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Indexes for the assessment of bacterial pollution in bathing waters from point sources: The northern Adriatic Sea CADEAU service

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ABSTRACT

This paper presents a novel set of water quality indexes to identify the area potentially affected by point sources of bacterial pollution in coastal bathing waters. The indexes, developed in the framework of the CADEAU service, are evaluated on the results of a modelling system based on the integration of a high-resolution ocean model, remote sensing observations and in situ monitoring data for the northern Adriatic Sea. In particular, the system is a downscaling of the Mediterranean Copernicus Marine Environment Monitoring Service and exploits data produced within the Bathing Waters Directive, the Water Framework Directive and the Urban Waste Water Treatment Directive to create added value products. The aim of the proposed indexes is to support the identification of areas of influence for bathing waters by identifying the potential threat from point sources of bacterial pollution, both in standard conditions and peculiar events such as a total bypass of wastewater treatment plants. The results for the Chioggia Municipality case study show the potential of the indexes to significantly improve the geographical identification and quantitative evaluation of the impacts of bacterial pollution sources on bathing waters, facilitating the design of mitigation measures. The proposed methodology represents a new management approach to support local authorities in defining the area of influence within the water bathing profile through the proper characterization of the point sources of bacterial pollution.

1. Introduction

Water quality classification in estuarine and coastal areas has recently garnered considerable public attention worldwide due to human occupation and the increase in the economic value of marine and coastal areas. Given the economic importance of the tourism industry in Europe (World Tourism Organization, 2018), the water quality of bathing areas, especially along tourist destinations, is becoming a highly important feature (Papadopoulou et al., 2018; Phillips et al., 2018).

The coastal environment is often the final recipient of several products of anthropogenic origin, which can compromise water quality and bathers' health as a direct result of microbiological pollution and organic supply from rivers and urban drains (Mallin et al., 2001; Huang et al., 2015a; Costa et al., 2018). In particular, the assessment of microbiological pollution sources is encouraged to prevent severe health problems, such as gastrointestinal diseases, cholera, typhoid, and hepatitis (WHO, 2018).

The adoption of bathing management practices to improve microbial water quality and to prevent the direct overland transport of faecal organisms to coastal waters has been revealed to be a complex problem (Karim et al., 2004; Hipsey et al., 2005; Reinoso et al., 2008; Huang et al., 2015a, 2015b, 2015b; Quilliam et al., 2019). This issue involves many environmental considerations and processes that vary in space and time, such as sewage outfalls and pipe networks, wastewater treatment methods and catchment management (Kashefipour et al., 2002; Ackerman and Weisberg, 2003; Byappanahalli et al., 2015; Fan et al., 2015), weather conditions, sea currents, waves, and sediment transport (Wither et al., 2005; Wright et al., 2009; Converse et al., 2012; Gao et al., 2013).

Advances achieved in bathing water quality policy and management

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procedures to ensure good-quality water for the environment and human safety are the basis of the EU Bathing Waters Directive 2006/7/EC (BWD). In accordance with the EU Water Framework Directive 2000/60/EC (WFD), which provides the general framework to which the BWD is linked, the core principle of the BWD is the identification of the entry points of different faecal pollution sources into the aquatic environment, leading to actions to achieve acceptable exposure levels (Giorgos and Butler, 2001).

The BWD establishes the use of faecal bacteria indicators (FBIs) as microbiological pollution indicators that are easily linked with other environmental parameters (e.g., nitrogen, phosphorus, chlorophyll-a, water temperature, dissolved oxygen) and virus presence. Due to the difficulties associated with the direct measurement of pathogens, FBIs are used worldwide to assess the compliance of the concentration of the major bacterial groups (e.g., total coliform, faecal coliform, *E. coli* and intestinal enterococci) in bathing waters (Thomann and Muller, 1987; Sanders et al., 2005; Field and Samadpour, 2007; Jusup et al., 2007).

All of these aspects are addressed in the bathing water profiles (BWPs), intended by the BWD to be a proactive tool to enforce better set up of management measures and pollution risk assessment. The BWPs must contain information on bathing water features, including the point and nonpoint sources of bacterial pollution (outfalls, combined sewer overflows, Urban Waste Water Treatment Plants, or UWWTPs, diffuse source inputs) and their potential dispersion routes (Kashefipour et al., 2006), also specifying the possibility of short-term pollution events. Following the principles of BWPs, the identification of the area of influence of bathing water, intended as the portion of a drainage basin that can affect bathing water through point and nonpoint sources of pollutants, is a key issue for effective management (Alderisio and De Luca, 1999; Suñer et al., 2007; Mansilha et al., 2009; Cho et al., 2010a, 2010b, 2016, 2010b; López et al., 2013; Oliver et al., 2015). It allows us to identify the major bacterial pollution sources and to support the assessment of microbial contamination in the aquatic environment as strictly correlated with the local environmental conditions that affect its release, transport and inactivation, such as rainfall events, salinity, water temperature, solar radiation and current velocities (Burkhardt et al., 2000; Steets and Holden, 2003; Boehm et al., 2005; Hou et al., 2006; Cho et al., 2010a). Thus, the quantification of FBI concentrations at different distances from pollution sources is of paramount importance (Atwill et al., 2003; Sanders et al., 2005; Strobl et al., 2006; Kay et al., 2010; de Brauwere et al., 2011; Ge et al., 2012; Lušic et al., 2013; Gao et al., 2015) for the definition of BWPs and to identify the extension of the area of influence.

Several studies have emphasized how tracking faecal organisms and predicting their transport processes from sources can be limited by the low spatial and temporal resolution of bacterial pollution data that are generally available (Boehm et al., 2005; de Brauwere et al., 2014; Bonamano et al., 2021). Standard methods of faecal contamination monitoring alone, even if performed according to the monitoring programme principles of the BWD (i.e., at least 4 measurements for the whole bathing season), do not allow the identification of pollutant sources. Thus, mathematical models are considered useful tools for faecal source tracking and assessing the pressure-impact link on bathing water quality. In particular, mathematical models coupled with baseline monitoring allow for a comparative assessment of FBIs discharged by different types of sources and weather conditions within the area of influence (Lipp et al., 2001; Kashefipour et al., 2002, 2006, 2006; Ackerman and Weisberg, 2003; Falconer and Lin, 2003; Lòpez et al., 2013), such as river outflows under normal or storm conditions and discharges from UWWTPs under normal or uncontrolled operation (e.g., for intense rainfall or failures). Model implementation can also support a participative approach for preventing and characterizing short-term pollution events, allowing for the timely assessment of the consequences of different management alternatives and a quantitative microbial risk assessment (Castelletti and Soncini-Sessa, 2007; Chan et al., 2013). Therefore, the use of models and related statistical indicators is increasingly encouraged by research studies (Field and Samadpour, 2007; Yuan et al., 2007; Lòpez et al., 2013; Bedri et al., 2015; Cho et al., 2016) for management policies of bathing waters, in accordance with BWD and other recent legislative acts (Mansilha et al., 2009; USFDA, 2011; WHO, 2018).

The assessment and prevention of significant faecal contamination events through modelling results requires knowledge of baseline conditions and of water quality standards defined by specific monitoring surveys (Ashbolt et al., 2001; Noble et al., 2003). On the other hand, numerical results can be useful to determine whether these standards are met (or not) under site-specific weather and management conditions and to optimize the quality monitoring assessment programme required to control the microbial quality of the bathing water, e.g., driving the choice of the proper location of the monitoring control points to timely assess the environmental suitability of bathing waters (Aguilera et al., 2001; Strobl et al., 2006). In this context, the integrated use of modelling and monitoring (field and remote sensing) techniques represents an important tool to assess pollutant behaviour in coastal waters (Huang et al., 2015a, 2015b, 2015b; Lega and Endreny, 2016; Lisi et al., 2019).

Lòpez et al. (2013) suggest the analysis of the horizontal variability for each water quality parameter alteration produced by discharges, based on statistical methods with predictive capabilities, to support management procedures. More generally, statistical methods facilitate the analysis of enormous amounts of modelling and monitoring data (Aguilera et al., 2001; Lušic et al., 2013; Fan et al., 2015; Jha et al., 2015; Banda and Kumarasamy, 2020; Ma et al., 2020) and their assessment makes reference to established standards or baseline concentrations for water quality. Currently, national and local administrations are showing growing interest in the use of water quality indexes (Colford et al., 2007, 2012, 2012; Griffith et al., 2009; Jagadeeswari and Ramesh, 2012; Jha et al., 2015; Kondum et al., 2021; Uddin et al., 2021) to represent the pollutant distribution in synthetic maps. This responds to the need for decision makers to utilize more systematic and holistic methods for the management of coastal bathing areas, the reduction of pollutants from effluents flowing from farming and industrial areas and the assessment of potential impacts of bacterial pollution on other activities along coastal areas (e.g., shellfish farming).

