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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 Directive, which is focused on the achievement of Good Environmental Status (GES) by all Member States by 2020. 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 modules that provide integrated information to be used in different fields of the environmental research. The long term observations acquired by the fixed stations are integrated by in situ surveys, periodically carried out for the monitoring of the physical, chemical and biological characteristics of the water column and marine sediments, as well as of the benthic biota. 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 analyses and forecasting of the dynamics of conservative and non-conservative particles under different conditions. As examples of C-CEMS applications, two case studies are reported in this work: (1) the analysis of faecal 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 *Posidonia oceanica* distribution and bathing areas presence in order to resolve the conflicts between coastal uses (in terms of stress produced by anthropic activities) and sensitivity areas management.

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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 (Douvere, 2008) has the ability to create user-user and user-environment conflicts 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. Within European environmental policy, the Water Frame Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) were recently approved to protect estuarine and coastal seas from increasing pressures and impacts and to move toward marine integrative management. Contrary to the WFD, which follows a "deconstructing structural approach" to achieve a Good Ecological Status for all European water bodies by 2015, the MSFD requires the achievement of a Good Environmental Status GES for all European seas by 2020 through a "holistic functional approach". A GES is based on the analysis of 11 descriptors that collectively represent the state and functioning of the whole system (Borja et al., 2008, 2010). In keeping with the holistic nature of the MSFD, the achievement and the maintenance of European marine ecological standards requires detailed knowledge of the pressures exerted on marine environments, monitoring of physical, chemical, and biological components, and analysis of the services provided by ecosystems and the sustainable use of marine resources. A recent study by Crise et al. (2015) revealed a lack of data in the South European Seas (SES), highlighting the existence of a clear North–South "data and knowledge gradient" due to the chronic scarcity of marine data. 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. The correct management of coastal resources and environments requires climatologies deriving from physical and biological time series data as well as the capacity to forecast specific events (Schofield et al., 2002).

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Many efforts have been dedicated to the development of coastal ocean observatories, and 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 paper, we provide a thorough description of the Civitavecchia Coastal Environment Monitoring System C-CEMS observational network and its utilization for environmental research. Moreover, we present the main results of C-CEMS applications focusing on the analysis of fecal bacteria dispersion for bathing water quality assessment, and the evaluation of the effects of the dredged activities on *Posidonia oceanica* meadows in the Civitavecchia coastal area in the Italian western Mediterranean Sea. We used the integrated responses provided by C-CEMS to create an observatory and forecast system that can provide rapid and comprehensive information for the management of coastal conflicts and the potential effects of pollution.

2 Study area

The study area extends from Marina di Tarquinia to Macchia Tonda in the northern Latium region of Italy, as shown in Fig. 1a, and includes Civitavecchia city, which is a populated area characterized by the coexistence of industrial and human pressures with environmental resources and values. The Civitavecchia harbor is one of the largest harbors 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

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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, 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 Sites of Community Importance (SCI) included in the seventh updated list of the Natura 2000 database based on the Italian Environmental Minister decree as an enactment of European Commission decision 2013/739/EU. SCIs 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, which can be affected by direct and indirect impacts of port activities.

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 caused untreated water to be frequently discharged into bathing areas. This situation is in direct conflict with the recreational use of the coastal zone. Along the coast, between Civitavecchia harbor and the Punta del Pecoraro bathing areas, four discharge points have been identified as shown in Fig. 1b. These discharge points present high concentrations of pathogenic bacteria that have been potentially affected by fecal contamination episodes.

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3 Components of the C-CEMS

C-CEMS is a multi-platform observing system implemented along the coastal area of Civitavecchia (Latium, Italy). It is analogous to a coupled system in which all of the data are assimilated by mathematical models to forecast specific events or impacts and to improve and optimize survey strategies. The C-CEMS includes different modules (fixed stations, in-situ measurements and samplings, satellite observations, and numerical models) that provide integrated information that can be used in different fields of environmental research (Bonamano et al., 2015b).

