



## A roadmap for designing a virtual interface to explore a digital twin of the oceans for marine ecosystems monitoring

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### ABSTRACT

Many marine monitoring infrastructures continuously collect biological and abiotic data, yet user-friendly interfaces for visualizing and translating this knowledge remain limited. This gap persists due to challenges associated with effective frameworks and tools for processing and analysing biological data in real-time. In this paper, we outline a roadmap for developing a Graphical User Interface (GUI) tailored to the continuous monitoring of ecological data with a focus on supporting marine scientists and engineers. To guide this process, we reviewed existing GUIs for visualizing marine ecological data and surveyed 43 experts to identify current gaps and key priorities. Our findings revealed a key dichotomy: GUIs either represent diverse array of biological data or perform inadequately when attempting to transfer qualitative observations to quantitative insights. Finally, we propose a stepwise roadmap for GUI development within the Digital Twin of the Ocean framework by starting from spatial mapping and progressing to data navigation. Ultimately, this study outlines critical considerations for integrating complex ecological data from diverse sources into an effective GUI. This GUI aims to support real-time monitoring, control remote monitoring for data collection, inform policymakers, and enhance public engagement in marine science.

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## 1. Introduction

In light of the accelerating loss of marine habitat and biodiversity (He and Silliman, 2019; Mizuno et al., 2024; Ramirez-Llodra et al., 2011), there is an imperative to upscale marine monitoring efforts (Woodall et al., 2018; Simeoni et al., 2023). Responding to this need, recent years have seen the rapid development of new methodologies and tools designed to expand the spatial reach, temporal resolution, and autonomy of ecological monitoring, thereby our capacity to collect near real-time data (Aguzzi et al., 2019, 2020a, 2020b). Yet, this has also increased the requirements to integrated systems that can unify data storage, visualization, and assimilation. These requirements converge in the concept of a Digital Twin of the Ocean (DTO), understood here as an ensemble of services that handle databases to provide reliable, interactive, and digitized information whether collected directly by monitoring instruments or generated through simulations based on real-world inputs.

Underwater cabled observatories stand out as key data suppliers for DTOs (Aguzzi et al., 2025). Cabled observatories have revolutionized marine ecological research (Aguzzi et al., 2020a; Danovaro et al., 2017) due to their capability to provide a real-time stream of environmental and biological data to remote users (Matabos et al., 2017; del Rio et al., 2020; Dañobeitia et al., 2023; Francescangeli et al., 2025). These observatories are highly versatile, capable of hosting diverse payloads such as underwater cameras, hydrophones, oceanographic sensors, time-lapse systems for water sampling, filtering, and fixation for environmental DNA (eDNA) as required for its post laboratory processing (Mirimin et al., 2021; Tibone et al., 2025), and larval traps (Kulin et al., 2021). They also function as underwater laboratories, enabling the integration of structures (e.g., benthic chambers, Autonomous Reef Monitoring Structures, cetacean carcasses; Glover et al., 2010; Obst et al., 2020) and mobile robotic platforms for experimental purposes (Chatzievangelou et al., 2022; Falahzadeh et al., 2023; Henthorn et al., 2010; Purser et al., 2013). While most platforms currently stream environmental data in real-time, future innovations will likely enable the automatic extraction of the basic biological information from imaging outputs (i.e., visible specimens taxonomically classified and counted) (Ottaviani et al., 2022; Ferrari et al., 2025; Ortenzi et al., 2024) and may be coupled with other data generation tools, for example in repositories for genetic sequences (Stefanni et al., 2022).

Most in situ monitoring activities rely on Graphical User Interfaces (GUIs), which, while effective for data access and display, often provide limited support for extracting meaningful insights from biological data. Once collected, data are often centralized and stored in open access or institutional repositories (e.g., European Marine Observation and Data Network; EMODnet, Global Biodiversity Information Facility: GBIF, Ocean Network Canada; ONC Oceans 3.0, and Integrated Ocean Observing System, IOOS). Traditionally, academic researchers process the collected data and create reports and scientific articles, which can be used to advise governmental agencies and policymakers (e.g., Aguzzi et al., 2020c; Francescangeli et al., 2025). GUIs play a role here in helping researchers to interactively explore and visualize the collected data. However, interacting with such tools often requires previous knowledge or specialized training. Simply put, displaying data is rarely sufficient and we must strive to synthesize complex datasets into an easily accessible and interpretable format. Indeed, research in Human Computer Interaction emphasizes that an interactive GUI can enhance decision making by reducing the cognitive load (Sweller, 1988). Thus, an effective GUI for ecological data should balance complexity with usability, enabling both experts and non-experts in making sense of collected and simulated data for interpretations and informed decisions.

Historically, biological data visualization has lagged behind compared to water masses properties in observatories' GUI. This is probably due to the more straightforward nature of sampling and estimating them, thus shaping the technological development of platforms for remote and in situ monitoring (Mackenzie et al., 2019). This gap

highlights the need for improved representations that effectively capture ecological dynamics and make biological insights more accessible to users. From a baseline of biological data in spatial and/or temporal dimensions, a synthetic representation of ecological processes can be derived and can serve as an interpretable handout of the monitoring reality and ecological changes. Organizations such as the International Council for the Exploitation of the Sea (ICES) and the Society for the Ecological Restoration (SER) employ visually impactful tools to display time series trends for multiparametric biological and environmental data and their processed output as ecological indicators. For example, the Kobe plot (WP Council, 2020) and the Recovery wheel (Young et al., 2022) provide clear visual summaries of marine resources and are commonly used in fisheries stock and ecosystem restoration assessments, respectively. These tools often use indicators derived from an array of ecosystem characteristics (e.g., fishing mortality and spawning biomass in the Kobe plot) and then visualize these indicators with easily interpretable labels or graphics, such as green for healthy values to represent optimal conditions. The search for effective representations of ecological metrics is, therefore, a critical endeavour to create engaging and user-friendly GUIs that facilitate understanding and decision-making.