This paper presents an analysis of the results obtained in the framework of the CADEAU (assimilation of national water quality data in Coastal Areas for a marine Directives oriEnted downstreAm prodUct) project (Silvestri et al., 2020), a downstream coastal application of the Copernicus Marine Environment Monitoring Service (CMEMS), based on a coupled hydrodynamic-biogeochemical modelling system integrated with observational data. CADEAU is generally aimed at providing tailored products that are helpful in the enforcement of UE BWD and other directives related to marine and coastal areas, such as the WFD, the Marine Strategy Framework Directive (2008/56/EC) and the Maritime Spatial Planning Directive (2014/89/EU). In particular, CADEAU offers products useful for the assessment of the impact of pollution point sources (e.g., river and UWWTP outflows), with specific reference to FBI considered by the BWD. The paper focuses on indexes for the assessment of the impact of FBI point sources, providing an example in the Chioggia case study (northern Adriatic Sea, Italy, Fig. 1) carried out within the CADEAU project. The results highlight the capabilities of the proposed indexes to assess the area of influence of bathing waters, identifying potential impacts from specific point sources present in the area, and thus supporting local authorities in selecting management procedures within BWPs.

2. Study area

The city of Chioggia (Italy) hosts 50,000 inhabitants and is located along the northwestern Adriatic coast in the southern part of the Province of Venice (Fig. 1). This area is one of the most sensitive areas in Italy because of its precarious environmental conditions, which are subject to both natural changes and anthropogenic pressures. The main problems

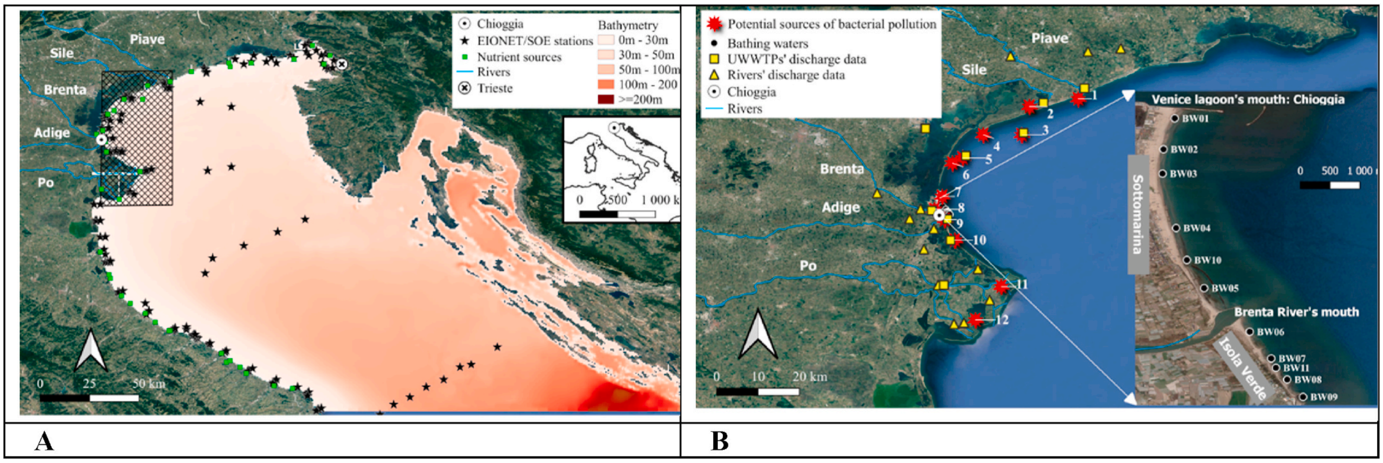

Fig. 1. 1-A) -inset- Study area along the northern Adriatic Sea (Chioggia, Italy). **1-A)** Bathymetry of the computational domain of the modelling system at the regional scale; city of Chioggia (circle); in situ monitoring stations from the EIONET/SOE database (black stars); land-based nutrient sources from UWWTPs, river mouths and lagoon inlets (squares); area of the case study (black hatched area). **1-B)** Zoom on the Chioggia study site. On the left, potential sources of bacterial pollution (stars with labels): 1: Piave River (Eraclea UWWTP close to the mouth), 2: Sile River (Jesolo UWWTP close to the mouth), 3: UWWTP Cavallino, 4: Venice lagoon mouth – Venezia Lido, 5: UWWTP Laguna di Venezia, 6: Venice lagoon mouth – Malamocco, 7: Venice lagoon mouth – Chioggia, 8: Brenta River (UWWTP Chioggia Brondolo close to the mouth), 9: Adige River (UWWTP Rosolina Mare close to the river mouth), 10: UWWTP Isola Albarella, 11: Po River, 12: UWWTP Goro. Squares and triangles represent in situ data provided by ARPAV for UWWTPs and rivers, respectively. On the right, bathing waters managed by the Chioggia Municipality. For the sake of readability, the official identification code of each bathing water has been abbreviated substituting “IT0050270080” with “BW” (e.g., bathing water BW01 corresponds to bathing water with official code IT005027008001). Map data: Google, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Landsat, Copernicus.

concerning natural forces in this low-lying area are related to land subsidence phenomena, periodic flooding during severe winter storms, and saltwater intrusion. Furthermore, tourism activities and marine resource exploitation strongly affect the status of the marine ecosystem, which is linked in turn to nutrient loads and to consequent eutrophication phenomena (De Franco et al., 2009).

The most critical situation in terms of faecal contamination along the coast was detected in the southern part of the province (Ostoich et al., 2011), amongst the Ca’ Roman, Sottomarina and Isola Verde shores (Fig. 1B). These higher levels of faecal contamination were mainly attributed to the Brenta and Adige rivers (Fig. 1B). Past studies (Cho et al., 2010; Brigolin et al., 2011; Ostoich et al., 2011) assumed that there is a strict correlation between the rain intensity and the FBI concentration discharged at the Brenta River mouth and that FBI concentrations are significantly influenced by meteorological conditions. On the other hand, the Venice lagoon waters seem to be a potential secondary source of contamination.

Sottomarina Beach (Fig. 1B), located near the city of Chioggia and outside the Lagoon, is one of the bathing areas managed by the Chioggia Municipality. It is a 5 km long sandy beach that features the typical morphology of the northwestern Adriatic Sea, with water depths of approximately 10 m at approximately 1 km from the shoreline (Brigolin et al., 2011). The beach borders an inlet of the Venice lagoon on the left, while on the right-hand side, there is the mouth of the Brenta River, which is characterized by a large hydrographic basin hosting approximately 1.5 million people and agricultural and industrial activities. Data gathered in the framework of the BWD monitoring programme show that Sottomarina beach is often subject to the banning of bathing due to *E. coli* concentrations higher than the limit imposed by National Decree March 30, 2010 (47 events in the period 2010–2019, with a maximum of 17 events in 2019). Better quality bathing waters are found at the northern end of Chioggia’s bathing waters, close to the lagoon inlet, where threshold trespassing is less frequent. This could be justified by a greater distance from major sources of bacterial pollution and by the general circulation, which shows a mean southward flow, reducing the impacts from the closest river outflows (Brenta and Adige rivers) located downstream (south) of these areas.

3. Materials and methods

The aim of this paper is to present and describe the indexes developed to link the sources of bacterial pollution to their impacts on bathing waters. To show the significance and use of such indexes, we exploited the data produced in the framework of the CADEAU service. Hence, we propose in the following a brief description of CADEAU, mainly relying on cited documents for any additional detail on the modelling system and its integration with remote sensing and in situ data. Then, we focus on the detailed descriptions of the indexes.

3.1. *The CADEAU service: an operational modelling system*

CADEAU is a downstream coastal application of the Copernicus Marine Environment Monitoring Service (CMEMS, https://marine.copernicus.eu). It is a downscaling of the Mediterranean CMEMS modelling system integrated with observational data, and it is based on the high-resolution MITgcm-BFM coupled hydrodynamic-biogeochemical model (Cossarini et al., 2017). CADEAU focuses on nutrient dynamics, eutrophication, and bathing water quality in coastal areas. In particular, its derived products are designed to provide information on the space-time distribution of the major parameters related to water quality. The service has been tested on the Italian coastal area of the northern Adriatic Sea (Fig. 1A), since this is one of the most sensitive areas along the Italian shoreline, where eutrophication and marine resource exploitation influence and depend on the quality of the marine ecosystem (Solidoro et al., 2009).