As shown in Fig. 2, C-CEMS outcomes can be used to assess the conflicts between the pressures on both marine coastal resources and the environment and human health. Since marine coastal ecosystems have been acknowledged as providing the most benefits among all terrestrial and marine ecosystems (Costanza, 1997), assigning an economic value to these natural resources is essential for correct planning of marine coastal areas.

The block diagram, shown in 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) makes it possible to acquire wind speed, wind direction, air temperature, air pressure, humidity and solar radiation; two buoys (WB1 offshore, WB2 nearshore) make it possible to collect wave statistical parameters (significant height, peak period, and mean direction); an ADP (WCS), deployed in a Barnacle seafloor platform, acquires both current velocity and direction and wave height and direction; three water quality fixed stations, one buoy (WQB) outside the Civitavecchia harbor and two coastal stations (WQS), make it possible to continuously acquire sub-superficial sea temperature, conductivity (salinity, density), pH, dissolved oxygen, fluorescence of

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chlorophyll *a*, and turbidity. The details of the C-CEMS sensors and platforms are listed in Table 1.

All of the data deriving from the fixed stations are transmitted to a website to enable a first look at data trends. Furthermore, this arrangement makes it possible to quickly respond in case of a malfunction. The data are then processed and organized as follows.

Data processing and standardization: scientific research, particularly interdisciplinary research involving human impacts on the natural environment, depends on access to data provided by observatory networks. As highlighted in the EU INSPIRE directive (2007), the importance of the realization of network infrastructures for data sharing derives from the ability to provide useful information. Given the recent growth in large-scale collaborative oceanographic research programs, data quality control is essential. If quality control is not ensured, data from different sources cannot be combined or re-used. For this reason, the SeaDataNet (SDN) Infrastructure was developed in the EU FP6 framework program in order to realize an efficient, distributed Pan-European marine data management infrastructure for managing large and diverse datasets (Schaap, 2010). Thanks to this initiative, datasets are converted into data and metadata standard format by SDN software and tools. The University of Tuscia (LOSEM) is part of the SDN (under the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, OGS, collating center). Part of the data collected in the C-CEMS are already processed following the SDN parameter quality control procedures: daily validated datasets are produced in order to monitor in near real time the status of water quality, and Edios xml files are provided for monthly time series and stored following ISO 19 139 and ISO 19 115 formats provided for metadata.

The next step is to apply the processing procedure to all of the data produced by the observing system.

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 ap-

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proach. The field surveys typically include data acquired by multiparameter probes, acoustic instruments, water, sediments, and biological samples.

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). In this work, 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 chlorophyll *a*, total suspended matter (TSM), and sea surface temperature data. The MODIS data were downloaded from the NASA website at level L1-A (which contains raw radiance counts, spacecraft and instrument telemetry, and calibration data) and processed by the SeaDAS image analysis package that is freely distributed to users by NASA. The AVHRR data were downloaded from the NOAA website as a Local Area Coverage (LAC) dataset, at a resolution of 1.1 km. These data were then processed using ENVI software. The results of the chlorophyll *a* and suspended matter concentration analyses of in-situ water samples were used to compare and validate the remote sensing data. Our aim was to create a local algorithm for quantifying TSM and chlorophyll *a* concentrations in CASE II waters in detail to yield a better understanding of seasonal variations along these areas. These data are essential for providing synoptic maps of the spatial distribution of sea surface temperature, suspended materials, and phytoplankton in coastal waters.

Numerical models: mathematical models play a key role in the C-CEMS by making it possible to analyze 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 that we 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

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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. We solved the 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 m × 15 m in the Civitavecchia harbor area to 300 m × 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 $m^2 s^{-1}$ (Briere et al., 2011), and the k-ε turbulence closure model was taken into account (Launder and Spalding, 1974).

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 Jan-

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uary 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 error: 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 and 198° N (0.26; reasonable agreement) and lower between 2 and 3° N (< 0.01; excellent agreement), as reported in Fig. 4.

