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Listening to stakeholders: Development of water quality indicators for transitional environments using satellite data

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ABSTRACT

Transitional waters are increasingly threatened by anthropogenic pressures with water quality being a key worldwide issue relevant to human consumption, food production, industry, nature and recreation. Monitoring and maintaining good water quality are enshrined in European policy through the Water Framework Directive and Marine Strategy Framework Directive, and pivotal to fulfilling the United Nations Sustainable Development Goals. Remote sensing can provide useful, continuous and synoptic monitoring data and diagnostic tools, however, European Union Member States tend to follow different strategies for their individual reporting, leading to a strong need for tailored-made solutions that work across the continuum of reported water bodies. To address the above, user requirements were collected from interviews with users from 18 local and national stakeholder institutes/organisations in six European countries, leading to a selection of improved satellite-based water quality indicators for coastal and transitional environments. These indicators were developed based on new state-of-the-art remote sensing data and ensure compliance with user-specific monitoring requirements. The suite of remote sensing indicators ranges from those tailored to fulfil spatial planning and water resource management needs of industries and local authorities, to those that help to better understand ecosystem functioning and provide input to European Directives. They use estimates of total suspended matter and chlorophyll-a concentrations and include region-specific mean values, anomalies, percentiles, and trends, among others. A selection of these indicators and other multidisciplinary data were then integrated into a Social-Ecological System Vulnerability Index, aiming to showcase a framework that provides global overviews of transitional systems and highlights hotspots of vulnerability to climate change and other anthropogenic pressure. Here, we describe the approach we followed to maximise involvement of various types of user communities throughout the indicator co-development process, ensuring provision of processed information that meets their water quality assessment needs for water resource management. The co-developed indicators are also presented and discussed from a user perspective.

1. Introduction

Water quality is a worldwide issue and crucial for human consumption, food production, terrestrial and coastal aquaculture and fisheries, and safe recreational exploitation. Maintenance of good water quality is a fundamental consideration in industrial activities on land, in rivers and transitional waters along the coast (Bukata et al., 1981; Hirsch et al., 1982; Devlin et al., 2015; Harvey et al., 2015; Gohin et al., 2019; Braga et al., 2022). At international level, monitoring and maintaining good water quality are enshrined in European policy through the Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD) and pivotal to fulfilling the UN Sustainable Development Goals, notably 6 (Clean Water and Sanitation) and 14 (Life Below Water) (https://sdgs.un.org/goals). Due to the dynamic nature of processes that often involve fast ecological responses to anthropogenic pressure, a good understanding of the mechanisms involved is key (Brito et al., 2020). In this context, the development of simple and meaningful indicators that allow easy diagnosis of the direct effects of biogeochemical stressors (e.g., eutrophication) in water ecosystems, highlighting the pressure-impact relationship, is crucial. In addition, for users operating across multiple water bodies, the development of common or harmonised water quality products across the continuum of water bodies, from

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lakes to estuaries to coastal waters and offshore water, would be beneficial. Such products could be further considered for contributing to harmonisation of EU WFD and MSFD reporting across different water bodies and regions, making it possible to elaborate integrated management strategies (Sprovieri et al., 2021), especially where transboundary water bodies are concerned.

Remote sensing has since long provided an important source of geospatial information for quantifying and mapping water resources (Dube et al., 2023b; Politi et al., 2016). Contrary to traditionally used in-situ sampling, the synoptic, wide area coverage and frequent observations provided by satellite-based remote sensing provide an advantage over point-based, laborious and often sparse and infrequent in-situ data measurements (Dube et al., 2023a; Sheffield et al., 2018). Despite that, remote sensing is still not well established as a standard, universal method across water management practitioners (Sheffield et al., 2018), leaving both a gap and an opportunity to improve local and national monitoring programmes by integrating satellite-based water quality information with data derived from in-situ measurements.

Bridging the importance of ecosystems in coastal and transitional marine environments and the major role that satellite remote sensing can play in their monitoring and management, the European Copernicus programme freely provides water quality data and indicators through three Copernicus Services; namely, the Copernicus Climate Change Service (C3S; https://climate.copernicus.eu), the Copernicus Marine Environment Service (CMEMS; https://marine.copernicus.eu), and the Copernicus Land Monitoring Service (CLMS; https://land.copernicus.eu). However, the provision of water quality data and indicators between these three Copernicus Services has largely evolved independently. As a result, there are methodological differences as well as gaps in data provision, most notably in complex near-shore and inshore environments including estuaries and lagoons, which are transitional environments (Tagliapietra et al., 2009). This is partly due to the challenges that remote sensing has been facing in transitional aquatic environments, such as non-covarying water constituents (Morel and Prieur, 1977; IOCCG and Sathyendranath, 2000; IOCCG and Lee, 2006), the adjacency effect (Bulgarelli et al., 2014), the complexity of atmospheric influence on the satellite signal (notably, the aerosols present) (Ahmad et al., 2010; Antoine and Morel, 1999; Gordon and Wang, 1994; Moore et al., 1999), and the influence of bottom reflectance on the signal in clear shallow waters (Kutser et al., 2020; Lee et al., 1998, 1999; Maritorena et al., 1994). Presently, the lack of a harmonised approach across the Copernicus Services means that data consumers, including industrial actors and monitoring agencies whose remit covers coastal, estuarine or lake environments, scientists interested in connected lake-river-sea systems, or downstream service providers, would need to visit two or even three Services to obtain products that are in different formats, processed with different methods and with different characteristics. Users would also need considerable expertise in remote sensing to judge which sources are the most relevant to their needs in situations where there is overlap. In other cases, there are examples of water bodies that are not currently covered by Copernicus (e.g., estuaries). Therefore, providing user-based solutions to harmonise water quality indicators across the continuum of water bodies, whether this is for EU WFD/MSFD reporting or other scientific and monitoring purposes, remains a crucial need. For this purpose, the close interaction with key intermediate and final user communities, including industry, policy-makers and the academic community to ensure their specific requirements in monitoring water quality in transitional waters are met, is a fundamental step.

There are various practices on how to involve third parties for the purpose of receiving feedback and several approaches for consulting stakeholders, with the best-fitting approach depending on the question at hand. Usually, the interaction with users and stakeholders is the first step for the collection of user and technical requirements, when aiming at the definition of novel observational products or input towards management strategies. Such a bottom-up approach to managing transitional environments and their communities includes participation to the planning, co-production, and implementation of tools and strategies. In fact, it is widely recognised that involvement of stakeholders in the co-development of a water quality service is necessary to maximise relevance and uptake (El Serafy et al., 2023) and key to long-term resilience and sustainability (Butler et al., 2015).

Previous studies, as well as EU and non-EU projects, have involved practice actors in the development of products and indicators for water quality (e.g., Brotas et al., 2014) and the co-development of management strategies in transitional waters, such as lagoons (e.g., Davies-Vollum et al., 2021). In the FP7 AQUAUSERS (www.aqua-users.eu), a project aimed to support the growth of efficient and sustainable aquaculture production, periodic user meetings led to a definition of a user requirement document that set user-relevant and timely information based on the most up-to-date satellite data and innovative optical in-situ measurements (Brotas et al., 2014). This pioneering effort developed a web portal and mobile application that brought together satellite information on water quality and temperature with in-situ observations, developing regional optical algorithms, harmful algal bloom detection and aquaculture monitoring tools based on satellite-based estimates of chlorophyll-a, sea surface temperature and total suspended matter. The application of suchlike participatory approaches ensures coastal communities are central to the joint management of their resources and local environment.

Another such example is that of the Resilient Lagoon Network initiative (https://lagoonnetwork.org/) which organised in-person and online workshops aiming to bring together a multistakeholder group to discuss issues around the resilience of lagoon communities and maximise collaboration by engaging all interested stakeholders. In this participatory approach, community knowledge is used to bridge the gap between national policy, climate research, and lived experience of climate change (Clarke et al., 2013). However, this kind of effort does not encompass the co-development of remote sensing products and indicators that would constitute the basis for monitoring tools that are suitable for actual user needs. In the EU-funded H2020 project FORCOAST (https://forcoast.eu/) both producers and users of oceanographic services were involved in the consortium, aiming at the design of consistent high-resolution information services by incorporating water quality and met-ocean indicators for the improvement of planning and management in coastal marine aquaculture activities. In that case, the consultation process was conducted by means of surveys and/or dedicated workshops whose outcomes are reported in project outputs that, in turn, define technical specifications for tailored products. The approach, however, lacked an integrated community that spans from estuaries and lagoons to neighbouring coastal areas, and it aimed at the implementation of a downstream service rather than the development of back-end observational products.

Having realised the accessibility gap between users operating in transitional aquatic environments and satellite-derived information, we aimed to address the question: *how can we tailor remote sensing products that are fully compliant with these users' needs?* Our objective was, therefore, to develop and demonstrate cross-cutting remote sensing-based water quality indicators, suitable for transitional water monitoring and reporting purposes, using lagoons and estuaries as case studies. Specifically, we aimed to assess: a) whether the inclusion of tailored-made satellite-based water quality indicators can contribute to bridge the current gap between operational water quality monitoring and lack of continuous, synoptic data in transitional waters; and b) what types of products for water resources management in transitional waters can enable users and stakeholders to better monitor, manage and make decisions on water quality. To achieve this, we have closely interacted with key user communities aiming to ascertain their special requirements with respect to the quality and characteristics of the remote sensing-based information they would each require in their field of work, and that resulted in a suite of tailored-made indicators based on remote sensing data.

2. Methods

2.1. Identification and description of targeted users and stakeholders

The selection of users to engage with was based on several criteria. First, users would need to be operating in transitional waters (we focus on lagoons and estuaries), directly exploiting and/or benefiting from ecosystem services in these environments. In addition, to ensure variety and plurality in the collected requirements, the following criteria were further applied to our selection approach: (1) we targeted users from different sectors (e.g., water pollution, maritime safety, offshore energy, *etc.*) and with different interests (e.g., eutrophication, sediment loads, river-estuary interactions, dredging activities); (2) the users would need to have different levels of knowledge of and (potential of) interaction with remote sensing data (e.g., being direct upstream users or through downstream providers); and (3) we wished to cover a variety of types of stakeholders (e.g., local communities, private companies, local authorities, national institutes and agencies, and "brokers" of groups of services). This enabled us to select a wide diversity of users who focus on industrial, policy and environmental issues in transitional waters, and who were brought together in our collective user community.