The objectives in the manuscript are to identify key features for improving the display of marine biological data and to incorporate them into a roadmap for designing GUIs for the European DTO project DIG-I4ECO, applicable to any DTOs based on long-term ecological monitoring. These GUIs should effectively visualize interrelated historical and real-time dynamics to support scientific research, decision making, and public engagement. The scope is focused primarily on a GUI development for monitoring activities with underwater observatories, and secondarily from oceanographic surveys, fisheries, and other historical data sources that are spatially linked to the observatories. To develop the roadmap, we first reviewed the types of ecological data available and studied existing GUIs to showcase the gaps, needs and requirements in future ecological GUIs. For this scope, we designed an online questionnaire covering a range of specifications about GUIs and circulated it to experts with scientific, technical, and engineering backgrounds. Finally, we outlined recommended steps to design a GUI and effectively translate complex ecological data into an interactive and intuitive digital environment.

## 2. Review of existing GUIs for DTOs

### 2.1. Sources of quantitative biological data into a GUI

Here, we provide an overview of existing methods for biological data collection and the indicators derived from them within a monitoring framework. The focus is limited to data sources related to species occurrences, and, where possible, capturing visually identifiable characteristics such as sex, size, and behaviour. Multiple data collection methods exist, each with a specific utility that complements different ecological perspectives, facilitated by multifaceted monitoring platforms, such as underwater observatories, as well by separate sources like fisheries catches and sediment cores (Table 1). Data sources can also be sorted based on the autonomy of the data flow – that is, how quickly qualitative information is transmitted from sensors to a web-based GUI (Table 1). In particular, some sources provide near-real-time biological data thanks to autonomous robotic and sensor platforms that communicate with each other and transmit information to web-based resources on land. Transmission can either be wireless (e.g., by an Underwater Surface Vehicle - USV acting as a gateway between acoustic and radio/satellite communication) or tethered when individual platforms and vehicles are connected to cabled observatories. Other sources collect biological and environmental data in the form of collected samples (e.g., fishery catches, sediment cores), which require laboratory analyses performed by experts before the data can be integrated into the monitoring GUI. All biological data sources generate substantial storage

**Table 1**

Examples of most representative sources of biological data (extracted and modified from Danovaro et al., 2016) to be represented in the DTO's GUIs. AI: Artificial Intelligence; EBVs: Essential Biodiversity Variables (GEO BON, 2011) as presented in Muller-Karger et al. (2018).

Processing steps of qualitative data to a GUI	Source of qualitative data	Species Identification tool	Examples of derived EBV indicators, and Use	Targeted community
Autonomous – direct transmission of raw data, AI detection	Images/Videos	AI trained on colorimetric/morphological models (requiring expert validation)	Habitat structure, Ecosystem composition, Ecosystem extent  With animal-borne Camera: Field of View as proxy for the Eco-field (Farina and Belgrano, 2004)	Megafauna and Lebensspuren
	Flow cytometer	Flow cytometry	Phenology	Nanoplankton, picoplankton, virioplankton Megafauna
	Acoustic telemetry	Individualized acoustic pinger of bearing animals; with uni- or bidirectional tags	Migratory Behaviour (e.g., mobility, interactions and burrowing/homing behaviour), species distribution, Taxonomic diversity	Large epipelagic species (marine mammals turtles, fishes)
	Satellite telemetry	Tag-based identification	Species spatial distribution, behaviour, and abundance	Cetaceans, mammals, some fishes and crustaceans
	Passive Acoustic Monitoring (PAM)	AI trained on sound marks for species presence identification	Taxonomic and allelic diversity, surveillance of unwanted species	Macrofauna
Manual/ semi autonomous sample collection, taxa identification, or processing.	Water sample	Taxonomical identification based on molecular analyses	See first row	Megafauna and Lebensspuren
	Images/Videos	Manual image annotation and analysis	Population structure by age/size class, Phenology, Species spatial distribution, taxonomic and allelic diversity, surveillance of unwanted species	Megafauna, macrofauna, meiofauna, microorganisms

demands, either physical or digital, and often require significant time to process qualitative observations (e.g., species presence) into quantitative databases (e.g., species counts) through taxonomic identification.

Accessing databases with quantitative information, especially georeferenced and time-stamped species (or higher taxonomic group) counts, enables the calculation of a wide range of ecological indicators and descriptors (Directive 2008/56/EC; GEOBON 2011; Cao and Hawkins, 2019; Chao et al., 2014, 2024). These indicators play a pivotal role in ecological assessments by detecting trends and anomalies in ecosystem health. Among these, simple indicators, such as abundance and species richness are especially valuable in a GUI because they provide intuitive and globally relevant statistics. Their simplicity makes them accessible for interpretation by non-experts and non-academics alike. More complex and specialized indicators, such as diversity and functional indices and trophic and community structures can also be calculated and displayed online. However, these require a higher level of expertise to fully understand their implications within the context of monitoring activities.

## 2.2. GUIs with biological data visualization

Displaying ecological information in a GUI is an engaging and informative outcome for both experts and non-experts, enhancing the visibility and utility of collected data (Benson et al., 2021). To maximize this potential, recent studies have stressed the importance of strengthening the contribution of biological data within global repositories (Muller-Karger et al., 2018), helping to gradually reduce existing gaps relative to the abundance of environmental data. In particular, images/videos, PAM, and omics applications are at the top of data entries in terms of quality and quantity, portraying fauna presence, abundance and behaviour (Aguzzi et al., 2019; Rountree et al., 2020). These sensors can also deliver products of direct relevance to societal needs (e.g., monitoring megafauna dynamics and stock assessment; Aguzzi et al., 2020b; Danovaro et al., 2020). In this section, we review existing active GUIs containing ecological information associated with monitoring sites and we explore data visualization strategies to identify standards for best ecological data visualization.