4 C-CEMS applications

In this study, C-CEMS has been used to support the assessment of the potential effects produced by untreated waste-water discharge and dredging activities (coastal pressures) on bathing areas and SCIs (sensitivity areas), respectively. To analyze the dispersion of polluted substances in the coastal marine environment, we considered in both cases two periods with different weather conditions are considered: one reproduces a low wind intensity and low wave height (low condition, LC), and the other simulates the 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).

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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 continuous discharge of untreated wastewater 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. 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 2013 at the discharge points indicated in Fig. 1b to analyze the abundance of *E. coli* according to standard culture methods (APAT CNR, 2003).

To provide a map of the potential effects for bathers, we analyzed the dispersion of pathogenic bacteria in the Civitavecchia bathing area using 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). Since this parameter does not depend on the input load concentration, it can be used for evaluating potential effects on human health. 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 does a good performance of reproducing the bacterial load concentration near the discharge points (Zappalà et al., 2015). The HC and LC 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 hydrodynamical field obtained from coupling between DELFT3D-FLOW and SWAN and on the decay rate estimated with WQS1, WQS2, and WQB temperature and salinity and the WS solar radiation data.

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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 is 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). 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. 1a. 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

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rates of *Posidonia oceanica* can also be reduced if the sedimentation rate exceeds $5\,\text{cm}\,\text{year}^{-1}$ (Manzanera et al., 1995).

For these reasons, the health status of *Posidonia oceanica* meadows located in the two SCIs closest to the harbor (IT 6000005 and IT 6000006) has been monitored by in-situ samplings. The sampling activity and the results of the analyses allowed us to create a thematic map of the shoot density of the marine phanerogam, which is essential for estimating the direct and indirect impacts of sediment dispersion.

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 $2650\,\text{kg}\,\text{m}^{-3}$ 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 $0.314\,\text{kg}\,\text{s}^{-1}$. The transport, deposition, and resuspension processes associated with the fine particles was reproduced taking into account a settling velocity of approximately $0.25\,\text{m}\,\text{day}^{-1}$, a critical shear for sedimentation of $0.005\,\text{N}\,\text{m}^{-2}$, and a critical shear for resuspension of $0.6\,\text{N}\,\text{m}^{-2}$ (Alonso, 2010). The DELFT3D-WAQ simulations were run over the periods 26 November through 03 December 2012 (HC simulation) and 03–10 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). In the HC simulation reported in Fig. 6b, the dredged sediment dispersion is toward the north with higher concentration in the nearshore zone. Although the sediment plume extends 20 km from

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the source, the DPIA only affects the *Posidonia oceanica* meadow closer to the harbor (the southern part of SCI IT 6000005) (Bonamano et al., 2015b). 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 relatively close to the source (a maximum distance of approximately 2 km).

5 Conclusions

C-CEMS was implemented along the coast of Civitavecchia (Latium, Italy), which is a highly populated area characterized by the coexistence of industrial and human pressures with environmental resources and values.

We present the application of C-CEMS to two different case examples, which allow us to analyze the potential impacts on both the marine environment and human health.

In the first case, areas with high bacterial concentrations were found near the PI18 and PP24 discharges because the dilution of the contaminated waters was inhibited by artificial barriers. These unfavorable conditions may cause possible risks to human health and are related to the contamination of potentially infectious microorganisms in the nearshore waters. As a result, the bathing facilities located within this zone are at risk of suffering significant economic losses. On the contrary, as highlighted by the MPRA shown in Fig. 7a, the southern bathing area, where more bathers are found, is never affected by *E. coli* dispersion.

In the second case study, it was possible to observe the potential impacts on *Posidonia oceanica* meadows due to dredging activities, as reported in Fig. 7b. In the HC simulation, despite the suspended sediments being transported up to 20 km away from the source point, the area with a higher dredged material concentration (DPIA) includes a restricted zone of *Posidonia oceanica* meadow (8.84 ha) closer to Civitavecchia harbor characterized by high shoot density values (between 400 and 550 shoots m^{-2}). The fine sediment dispersion reproduced in the LC simulation does not reach the southern

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SCI (IT 6000006) where the seagrass meadows are characterized by poorer health than northern SCIs.