This community of users operates in six European transitional waters; three coastal lagoons and three estuaries. These six case studies (Fig. 1) were also carefully selected to be complementary, and to overlap in terms of service or user characteristics to avoid basing conclusions only on a single instance. Each of the six case studies involves one or more users and stakeholders.

Depending on their interaction with remote sensing products, our users can be characterised as "intermediate" or "final" users. Intermediate users are those who will take advantage of this work's outcomes by subsequently providing downstream services that use the baseline data and the derived indicators, proposed herein, to provide services for other end-users. Final users are those end-users that will directly benefit from our products by obtaining and using data directly for their own purposes. Both intermediate and final users were identified for all sectors under consideration (see Figs. 2 and 3), in which different users play a different role in being an intermediate or a final user, depending on the sector.

Figs. 2 and 3 provide a general overview of the number of engaged users, organised by the sectors that they operate in. The sector pertaining to "water pollution" is the most represented (Table 1) since it is relevant to all case study areas and for 14 of the 18 stakeholders (among final and intermediate users). Other sectors included: maritime safety, offshore energy, tourism and recreation, coastal protection, ports and shipping, sustainable marine living resources, weather and climate, basic and applied research. Beside these nine high-level sectors, we also recognised some more specific fields of interest, such as dredging and supply monitoring, data feeding for modelling activity, eco-geomorphology, and sustainable exploitation of reed beds – these are listed under "other" in Figs. 2 and 3.

A cross-case study, cross-sector, and cross-environmental matrix analysis of the engaged users was then performed. The basis of the analysis was the information gathered in the case study areas during one-to-one consultations with users. Based on these consultations, the targeted communities can be broadly grouped into:

- planners and managers from the industry and local authorities: users that require good and reliable information on water quality for industrial, commercial and/or recreational purposes, including

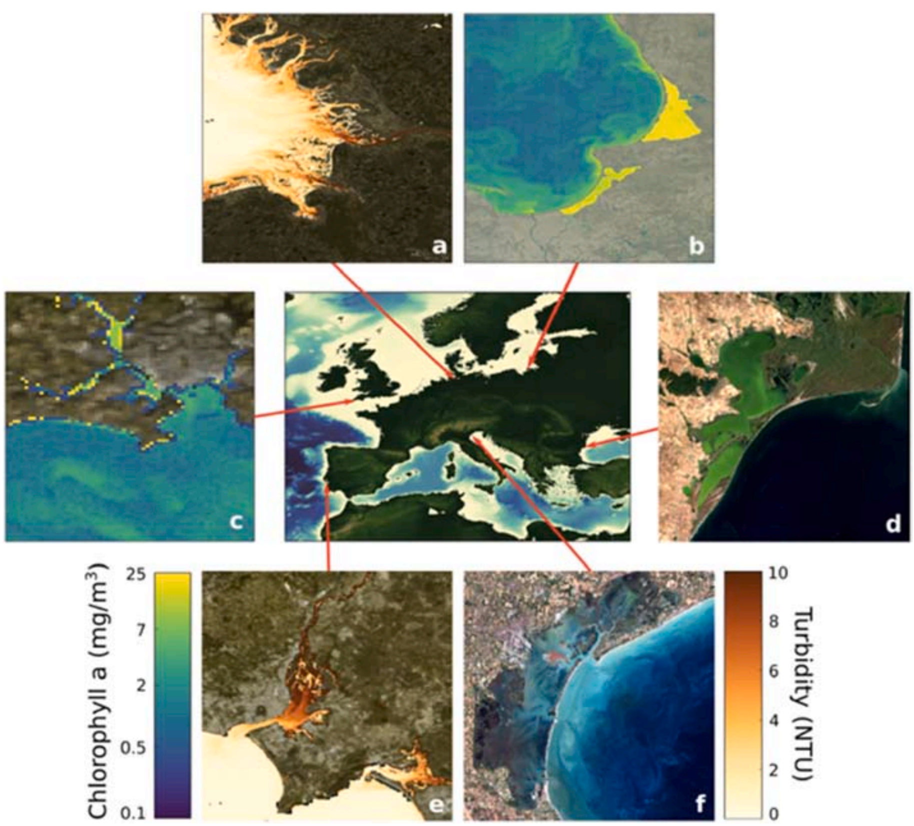

Fig. 1. Six case study areas a) Elbe estuary and German Bight: turbidity from Sentinel-3 Ocean and Land Colour Instrument (OLCI); b) Curonian lagoon, Sentinel-3 OLCI chl-a concentration; c) Tamar estuary: Sentinel-3 OLCI chl-a concentration; d) Razelm-Sinoe lagoons system: Sentinel-2 Multispectral Instrument (MSI) true colour composite; e) Tagus estuary: Sentinel-3 OLCI turbidity; f) Venice Lagoon: Sentinel-2 MSI true colour composite. All derived parameters are a blend of water quality retrieval algorithms; land is filled with true colour top-of-the-atmosphere radiance from the same image. True colour images are atmospherically corrected for Rayleigh scattering. The central map is bathymetry and topography from the General Bathymetric Chart of the Oceans (GEBCO).

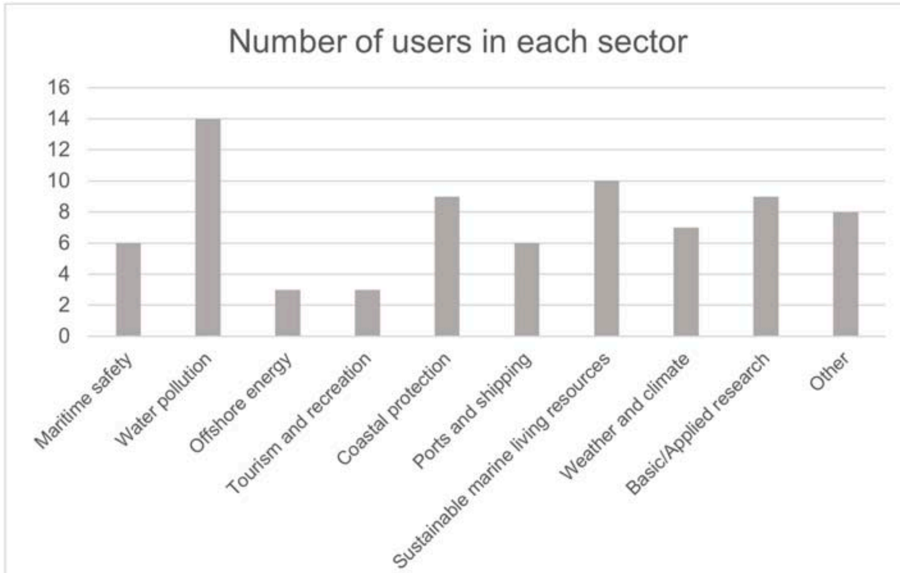

Fig. 2. Number of users engaged in each sector that are expected to benefit from the outcomes: users may operate in more than one sector.

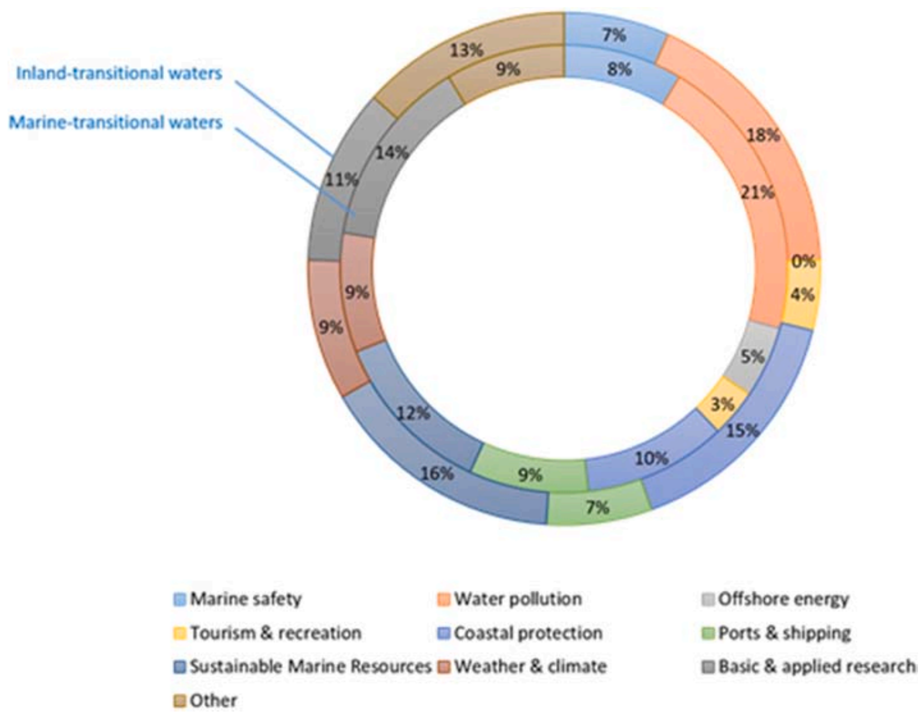

Fig. 3. Percentage of identified users by sector, split by geographical region: inland-transitional waters and marine-transitional waters.

maritime safety, port and shipping management, water pollution or tourism activities;

- managers reporting under EU Directives: entities at both national (e.g., institutes for environmental protection and research) and regional level (e.g., regional environmental protection agencies) that hold the responsibility of conducting ecological and environmental quality assessments, as well as reporting obligations in terms of the overall water quality conditions;
- scientific communities: research and scientific communities that investigate transitional water bodies and those needing a synoptic overview of the water bodies in their jurisdiction, including ecologists, geomorphologists, biologists, hydrologists, geographers, *etc.*

2.2. *Collection of user requirements prior to development*

User community requirements regarding the types of indicators needed were collected during one-to-one in-person and online consultations using a common questionnaire across all user types. Information regarding content, quality and technical requirements was collected. These consultations encompassed a review of existing products, methodologies and approaches implemented in existing Copernicus Services as well as in EU policy (WFD and MSFD) and industry (aquaculture, port authorities, *etc.*). They also aimed to identify target products and a suite of indicators suitable for industry (e.g., shipping and aquaculture), local authorities (e.g., port authorities) and regulators (e.g., environmental agencies in charge of reporting on MSFD and WFD). Finally, current gaps

Table 1
The sectors that are expected to benefit from the project outcomes in each case study area based on consultations with our engaged users: Danube Delta and Razelm-Sinoe Lagoons System (Black Sea), Venice Lagoon and North Adriatic Sea (Mediterranean Sea), Tagus Estuary (Atlantic Ocean), Plymouth Sound (English Channel), Elbe Estuary and German Bight (North Sea), Curonian Lagoon (Baltic Sea).