### 2.2.1. Discrete data

Discrete monitoring data are data collected at distinct time points, rather than continuously. Unlike continuous monitoring, discrete data are gathered as one-off sampling events or at set intervals, often with relatively low temporal frequency. These data are typically obtained through field surveys, which involve samples collection of species, in situ observations, or field work activities with underwater robots (Aguzzi et al., 2025). Key examples are annual fisheries-independent trawl surveys led by initiatives like the “Database of Trawl Surveys” managed by the ICES (<https://datras.ices.dk>) and the Mediterranean International Trawl Surveys (MEDITS; Abelló et al., 2002) in European waters, as well as reporting wildlife incidents (see Marine Wildlife in Table 2), or exploring coral reef life (Reef Life Explorer in Table 2).

GUIs with discrete monitoring data focus on conceptually displaying ecosystem indicators and dynamics in a non-3D virtualized fashion (Table 2). Despite discontinuous or sporadic data flows, synthetic representation of ecological knowledge is often tailored to the history of data collection (e.g., donut charts visualizing single events of monitoring activities; Mermaid's GUI in Table 2), the research objectives, and the scale of monitoring effort. Common approaches among these GUIs are mapping indicators and plotting time-series data. Discrepancies in units and indicators among locations restrict comparisons to relative spatial compatibility analysis (see Forage Fish in Ecowatch GUI in Table 2). More rarely, the GUIs display synthetic information such as easily interpretable labels on the ecological status of the monitored sites (Index score in Marine Monitoring Program, L50 in ICATMAR) and comparative graphs for a same indicator over time or space (see e.g., Pacific Rocky Intertidal, ICATMAR, Marine Monitoring Program).

### 2.2.2. Continuous data

Building on the previous section on discrete monitoring data, we define the high-frequency or continuously streamed (i.e., real-time) monitoring data. These datasets enable more detailed temporal analysis of ecosystem dynamics.

Focusing on GUIs for streamed data at underwater observatories (Table 3), several common features for ecological data can be identified:

- “Access to qualitative data in near real-time”. The most common data streams originate from acoustic, optical, and fluorescence sensors.

**Table 2**

Examples of GUIs displaying ecological indicators from discrete monitoring data. MCRS: Minimum Conservation Reference Size.

GUI	Data collection strategy	Indicators	User interactivity with indicators	Type of data charts	Comments
Pacific Rocky Intertidal	200 rocky intertidal monitoring sites over three decades	<ul style="list-style-type: none"> <li>Community characteristics;</li> <li>Species Cover;</li> <li>Species abundance;</li> <li>Species distribution;</li> </ul>	<ul style="list-style-type: none"> <li>Choice of metric category and metrics;</li> <li>Spatial Filtering;</li> <li>Comparison between management unit, occurrence, and location</li> </ul>	<ul style="list-style-type: none"> <li>Spatial and temporal barplots;</li> <li>Spatial bubble plot;</li> <li>Map</li> </ul>	Metric by monitoring location or by management designation
Marine Monitoring Program	Long-term inshore monitoring program since 2005	<ul style="list-style-type: none"> <li>Water quality;</li> <li>Seagrass resilience and abundance</li> </ul> <p>Coral cover and its change, juvenile density, community composition</p>	<ul style="list-style-type: none"> <li>Choice of sites; program and region;</li> <li>Choice of metrics;</li> <li>Display information by flashing the mouse on the graph</li> </ul>	<ul style="list-style-type: none"> <li>Barplot;</li> <li>Time series;</li> <li>Map</li> </ul>	Label of quality in regard to the measures; Possibility to have several indicators in one plot
Marine wildlife	Reported incident with wildlife between 2010 and 2022	<ul style="list-style-type: none"> <li>Animal count;</li> <li>Animal fate (alive, dead, or unknown)</li> </ul>	<ul style="list-style-type: none"> <li>Data filter;</li> <li>Display information by flashing the mouse on the graph;</li> <li>Filtering data by clicking on plots</li> </ul>	<ul style="list-style-type: none"> <li>Time series;</li> <li>Stacked barplot;</li> <li>Map</li> </ul>	
Mermaid	Repeated or single scientific observation of megafauna size and abundance associated with coral reefs.	<ul style="list-style-type: none"> <li>Fish biomass (kg/ha) by functional trophic group;</li> <li>Benthic cover (%);</li> <li>Coral bleaching (%);</li> <li>Habitat complexity</li> </ul>	<ul style="list-style-type: none"> <li>Choice of the site from the map or a filter window;</li> <li>Choice of the date if repeated sample</li> </ul>	<ul style="list-style-type: none"> <li>Map with sites quantity;</li> <li>Donut chart</li> </ul>	Quality processing when ingesting data; Information of the survey efforts; Metadata along visual
ICATMAR (Carreton et al., 2025, Ribera-Altimir et al., 2023)	Daily records of fishing catches since 2018	<ul style="list-style-type: none"> <li>Fish biomass (kg/km<sup>2</sup>);</li> <li>Fishing income (€/km<sup>2</sup>);</li> <li>Fishing time (h/km<sup>2</sup>);</li> <li>Size frequency (Count/km<sup>2</sup> and body length in mm)</li> </ul>	<ul style="list-style-type: none"> <li>Comparison by port and seasons;</li> <li>Filtering by species, port, season, catch composition (commercial, discard and marine litter), vessel transect;</li> <li>Display information by flashing the mouse over the graph</li> </ul>	<ul style="list-style-type: none"> <li>Frequency;</li> <li>Donut Chart;</li> <li>Map</li> </ul>	Possibility to have several indicators; Metadata; Information about ecological (L50) and economical (MCRS) markers
EcoWatch Coral reefs EcoWatch Forage fish	Various timeframes by region	<ul style="list-style-type: none"> <li>Scores (Coral Reefs);</li> <li>Catch per unit effort index score (Forage Fish);</li> <li>Biomass (in kg) observed per haul (Forage Fish);</li> <li>Abundance index score (Forage Fish);</li> <li>Total biomass in millions of tons (Forage Fish)</li> </ul>	<ul style="list-style-type: none"> <li>Selection of themes or regions;</li> <li>Display information by flashing the mouse over the graph</li> </ul>	<ul style="list-style-type: none"> <li>Composite gauge;</li> <li>Time series</li> </ul>	
Reef Life Explorer	Surveys by Citizen Science Diver worldwide	<ul style="list-style-type: none"> <li>Regional reef health (%)</li> <li>Reef Fish thermal Index (°C)</li> <li>Large reef fish (kg/500m<sup>2</sup>)</li> <li>Habitat cover (%);</li> <li>Shark and Ray density (animal count/500m<sup>2</sup>);</li> <li>Cryptic fish species (species/50m<sup>2</sup>);</li> <li>Sea Urchin density (animal count/ 50m<sup>2</sup>);</li> <li>Invertebrate species (species/50m<sup>2</sup>);</li> <li>Fish species (Species/500m<sup>2</sup>);</li> </ul>	<ul style="list-style-type: none"> <li>Selection of indicators;</li> <li>Selection of location;</li> <li>Display information by flashing the mouse over the graph</li> </ul>	<ul style="list-style-type: none"> <li>Time series;</li> <li>Heat map;</li> <li>Map</li> </ul>	Information of the survey efforts over time; Predictions; Explanation of indicators calculations; Access to data in external repository