The results of the two application cases show that C-CEMS is suitable for analyzing "urban discharge bathing area" and "dredging SCI" conflicts, as well as many other conflicts. C-CEMS is therefore a new useful tool for coastal zone management. The results of the C-CEMS observational network are a first step toward environmental and economical sustainable management of conflicts along the Civitavecchia coastal area.

The final goal of this system was to use this tool to address potential conflicts among the different human activities that persist on the coast using an ecosystem-based approach. In fact, the demand for resources, services, and space can exceed the capacity of marine areas to meet all of the demands simultaneously (Ehler, 2009).

C-CEMS can contribute to the achieving GES as requested in the context of the MSFD. C-CEMS can also contribute to the availability of marine observations and coastal data, which increases our knowledge of spatial and temporal variations in environmental status. In this way, public administrators and decision makers can acquire a clear view of the ecological and economic potential of a study area to ensure that the spatial planning process, as established by the Marine Spatial Planning Directive (2014/89/EU), can take into account easily accessible information about the importance of ecosystem benefits.

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Table 1. Specifications of C-CEMS sensors and platforms.

(WS) Weather Station Specifications			
	Range	Accuracy	Resolution
Wind Speed	0–60 m s^{-1}	±2 %	0.01 m s^{-1}
Wind Direction	0–360°	±3	1°
Air Temperature	−40–+60 °C	±0.3 K	
Relative Humidity	0–100 %	1.50 %	0.50 %
Air Pressure	600–1060 mbar	±0.5 mbar	±0.05 mbar
Total solar radiation	400–1100 nm	±3 %	±0.05
Precipitation		0.1 mm	±1 % till 10 mm h^{-1}
(WCS) Wave-Current Station Specifications			
	Range	Accuracy	Resolution
Current Velocity	±10 m s^{-1}	±1 % meas. Vel.	0.1 cm s^{-1}
Compass/tilt sensor		±1° (Heading)	0.1°
		±1° (Pitch, Roll)	
Wave Height (strain gage pressure sensor)		0.10 %	
Wave Direction	0.360°		±1°
(WB1-2) Wave Buoys Specifications			
	Range	Accuracy	Resolution
Wave Height	±20 m	better then 1 %	0.01 m
Period	1.5.33 s	better then 1 %	0.1 s
(WQB) Buoy Specifications			
	Range	Accuracy	Resolution
Pressure	0.100 dbar	0.10 %	0.03 %
Temperature	−3.+50 °C	0.003 °C	0.0005 °C
Conductivity	0–6.4 S m^{-1}	0.0003 S m^{-1}	0.0001 S m^{-1}
pH	0–14	0.01	0.001
Dissolved oxygen	0–50 ppm	0.1 ppm	0.1 ppm
Chlorophyll *a* Fluorescence	0–5 µg L^{-1}	0.025 µg L^{-1}	
Turbidity	0–100 NTU	0.05 NTU	
(WQS1-2) Coastal Stations Specifications			
	Range	Accuracy	Resolution
Pressure	0.100 dbar	0.10 %	0.03 %
Temperature	−3.+50 °C	0.003 °C	0.0005 °C
Conductivity	0–6.4 S m^{-1}	0.0003 S m^{-1}	0.0001 S m^{-1}
pH	0–14	0.01	0.001
Dissolved oxygen	0–50 ppm	0.1 ppm	0.1 ppm
Chlorophyll *a* Fluorescence	0–5 µg L^{-1}	0.025 µg L^{-1}	
Turbidity	0–100 NTU	0.05 NTU	