Sectors	Case study areas					
	Danube Delta and Razelm-Sinoe Lagoons System	Venice Lagoon and North Adriatic Sea	Tagus Estuary	Plymouth Sound	Elbe Estuary and German Bight	Curonian Lagoon
Maritime safety	X	X	X	X	X	
Water pollution	X	X	X	X	X	X
Offshore Energy				X	X	
Tourism & Recreation	X	X				
Coastal protection	X	X	X		X	X
Ports & Shipping	X	X	X	X	X	
Sustainable Marine living Resources	X	X	X			X
Weather & Climate	X	X		X		
Basic and applied research	X	X	X	X	X	X
Other	X	X		X	X	

in data availability from the Copernicus Services (jointly exploring what is available and how it could or could not be used) were discussed, followed by formulation of a set of minimum and ideal requirements to steer the development of useful indicators (selection of water quality parameters, spatial resolution/aggregation, *etc.*). This was considered a key step in the co-design process and set the basis for a fruitful relationship with users, encouraging bidirectional communication towards the development of indicators that aimed to be both useful and suitable for their reporting and monitoring purposes. Following collection of user requirements during these initial consultations, analysis of these requirements identified specific needs on the type of water quality parameter(s), data characteristics and response time range, which fed into the indicator development.

2.3. Development of indicators

During the indicator development process, we adapted existing methods from published literature and developed our own ideas, to be able to satisfy the breadth of our user community needs. Several methods to assess water quality changes, such as 90th percentile of chlorophyll-a (CHL) concentration (Park et al., 2010; Ferreira et al., 2011; Gohin et al., 2019), K-means clustering of CHL and Total Suspended Matter (TSM) concentration (Blondeau-Patissier et al., 2014), clustering water colour classes (Devlin et al., 2015) and climatological analyses (Beltrán-Abaunza et al., 2017; Braga et al., 2022) are based on statistical analysis of remotely sensed datasets. However, few of them provide metrics that are integrated for the whole water body.

Another type of indicator relevant to water resource management, is a vulnerability index. There are several approaches to developing vulnerability indices, but a lot tend to only focus on the ecosystem aspect only. For example, the commonly used Coastal Vulnerability Index (CVI; Gornitz, 1991) looks at coastal vulnerability to sea level rise and this is defined as the risk of erosion and/or inundation. More recently, the social and economic aspects of coastal zones and transitional water bodies have come into focus, due to those areas' unique location in the boundary between land and sea, where multiple human activities take place. There have been several studies where both the aquatic system itself and the social system operating in, and around it, are both considered. For example, McLaughlin and Cooper (2010) looked at coastal (geomorphological) characteristics and coastal (sea) forcing in combination with socio-economic information, such as land use, population and road infrastructure. The Freshwater Health Index (Vollmer et al., 2018) incorporated ecosystem vitality with ecosystem services, governance and stakeholders, looking at the biophysical context next to the socio-economic and political dimensions. Another example is the Circles of Coastal Sustainability (CCS) framework (de Alencar et al., 2020), where the environment and ecology are treated as equally important as economics, governance and policy, society and culture. The larger the number of variables into consideration, the more complicated a framework becomes, not least because it is often difficult to source all the required datasets at the desired spatiotemporal scales (e.g., McLaughlin and Cooper, 2010; de Alencar et al., 2020) or accuracy. However, none of these examples integrate remote sensing data alongside the other data sources.

Aiming to bridge adaptations of existing methodologies, with new and specific user needs, we developed three types of indicators:

1. Simple indicators based on statistical metrics (e.g., 90th percentiles and medians) over aggregated time periods and spatial regions in the water bodies, in alignment with the user needs to better monitor and report on their water resources.
2. Moderate-complexity indicators, for which more processing than simple aggregation and statistics are needed. This type of indicators aims to address spatiotemporal characteristics and trends/shifts in the water bodies, in alignment with the user need to better manage their water resources.
3. A high-complexity index, in alignment with the user need to have a holistic overview of their water resources and what specific pressures affect those.

To develop the indicators, freely available Copernicus Sentinel remote sensing data were used. These were processed under the H2020 CERTO project (https://certo-project.org/) to correct for atmospheric disturbance, mask invalid pixels (e.g., cloud cover and mixed) and apply water quality retrieval algorithms suitable for the six case study areas. The supplementary material attached to this manuscript lists the sources of other data used, where applicable.

2.4. Collection of user feedback during and post-development

Continuous interaction with the same group of users who were consulted prior to development was necessary to guide indicator co-development, and to receive final feedback in the end. Our continuous interaction with engaged users took the form of meetings and demonstrations of methods and drafts and were either done in-person or online over the course of the development process. As each user had identified their own needs during the initial consultations, these demonstrations were tailored accordingly to their specific interests.

In the end, feedback from users was collected using an online survey. This survey aimed to assess the adequacy and usefulness of the indicators developed following user requirement collection and was organised in several sections amongst which one related to the indicators themselves, and another related to general feedback and outlook. The survey contained 18 questions (Table 2) and could be

Table 2
Survey questions used to collect feedback on the developed indicators.

Question ID	Question text	Type of question
1	Please select below the category which fits best your work or sector of activities.	Responder can choose one of several predefined answers
2	How would you define yourself with regards to the use of these indicators?	Responder can choose between ‘intermediate’ and ‘final’ user
3	Are you experienced with Earth observation data/products?	Responder can choose from ‘no’, ‘a little (knowledge but no use’, ‘some (sometimes used)’ and ‘a lot (frequent usage)’
4	Which of the following indicators are you interested in?	Responder can choose multiple options from the developed indicators, or ‘none of the above’
5	How well did we meet your expectations?	Scale used 1–5, from ‘1’ being “not at all” and ‘5’ being “fully” with an option to select ‘No answer’
6	How well did we understand your needs?	(as above)
7	Were you satisfied with the indicators and information received?	(as above)
8	Were you satisfied with the quality of communication from our side?	(as above)
9	Would you use any of these indicators in your daily work?	(as above)
10	How do you rate the readability of the indicators/maps?	(as above)
11	If answered 0–2 in the question above, what made the maps difficult to read and how can the readability be improved?	Free text
12	How useful are the phytoplankton bloom phenology indicators for your applications?	Scale used from 0 (not useful) to 5 (very useful)
13	How useful is the CHL P90 indicator for Water Framework Directive reporting?	(as above)
14	How useful is the TSM P90 indicator for Water Framework Directive reporting?	(as above)
15	How useful is the Maximum Sediment Zone indicator for your applications?	(as above)
16	If you selected not useful in any of the above, what would make it more useful? E.g., more/less detailed information charts (plots, maps, statistics)? Other metrics?	Free text
17	How useful did you find SESVI for your applications?	Scale used from 0 (not useful) to 5 (very useful)
18	Please write below anything else you would like to share with us.	Free text

completed within 5–10 min.

The general feedback section of the survey (questions 1–11) gathered information on the individual or institution answering the survey (working/research sector, “intermediate” or “final” user, experience with remote sensing data or not, and the indicators of interest). This section also asked questions regarding the quality of the products provided, including whether these answered their needs, met their expectations, and were of value to them. The section dedicated to the indicators (questions 12–18) asked whether each indicator was considered useful for the user’s applications and needs, and also provided a free form text area in which the person answering the survey could also write any comment they wished to expand and/or explain their chosen answers. This was especially relevant for those answers where the user felt the indicator did not meet their needs.

3. Results

3.1. Analysis of user requirements

Our initial user consultations highlighted that most of the users (in particular, planners and managers for industry and local authorities) rely on *ad hoc* in-situ water sampling, at selected stations, to measure parameters such as temperature, chlorophyll concentration or turbidity. These samples are either performed in person during sampling campaigns, spread out over a given period, or with the help of automated systems carrying instruments. According to the survey responses, modelling is also a useful tool to assess and plan water transport, especially around port activities, although strongly affected by the lack of proper calibration and validation.

The consulted users agreed that *adding high quality remote sensing data would provide valuable, synoptic information* to their existing efforts. Providing aggregated remote sensing data in the form of indicators is highly relevant to local authorities who may be overwhelmed with the amount of data obtained daily; these indicators should be, however, tailored to their needs (e.g., maps of water distribution along the river), making the transition to using remote sensing products in their daily operations as simple as possible. In the two sub-sections below, we summarise the results of our user requirements analysis: (i) what user needs emerged in terms of types of parameters, and (ii) what user needs emerged in terms of the data characteristics, such as the spatio-temporal coverage and resolution, the preferred data format and required response time.

3.1.1. Parameter needs

The majority of consulted users require data in ‘Marine’ (14 users) and ‘Transitional’ (11 users) water bodies, with fewer users (6 users) additionally seeking ‘Inland’ water data. This puts the emphasis on indicators targeted to transitional-to-open waters, without excluding the possibility of extending their application to inland water bodies. These users require data on the biological structure, composition and overall quality of water. These include parameters such as CHL, TSM and basic physico-chemical water properties that may have an effect on the biogeochemical dynamics of the water body, such as Sea Surface Temperature (SST). CHL and TSM, in particular, were identified by more than ten users as relevant information/data for their activities. This was confirmed by users from all case studies, i.e., Danube Delta and Razelm-Sinoe Lagoons System, Venice Lagoon, Tagus estuary, Plymouth Sound, Elbe estuary and Curonian Lagoon. Other properties, such as SST, water turbidity (TUR), salinity and Dissolved Oxygen (DO) of the water column were also considered valuable products by nine, seven, six and five users, respectively. An SST product was considered important by users from all case studies, except Plymouth Sound and Elbe Estuary. Water turbidity was considered important in all case studies, except Venice Lagoon. Salinity was only considered relevant by users from the North Adriatic Sea (i.e., Venice Lagoon and Po River Delta coastal area) and Tagus Estuary. DO was considered important by users from the Danube Delta, Venice Lagoon and Tagus Estuary.