- “Visualization of data streams”. Optical streams, including videos and images, are available under specific conditions, such as at scheduled intervals during the day.

- “Access to historical data”. Historical datasets are often accessible for retrospective or comparative analysis.

- “Dashboard displays”. These allow users to simultaneously view environmental measurements alongside ecological data streams.

- “Limited quantitative ecological data”. Representations of quantitative ecological data are either absent or presented in a simplified manner. Most of the charts plotted in these GUIs represent variations in unidentified biological data, such as chlorophyll concentration.

- “Maps as means to access data”. Maps is a way to select data sources (e.g., ONC in Table 3) in addition to displaying where the data are collected. However, contrary to maps from discrete monitoring data, quantitative information from biological indicators is not visualized.

Some observatories, such as those operated by Ocean Networks

Canada (ONC) and at Holyrood, include manual annotations of observed specimens in historical videos and images, along with timelines for easier retrieval of observations. Methodologies for automatic, including near-real-time, processing of video/image data into occurrence data are developed (Aguzzi et al., 2025 and references herein) and already have outcomes (e.g., Baños Castelló et al., 2025). However, these data and their derived indicators have yet to be displayed in the GUI with chart types like the ones listed in Table 2. Similarly, acoustic data are often presented without real-time analysis or correlation to animal detection, leaving live interpretation challenging. As a result, observatory-associated GUIs currently do not allow for direct interpretation of ecological data. Existing algorithms can annotate images (e.g., from datasets like <https://www.emso-fr.org/Data/Data-catalogue#/metadata/seanoec:87389>) and enhance image quality before annotation. However, species identification from annotated specimens still requires off-line analysis, highlighting the need for advancement in real-time

**Table 3**

Examples of active observatories in 2025 with biological data collection and graphical interaction with parameters. \* The condition is associated with an imaging service that works at a specific frequency for a specific duration as in the case of time-lapse scheduling (e.g., 5 min of images every 4 h). W: western, E: eastern; N: North; NW: northwestern; NE: northeastern.

GUI	Data collection strategy	Variables	Graphical interactivity with Parameters	Type of data charts	Comments
OBSEA	W Mediterranean Sea:	<ul style="list-style-type: none"> <li>Chlorophyll</li> <li>Multi-frequency acoustic backscatter</li> </ul>	<ul style="list-style-type: none"> <li>Temporal filtering</li> <li>Display information by flashing the mouse on the graph</li> </ul>	<ul style="list-style-type: none"> <li>Time Series</li> <li>Spectrogram</li> </ul>	Information about no available data, Label of quality in regard to the measures;
SmartBay	E Atlantic:	<ul style="list-style-type: none"> <li>Images</li> <li>Chlorophyll a</li> <li>Multi-frequency acoustic backscatter</li> <li>Images</li> </ul>	<ul style="list-style-type: none"> <li>Display information by flashing the mouse on the graph</li> <li>Temporal filtering</li> </ul>	<ul style="list-style-type: none"> <li>Time Series</li> <li>Spectrogram</li> </ul>	Information about no available data
Ocean Observatories Initiative	NE Pacific (Axial Seamount):	<ul style="list-style-type: none"> <li>Chlorophyll a, CDOM Concentration, and optical backscatter</li> </ul>	<ul style="list-style-type: none"> <li>Display information by flashing the mouse on the graph</li> <li>Temporal filtering and scaling data</li> <li>Calculation of basic statistics</li> </ul>		
	NE Pacific (Coastal endurance):	<ul style="list-style-type: none"> <li>Chlorophyll a, CDOM Concentration, and optical backscatter</li> <li>Multi-frequency acoustic backscatter</li> <li>Images</li> </ul>	<ul style="list-style-type: none"> <li>Display information by flashing the mouse on the graph</li> <li>Temporal filtering and scaling data</li> <li>Temporal selection of images</li> <li>Calculation of basic statistics</li> <li>Display of vertical profiles</li> <li>Nominal Frequency selection</li> </ul>	<ul style="list-style-type: none"> <li>Time series</li> <li>Bar plot</li> <li>Heat map</li> </ul>	Label of quality in regard to the measures; Information about the measuring efforts; No plots for DNA and videos; Access to historical data; Annotation Metadata;
	NE Pacific (Global Station Papa); NW Pacific (Goastal Pioneer); N Atlantic (Global Irminger Sea):	<ul style="list-style-type: none"> <li>Chlorophyll a, CDOM Concentration, and optical backscatter</li> <li>Multi-frequency acoustic backscatter</li> </ul>	<ul style="list-style-type: none"> <li>Display information by flashing the mouse on the graph</li> <li>Temporal filtering and scaling data</li> <li>Calculation of basic statistics</li> <li>Display of vertical profiles</li> <li>Nominal Frequency selection</li> </ul>	<ul style="list-style-type: none"> <li>Time series</li> <li>Bar plot</li> <li>Haet map</li> </ul>	
	NE Pacific (Global Station Papa); NW Pacific (Goastal Pioneer); N Atlantic (Global Irminger Sea):	<ul style="list-style-type: none"> <li>Bio-acoustic Sonar,</li> <li>Fluorometer</li> </ul>			
AWI webpage	N Atlantic (LTER observatory Hausgarten)	NA	NA	NA	All data are stored in the Pangea Repository
	<ul style="list-style-type: none"> <li>HD Video Cameras,</li> <li>Push-corer,</li> <li>Box-corer,</li> <li>Sediment trap</li> </ul>				
ONC	NE Pacific (Barkley Canyon; Campbell River; China Creek, Douglas Channel); Arctic (Cambridge Bay)	<ul style="list-style-type: none"> <li>Chlorophyll</li> <li>Images</li> <li>Power Spectral density</li> </ul>	<ul style="list-style-type: none"> <li>Display clean or raw data</li> <li>Display information by flashing the mouse on the graph</li> <li>Temporal filtering and scaling data</li> <li>Display basic statistics (min-max, or average)</li> <li>Image selection from taxonomic annotation</li> </ul>	<ul style="list-style-type: none"> <li>Time series</li> <li>Barplot</li> <li>Tables</li> <li>Spectrogram</li> </ul>	Downloading plots/dataset/images; Add plot/data to chart; Information about no available data; Possibility to add several plots in same window; Possibility to overlap statistics in same plot; Downloading plots/datasets/images;
	NE Pacific (Clayoquot slope; Endeavour – NEPTUNE)	<ul style="list-style-type: none"> <li>Images</li> <li>Power Spectral density</li> </ul>	<ul style="list-style-type: none"> <li>Temporal filtering and scaling data</li> <li>Image selection from taxonomic annotation</li> </ul>	<ul style="list-style-type: none"> <li>Table</li> <li>Spectrogram</li> </ul>	
	NE Pacific (Folger Pinnacle – NEPTUNE)				
	NE Pacific (Folger Pinnacle – NEPTUNE)				
	NE Pacific (Digby Island)	<ul style="list-style-type: none"> <li>Images</li> </ul>	<ul style="list-style-type: none"> <li>Temporal filtering and scaling data</li> <li>Image selection from taxonomic annotation</li> </ul>	<ul style="list-style-type: none"> <li>Table</li> </ul>	
	NE Pacific (Digby Island)				
	NE Pacific (Digby Island)				