Model resolution and setup (details in Section 3.2) guarantee a proper simulation of the main oceanographic features of the northern Adriatic Sea at the basin and subbasin scales from both hydrodynamic and biogeochemical points of view. The model is initialized and driven at the southern open boundary by a downscaling operational procedure (i.e., linear spatial interpolation from 1/24° to 1/128° grid resolution) of the freely accessible hydrodynamics and biogeochemistry CMEMS products (Table 1). A decadal model simulation was performed for the 2006–2017 period by integrating the coupled MITgcm-BFM model with coastal in situ nutrient data from the Italian monitoring system and with sea surface temperature data from CMEMS satellite products.

Furthermore, the modelling system includes sewage inputs from point sources discharging both into the sea and along the rivers (close to the mouth). Wastewater loads are derived from the EU Urban Waste Water Treatment Directive (UWWTD) questionnaires on UWWTPs.

In particular, the bacterial pollution fate and transport are simulated in the model by adding to the native MITgcm advection-diffusion algorithms a first-order decay law, where a generic concentration C (CFU/100 ml), considered as a proxy for bacterial pollution) decreases at the rate

$$\frac{dC}{dt} = -kC \tag{1}$$

The decay rate k (s^{-1}, varying in space and time) is computed as follows (Chan et al., 2013):

$$k(x,y,z,t) = [k_b + k_S S(x,y,z,t)]\theta^{T(x,y,z,t)-20} + k_I I(x,y,t)e^{-e_t z} \tag{2}$$

where x, y, z indicate the position in the domain, t is time (s), S and T are seawater salinity (PSU) and temperature (°C), I is the solar radiation (W m^{-2}), k_b is the basic decay rate (at complete darkness, zero salinity and temperature of 20 °C), ks is the empirical constant for salinity, k_I is the constant on solar radiation, e_t is the light extinction coefficient and θ is a temperature-dependent constant. The constants are set to the following values: $k_b = 0.8\ s^{-1}$, $ks = 0.017\ s^{-1}$, $k_I = 0.086\ s^{-1}\ W^{-1}\ m^2$, $e_t = 0.5\ m^{-1}$ (water characterized by higher transparency) and $\theta = 1.07$.

The CADEAU service provides integrated model results for assessing the biogeochemical conditions of coastal waters in connection with water quality alteration due to bacterial pollution. Here, we focus on products developed according to the principles of the EU Bathing Directives, but the service also provides products of benefit for other EU Directives concerning coastal and marine environment management policies (i.e., WFD, UWWTD, and MSFD). The available products include time series of the main water quality parameters and indexes: sea surface temperature (SST), dissolved oxygen (DO), chlorophyll *a* (Chl-a), nitrates and nitrites (NOx), ammonia (NH4), total phosphorus (TP), dissolved inorganic nitrogen (DIN) and trophic index (TRIX). In this study, specific indexes are proposed to characterize the area impacted by potential bacterial pollution sources to support decision-makers in the overall environmental planning process. In particular, these synthetic statistical indexes are useful tools for the identification of the main river discharges of bacterial pollution and the definition of the related potential impact on bathing waters (more details are provided in Section 3.3).

3.2. Model setup: integration between the MITgcm-BFM model, the downscaling of CMEMS and field data

The modelling system is based on the MITgcm (Massachusetts Institute of Technology general circulation model) hydrodynamic and transport modules (Marshall et al., 1997; Campin et al., 2020, http://mitgcm.org/), while the biogeochemical processes solved by the BFM (Biogeochemical Flux Model, Vichi et al., 2015, http://bfm-community.eu/) are included in the coupled system via the BFMcoupler package and integrated in space and time by the MITgcm (Cossarini et al., 2017). SST and nutrient concentrations were assimilated using native MITgcm nudging algorithms.

The model domain for the northern Adriatic Sea spans north of latitude 43.5° N (Fig. 1A), and it has been discretized with a horizontal resolution of 1/128° (~850 × 600 m) and 27 unequally spaced vertical levels. The simulated time period covers a 12-year period (2006–2017), and initial and open boundary conditions are derived from the CMEMS products (Section 3.2.1).

The model explicitly considers the 19 major rivers flowing into the basin. Daily discharge rates are available for the Po River and for the two major rivers flowing into the Gulf of Trieste (Fig. 1A). The daily data are provided by different local authorities: the Regional Agency for Environmental Protection and Energy of Emilia-Romagna (ARPAE - SIM Hydrology Area) for the Po River and the Friuli Venezia Giulia Region (Environmental Management - Hydrographic Unit) and AcegasApsAmga (water department: analysis laboratory) for the Gulf of Trieste rivers. The other flow rates have been derived from an up-to-date climatology (Janeković et al., 2014) modulated to reproduce the maximum and minimum values in spring/autumn and summer/winter, respectively.

Regarding the nutrient input in the model setup, nitrogen and phosphorus loads [mmol/s] discharged by the rivers are derived from nutrient concentrations [$mmol/m^3$] provided by the Perseus project (PERSEUS, 2015) multiplied by the flow rate [m^3/s] of each river.

The meteorological forcing is obtained from the Regional Climate Modelling system RegCM4 (Giorgi et al., 2012) and from the COSMO-I2 model, implemented by ARPAE Emilia-Romagna (IdroMeteoClima Service). The RegCM and COSMO datasets cover the 2006–2012 and 2013–2017 time periods, respectively, with different horizontal resolutions: 12 and 2.8 km. Both models include the atmospheric parameters needed to drive the coupled model (air temperature, pressure and humidity, wind velocity, heat fluxes and precipitation).

The in situ data are gathered from already existing datasets freely available on the EOINET-SOE database (http://cdr.eionet.europa.eu/), acquired by diverse existing national coastal monitoring programmes and activities operated by the Regional Environmental Protection Agencies (i.e., ARPA-FVG, ARPAV, ARPAE, ARPA Marche). Nutrient in situ data have been assimilated in the modelling system, while independent in situ data of other parameters have been used to validate the system (see Section *3.2.2*).

Further details on the implementation of the MITgcm-BFM modelling system are provided in Querin et al. (2016), Cossarini et al. (2017) and Silvestri et al. (2020).

3.2.1. CMEMS model and satellite data

CMEMS products have been used to drive, validate and optimize the model through data assimilation techniques. Both satellite and model data covering the Mediterranean basin have been downloaded from the CMEMS portfolio. Satellite SST data have been assimilated into the hydrodynamic model, while ocean colour images have been used as a reference for biogeochemical model results. Initial and open boundary conditions are derived from the CMEMS modelling system: we extracted the initial conditions for January 2006, and we processed the CMEMS dataset to obtain the daily open boundary conditions on the southern side of the domain during the simulated time period.

A brief description of the data used by the modelling system is summarized in Table 1.

In particular, the CMEMS hydrodynamics and biogeochemistry reanalysis products (CMEMS_PHYS and CMEMS_BIO) have been used to build the initial and open boundary conditions (vertical section at latitude 43.5°N) of the hydrodynamic and biogeochemical variables of the MITgcm ocean model and the BFM biogeochemical model, respectively. The data were interpolated from the 1/16° resolution of the CMEMS product to the 1/128° resolution of the northern Adriatic high-resolution reanalysis.

Furthermore, CMEMS satellite observations of sea surface temperature (CMEMS_SST) have been used for the assimilation of SST in the reanalysis run, and chlorophyll concentration (CMEMS_CHL) has been used for the validation of surface chlorophyll maps.

The proper interpolation of the low-resolution Mediterranean data resulted in a smooth transition from the basin-scale model to the high-resolution northern Adriatic model. Moreover, the assimilation of satellite SST corrected the biases in the model results, which tended to underestimate the surface temperature, especially during the stratified season (spring-summer). Additionally, the comparison of surface chlorophyll maps provided satisfactory results, even if particular attention is required when focusing on coastal areas.

Further details are provided in Silvestri et al. (2020).

Table 1
Copernicus products used in CADEAU.

Reference name in this paper	Product name	Source Type	Use in CADEAU
CMEMS_PHYS	MEDSEA_REANALYSIS_PHYS_006_004	Numerical model	Initial conditions and boundary conditions for the MITgcm model.
CMEMS_BIO	MEDSEA_REANALYSIS_BIO_006_008	Numerical model	Initial conditions and boundary conditions for the MITgcm-BFM model.
CMEMS_SST	SST_MED_SST_L4_REP_OBSERVATIONS_010_021	Satellite	Assimilation.
CMEMS_CHL	OCEANCOLOUR_MED_CHL_L3_REP_OBSERVATIONS_009_073	Satellite	Validation of the modelling system.

3.2.2. Field data: physical and microbiological data collection

In situ data collected from the national and regional monitoring activities were extracted and processed to drive and validate the modelling system.