It is important to note that these results are also likely to reflect the ongoing monitoring programmes in place at the different case study regions, as well as the users’ current ability to access data. For example, SST is a standard product that is useful for understanding local dynamics. Nevertheless, it was not identified as critical by users in the Plymouth Sound and Elbe Estuary. These are sites where in-situ monitoring systems are frequently implemented and, therefore, a lot of in-situ data are available. Users from the Venice Lagoon did not identify TUR as one of the most important needs because they have access to this parameter already. However, in the Northern Adriatic Sea, some users indicated that real-time data on TSM and TUR would be key for modelling approaches of storm surges. In particular, TUR is recognised as a useful parameter, able to provide general information on water quality, including both biogeochemical elements and terrigenous suspended (or re-suspended) material. However, many users highlighted the need for a more quantitative parameter, such as TSM, which would better assess issues related to geomorphological instabilities or modifications due to extreme events and, in particular, floods, surges, storms, sediment resuspension due to cruise ship traffic, *etc.* Estimation of TSM may also work for the assessment of the trade-off between coastal restoration and eutrophication, a topic that is crucial for those sites that are sensitive to eco-geomorphological issues. A specific recommendation for those two parameters (in river systems) concerned the ability to relate them to the local hydrodynamic regime of the river (i.e., velocity of the river flow or bed shear stress) and, thus, to have a synoptic visualisation of TUR/TSM within the fluvial channel. This information should go along with the possibility to extract time series and to recognise anomalies, with respect to a given climatology within the estuaries and lagoons. A further improvement of TUR and TSM parameters is the estimation of grain-size distribution of suspended material (Pitarch et al., 2019).

Overall, all users are interested in these standard products; namely, CHL, TSM, SST and TUR. In most cases, however, they expect improved products, in terms of higher spatial and temporal resolutions and harmonised for the water continuum, as well as processed information in the form of trend analysis, anomalies, spatio-temporal aggregations, percentiles, *etc*. This seems crucial for helping users in their local responsibilities, such as decision-making, licensing and EU Directives reporting.

Some entities have also requested products related to nutrient concentrations, Remote sensing reflectances (Rrs), pH values, Sea Surface Height (SSH), and microplastic concentration. Rrs data seems to be very important for intermediate users. Nutrients, pH, SSH and microplastic were only requested sporadically and do not form the basis of what the majority of users are generally seeking. What is more, with the exception of SSH, these products cannot be derived from remote sensing data. As this study focused on indicator development with the goal to improve user interfacing with remote sensing data, products not derived from remote sensing data were outside the study scope.

During the user consultations, it also became apparent that there is a strong need for indicators that better describe aquatic systems and their potential change in a wide context in terms of their anthropogenic use and landscape setting. To fulfil this need and to serve as a showcase of the value of remote sensing to the users when that is integrated with diverse sources of data (social, economic, and modelled data), a complex index was developed: the Social-Ecological System Vulnerability Index (SESVI), building on existing methodologies.

3.1.2. Data characteristics and response time

For each case study area, information was collected on the most suitable service and technical requirements that the users envisioned for the desired parameters and indicators. In particular, users were asked to provide information on (Figs. 4–6):

- spatial and temporal resolutions required for indicator development;
- type of aggregation (i.e., daily, weekly means, monthly means, seasonal means, or climatological means);
- production mode (i.e., near real-time or reanalyses);
- data format (i.e., GeoTIFF, NetCDF, single point/boxed averaged time series, *etc.*);
- type of service (operational, on demand).

In terms of temporal resolutions for the provision of remote sensing information and indicators, daily and weekly products were identified as the most preferred (Fig. 4). Some users, however, highlighted the need for further processed information. This results from the fact that several users cannot handle a direct provisioning of data and products, but rather, they would prefer a user-friendly visualisation of indicators, along with an *ad hoc* analysis to highlight trends and anomalies in time and space. Some users asked for smart visualisation tools (e.g., apps for

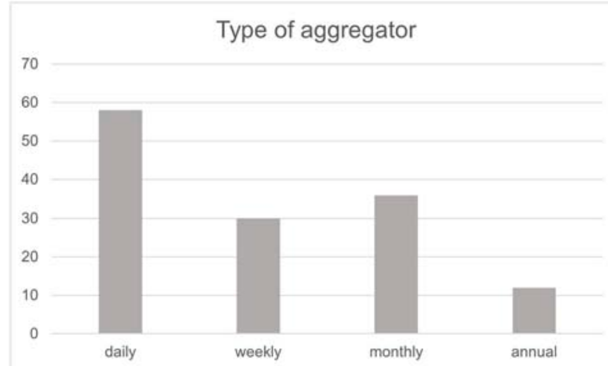

Fig. 4. Statistical representation (%) of the outcomes from the user consultations regarding the type of aggregator. About 60% of users would prefer daily products, almost 40% and 30% of users asked for monthly and weekly means, respectively. Few users (∼10%) are interested in annual means.

Fig. 5. Statistical representation (%) of the outcomes from the user consultations regarding the production time. About 60% of users would prefer real-time products while approximately 40% of users asked for reprocessed (not real-time) products.

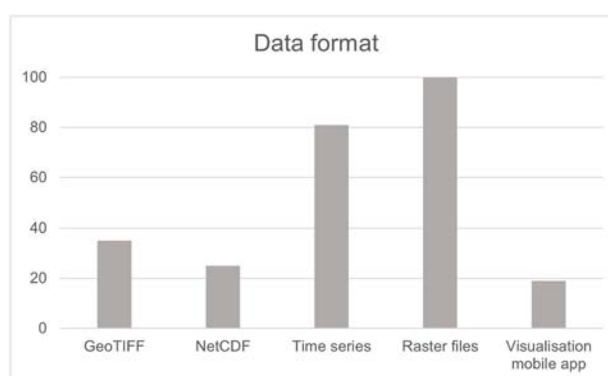

Fig. 6. Statistical representation (%) of the outcomes from the user consultations regarding data format. All users asked for raster images while 80% would also prefer time series in the form of spreadsheet files. Few users are interested in GeoTIFF (35%) and NetCDF (25%) files. It is worth noting that 20% of users would also prefer product visualisation for smartphones.

mobile phones) to be able to access the water quality information in an easy and portable format (Fig. 6).

Datasets should be provided to users as either high-level processed data or in the form of static maps or reports, available with little or no additional processing required by the users themselves. Reports can be in a form suitable for addressing EU Directives, such as WFD and MSFD. Research-oriented institutions additionally requested the availability of lower-level processing data for the purposes of forecasting, research, or modelling. Spatial resolutions are generally requested to lie towards the finer scales, and datasets are desired in the 10–100 m range.

User requirements are split evenly in terms of the need for real-time data (Fig. 5). In general, most users operating in the Danube Delta and Razelm-Sinoe Lagoons System, Venice Lagoon, and Tagus Estuary do not require real-time data. Users in the Elbe Estuary, Curonian Lagoon, and Plymouth Sound are seeking real-time data, where possible. Finally, users interviewed across all regions are seeking both an operational and/or an on-demand service, wherever each is possible depending on the product, region, and context of the dataset requested.

It is worth noting that some requirements expressed by end-users represent a demand for improved quality of data to which users already have access. Remote sensing products can also be reprocessed and reanalysed to produce mean values or trends. For example, this could include common indicators such as the CHL 90th percentile or other similar existing products that could be refined in accordance to the users' needs. Of special interest for discussion was the production of more integrated indicators for water quality, including various parameters (e.g., TSM, TUR) into specific indicators, harmonised across the six study areas for application across sites.

Following analysis of the information gathered during the user consultations, a suite of indicators was selected as the most suitable and feasible based on satellite data, aiming to serve each of the user communities.

3.2. Resulting indicators

Here we present the suite of indicators developed with the aim to serve our user community. All the indicators are described in the Supplementary Material that accompanies this manuscript.

3.2.1. TSM-based indicators

The indicators presented in this section focus on the influence of sediments and are based on standard remote sensing products of TSM, which can already be considered primary indicators (Falcini et al., 2012; Brando et al., 2015; Braga et al., 2020). Two sets of indicators were developed:

- *Simple TSM spatial metrics*, such as the 90th percentile (TSM P90) for selected water bodies over different periods of time. The aggregated statistics can help management entities better evaluate intra- and inter-annual variabilities for the water bodies they are responsible for, especially when operating in rather dynamic environments such as estuaries or intertidal areas (Fig. 7).