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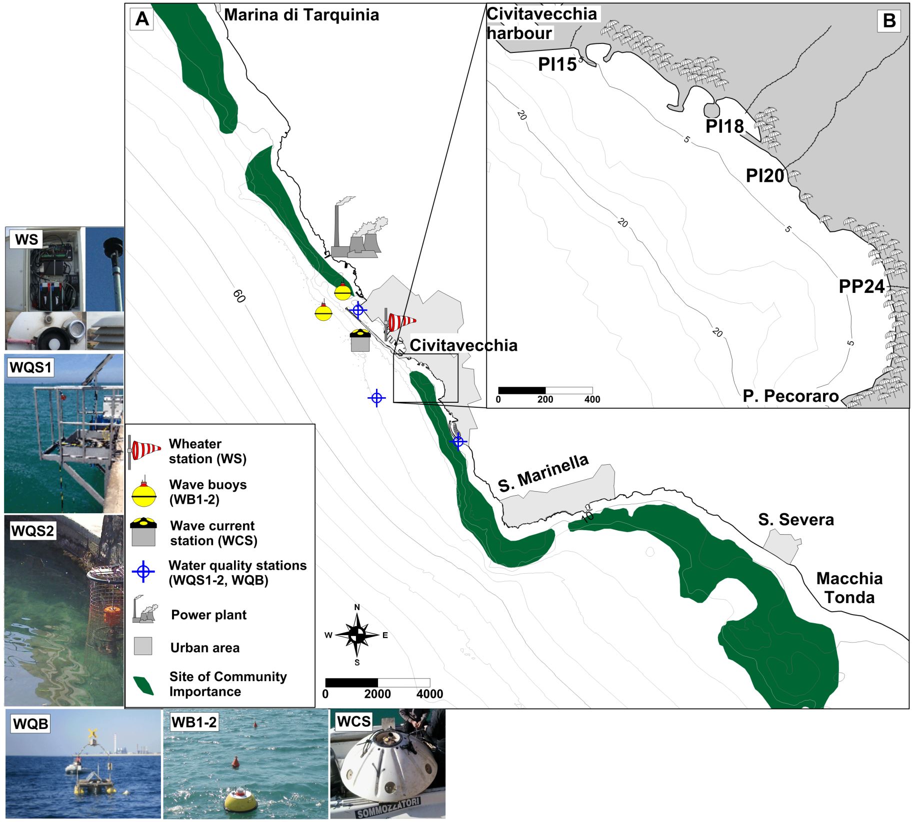

Figure 1. Study area with the location of coastal uses, SCIs, and measurement stations indicated **(a)** and zoom-in on the Civitavecchia bathing areas with discharge points and bather density indicated (1 umbrella corresponds to 5 bathers) **(b)**. The fixed station pictures are reported in the bottom-left corner of the figure.

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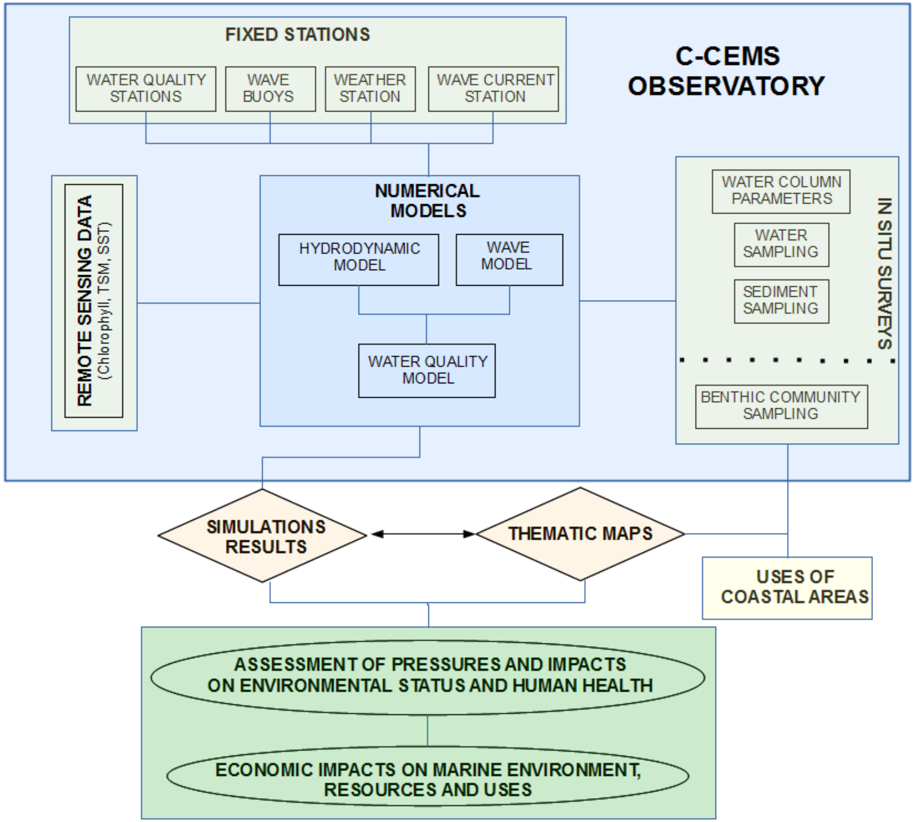