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Table 3 (continued)

GUI	Data collection strategy	Variables	Graphical interactivity with Parameters	Type of data charts	Comments
Smart Atlantic / ONC	NW Atlantic (Holyrood) <ul style="list-style-type: none"> <li>• Streaming of Video Camera under conditions*,</li> <li>• Hydrophone,</li> <li>• Fluorometer</li> </ul>	<ul style="list-style-type: none"> <li>• Images/Video</li> </ul>	<ul style="list-style-type: none"> <li>• Temporal filtering and scaling data</li> <li>• Image selection from taxonomic annotation</li> </ul>	<ul style="list-style-type: none"> <li>• Table</li> </ul>	Downloading images

ecological monitoring and data processing in underwater observatories, while requiring expert validation.

### 2.2.3. Common features and gaps in GUIs

Several interactive features across these GUIs highlight strategies for developing a user-friendly GUI. These include the ability to select monitoring sites on a map and specify the available metrics to display in an embedded window (see Table 2). Mapping the dataset location at the monitoring site enhances GUIs navigation and simplifies data access. Datasets from repeated monitoring activities are grouped at the same coordinates, even if their metadata (e.g., observers, funding project) differ. Spatially scattered access points may be misinterpreted as separate datasets, leading to confusion and inefficiencies in retrieving information.

Having the possibility to get a global overview but to be able to dive down into finer subsets is useful and found in most interfaces. This can be achieved by filtering, which is particularly useful for displaying monitoring sites sharing common indicators while also highlighting sites that have under-represented ones (e.g., the benthic cover indicator in “Mermaid”; see Table 2). It can also be achieved by customised aggregation control over indicators and parameters by users. For instance, users can adjust the level of biological detail, starting with the total abundance at the monitoring infrastructure and ending with abundances displayed by categories (e.g., diet types in Mermaid and catch in ICATMAR; see Table 2). In case sensors are failing, modelling methods are being developed to estimate missing observations (Francescangeli et al., 2025), especially when the data gaps are brief and pertain to specific taxa.

Comparing biological representation in GUIs of discrete and continuous data source reveals that significant progress is still needed to develop tailor-made representations of indicators. GUIs supplied with data from discrete monitoring activities often feature a greater variety of graphical outputs compared to those based on continuous monitoring. This discrepancy is likely due to the greater effort dedicated to animal identification with discrete data and our inability, until recently, to process continuous cabled observatory data. Overall, visual combinations of ecological indicators with environmental information remain underrepresented, potentially due to the complexity in their calculation (i.e., high requirements for both computational power and mechanistic models connecting processes) and interpretation (e.g., it is harder to create a digestible output for loss of an ecosystem function than for temperature rise), highlighting another area for GUI improvements. Bridging these differences requires both technological advances in automated biological data processing and a shift in design priorities to balance temporal resolution with biological detail.

## 3. Expert opinion on GUI design and content

### 3.1. General

Between September 2024 and December 2024, a questionnaire was distributed via Google forms to consortium members of the Horizon Europe project DIGI4ECO (Grant number 101112883) on the development of a Digital Twin of the Ocean for long-term marine monitoring networks in four coastal ecosystems (<https://digi4eco.eu/demos/>). The survey was composed of 26 questions with a varied response format,

including grading scales, open text responses, multiple choices or single answer options. The questions were grouped into six sections (see Supplementary Material 1) covering: a) considerations for the GUI, b) data generation services, c) comparison of user experience in four existing and established web-based GUIs, d) priorities for the GUI development, e) optional features in the GUI, and f) the integration of the GUI with EDITO, the European DTO.