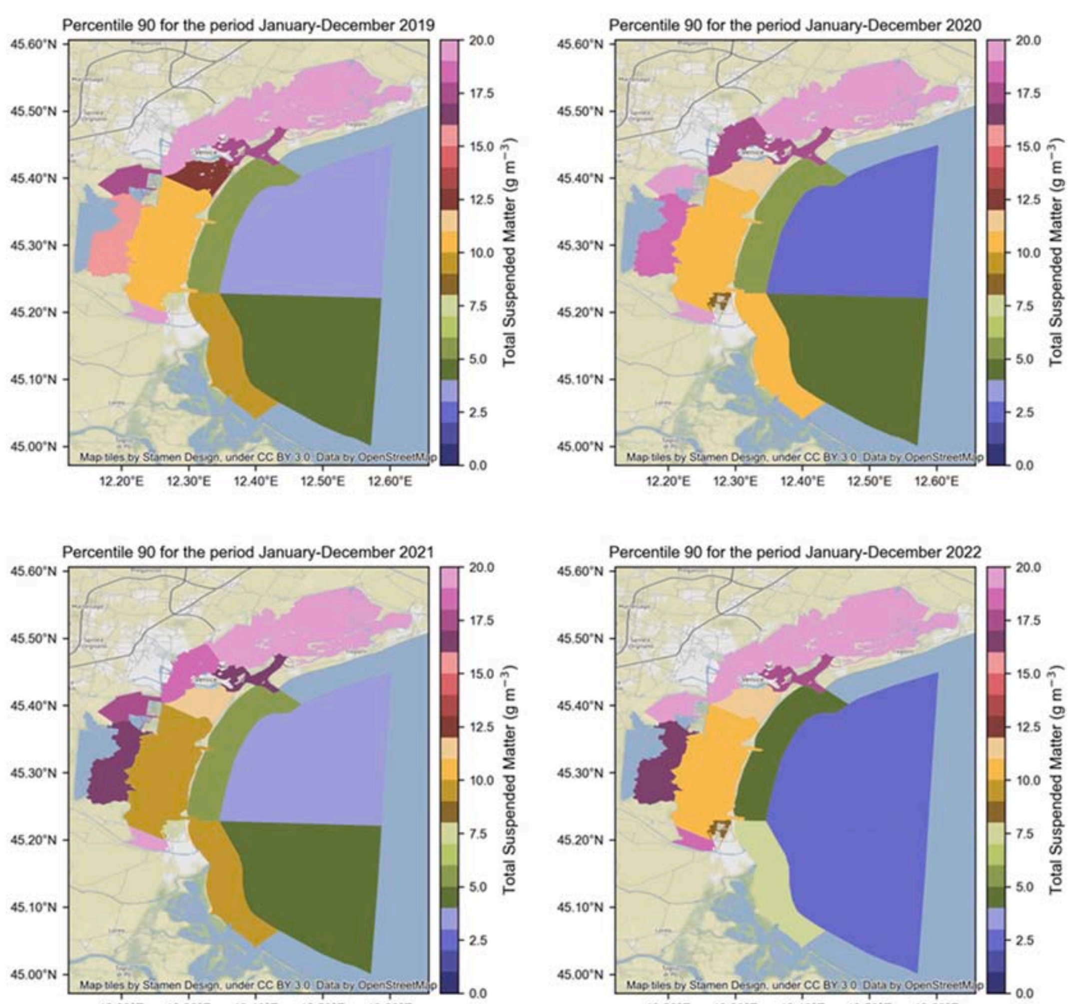

Fig. 7. Distribution of total suspended matter 90th percentile (TSM P90) in the different reporting regions identified for the Water Framework Directive in the greater Venice Lagoon area in the years 2019–2022.

- Indicator for *maximum sediment zone/high loads zone.* The main objectives are to analyse spatial shifts and seasonal trends, as well as to account for tide and river parameters (such as ebb and flood periods, river runoff) and evaluate their impacts (Fig. 8).

The detailed methodology followed for the two TSM indicators is described in the Supplementary Material (SM1).

3.2.2. CHL-based indicators

The analysis of user requirements evidenced that CHL is a crucial parameter, mandatory for any monitoring activity to support EU Directives such as MSFD and WFD, as well as for aquaculture activities. Most of the users interviewed must perform ecological and environmental assessments for EU Directives. For this, improved remote sensing based CHL datasets, which are able to represent the temporal and spatial variation of phytoplankton biomass in transitional areas, are highly needed. In addition, high-level processed data for transitional waters, with increased temporal and spatial coverage, can fulfil important needs of most users, especially when they are provided aggregated spatially and/or temporally.

Two sets of common indicators were, thus, selected:

- *Simple chlorophyll-a metrics*, such as the 90th percentile (CHL P90), used as an indicator of the highest biomass values produced during the most important phytoplankton blooms. CHL P90 is calculated using continuous remote sensing datasets over the growing season in each site (e.g., Brito et al., 2012; Devlin et al., 2007; Revilla et al., 2009, 2010).
- *Phytoplankton bloom phenology metrics* (e.g., Platt and Sathyendranath, 2008; Koeller et al., 2009; Racault et al., 2012; Ferreira et al., 2021). Phenologically-important aspects of the phytoplankton growth are determined by the time of bloom initiation, peak, and end, the main bloom duration, and the number of blooms.

The detailed methodology followed for the CHL indicators is described in the Supplementary Material (SM2).

To assist with EU Directive reporting, CHL P90 is provided per reporting water body (Fig. 9 bottom), whilst for other applications this indicator is provided per satellite pixel for the entire water body system (Fig. 9 top). Timewise, it can be provided temporally aggregated through the climatological average (Fig. 9 top) over multiple years (see SM2) or computed yearly (Fig. 10).

The bloom start, peak and end, as well as the duration of the main bloom and number of blooms are demonstrated for the Tagus Estuary in Fig. 11. The analysis of phenological metrics can be used to study the dynamics of phytoplankton blooms, following the rationale that significant pressures imposed on the system should be reflected in terms of changes in the timing of phytoplankton bloom development (Ferreira et al., 2021). Therefore, this indicator provides information on ecosystem health.

3.2.3. The Social-Ecological System Vulnerability Index

The Social-Ecological System Vulnerability Index (SESVI) is a framework for lagoon systems and estuaries that provides quantitative information on how vulnerable a water body system is to pressure or change, based on the system's socioeconomic and environmental characteristics. SESVI combines a wide variety of datasets and information about the system it aims to describe and is, thus, an excellent exemplar of the added value of remote sensing when integrated with other data sources. It includes a suite of indicators that describe the three major components of a vulnerability assessment: exposure, sensitivity and adaptive capacity (IPCC 2001). It also considers both the social system operating around and within the water body and the ecosystem itself,

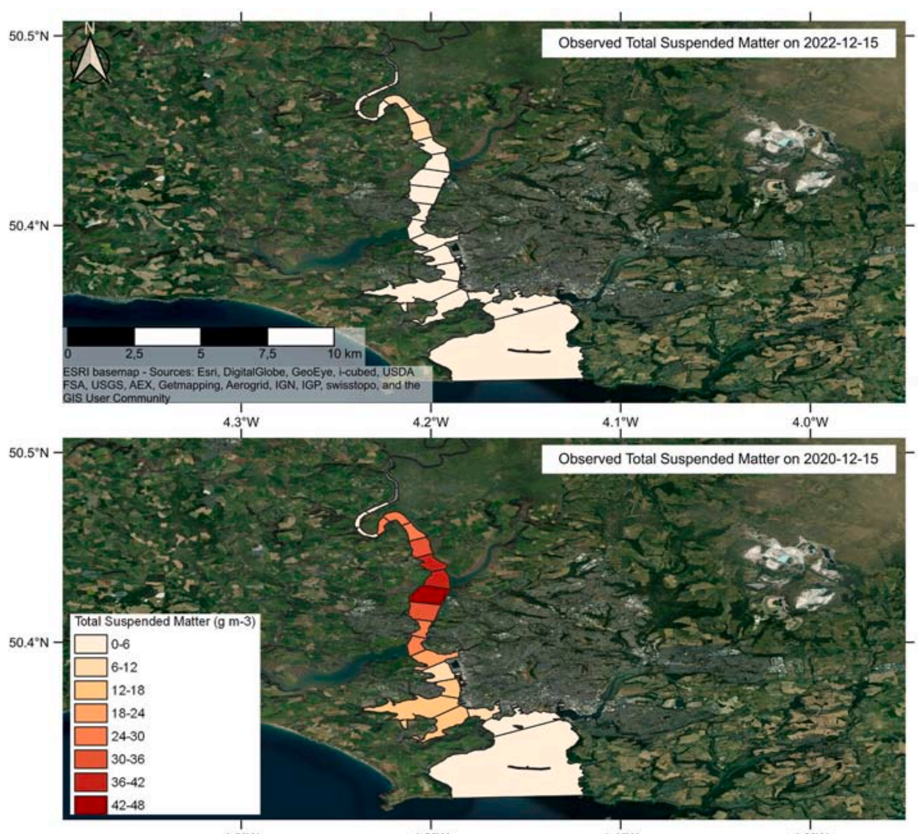

Fig. 8. Median total suspended matter distribution along the river Tamar, delimited in 1 km segments over the same two days in 2022 (top) and 2020 (bottom) highlighting the differences between the two years.

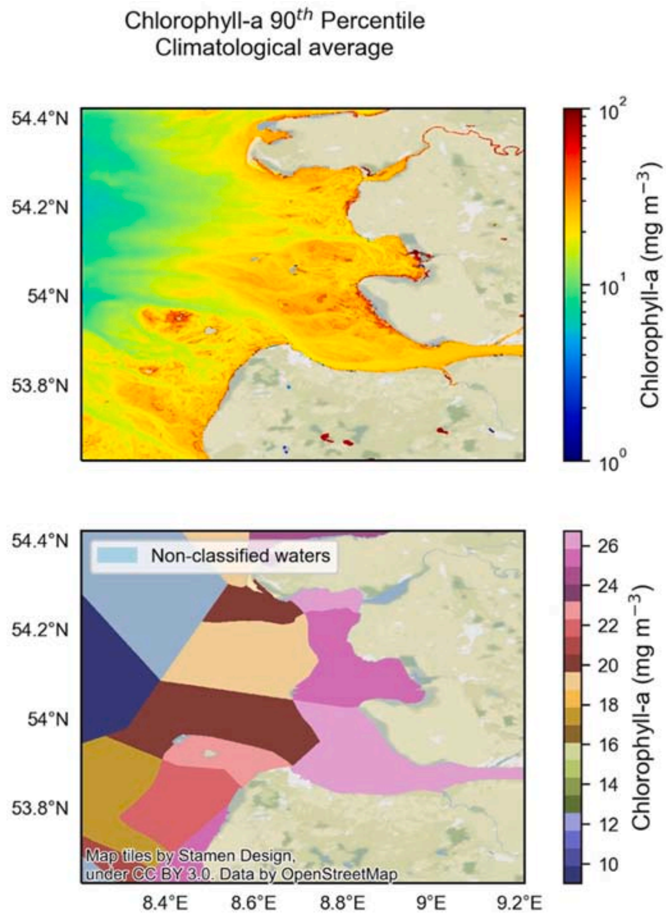

Fig. 9. Climatological average of chlorophyll-a percentile 90 (CHL P90) per pixel (top) and per reporting water body (bottom) for the Elbe Estuary. The climatological average was calculated in the growing season over the years 2017–2022.

taking into account the inherent characteristics of the system and the external forces that can affect its ecological functions and, by extent, its ecosystem services functions. As a result, SESVI reveals the most relevant pressure factors in each water body.

To assist interpretation of the information included and quick comparisons across sites, SESVI is conceived as a wheel, in which a multi-level approach is shown (Fig. 12). Starting from individual indicators (outermost wheel), one can calculate the scores of the three vulnerability assessment components; namely exposure, sensitivity and adaptive capacity (middle wheel), and finally the total SESVI score by aggregation (centre of the wheel).