Data regarding the main oceanographic parameters (water temperature, oxygen saturation, pH, Secchi depth, Chl-a, total nitrogen and phosphorus, silicate, nitrates, orthophosphates) were collected from the official database of the European Environment Agency water quality monitoring network (EIONET/SOE), covering the period 2006–2017, for the 596 monitoring stations within the computational domain (Fig. 1A).

This dataset includes in situ coastal data gathered through national environmental monitoring programmes carried out in the framework of national environmental legislation (including EU directives transposed into national laws). Since such data were collected by different regional agencies, they were thoroughly checked, harmonized (e.g., uniform to the same unit of measurement) and validated to minimize inhomogeneities.

Data on bathing water quality for the 2006–2017 period, with measures of *E. coli* and intestinal enterococci on 11 bathing waters managed by the Chioggia Municipality, were collected through the Italian Ministry of Health database from routine monitoring carried out by ARPAV in the framework of the BWD. Since BWD was enforced in Italy in 2010, data in the period before 2010 referred to different parameters. To consider field data in the same period of the numerical simulation, the following equivalence (also used, according to the national law, in the first classification in 2010) of parameters pre- and post-BWD was used: “faecal coliforms” = “*E. coli*”, “faecal Streptococci” = “Intestinal enterococci”.

Regarding the dataset of urban wastewater discharge points, we collected data/information from the Italian UWWTD reporting. UWWTD requires member states to collect monitoring data on the status of compliance for agglomerations and treatment plants and to report the results of this monitoring to the European Commission. From these questionnaires, we focused on the following parameters: the type of treatment (based on total generated load in population equivalent, aka p.e., of all agglomerations $\geq$ 2000 p.e.), the load entering, the capacity of the plant, the amount of nitrogen and total phosphorus discharged directly into the Adriatic Sea or near the coastline and in the rivers for the period 2007–2015.

3.2.3. Integration of the numerical model and the in situ dataset

In situ data from the EIONET-SOE database (Fig. 1A) have been included in the modelling system through a nudging assimilation scheme (i.e., relaxation to prescribed values in specific areas of the domain), enhancing the performance of the model, which shows good agreement with available climatology (Solidoro et al., 2009), other in situ observations and satellite data (Silvestri et al., 2020).

Furthermore, UWWTP data were integrated into the model as local bottom sources of nutrients. We updated the model routines to include this new type of source for biogeochemistry. Since discharge loads were not available for several treatment plants, we computed the average load (for p.e.) and the average efficiency of the known systems, and we extended these (averaged) estimates to the other plants, for which only the p.e. is known. Then, the investigation of the bathing waters in the Chioggia Municipality was performed considering the environmental pressures linked to the main existing local sources (e.g., UWWTPs and river discharges) that potentially affect the bathing water quality. These discharge points were selected considering the coastal area belonging to the Chioggia Municipality and extending towards the sea and inland along the rivers. The extent of the investigated area, covering the sea and the rivers, is linked to the local mean currents and to the mean decay time for bacteria. The annual average of the vertically averaged current velocity in the area can be estimated to be approximately 0.15 m/s (Melli et al., 2017). Given this value, we computed the mean path along an average streamline for 1 day, which is slightly less than 13 km. Since the decay time of bacterial pollution in the sea can be roughly estimated to be 3 days, we evaluated whether the area including the discharge points that could affect the coasts of the Chioggia Municipality has a width of 39 km (Fig. 1A).

We also considered the potential bacterial pollution released by the river mouths (i.e., Po, Adige, Brenta, Sile and Piave) and the Venice lagoon inlets due to discharges along the river paths and inside the lagoon, respectively.

All rivers and lagoon mouths in the area (9 sources) and the UWWTP discharging directly into the sea (3 sources) were taken into account for a total of 12 sources of potential bacterial pollution (Fig. 1B).

In the model, we imposed the release of a passive tracer from each of the selected sources (using 12 different tracers) with a first-order decay law that simulates *E. coli* bacteria (Chan et al., 2013), as shown in Section 3.1 (equations 1) and 2)).

3.3. Indexes for bathing and coastal water quality assessment

The goal of this paper is to present a novel set of indexes to synthesize the information produced by the modelling system on bacterial transport and fate. According to the BWP definition, we highlight the effectiveness of the proposed indexes in managing bathing areas (i.e., for preventing the impacts from short-term pollution events and abnormal events, for supporting the definition of the area of influence and for planning mitigation measures). As described in Section 3.2.3, each potential source of bacterial pollution considered in the case study was identified by a different passive tracer to differentiate the origin of each plume and to link the observed bacterial pollution events to the specific source.

In particular, the indexes are mainly aimed at identifying which of the considered sewage discharge points with a risk of bacterial pollution can produce an impact on the different bathing waters in the area.

To estimate the severity of different source-specific impact levels, two classes of indexes have been developed, named Dilution Indexes (DI) and Correlation Indexes (CI).

The first class of indexes (DI) is composed of four synthetic indexes (DI_{rel}, $DI_{max,rel}$, DI_{fr}, $DI_{max,fr}$). This class is designed to characterize how the bacterial plume generated by each source can affect the different bathing waters. The indexes are thought to provide information on the conditions under which higher impacts can occur. Considering that the monitoring carried out in the framework of the current legislation does not provide enough in situ data to exactly quantify the bacterial load discharged by the different sources (Boehm et al., 2005; de Brauwere et al., 2014; Bonamano et al., 2021), we opted to work with normalized values. This solution, once the modelling system is correctly set up to represent the sewage water outflow from bacterial sources, allows correct identification of the areas impacted by the bacterial plume in terms of dilution coefficients with respect to a reference bacterial load. Then, if one aims at obtaining the quantification of the bacterial impact of a source on a certain point in the computational domain, it is only necessary to multiply the dilution coefficient by the estimated reference load associated with the specific source.

To make it easier to quickly understand the order of magnitude of pollution reduction at different distances from the source, all indexes in this class are evaluated as $\log_{10}$ values. When the argument of $\log_{10}$ is equal to 0, corresponding to the absence of impact, the DI indexes are set equal to a formal value, represented by the symbol "*" (see Tables 3–8, Section 4). The same holds when the argument of $\log_{10}$ is so small that it can be considered equal to 0 (less than 10^{-5} in this paper).

1) DI_{rel}: this index shows the mean relative impact of a source on bathing water. As shown by (3)

$$DI_{rel}(i,j) = log_{10}\left(\frac{\sum_t \frac{\sum_z Tr\left(i,j,z,t\right)}{\sum_{z=z_{0a}}^{z_{0b}} Tr\left(i_0,j_0,z,t\right)}}{t}\right). \tag{3}$$

The index is evaluated by comparing the tracer value (Tr, daily means in CFU/100ml) in a wet grid cell (i,j) of the computational domain (summing all vertical levels, taking into account the volume of each grid cell) and the tracer value at the source point (i_0,j_0) (specific vertical levels occupied by the outflow, from z_{0a} to z_{0b} in the formula). Then, the mean over time is considered. This index represents the average normalized concentration with which the bacterial pollution released from a source reaches a given point in the computational domain under average hydrodynamic conditions.

2) $DI_{max,rel}$: this index shows the maximum of the relative impact of a source on bathing water. As shown by (4)

$$DI_{max,rel}(i,j) = log_{10}\left(max_t\left(\frac{\sum_z Tr(i,j,z,t)}{\sum_{z=z_{0a}}^{z_{0b}} Tr\left(i_0,j_0,z,t\right)}\right)\right). \tag{4}$$

The index is evaluated by comparing the tracer value (Tr) in a wet grid cell (i,j) of the computational domain (summing all vertical levels) and the tracer value at the source point (i_0,j_0) (specific vertical levels occupied by the outflow, from z_{0a} to z_{0b} in the formula). Then, the maximum of such values over time is considered. This index represents the normalized concentration with which the bacterial pollution released from a source reaches a given point in the computational domain under the most unfavourable hydrodynamic conditions, i.e., those that produce the lowest dilution (the highest value of the normalized bacterial concentration).

3) DI_{fr}: this index shows the fraction of a plume released by a source impacting bathing water. The plume is defined as the total quantity of tracer released from a certain source present in a fixed moment in the whole computational domain. As shown by (5)

$$DI_{fr}(i,j) = log_{10}\left(\frac{\sum_t \frac{\sum_z Tr\left(i,j,z,t\right)}{\sum_{n,mj,z} Tr\left(n,m,z,t\right)}}{t}\right). \tag{5}$$

The index is evaluated by comparing the tracer value (Tr) in a wet grid cell (i,j) of the computational domain (summing up all vertical levels) and the plume. Then, the mean over time is considered. The idea of considering the whole plume is attributable to the following factors. When a total bypass occurs, pollution affects the sea for a few days. Considering that the bacterial load released during this event is many orders of magnitude greater than the standard bacterial load released by a specific source (10^7–10^9 CFU/100 ml compared to 10^1–10^3 CFU/100 ml) and that this bacterial pollution will affect the sea for a few days, referring to the total plume roughly equals considering the pollution load released by the total bypass event. This index represents the portion of the total bacterial pollution released in the sea by a source present at a given point in the computational domain with average hydrodynamic conditions.