A key component of the survey was the comparative section, designed to identify essential functionalities and design elements needed to integrate the ecological component into established GUIs of cabled monitoring observatories. The four examined web-based GUIs (all accessed in March 2025) were:

- Digital Ocean (<https://www.digitalocean.ie>), a platform centred on Irish monitoring sites for both recreational (e.g., diving spots) and commercial (e.g., harbours) sites. It includes mapped visualization of monitoring platforms' location, a dashboard displaying time series data, and options for data access and export. Digital Ocean also provides access to SmartBay, an underwater cabled observatory demo-site of the DIGI4ECO project with continuous image collection and broadcasting.

- EMODnet (<https://emodnet.ec.europa.eu/en/biology>), a European portal for in situ marine data services, covering European and international waters. It gathers and provides access to formatted data classified in seven disciplines (called “themes”) either from a catalogue (acting like a repository) or an interactive spatial viewer (maps) with data overlay capabilities. One of the thematic areas provides access to biological data.

- ICATMAR (Ribera-Altimir et al., 2023; <https://www.icatmar.cat/en/>), a scientific initiative developed in collaboration with Catalan fisheries and local governmental institutions. This platform regularly uploads oceanographic and fisheries data to two online portals with visual and data access services. The visualization tools include maps displaying fishing tracks between the 40° and 43° N along the Mediterranean Spanish coast, with the option of overlaying multiple data layers.

- Ocean Networks Canada (ONC; <https://www.oceannetworks.ca>), a pioneer global leader in ocean observation that focuses on data collection exclusively from ocean-based platforms. The ONC portal offers various functionalities for data navigation and visualization, with ecological data mostly provided by videos and annotated species detected on the images.

We quantified answers depending on their question type:

- For a single-choice or dichotomous question, each response was counted as one selection. For example, if 39 participants answered “Yes” and 4 answered “No”, the responses were recorded accordingly, summing a total of 43.

- For multiple-choice questions, each selected response was counted as one entry, meaning that participants could contribute to multiple answer categories, thus the total number of answers was higher than the number of participants.

- For the rating questions in Q19 (scale between 1 and 10), values were averaged across participants.

- For open-ended questions (Q2 to Q4), participants provided single-text responses that often covered multiple aspects of the GUI. To systematically analyse these answers, responses were classified into categories (for Q3 and Q4) and subcategories (for Q2) and to justify this classification, text segments belonging to one category were extracted

from the answer (Table S2). If a response covered multiple aspects or its meaning was unclear, a text segment could be assigned to multiple categories. The structured categorization of responses is detailed in Tables S1–3. Then, we counted the total occurrence of a subcategory.

We anonymously collected answers from 43 participants, including PhD students, engineers, technicians, postdoctoral and senior researchers (98 % of them based in European countries) of the DIGI4ECO project consortium (Supplementary Material 2). Among them, 44 % were familiar with GUIs, which implies they are using them and understand their functionality (Q1; Fig. 1). A small percentage of participants (12 %) were highly proficient, either possessing extensive experience with GUIs or having the capability to develop it.

### 3.2. Visual features

#### 3.2.1. Overall GUI aspect

An overview of user experience and interface was got in the comparative section of four existing GUIs platforms in Q11, Q12, and Q13. The majority of the participants ranked Digital Ocean and ICATMAR as the most user-friendly GUIs (Fig. 2) and graded them as being “Friendly” to “Very friendly” (> 75 %). In contrast, ONC largely overwhelmed 51 % of the participants, and EMODnet GUI was associated with the highest percentages (19 %) of answers classifying it as “Hard to navigate”. A GUI for ecological monitoring should open onto an interactive map, as in “Digital Ocean”, according to 26 participants. Many commented that a simple intuitive and modernly designed map with the possibility to enrich the visual by adding layers was a primary asset for the users. An overwhelming GUI would be when the user needs time to acclimate to the display of GUI features and fill its objective, for example, the opening screen shows too many options (data, services) at a time or where too many steps have to be taken to access a service. Among the attractive features (see Q14, Fig. S1) of the GUIs, a group of answers about mapping elements were the most selected (56 %) and credited to the clear map visual and ease of overlaying information. A second group of answers classified features in a theme related to the monitoring platforms (27 %), including their easy identification and selection of the platforms and a simple preview of their collected data. The remaining 19 % of features belong to a group associated with the user experience, mostly driven by smooth access to the data.

Preview of collected data in GUIs is delivered in a dashboard, featuring widgets, as small windows displaying information for one variable (e.g., ONC, Digital Ocean). In Q16, participants mainly selected (~72 %) to have relative freedom in selecting which widget appears in the dashboard, either with the possibility to add widget over automatically present widgets (28 %), and/or to have data-associated widgets tagging along with one added (44 %). This control over widgets, with regard to ecology, allows for limiting the quantity of ecological data displayed at once. A suggestion for default biological widgets was time series of observed abundance or biodiversity indicators based on a group of species, as specified in Q8.

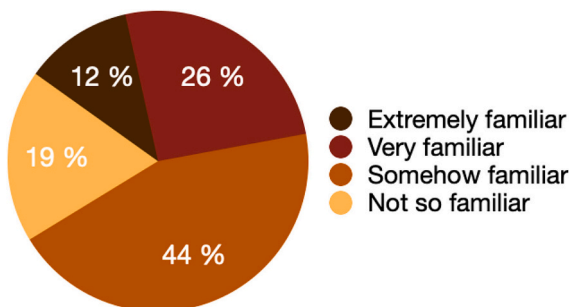


Fig. 1. Distribution of the participants based on GUI familiarity. Information provided by responses of Q1 in the questionnaire.