Suitable indicators based on socioeconomic, terrestrial landscape, ecological and geomorphological variables from existing local and global datasets were compiled to (i) identify the level of exposure of the system, (ii) assess its inherent sensitivity to external pressure and (iii) quantify the level of adaptive capacity of the social system. Each indicator is categorised (from blue (="best status") to red (="worst status")) based on thresholds derived from statistics and/or the literature, as applicable. All the indicator scores under each component were aggregated to provide the score of that component (exposure, sensitivity and adaptive capacity), and the total SESVI score is then defined as the combination of the three component scores. The detailed methodology followed for SESVI, including the datasets used, are described in the Supplementary Material (SM3).

SESVI is demonstrated here for the Curonian Lagoon (Lithuania, Russia) (Fig. 13) and Razelm-Sinoe Lagoons System (Romania) (Fig. 14).

In Fig. 13 one can already see that in the Curonian Lagoon the main areas of concern appear to be relatively high exposure of the system (high fertiliser use, high livestock density, high projected sea level rise and relatively low natural land cover) and relatively low adaptive capacity (high urbanisation, few Natura, 2000 protected areas, relatively low community wealth as expressed in GDP per capita). All these factors can be considered a high risk in terms of the level of pressure that the Curonian Lagoon is exposed to and the local community's adaptive capacity to, for example, climate change and extreme weather phenomena. In addition, the Curonian lagoon catchment is shared and managed by multiple counties (Lithuania, Russia, Belarus and to a lesser extent Poland), posing a need for collaborative cross-border coordination towards effective river basin management.

On the contrary, in the Danube Delta and the Razelm-Sinoe Lagoons System (Fig. 14), one can see that the relatively long residence time (more than 1 year) and the large area of coastal flood prone areas appear to increase the sensitivity of the system to pressure. In addition, the Razelm-Sinoe Lagoons System has moderate to poor ecological status in terms of its water quality, which appears to be the main pressure in the system. Factors that contribute to the site being overall less vulnerable by comparison to the Curonian Lagoon include the large, protected areas, low population density, significant natural land cover and relatively low projected sea level rise.

3.3. *User feedback*

In total, 40 persons from 18 institutes/organisations were sent the online feedback survey, which included those users engaged during the consultations and indicator development. From the survey responses received, slightly more than half (57%) are involved in research; the other half are involved in several working sectors (water pollution for most, but also coastal protection and sustainability, Fig. 15). This is reflected in how the users saw themselves regarding the products: 63% identified with being intermediate users, and 47% identified as final users (note users could click both boxes). This correlates with their experience with remote sensing data, with nearly 50% having none to just a little experience with it.

Overall, users were satisfied (92%) with the indicators and how they were presented to them during the demonstrations (68% were a lot to fully satisfied). They were appreciative of the communication with their case study partners (81% very satisfied) and 89% felt that we managed to understand their needs (from somewhat to fully understood). The study not only understood user needs but also managed to fulfil those for 78% of the users who replied to the survey.

CHL metrics for WFD or MSFD reporting were considered rather useful to very useful by 70% of the users who answered the question. These metrics are highly relevant for people reporting on water quality and eutrophication to the EU as they offer added value to the main observations used for WFD reporting, which are in-situ data. It is known that in-situ data may be sparse in space and time, with sampling campaigns happening a few times per year at dedicated stations. Having access to the higher spatial and temporal information provided by the remote sensing data was considered of great interest in helping the assessments and reporting. CHL P90 was, therefore, recognised by users to be particularly useful to detect spatial patterns of eventual biogeochemical anomalies within estuaries and lagoons, also supporting EU monitoring plans for both MSFD and WFD. In coastal and lagoon environments, CHL P90 is recognised by users as a key indicator for water quality that may help to understand where the best fishing areas are and it can indicate low water levels or stagnant water, also in the light of global change or anthropogenic effects.

The same applied to TSM metrics for WFD reporting. Most users (75%) replied saying that these metrics were rather useful to very useful for them. For monitoring purposes, having a higher spatial and temporal resolution of information is a great addition to the in-situ sampling data that many users work with: these metrics allow to see spatial and temporal patterns more easily.

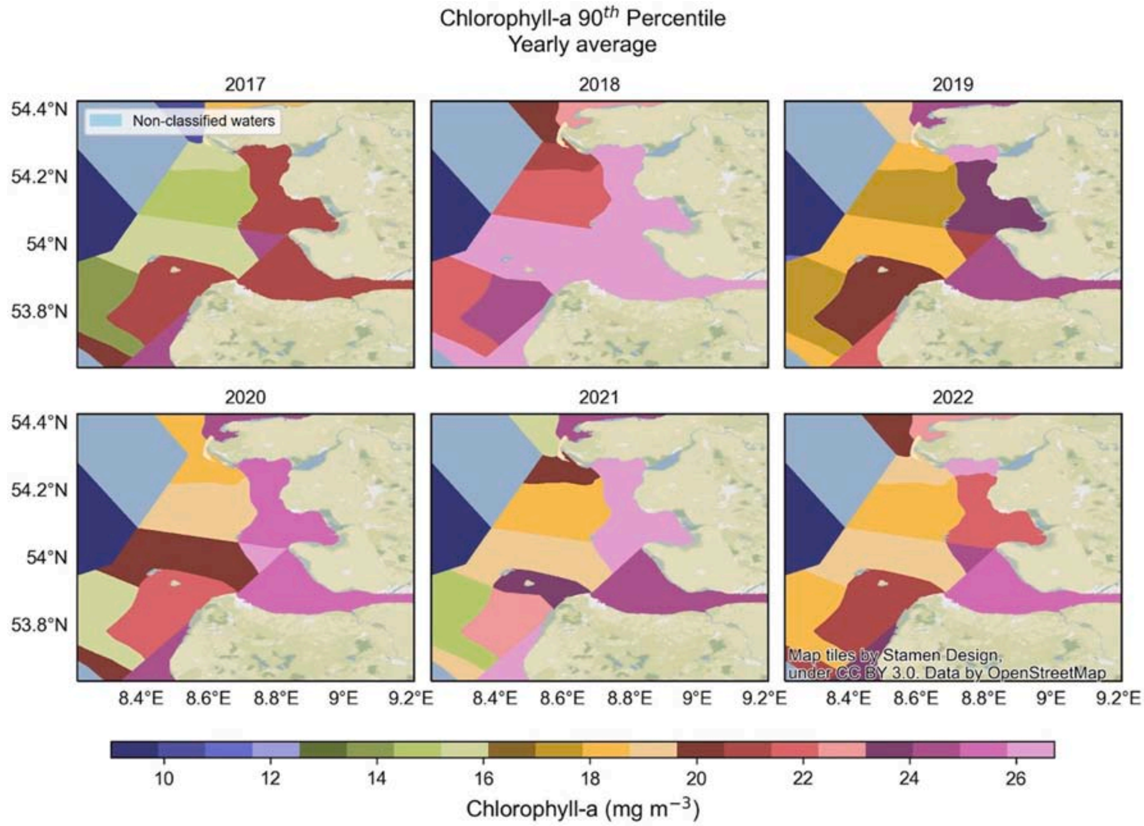

Fig. 10. Yearly average of chlorophyll-a percentile 90 (CHL P90) per reporting water body for the Elbe Estuary in the years 2017–2022.

Concerning the MSZ indicator, those users (75%) that were interested in it found it somewhat useful to very useful. Fewer respondents answered this question (Fig. 16), which is due to the fact that not all users were interested in this indicator. Users appreciated the linked information between river runoff and/or tide and the presence of the maximum sediment zone. They found the correlations drawn quite relevant for monitoring purposes. The maps provided showing the distribution of the sediments along the river were deemed very useful. According to feedback received, the MSZ indicator would fit in the Venice lagoon for the assessment and monitoring of impacts related to the activation of MOSE, i.e., the dam system that prevents the city of Venice from flooding events. In estuarine case studies, this indicator is useful for relating river hydrology to the activation (release) of upstream dams as well as for monitoring the morphodynamics of river backs and mouths. It would also be useful to study spatial and temporal variation of coastal plumes and will complement the information needed for improvement of daily management of dredging activities. Finally, users stated that such an indicator would help identify areas with high sediment deposition/clogging tendencies in channels and lakes.

For the phytoplankton bloom phenology indicators, 79% of the users interested in these found them somewhat useful to rather useful. Many found the maps representing the spatial distribution of the bloom very interesting, especially when compared with in-situ data campaigns, which are often at fixed locations, and only provide information for a limited area within the overall region of interest. Additionally, maps showing the timing of the start and the end of blooms in space were very valuable information for those users that did not have access to fixed mooring stations, providing continuous in-situ data. These indicators were recognised by local users as an innovative tool, potentially useful for further development of WFD and MSFD indicators if their application is achieved for both coastal and offshore waters. Moreover, users stated that the phenology indicators could be key for the EU Bathing Water Directive. Due to their ability to recognise potentially harmful blooms, it may help with understanding where the best fishing areas are, may provide indication of oxygen levels in water, and indicate stagnant or shallow water in those environments that experience significant blooms. Some users pointed out that the information provided by these indicators should go along with additional parameters, such as sea surface temperature and salinity, to diagnose the cause and effect of bloom dynamics.

For SESVI the replies were mixed, with fewer users answering the question (Fig. 16). Those who responded, however, showed high interest and found SESVI useful for their applications (with 55% of the responders rating it as "very useful"). The lower number of users replying here can be explained by the very complex nature of SESVI, which relies on very many different data inputs. Given the complexity of this index, its use may be limited to fewer users such as policy makers. When considering that around 30% of users identified with the "sustainable marine living resources" and "weather and climate" work sectors, which are sectors linked to policy makers, this result is indeed a very good sign and shows the potential of SESVI.

Additional feedback survey results are provided in the Supplementary Material (SM4).

4. Discussion

We have co-developed and demonstrated a suite of indicators stemming from direct consultation and dedicated engagement with users from 18 stakeholder institutes/organisations in six European counties. We found that these users were interested in products with the highest possible temporal and spatial resolutions, which are robust and directly applicable to transitional environments, unlike other existing services and products that focus mainly on inland waters (e.g., Copernicus Land Monitoring Service) or open-sea waters (e.g., Copernicus Marine Environment Monitoring Service). About 60% of users would prefer daily products and 60% of users would prefer real-time products.