Figure 2. Block diagram of C-CEMS.

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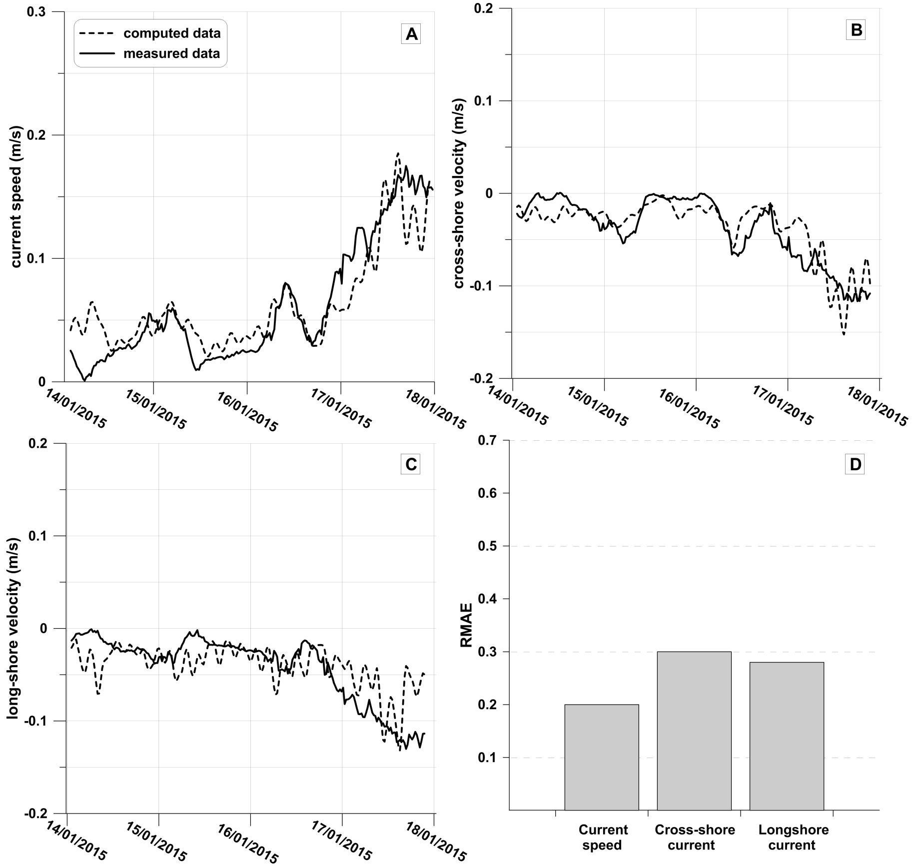

Figure 3. Validation of current speed **(a)**, cross-shore **(b)**, and along-shore **(c)** components. The solid and dotted lines represent the measured and computed time series, respectively. Statistics (RMAE) for current speed, cross-shore, and along-shore components are reported in **(d)**.