4) $DI_{max,fr}$: this index shows the maximum fraction of a plume released by a source impacting bathing water. As shown by (6)

$$DI_{max,fr}(i,j) = log_{10}\left(max_t\left(\frac{\sum_z Tr(i_c,j_c,z,t)}{\sum_{n,m,z} Tr\left(n,m,z,t\right)}\right)\right). \tag{6}$$

The index is evaluated by comparing the tracer value (Tr) in a wet grid cell (i,j) of the computational domain (summing up all vertical levels) and the plume. The maximum over time of such values is considered. This index represents the portion of the total bacterial pollution released in the sea by a source present at a given point in the computational domain with the most unfavourable hydrodynamic conditions.

The second class of indexes (CI), composed of two synthetic indexes (CI_{ie}, CI_{ec}), relates in situ measurements of bacterial pollution to the modelled plume presence. These indexes show which sources should be investigated to identify the cause of past pollution events:

1) CI_{ie} is the cross-correlation, with no time lag, between the intestinal enterococci in situ data (from BWD monitoring) and the quantity of tracer (summing up all vertical levels) provided by the model (model data selected from the wet grid cell closest to the bathing water and considering the model output time steps closest to the date of in situ measurement), as shown by (7).

$$\begin{cases} mean(x(t)) = \dfrac{\sum_{t=1}^{T} x(t)}{T} \\[2ex] stddev(x(t)) = \sqrt{\dfrac{1}{(T-1)}\displaystyle\sum_{t=1}^{T}}\,(x(t) - mean(x(t)))^2 \\[2ex] CI_{ie}(i,j) = \dfrac{\sum_{t=1}^{T}\left\{\left[\displaystyle\sum_z Tr(i,j,z,t) - mean\left(\sum_z Tr(i,j,z,t)\right)\right][M_{ie}(t) - mean(M_{ie}(t))]\right\}}{stddev\left(\displaystyle\sum_z Tr(i,j,z,t)\right) stddev(M_{ie}(t))} \end{cases} \tag{7}$$

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where M_{ie} is the time series of intestinal enterococci measurements.

To better identify the relation between plume presence and high bacterial contamination, only bacterial concentrations higher than 20% of the threshold in Decree March 30, 2010 (i.e., values $\geq$ 40 n*/100 ml, where n* means CFU or MPN) were taken into account, and all other data were set to 0. Hence, T in the formula represents the number of intestinal enterococci measurements above (or equal to) 40 CFU/100 ml.

2) CI_{ec} is the cross-correlation, with no time lag, between the *E. coli* in situ data (from BWD monitoring) and the model data (selected as in the previous case), as shown by (8).

$$\begin{cases} mean(x(t)) = \dfrac{\sum_{t=1}^{T} x(t)}{T} \\ stddev(x(t)) = \sqrt{\dfrac{1}{(T-1)}\sum_{t=1}^{T}(x(t) - mean(x(t)))^2} \\ CI_{ec}(i,j) = \dfrac{\sum_{t=1}^{T}\left\{\left[\sum_{z} Tr(i,j,z,t) - mean\left(\sum_{z} Tr(i,j,z,t)\right)\right][M_{ec}(t) - mean(M_{ec}(t))]\right\}}{stddev\left(\sum_{z} Tr(i,j,z,t)\right) stddev(M_{ec}(t))} \end{cases} \tag{8}$$

where M_{ec} is the time series of *E. coli* measurements.

To better identify the relation between plume presence and high bacterial contamination, only bacterial concentrations higher than 20% of the threshold in Decree March 30, 2010 (i.e., values>=100 n*/100 ml) were taken into account, and all the other data were set to 0. Hence, T in the formula represents the number of *E. coli* measurements above (or equal to) 100 CFU/100 ml.

Cross-correlation ranges from −1 to 1, where values close to 1 indicate a strong similarity in the trends of the two time series, i.e., linking the presence of the plume to bacterial pollution.

4. Results

The results obtained by the use of the proposed indexes as predictive tools for identifying the point sources of bacterial pollution with a major risk of impact on bathing waters for the Chioggia (Italy) case study are reported in the following section. The Chioggia Municipality is characterized by the presence of 11 bathing waters and 12 potential sources of bacterial pollution (Fig. 1B). These potential sources, selected as described in Sect. 3.2.3, include the main river mouths and UWWTPs in the area.

To obtain information through the Dilution (DI) and Correlation (CI) Indexes on the conditions (hydrodynamic features and distance from point source) in which high levels of this impact can occur, we refer to the threshold enforced by the current national legislation (Italian Decree March 30, 2010) as baseline values for reference in the assessment.

In particular, we refer to the threshold of 500 n*/100 ml for the *E. coli* concentration over which a temporary banning of bathing is imposed (Italian Decree March 30, 2010) as a reference level for evaluating if a source has an impact on a certain location or not. Since the proposed indexes must be interpreted as dilution coefficients, we also have to estimate the reference level characterizing the sources. According to Italian law (Legislative Decree 152/2006), a threshold not higher than 5000 CFU/100 ml (ten times the threshold of 500 n*/100 ml) is suggested for UWWTP outflows (for plants with a p.e. of at least 2000 people). Hence, even under normal working conditions, bathing water impacted by only one tenth of the concentration at the source may be highly impacted. Using the proposed indexes, this implies that with DI_{rel} higher than −1, the source may have an impact.

Table 2
Number of events in the period 2000–2019 with a high presence of bacterial pollution. Source: in situ data from WFD and UWWD monitoring programmes in the period 2000–2019 (mixed units CFU/100 ml and MPN/100 ml) provided by ARPAV.

		Number of events			
		>250 n*/ 100 ml	>500 n*/ 100 ml	>5000 n*/ 100 ml	>10^6 n*/ 100 ml
Monitoring site	**Rivers**	649	457	56	0
	UWWTPs	166	137	76	10

Furthermore, considering that the concentration of *E. coli* in untreated wastewater is approximately $10^7/10^9$ CFU/100 ml (Acquedotto Pugliese, 2019), in the case of total bypass of an urban wastewater treatment plant (i.e., untreated wastewater), the plume would impact the bathing water quality even when reaching bathing water with a normalized concentration of 10^{-5}. This is identified by index values of DI_{fr} greater than −5 (considering the total bypass of bacterial load as 10^7 CFU/100 ml).

Historical in situ data sources from 2000 to 2019, with mixed units CFU/100 ml and MPN/100 ml, provided by ARPAV (Fig. 1B), show that both river mouths and UWWTP outflows can trespass the threshold of 5000 CFU/100 ml and even reach bacterial concentrations higher than 10^6 CFU/100 ml (indicating possible total bypass events, Table 2).

Official BWPs for bathing waters in the Chioggia Municipality highlight the potential risk of bacterial pollution originating from the Venice lagoon inlet of Chioggia, the Brenta and Adige River mouths and the Chioggia Brondolo UWWTP (discharging close to the Brenta River mouth), with differences in the profiles due to the proximity of each bathing water to different sources. The results of the 12-year simulation and the computation of indexes are shown in Tables 3–8 for the four DIs and the two CI.

Each table reports the values of the index computed for any given couple between the point sources (columns) and the bathing water sites (rows). The results obtained by the application of the DIs show their usefulness in evaluating the potential bacterial pollution that can be induced by each of the 12 considered sources.

As shown in Tables 3–6, the DIs confirm the high impact from the sources listed in the official BWPs (i.e., Brenta and Adige rivers and Venice lagoon mouths) but show that even plumes released by other pollution sources may reach bathing waters in Chioggia with concentrations that may impact bathing water quality in certain cases.

Table 3

DI_{rel} for bathing waters and potential pollution sources considered in the Chioggia case study. Shades from lighter to darker highlight greater potential impact (considering the following bins from light to dark colours: >=-5 and <-4; >=-4 and <-3; >=-3 and <-2; >=-2 and <-1; >=-1). See legend in Fig. 1 for the location of identification codes of potential source and bathing waters. Bathing waters are listed southward.