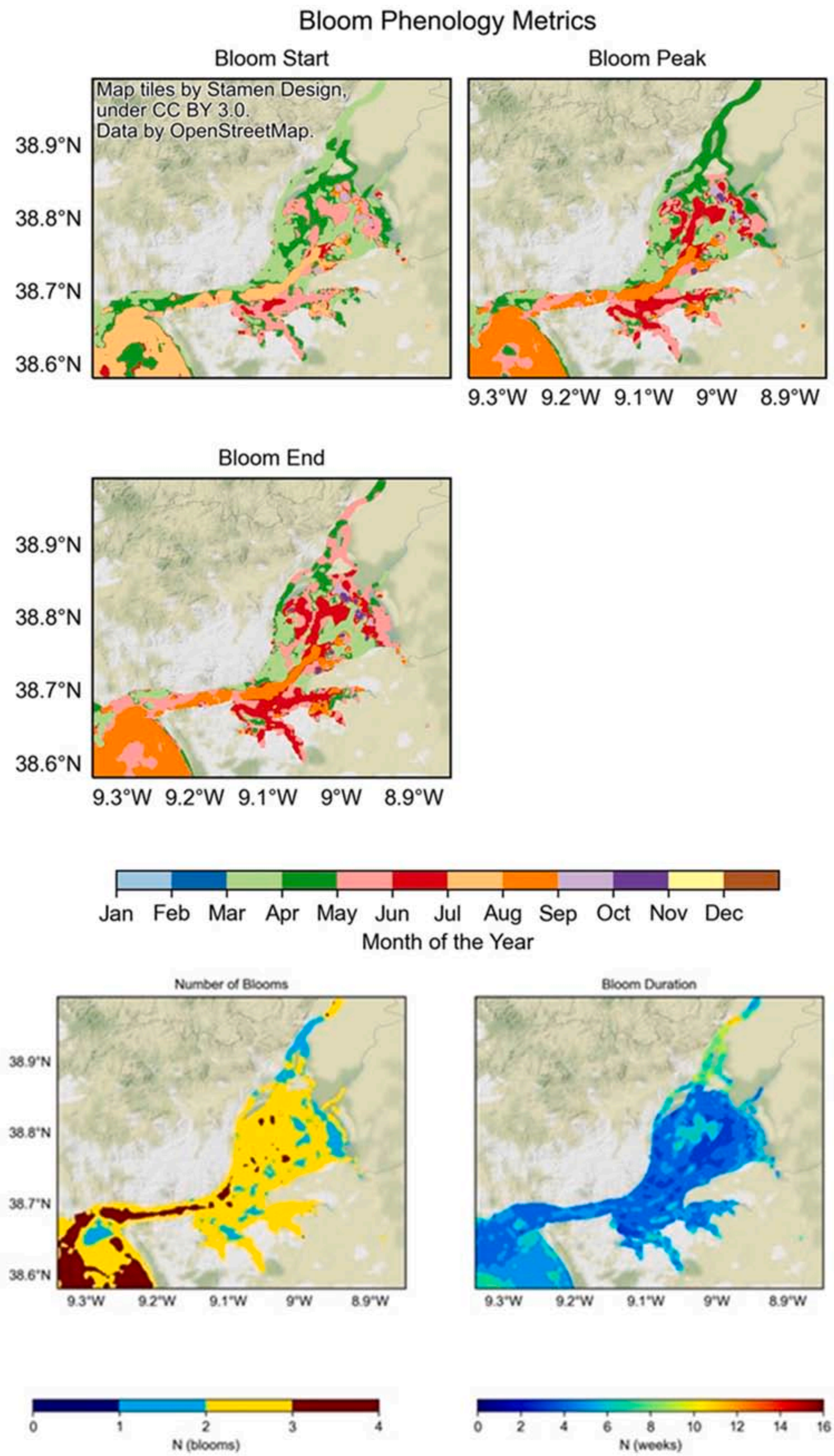

Fig. 11. Mean dates of phytoplankton bloom initiation (Bloom Start), peak (Bloom Peak) and termination (Bloom End); the mean bloom frequency (Number of Blooms) and average durations of blooms in weeks (Bloom Duration) during 2017–2022.

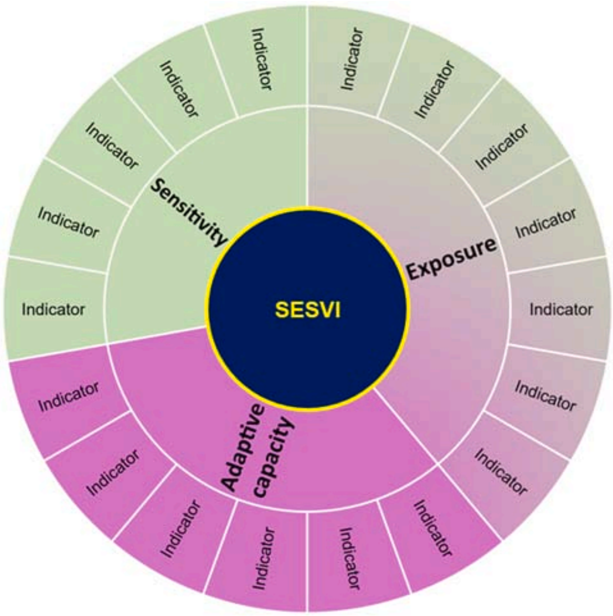

Fig. 12. Conceptualisation of the SESVI wheel showing the multi-level approach. Starting from the individual indicators (outermost wheel), which give the score of each vulnerability assessment component (middle wheel), finally to be aggregated into the total SESVI score (centre of the wheel).

Almost all users prefer fine spatial scales with datasets desired in the 10–100 m range.

Because several of the consulted users in this study have reported that they do not have the necessary resources to manage and analyse large amounts of data, an emergent need that stemmed out of the consultations is that of high-level information, mature enough for management decisions. This includes the need for processed satellite-based information in the form of statistical measures such as percentiles, anomalies and trends over specific time periods. The need for information on the biogeochemical status of the lagoon or estuarine system in question, which is pre-analysed by experts and summarised into clear and concise messages for the end-user was also mentioned.

In addition, some users highlighted the need for user-friendly visualisation tools that enable expert and non-expert satellite data users to view and display satellite information, perform *ad hoc* data analysis such as create a time series from satellite data, and highlight temporal trends and spatial anomalies on figures and maps. Another key aspect that would greatly benefit users would be an alert system, such as a routine that analyses daily images, highlights potential problems and sends alerts to users in relation to potential problems, such as increasing chlorophyll concentrations in a given water body. In terms of data format and delivery, all users preferred raster files, while 80% of them would prefer time series shared in the form of spreadsheet files. Even though an alert system was out of scope for this study, a viewer is available open access, from which interested users can view and download maps of the CHL and TSM indicators developed in this study (https://engage.certo-project.org/data/), thus, contributing to open science.

The co-developed indicators draw a common line between entities and users that need to analyse data to improve the local management of transitional and neighbouring coastal environments. In aiming at high spatial resolutions (10–100 m), these indicators and parameters were found to be particularly suitable for supporting EU monitoring plans for both EU WFD and MSFD, as well as the EU Habitat and Shellfish Directives and Bathing Directives, which had not been considered at the beginning of the consultations. This is because these water quality products are processed by using aggregation and trend analysis, such as inter-annual variability assessments, trend lines, anomalies and climatologies that are report-ready analyses. In addition, the high-resolution synoptic satellite information provided by satellite data is particularly useful to ecological studies, and can potentially also support fishing activities and aquaculture, among others, as users operating in these

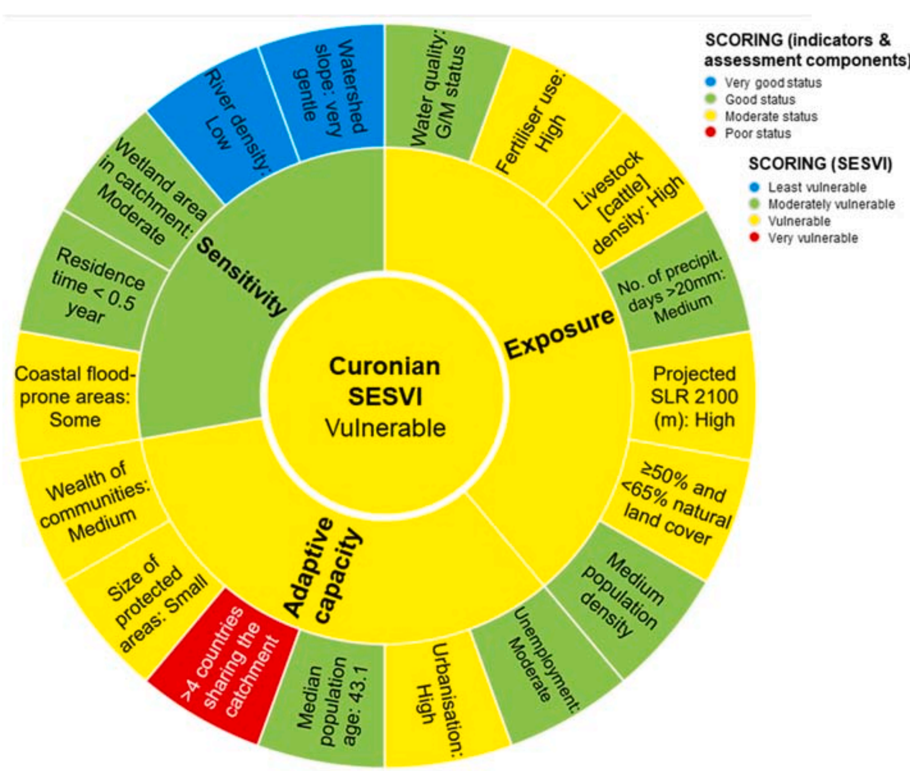

Fig. 13. SESVI applied to the Curonian Lagoon (Lithuania, Russia).