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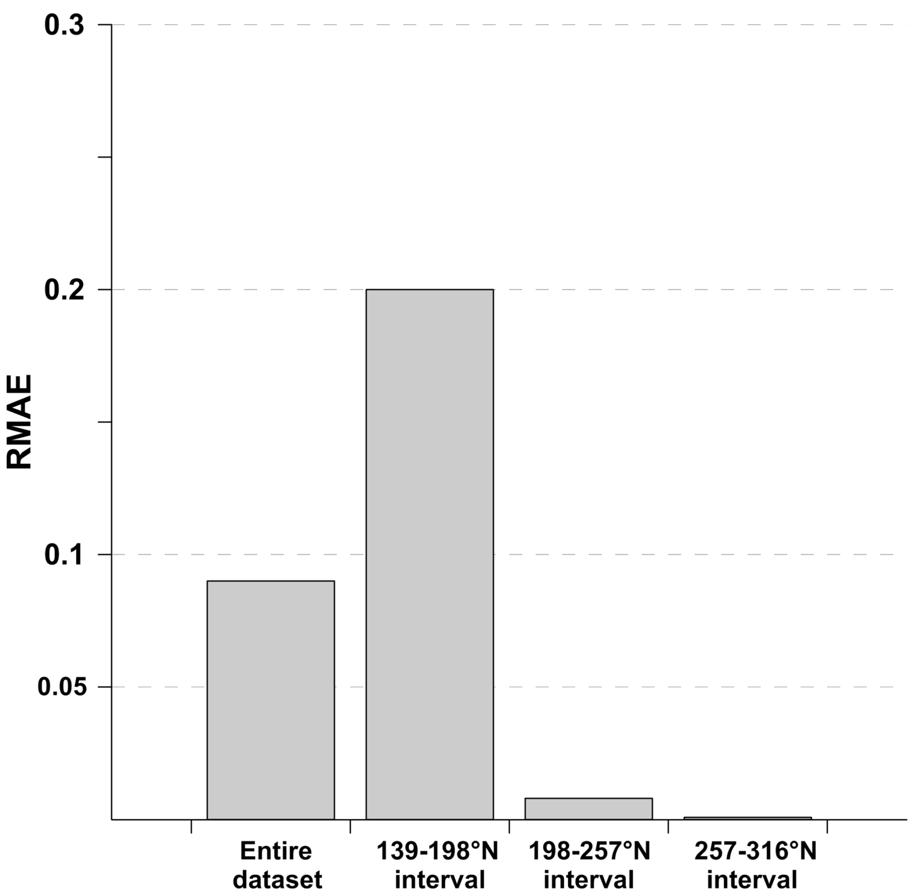

Figure 4. Validation of the SWAN model using RMAE values calculated both for the entire dataset and for three wave direction intervals.

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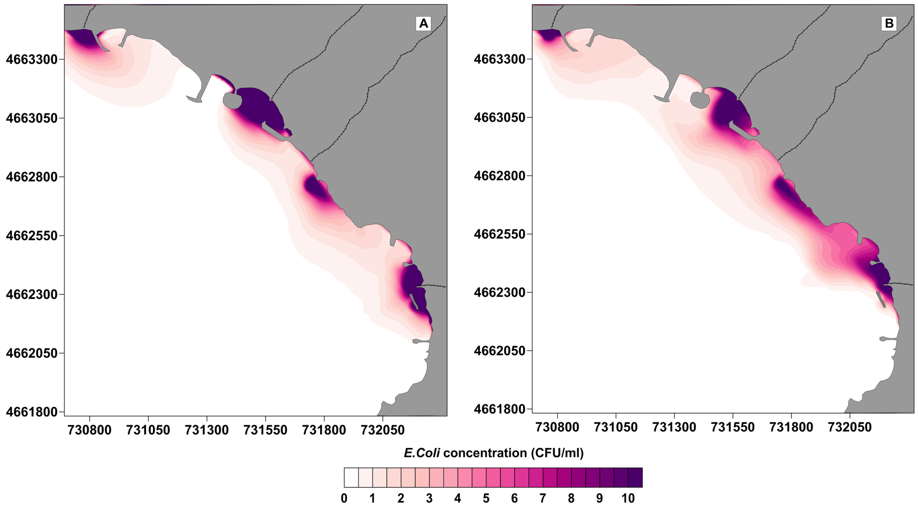

Figure 5. LC **(a)** and HC **(b)** simulations results of the bacterial dispersion in the Civitavecchia bathing areas. The distribution of *E. coli* concentration refers to the end of the simulation period.