DI_{rel}													
		Sources											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Bathing waters	BW01	-4.5	-5.0	-4.4	-3.2	-3.2	-2.7	-1.1	-3.2	-4.3	-4.7	*	*
	BW02	-4.4	-5.0	-4.0	-3.0	-2.8	-2.5	0.1	-2.8	-4.0	-4.4	*	*
	BW03	-4.4	-5.0	-3.9	-3.0	-2.8	-2.5	-0.7	-2.5	-4.0	-4.4	*	*
	BW04	-4.4	-5.0	-4.0	-3.0	-2.8	-2.6	-0.9	-2.3	-4.0	-4.4	*	*
	BW10	-4.7	-5.0	-4.3	-3.4	-3.2	-3.0	-1.5	-2.1	-4.2	-4.5	*	*
	BW05	-4.7	-5.0	-4.2	-3.3	-3.1	-3.0	-1.9	-1.0	-3.9	-4.3	*	*
	BW06	-5.0	*	-4.2	-3.5	-3.1	-3.1	-2.2	-0.6	-3.8	-4.3	*	*
	BW07	-4.7	-5.0	-4.1	-3.4	-3.0	-3.0	-2.2	-0.8	-3.4	-4.0	*	*
	BW11	-4.5	-5.0	-3.7	-3.0	-2.7	-2.6	-2.1	-1.3	-2.8	-3.7	*	*
	BW08	-5.0	*	-4.2	-3.4	-3.1	-3.1	-2.5	-1.6	-2.7	-3.5	*	*
	BW09	-5.0	*	-4.2	-3.4	-3.1	-3.1	-2.5	-1.6	-2.7	-3.5	*	*

Table 4

$\mathrm{DI}_{max,rel}$ for bathing waters and potential pollution sources considered in the Chioggia case study. Shades from lighter to darker highlight greater potential impact. See legend in Fig. 1 for the location of identification codes of potential source and bathing waters. Bathing waters are listed southward.

$\mathrm{Di}_{max,rel}$													
		Sources											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Bathing waters	BW01	-1.8	-2.5	-2.1	-1.0	-1.4	-1.0	-0.2	-1.1	-1.6	-1.6	-4.7	*
	BW02	-1.6	-2.3	-1.8	-0.8	-1.2	-0.8	0.3	-0.9	-1.4	-1.3	-4.4	*
	BW03	-1.6	-2.3	-1.8	-0.8	-1.2	-0.8	0.1	-0.8	-1.3	-1.3	-4.4	*
	BW04	-1.7	-2.4	-1.8	-0.8	-1.3	-0.8	0.2	-0.7	-1.4	-1.3	-4.3	*
	BW10	-1.9	-2.6	-2.3	-1.1	-1.5	-1.0	-0.3	-0.6	-1.4	-1.5	-4.5	*
	BW05	-1.9	-2.6	-2.1	-1.1	-1.5	-1.0	-0.5	-0.2	-1.3	-1.5	-4.3	*
	BW06	-2.0	-2.8	-2.1	-1.3	-1.6	-1.2	-0.8	0.1	-1.4	-1.5	-4.4	*
	BW07	-2.0	-2.7	-2.0	-1.2	-1.5	-1.2	-0.7	-0.1	-1.0	-1.4	-4.0	*
	BW11	-1.8	-2.5	-1.6	-1.0	-1.3	-0.9	-0.7	-0.6	-0.8	-1.1	-3.7	*
	BW08	-2.0	-2.7	-2.0	-1.2	-1.6	-1.1	-0.9	-0.6	-0.6	-0.9	-3.7	*
	BW09	-2.0	-2.7	-2.0	-1.2	-1.6	-1.1	-0.9	-0.6	-0.6	-0.9	-3.7	*

Table 5

DI_{fr} for bathing waters and potential pollution sources considered in the Chioggia case study. Shades from lighter to darker highlight greater potential impact. See legend in Fig. 1 for the location of identification codes of potential source and bathing waters. Bathing waters are listed southward.

DI_{fr}													
		Sources											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Bathing waters	BW01	*	*	*	-4.5	-4.5	-3.6	-1.6	-4.0	-5.0	*	*	*
	BW02	*	*	*	-4.3	-4.0	-3.4	-0.3	-3.6	-5.0	-5.0	*	*
	BW03	*	*	-5.0	-4.3	-4.0	-3.4	-1.2	-3.2	-4.7	-5.0	*	*
	BW04	*	*	*	-4.4	-4.0	-3.5	-1.5	-3.0	-5.0	-5.0	*	*
	BW10	*	*	*	-4.7	-4.4	-3.9	-2.1	-2.8	-5.0	*	*	*
	BW05	*	*	*	-4.7	-4.3	-3.9	-2.5	-1.7	-4.7	-5.0	*	*
	BW06	*	*	*	-4.7	-4.3	-4.0	-2.8	-1.3	-4.5	-5.0	*	*
	BW07	*	*	*	-4.7	-4.2	-3.9	-2.8	-1.5	-4.2	-5.0	*	*
	BW11	*	*	-5.0	-4.3	-3.9	-3.6	-2.8	-2.0	-3.6	-4.5	*	*
	BW08	*	*	*	-4.7	-4.4	-4.0	-3.2	-2.3	-3.4	-4.4	*	*
	BW09	*	*	*	-4.7	-4.4	-4.0	-3.2	-2.3	-3.4	-4.4	*	*

Table 6

$DI_{max,fr}$ for bathing waters and potential pollution sources considered in the Chioggia case study. Shades from lighter to darker highlight greater potential impact. See legend in Fig. 1 for the location of identification codes of potential source and bathing waters. Bathing waters are listed southward.

		$Di_{max,fr}$											
		Sources											
		1	2	3	4	5	6	7	8	9	10	11	12
Bathing waters	BW01	-3.2	-3.3	-3.7	-2.7	-2.6	-2.0	-1.0	-1.9	-2.5	-2.6	*	*
	BW02	-3.1	-3.1	-3.3	-2.5	-2.4	-1.9	0.0	-1.7	-2.3	-2.3	*	*
	BW03	-3.1	-3.1	-3.2	-2.5	-2.5	-1.9	-0.5	-1.7	-2.2	-2.3	*	*
	BW04	-3.1	-3.2	-3.3	-2.5	-2.5	-2.0	-0.7	-1.6	-2.3	-2.3	*	*
	BW10	-3.3	-3.4	-3.7	-2.8	-2.8	-2.3	-1.2	-1.6	-2.3	-2.4	*	*
	BW05	-3.3	-3.4	-3.6	-2.8	-2.8	-2.4	-1.4	-1.2	-2.2	-2.4	*	*
	BW06	-3.5	-3.6	-3.6	-3.0	-2.9	-2.6	-1.7	-0.9	-2.3	-2.5	*	*
	BW07	-3.4	-3.5	-3.5	-2.9	-2.8	-2.5	-1.7	-1.1	-2.0	-2.3	*	*
	BW11	-3.2	-3.3	-3.1	-2.6	-2.6	-2.2	-1.8	-1.5	-1.7	-2.0	*	*
	BW08	-3.4	-3.5	-3.4	-2.9	-2.9	-2.5	-2.0	-1.5	-1.6	-1.9	*	*
	BW09	-3.4	-3.5	-3.4	-2.9	-2.9	-2.5	-2.0	-1.5	-1.6	-1.9	*	*

The CI index results (Tables 7 and 8) highlight which sources should be investigated when seeking the origin of high pollution events in the past.

In particular, Table 8 shows the cross-correlation between the presence of the plume released by the different sources and the historical data of *E. coli* presence in bathing waters.

Table 7

CI_{ie} for bathing waters and potential pollution sources considered in the Chioggia case study. Shades from lighter to darker highlight higher cross correlation. See legend in Fig. 1 for the location of identification codes of potential source and bathing waters. Bathing waters are listed southward.

		CI_{ie}											
		Sources											
		1	2	3	4	5	6	7	8	9	10	11	12
Bathing waters	BW01	Not enough high concentration data to evaluate the index											
	BW02												
	BW03												
	BW04	0.53	0.53	0.53	0.53	0.53	0.82	0.96	0.97	0.84	0.84	0.87	0.94
	BW10	0.42	0.42	0.42	0.42	0.42	0.59	0.85	0.55	0.47	0.47	0.56	0.63
	BW05	0.16	0.16	0.2	0.17	0.24	0.25	0.57	0.82	0.18	0.18	0.19	0.3
	BW06	0.51	0.49	0.5	0.49	0.51	0.58	0.22	0.83	0.22	0.27	0.19	0.47
	BW07	0.32	0.49	0.27	0.5	0.56	0.24	0.19	0.9	0.3	0.13	0.13	0.13
	BW11	0.38	0.8	0.32	0.66	0.7	0.3	0.24	0.76	0.31	0.24	0.25	0.43
	BW08	0.58	0.58	0.58	0.58	0.58	0.71	0.58	0.94	0.36	0.3	0.3	0.32
	BW09	0.21	0.51	0.25	0.35	0.51	0.23	0.24	0.95	0.38	0.23	0.23	0.24

More generally, each row of Tables 3–6 provides information on which sources should be investigated when defining the area of influence of bathing water. On the other hand, each column of Tables 3–6 provides information on which bathing waters may be impacted by a specific source.

