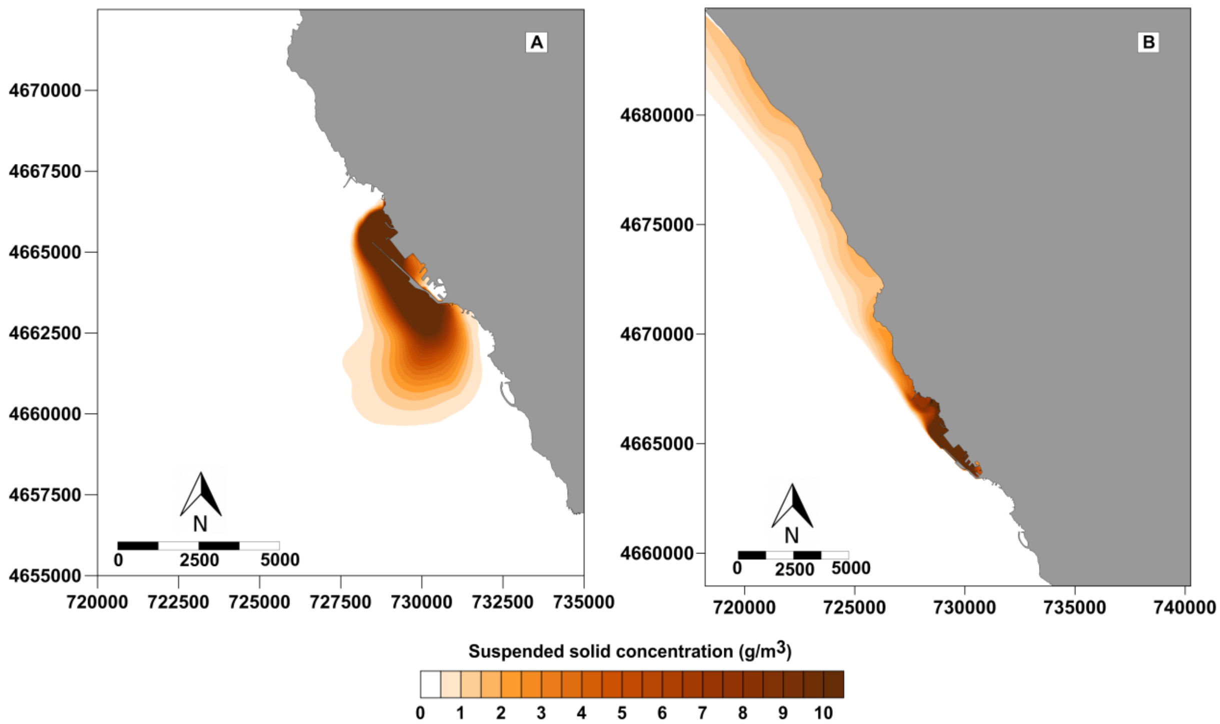

Figure 6. LC (A) and HC (B) simulations results of the dispersion of dredged materials in the study area. The distribution of fine sediment concentration refers to the end of the simulation period.

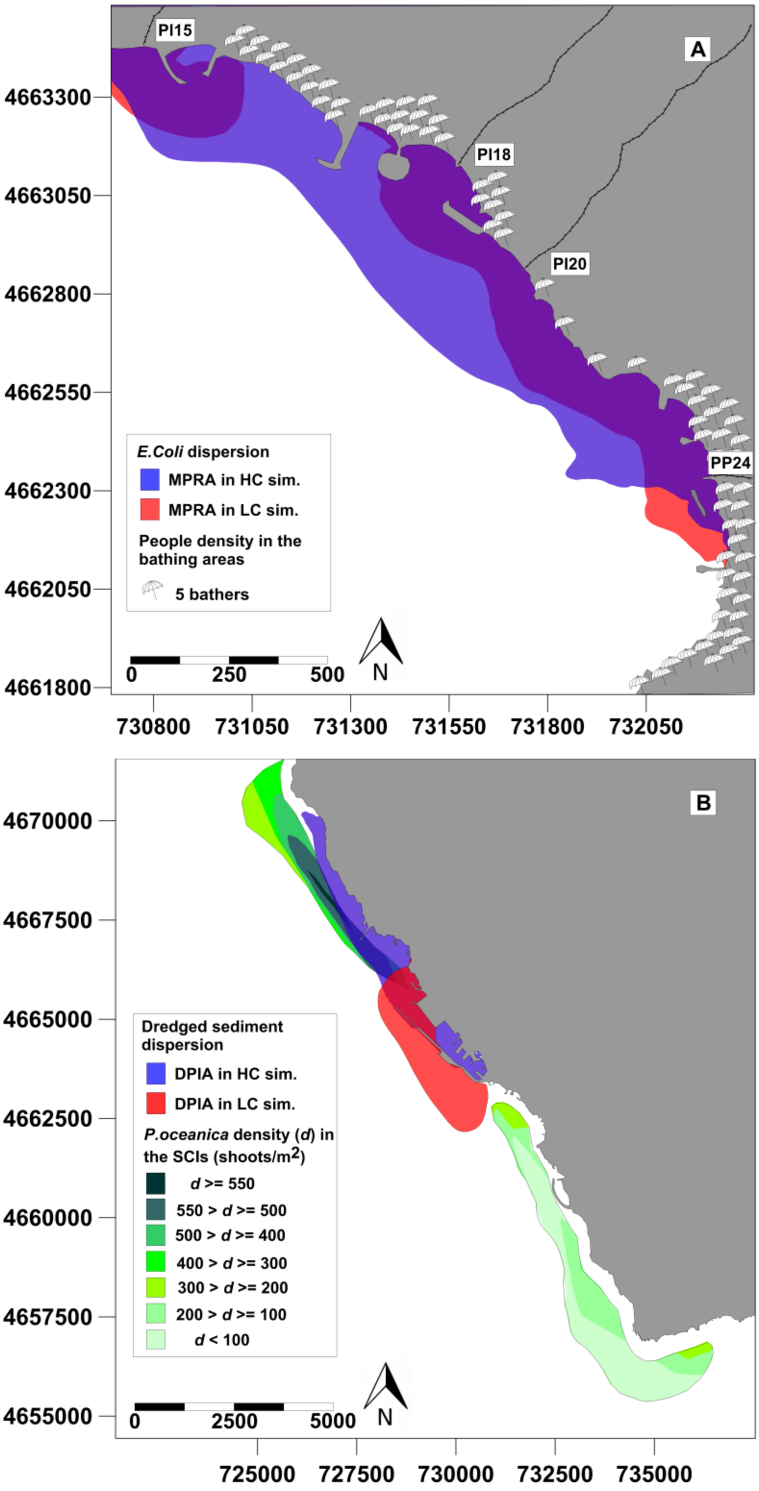

Figure 7. Overlap between anthropic pressures indicated by the 'potentially-polluting zoning indicators' (MPRA and DPIA) and sensitivity areas represented as thematic maps to analyse 'urban discharge bathing area' (A) and 'dredging SCI' (B) conflicts.