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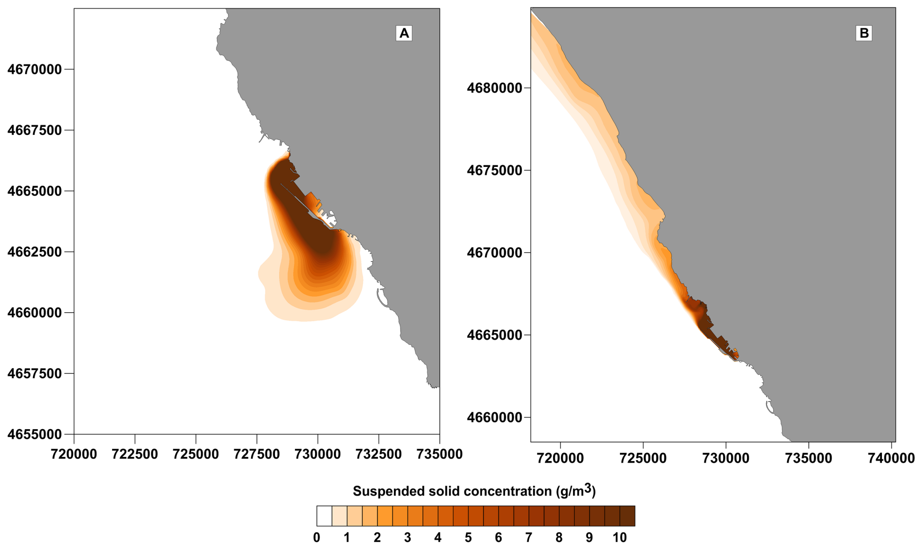

Figure 6. LC **(a)** and HC **(b)** simulations results of the dispersion of dredged materials in the study area. The distribution of fine sediment concentration refers to the end of the simulation period.

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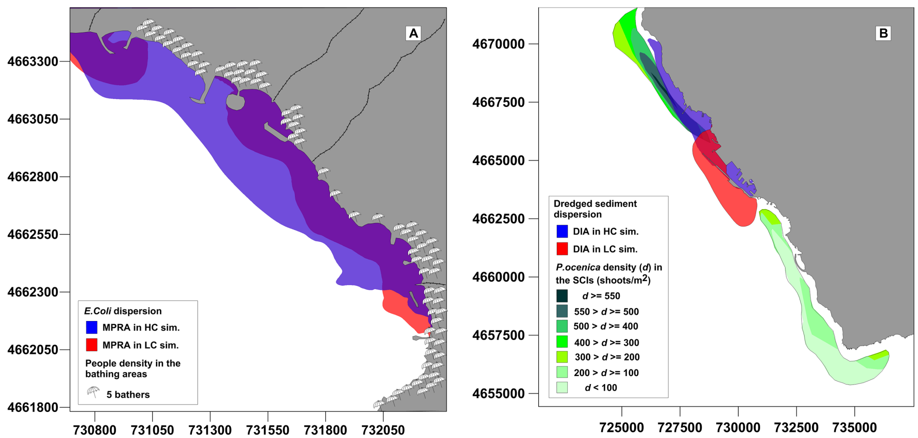

Figure 7. Overlap between anthropic pressures indicated by the simulation results and sensitivity areas represented as thematic maps to analyze "urban discharge bathing area" **(a)** and "dredging SCI" **(b)** conflicts.

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