An interesting case that highlights the amount of information provided by the different indexes concerns the Sile River (Jesolo UWWTP close to the mouth) and bathing water BW02 (actually named IT005027008002 in the BWD official documents). The second row in Table 8 shows a CI_{ec} value of 0.86, which may seem anomalous given the distance of approximately 36 km between the river mouth and the bathing water. Fig. 2 shows a good correspondence of peaks of plume presence from the Sile River in the bathing water and peaks of *E. coli* presence in the bathing water, hence justifying such a high value of CI_{ec}.

Although the high value reported in Table 8 does not identify the Sile River as the actual source responsible for bacterial pollution in BW02, it provides a reminder to pay attention to that source when addressing BW02 water quality problems. On the other hand, the combination of DI and CI provides further information. In fact, the corresponding DI_{rel} index values (Tables 3 and 4) are too low to identify a potential impact of the Sile River on BW02 under normal conditions (values lower than -1). In contrast, Table 6 on $DI_{max,fr}$ shows that during a total bypass, the fraction of the plume that could reach the bathing water in unfavourable environmental conditions may cause an impact (values greater than -5).

Another example of how to use the indexes is provided in Fig. 3. It shows the maps of $DI_{max,rel}$ and $DI_{max,fr}$ indexes associated with one specific source for each point of the computational domain. The results show that the bacterial plume released by the Adige River mouth (and the Rosolina Mare UWWTP close to its mouth), due to the environmental conditions, is mainly directed southward, in agreement with the considerations on the general circulation in the area (end of Section 2). Hence, under normal operating conditions, the Adige River can only affect the most southward bathing waters of the Chioggia Municipality

Table 8

CI$_{ec}$ for bathing waters and potential pollution sources considered in the Chioggia case study. Shades from lighter to darker highlight higher cross correlation. See legend in Fig. 1 for the location of identification codes of potential source and bathing waters. Bathing waters are listed southward.

		CI$_{ec}$											
		Sources											
		1	2	3	4	5	6	7	8	9	10	11	12
Bathing waters	BW01	0.19	0.65	0.73	0.99	0.68	0.2	0.98	0.98	0.98	0.98	0.19	0.19
	BW02	0.65	0.86	0.96	0.86	0.94	0.51	0.92	0.85	0.85	0.85	0.36	0.4
	BW03	0.29	0.55	0.3	0.6	0.66	0.54	0.31	0.53	0.52	0.52	0.55	0.31
	BW04	0.59	0.43	0.6	0.53	0.76	0.82	0.61	0.57	0.31	0.22	0.21	0.21
	BW10	0.58	0.32	0.2	0.33	0.39	0.34	0.18	0.53	0.09	0.03	0.01	0.01
	BW05	0.12	0.12	0.13	0.13	0.18	0.21	0.14	0.69	0.13	0.13	0.03	0.1
	BW06	0.34	0.66	0.51	0.74	0.73	0.38	0.28	0.54	0.1	0.11	0.07	0.07
	BW07	0.63	0.48	0.42	0.46	0.48	0.2	0.09	0.55	0.11	0.05	0.08	0.05
	BW11	0.54	0.78	0.29	0.6	0.64	0.24	0.18	0.71	0.21	0.2	0.22	0.19
	BW08	0.21	0.8	0.26	0.45	0.22	0.25	0.22	0.34	0.23	0.21	0.2	0.13
	BW09	0.21	0.8	0.43	0.61	0.65	0.39	0.37	0.24	0.06	0.09	0.08	0.07

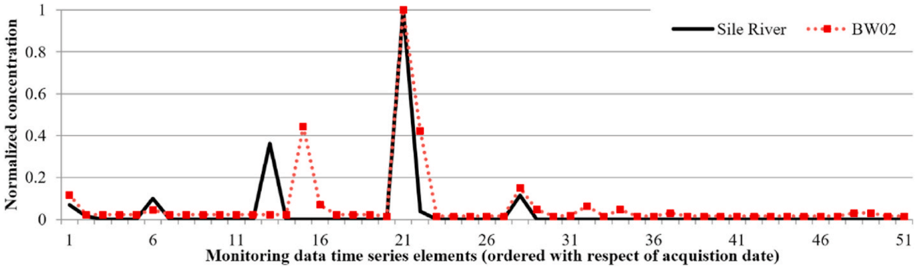

Fig. 2. Concentration of *E. coli* in bathing water BW02 (normalized with respect to its maximum value) in the available 51 monitoring data points (ordered with respect to time) and concentration of tracers released by the Sile River (normalized with respect to its maximum presence in the bathing water) on the same days (daily average data).

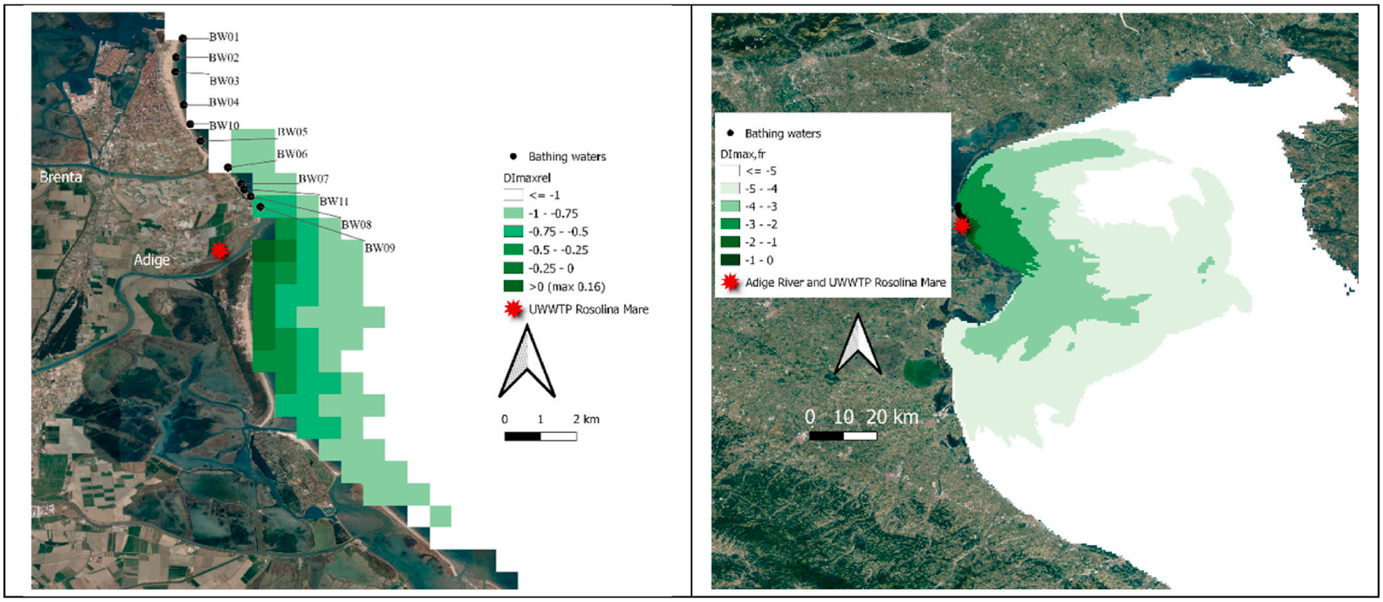

Fig. 3. Examples of dilution indexes (DI$_{mar,rel}$ on the left and DI$_{max,fr}$ on the right) calculated to support the assessment of potential impacts induced by the Adige River (Rosolina Mare UWWTP close to the mouth) on local bathing waters. Map data: Google, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Landsat, Copernicus.

(i.e., up to approximately a couple of kilometres northward of the river mouth). The picture on the right in Fig. 3 shows that the area affected by the plume extends for several tens of kilometres in the case of total bypass (in the most unfavourable environmental conditions).

The two examples show how the proposed indexes can confirm and support the already known connections between the nearby sources of bacterial pollution and bathing waters but also allow us to consider effects that can be produced in rare events (total bypass and most unfavourable environmental conditions) with sources that are even tens of kilometres away.

5. Discussion

The results presented in this research are obtained by a well-established modelling approach based on the coupling of hydrodynamic and biogeochemical models for simulating the behaviour of a tracer (proxy of faecal bacteria) in the marine environment. The adopted formulation links the main environmental parameters to the specific bacterial decay (Mancini, 1978; Chan et al., 2013; Bedri et al., 2015; Bonamano et al., 2015; Gao et al., 2015; Huang et al., 2015a; Leonardi et al., 2020). In particular, this paper is focused on the development of specific techniques to analyse and synthesize the numerical results obtained for the Chioggia Municipality coastal area case study. The extracted set of novel indexes has been shown to be useful for supporting the management of bathing waters according to the BWD core principles.