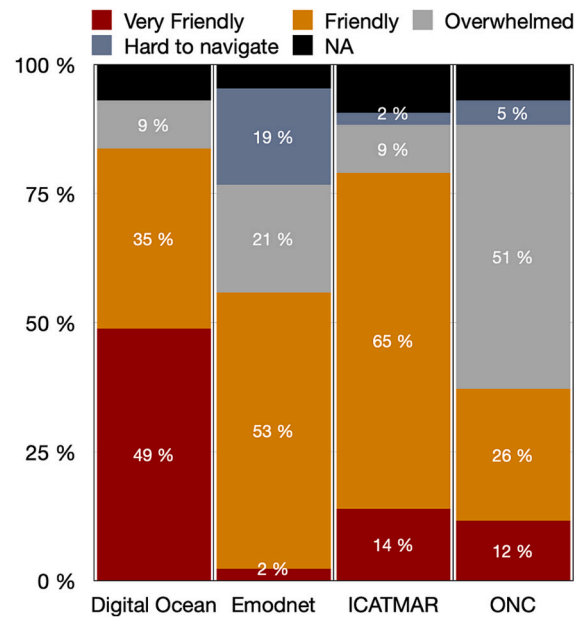


Fig. 2. Proportion of answers classifying the ease of use of four virtual GUIs of ocean monitoring data. ONC: Ocean Networks Canada. NA: Non-Available. Information provided by responses of Q11 in the questionnaire.

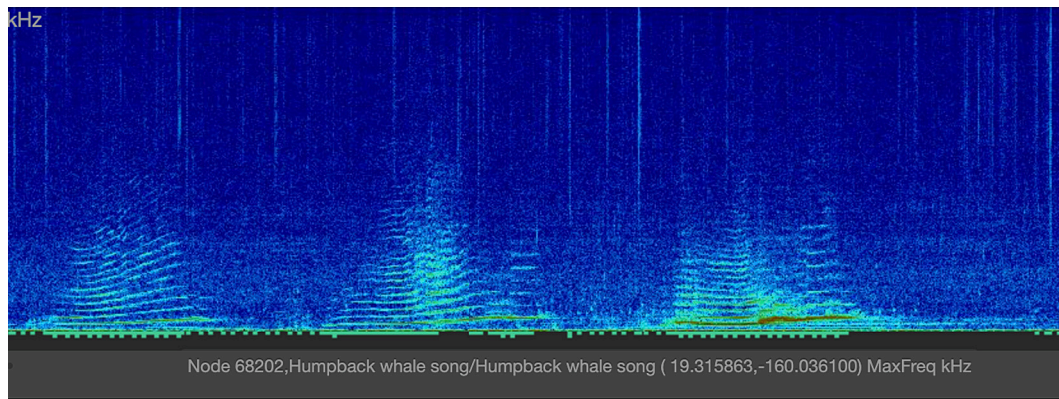
#### 3.2.2. Display of biological data

##### a) Imagery and eDNA.

Questions Q17 and Q18 addressed the preferred display of species through imagery and eDNA, respectively, assuming species had already been identified. For imagery, the majority of the participants (~60 %) preferred a display listing identified species alongside their appearance timestamps. Another 34 % suggested timeline-linked table showing species detections across the imagery sequence. This method is already used in the Holyrood GUI and the LTER observatory dataset (see Tables 2 and 3) and resembles the annotation dashboard of Ocean Network Canada 3.0 (see Table 3). In both cases, the degree of confidence in taxonomic identification and metadata on the identification process are essential. An alternative display method, irrespectively of the categories reported above, mentioned by a participant, involves overlaying annotations directly on the videos/images, such as bounding box around detected animals with the You Only Look Once model (YOLO, Redmon, 2016). For eDNA, most participants (~58 %) preferred a simplified display listing species identified by molecular analyses, along with access to sample metadata and genetic sequences. Another 39.5 % favoured displaying only the occurrence of eDNA collection and linking the user to the database, without directly showing the species detected.

##### b) Acoustic data and GUI representation.

Although no specific question addressed acoustic data, it is comparable to imagery in that it can provide qualitative outputs in the dashboard, especially through PAM. This latter enables the collection of multidisciplinary soundscape data, reflecting ecological, physical, geological, and anthropogenic signals. However, visual representations such as spectrograms (Fig. 3) does not offer intuitive and conclusive evidence of animal detections for general users. This is due to both the variability in species’ sound emission and the limited performance of automated detection models, which are further constrained by scarce species-specific acoustic knowledge. Currently, several techniques allow for real-time detection and identification of animal vocalizations, and some are already implemented in interactive web platforms, when sufficient ethological knowledge of species communication is available (e.g., Whales of New York, Autonomous real-time marine mammals’ detection, Listen to the Deep). Besides, challenges persist, especially in representing detection from tagged individuals, where acoustic pings correspond to individual animals and could convey additional attributes



**Fig. 3.** Spectrogram of frequencies between 0 and 24 kHz (blue to red colors), detecting humpback whale call (green squares below the spectrogram) at Station 68,202 Pacific Ocean on June 30th, 2021. Credits: “Listen to the Deep”. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

such as species, size, sex.

### 3.2.3. Spatiotemporal data visualization

In long-term monitoring, cabled observatories would greatly benefit from appropriate display of collected multi-dimensional data. As observed in the many existing GUIs, there are numerous types of charts for ecological data, but to respond to the concerns of the survey participants, visual consistency across sensors and disciplines should be preserved for GUI intuitiveness.

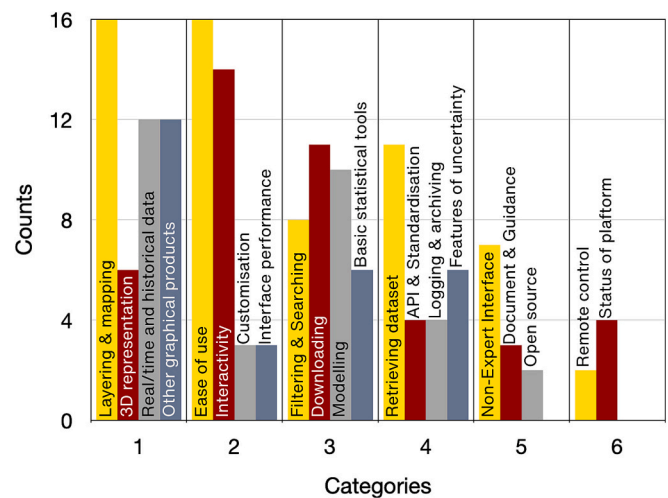
The most recurrent graphs are time series, which are de facto appearing on dashboards of a monitoring location as widgets. Time series are convenient representations which allow for overlaying multiple variables in the same plot – rated as a priority with 8.3 out of 10 in Q19, observing trends, and aggregating for a specific interval of time. In addition to being a default display, time series is also one of the methods to upscale ecological variables, selected in 31 % of the answers to Q7. Temporal upscaling accounts for matters such as updating data with historical source and/or real-time streams and filling up the gaps between collections. Moreover, upscaling data over time is one action for keeping an actively functional GUI, enabling a relatively continuity in data visualization.