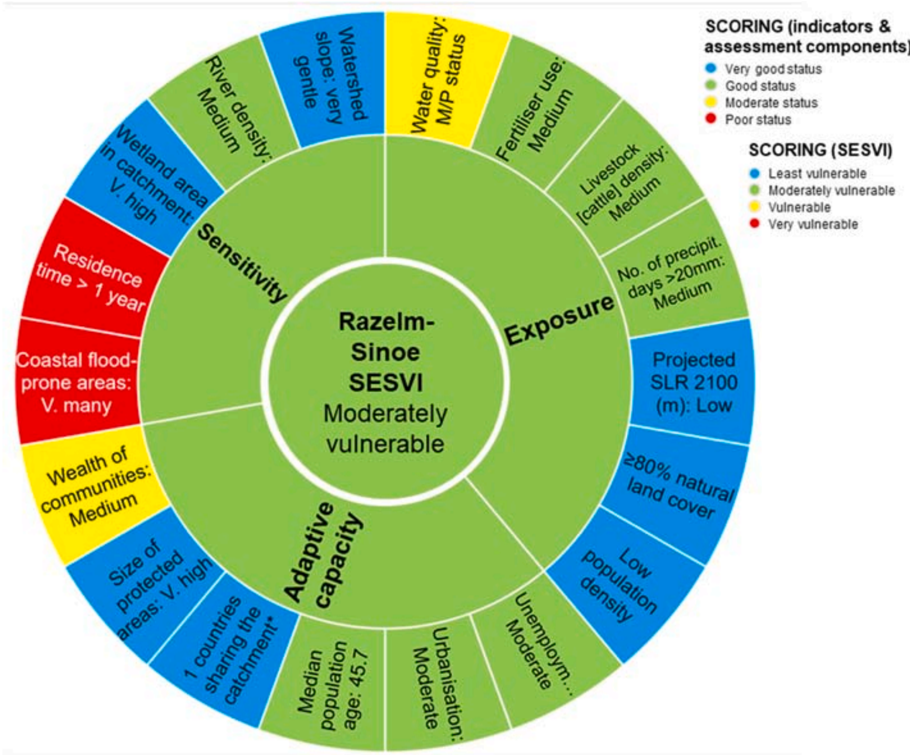

Fig. 14. SESVI applied to the Razelm-Sinoe Lagoons System (Romania).

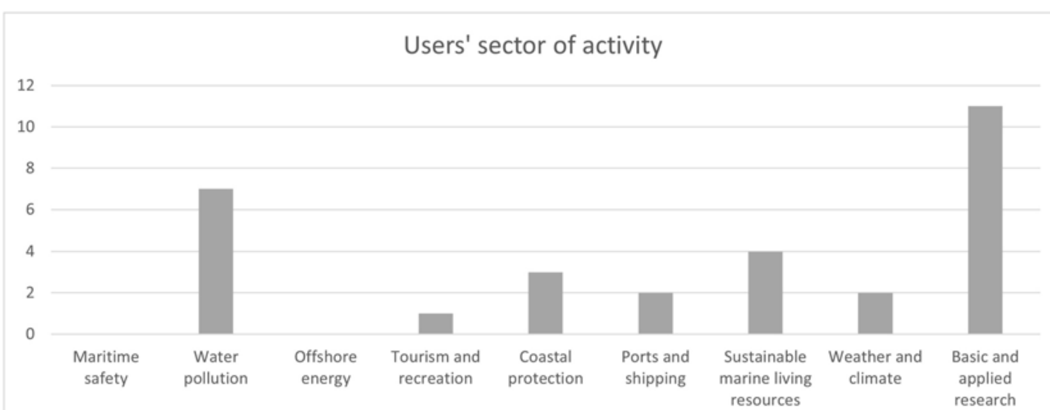

Fig. 15. Distribution of the working sectors the users identified most with, based on responses to the online feedback survey (question 1).

specific sectors reported to us.

The CHL and TSM indicators presented in this study were developed to respond both to user needs requiring a high temporal and spatial resolution, as well as to those wanting aggregated remote sensing data. The maximum sediment zone indicator is one such, that can be run daily (provided there is a relevant daily satellite overpass) and provides the interested parties with near-real time information about the current state of sediment loads in their region of interest. With the integration of river runoff and/or tide data, we could also combine those over time with the maximum sediment zone indicator to showcase the importance of one or the other on the location of the zone for a given year, for example. The phytoplankton bloom phenology indicators on the other hand, allowed the aggregation of appropriate CHL data over time to provide a spatially detailed representation of information aggregated over time on bloom characteristics. The CHL and TSM metrics, such as P90 or average of selected regions relevant for MSFD or WFD reporting combined both spatial and temporal information, thus providing high level managers and stakeholders with value added information on a simple map or graph, without the need to analyse thousands of single data points.

There exist various approaches to producing so-called vulnerability indices, but a lot tend to only focus on the ecosystem aspect only. For example, the commonly used Coastal Vulnerability Index (CVI; Gornitz, 1991) looks at coastal vulnerability to sea level rise and this is defined as the risk of erosion and/or inundation. More recently, the social and economic aspects of coastal zones and transitional water bodies have come into focus, due to those areas' unique location in the boundary between land and sea, where multiple human activities take place. There have been several studies where both the aquatic system itself and the social system operating in, and around it, are both considered. For example, McLaughlin and Cooper (2010) looked at coastal (geomorphological) characteristics and coastal (sea) forcing in combination with socio-economic information, such as land use, population and road infrastructure. The Freshwater Health Index (Vollmer et al., 2018)

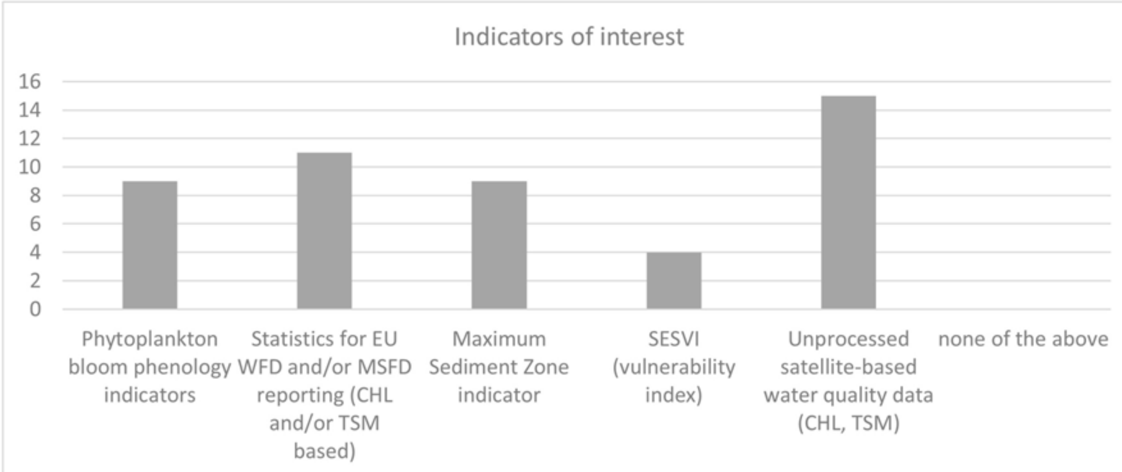

Fig. 16. Number of users interested in each indicator, based on responses to the online feedback survey (question 4).

incorporated ecosystem vitality with ecosystem services, governance and stakeholders, looking at the biophysical context next to the socio-economic and political dimensions. Another example is the Circles of Coastal Sustainability (CCS) framework (de Alencar et al., 2020), where the environment and ecology are treated as equally important as economics, governance and policy, society and culture. The larger the number of variables into consideration, the more complicated a framework becomes, not least because it is often difficult to source all the required datasets at the desired spatiotemporal scales (e.g., McLaughlin and Cooper, 2010; de Alencar et al., 2020) or accuracy. However, none of these examples integrate remote sensing data alongside the other data sources. This is the novelty of the Social-Ecological System Vulnerability Index (SESVI), which was designed as a unique exemplar of how remote sensing can add value to other sources of data towards the holistic management of transitional waters. Providing global overviews of transitional systems and highlighting hotspots of vulnerability to climate change and other anthropogenic pressure, SESVI is a synthesis of various types of datasets and indicators in one infographic, the SESVI wheel, making possible the parallel interpretation of various socioeconomic and environmental factors. Even though the results presented herein are European focused and the thresholds often adapted to our six case study sites following user and local expert consultations, they help demonstrate the strengths and benefits of SESVI. SESVI is, therefore, considered a useful tool for researchers, scientists, environmental managers and resilience officers aiming to understand where environmental and climate change pose a risk to local communities, and which are the critical factors that may render a site more or less vulnerable to environmental pressure and climate change.

5. Conclusions

Based on feedback we received from our user community, both the discussions during the initial consultations and the feedback collected based on the resulting indicators, this work has increased the awareness of engaged users to the potential that remote sensing holds for satisfying several aspects of their water monitoring purposes from simpler to more complex indicators. Both CHL and TSM indicators were found to be very suitable for most users. A common denominator for the consulted users, which other policy makers may also benefit from, was the opportunity to have both synoptic information at daily frequencies and long-term coverage suitable for climatological analyses (e.g., trends and anomalies) based on one data source: remote sensing. SESVI was also welcomed as an exemplar of using multiple origin data sources including remote sensing, by those users who need an overview of climate change-related and other anthropogenic pressures on their natural ecosystem.

By bridging the gap between users and satellite-based products, our work presented a user-led approach to deriving *ad hoc* remote sensing-based indicators and processed information to fulfil needs of user communities towards water quality assessments. The novelty of our approach lies in using knowledge integration from a diverse multidisciplinary user community toward the co-development of new/improved indicators that can be used as monitoring and analysis tools in the sustainable management of transitional waters. These indicators are metrics that are integrated over the whole water body and can be spatially and temporally aggregated to suit reporting needs. They are also based on remote sensing water quality products, which are transferable and applicable across different estuarine and lagoon sites.

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CRediT authorship contribution statement

Eirini Politi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Ana C. Brito:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Mara Ramos Gomes:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Formal analysis, Investigation. **Carole Lebreton:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Federico Falcini:** Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization, Writing – review & editing.

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.

Data availability

The data used for this work are open access, the data source URLs are provided in the manuscript and supplementary material. Code available upon request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107140.

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