The BWD highlights the importance of prevention in the management of bathing areas based on the BWP. It attempts to guarantee bathers' health through the comprehensive management of the urban water cycle and the enforcement of infrastructure (e.g., the building of water detention tanks) or contingent responses (e.g., beach closures or installation of warning signs for bathers) in case of non-compliance with EU Directives standards. Moreover, the BWD promotes alert systems with short response times when bathing waters are subjected to short-term pollution events, properly defined by the directive, such as sewer system overflows (Mansilha et al., 2009; Brigolin et al., 2011).

In this framework, BWPs dedicate a section to the description and characterization of all pressures within the area of influence of the bathing water.

According to various best practices and guidance (Bartram and Rees, 2000; Anon, 2002; Bathing Water Committee, 2009; Pond, 2013), the developed indexes respond to the key principles of the BWPs. In particular, the new indexes help in the definition of the area of influence (Suñer et al., 2007; Mansilha et al., 2009; López et al., 2013) through the quantitative characterization of the main local natural and anthropogenic point sources of bacterial pollution.

The indexes support the drafting of BWPs with reference to (i) assessing the relationship between sources of pollutants and environmental drivers affecting the FBI concentration, (ii) identifying the most impactful sources among those present, (iii) highlighting possible sources of short-term pollution events, and (iv) supporting and optimizing the Quality Monitoring and Assessment Program required for fulfilment of the Bathing Directive.

One of the main difficulties in identifying the sources of bacterial pollution affecting bathing waters is the small number of available measurements. BWD enforces bathing water monitoring at least 4 times during the bathing season (e.g., from May to October). On the other hand, the WFD indicates that the monitoring of bacterial pollution at river mouths should be performed at least every 3 months (i.e., 4 data points per year), while the UWWTD requires a minimum of 4 data points and 12 data points per year to be collected near UWWTP discharges for plants between 2000 and 9999 p.e. and above 10000 p.e., respectively.

A further complication is related to the short bacterial life cycle duration in marine waters, approximately three days, which makes it nearly impossible to match data in bathing waters with data from nearby sources.

The majority of indexes developed for bathing water quality combine the dispersion, transport and spatial behaviour of pollution released by a specific source (Schernewski et al., 2012; Huang et al., 2015a; Bonamano et al., 2015, 2021; Korajkic et al., 2019; Weiskerger et al., 2020). Other indexes are related to microbial risk, focusing on the concentration of bacteria to evaluate pathogen loads (Federigi et al., 2020). The originality of the indexes proposed in this document, specifically the dilution indexes (DI) and correlation indexes (CI), is the ability to differentiate the origin of each plume and to link local potential sources to specific observed bacterial pollution events. The DI_{rel} indexes can also be used for early warning. Early warning systems developed on this topic are predictive systems based on (i) simple relationships between the observed rainfall, river discharge levels or salinity and faecal microorganism concentrations or on (ii) complex models of the dominant mixing and transport processes. They are predictive tools based on the observation of the most relevant environmental parameters involved in water degradation, such as salinity variations, sewage or river discharge (Gourmelon et al., 2010). DI_{rel} indexes can be considered coefficients (in the form of 10^{DIrel}) to obtain a first estimate of the range of variability of the impact produced by a source on a specific bathing water once the bacterial pollution at the source is identified (i.e., through a direct measurement). DI_{fr} indexes may be used in a similar way. Since DI_{fr} relates the fraction of the modelled plume arising from a specific source in the bathing water with respect to the total concentration of bacterial pollution realized by all sources involved in the computational domain, this class of index should be used only when a large quantity of bacterial pollution is released all at once in the sea (e.g., total bypass events in UWWTPs). In general, several orders of magnitude greater than the bacterial pollution concentration produced by one specific source under standard conditions are recommended for a proper approximation of the total bacterial pollution in the domain. This limitation is attributable to the necessity of knowing the reference level (or baseline condition) for a bacterial concentration to conduct a proper assessment of impact levels following index estimation. Estimating these reference levels can be easy when the bacterial pollution load is released in the sea by a specific total bypass event, but it is quite difficult to estimate the total pollution present in the sea released by a specific source over a longer time period.

Many indexes have been developed in different management contexts, and each index has its special virtues and shortcomings. As with the general water-quality indexes, there is no procedure yet in place to compare their performance, and all that can be done is to look at complementary information, the credibility of measurements, the transparency of index formulation, the relevancy of key parameters selected, and the comparability of results to make a qualitative judgement regarding the suitability of the water use (Abbasi, 2012; Uddin et al., 2021).

In this context, the results of the case study shown in this paper demonstrate that the proposed indexes can help in the identification of the area of influence of bathing waters without enforcing expensive monitoring programmes for bathing water and all potentially connected pressures.

This also corroborates the importance of using well-established deterministic predictive models as supporting tools for bathing water management purposes (Bedri et al., 2016).

Furthermore, the easy reproducibility of the proposed methodology allows us to overcome the limitations that generally occur when BWPs are drafted only through expert knowledge (although this is allowed by the Italian National Decree March 30, 2010, Attachment E).

According to Oliver et al. (2016), each predicting microbial water quality model should be capable of understanding the contributions of FBIs delivered to receiving waters via different hydrological pathways to inform mitigation and management and should enable screening to guide regulators and/or policymakers in prioritizing decisions.

The indexes presented in this paper answer both questions, as they are able to estimate the severity of different source-specific impact levels and address policy makers' decisions.

6. Concluding remarks

In this paper, a novel set of indexes is proposed as a supporting tool for the management of bathing waters according to the BWD principles. In particular, the indexes allow the identification of the area of influence of bathing water and the characterization of potential point sources of bacterial pollution. The indexes were developed and tested in the framework of the CADEAU project, a downstream coastal service of the regional Mediterranean CMEMS modelling system, based on the integration of a high-resolution coupled MITgcm-BFM modelling system and assimilating national environmental monitoring data.

The first set of indexes, named DIs allows us to identify the features of bacterial plumes as average values or worst-case values, both for bacterial pollution expected under standard conditions and in the case of total bypass of a UWWTP. A second set of indexes, named CIs, links past events of high bacterial pollution in bathing waters (taking advantage of the data gathered in the monitoring programme enforced by the BWD) with the peaks of sewage plumes from different sources.

The results obtained by the application to the Chioggia case study (northern Adriatic region, Italy) show the capabilities of these indexes to characterize the complex temporal and spatial variability of the bacterial pollution plumes arising from the main anthropogenic and natural point sources (river mouths, lagoon inlets and UWWTPs) under standard and unfavourable environmental conditions. In particular, the elaboration of the indexes into synthetic tables and maps allows us to easily identify both the key features of FBI distribution on a large scale and their relationship with the main point sources of bacterial pollution in the area.

The results also highlight how the proposed indexes may support local authorities in managing bathing according to key BWP aspects, helping in the planning of mitigation strategies such as the assessment of the area of influence and the identification of potential sources of short-term pollution events (e.g., total bypass and peculiar environmental conditions).

Finally, the indexes help in the implementation of early warning systems, providing a first estimate of the impact on the different bathing waters once the concentration of bacterial pollution released by a source is known.

Future updates of the indexes will be aimed at correlating microbiological contamination with other environmental parameters (e.g., according to WHO and EU WFD). In particular, the next step of this work will be to verify the utility of this kind of index to support shell farming, where it is important to harvest products with a low concentration of bacterial pollution.

Credit author statement

Antonello Bruschi Data Curation; Writing – original draft; Writing – review & editing; Visualization; Investigation; Formal analysis; Validation; Methodology; Conceptualization; Funding acquisition; Software Iolanda Lisi Writing – Original Draft; Writing – review & editing; Visualization; Validation, Conceptualization, Roberta De Angelis Data curation; Writing – review & editing; Investigation; Validation; Methodology; Conceptualization Stefano Querin Writing – Original Draft; Writing – review & editing; Investigation; Software; Methodology; Conceptualization Gianpiero Cossarini Writing – Review & Editing; Formal analysis; Software; Methodology; Conceptualization; Funding acquisition Valeria Di Biagio Writing – Review & Editing; Data curation; Software Stefano Salon Writing – Review & Editing; Conceptualization; Funding acquisition Cosimo Solidoro Supervision; Writing – review & editing; Conceptualization; Funding acquisition Daniel Fassina Data curation; Writing – review & editing; Validation Sara Ancona Data curation; Writing – review & editing; Validation; Cecilia Silvestri Writing – Original Draft; Writing – review & editing; Supervision; Project administration; Investigation; Validation; Methodology; Conceptualization; Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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