Representation of ecological indicators over space was absent in the observatory interfaces reviewed (Table 3). Their visualization can occur in one dimension (e.g., along a bathymetric gradient or latitudinal axis, as in the Pacific Rocky Intertidal GUI; see Table 2), two dimensions (e.g., across a map), or three dimensions (for geomorphological structures of the seabed got by photomosaic; rated 7.6 out of 10 in Q19, or for immersive visualizations; see section 4.3.3). The latter approaches may be particularly well suited to monitoring platforms deployed at relatively close distances. Mapping ecological data is another effective upscaling technique - selected by 38 % of the answers in Q7 - and facilitate intuitive visualization on the monitoring area’s spatial extent (rated 7.7. out of 10 in Q19) and data variability among sensors. Indicators may be displayed using scatter dots, where dot size or colour reflects categorical or quantitative features (e.g., Pacific rocky intertidal maps in Table 2) or, through spatial gridding and numerical interpolation to estimate values between and around platforms (see section 3.4.2).

## 3.3. Highlights for the GUI development

### 3.3.1. Expectations

Expectations regarding the GUI (Q2, Table S1) covered various aspects, including design, data manipulation, access to the cabled observatory, and user accessibility. Three main categories emerged as the highest priorities (Fig. 4). Category 1, titled “Data Visualization”, gathered 46 occurrences and encompassed expectations such as



**Fig. 4.** Expectations of the participants for a GUI, grouped per Categories (digits between 1 and 6). 1: Data visualization, 2: User Experience, 3: Functionalities for data interactions and analyses, 4: Data management and Access, 5: Accessibility, 6: Control and Monitoring of platforms. Information provided by responses of Q2 in the questionnaire and findable in Table S1.

“Layering and mapping”, “3D representation”, “Real-time and historical data”, and “Other graphical products”. Participants expressed a strong interest in having a coherent and comprehensive visualization of data, particularly through 2D representations such as maps, time series, and other graph types. Category 2, titled “User Experience”, received 36 occurrences and included expectations related to “Ease of use”, “Interactivity”, “Customization”, and “Interface performance”. Respondents highlighted the need of an intuitive and user-friendly GUI, along with interactive elements that provide users with control over how they explore and engage with data. Q19 specifically evaluated the priority of different features within this category (Fig. S2). The interactive selection of timeframes for plotting and analysis received the highest rating (~8.7 out of 10), followed by the display of value information when interacting with graphs (8 out of 10). Customisation - either of the GUI or the plots – received slightly lower ratings, ranging from 6.2 to 6.8 out of 10. Category 3, titled “Functionalities for data interactions and analyses” gathered 35 occurrences, including “Filtering and Searching”, “Downloading”, “Modelling”, and “Basic Analytical tools”. This category reflects the need for data manipulation capabilities and the ability to query and filter multidisciplinary datasets following the FAIR principles (Wilkinson et al., 2016; Schoening et al., Cooley et al., 2022) and relate the parameters among them.

Categories with fewer responses were related to technical components of the GUI. Category 4 compiled responses for “Data Management and Access”, which includes expectations for “Retrieving dataset”, “Application Program Interface (API) and Standardization”, “Logging and archiving”, and “Features of Uncertainty/Quantity”. Participants highlighted the need for an interoperable system where users can provide new data inputs and updates. Expectations for featuring “Accessibility” into the GUI were listed (Category 5). Participants emphasized the importance of making the GUI accessible to “non-experts” with clear “documentation and guidance” on data collection and processing. Providing guidance - specifically displaying information and references - was rated 8.2 out of 10 in Q19. Finally, there was mentions for an “open source” approach to the GUI – meaning it should be free to use and has access to its underlying codes. Questions Q5 and Q26 brought further perspectives for global GUI accessibility. A majority of participants (51 %) agreed on the importance of developing an open-access GUI tailored to a project’s objectives (Q5; Fig. S3), with the option to incorporate external data sources from other monitoring sites once the GUI is fully developed. One response of Q5 also mentioned the ability for the GUI to be integrated into a broader DTO framework – an idea directly linked to Q26. Q26 asked about potential synergies between GUI products and an overarching DTO. In response, participants agreed to a wide range of suggestions, with preferences nearly evenly distributed across different types of GUI outputs that could be shared within a DTO context. These were, in descending order of answer rates: the collected data (28 %), the whole GUI (23.5 %), the data analysis and models (24.2 %), and the data acquisition program (19.5 %). Finally, Category 6, “Control and Monitoring of Platforms”, focused on expectation toward the deployed platforms connected to a cabled observatory. Some participants replied about authorized users having a “Remote control” for activation of sensors by sending commands and an access to the “Status” of the platforms.

3.3.2. Concerns

Concerns focused on GUI elements that might fail to meet expectations. Of the 43 participants, 15 responses were sufficiently detailed to be associated up to six out of eight thematic categories of concerns (Q3, Table S2). This process resulted in a total of 71 groups of text segment (Fig. 5). The primary concern was “usability and the user experience” (30 %), highlighting issues related to the intuitiveness and complexity of the GUI, including navigation difficulties and user capacity for plot generation. The second most frequently mentioned concerns were “data visualization and presentation” (14 %), and “scope of the interface” (14 %). Participants were concerned about how the GUI would handle and visualize large, multidimensional datasets in addition to data uncertainties from monitoring, processing and modelling. A poorly designed GUI could overwhelm users with large datasets, making data exploration and visualization ineffective and tedious. Regarding scope of the GUI (14 %), participants noted the importance of clearly defining its purpose to balance general and specialized functionalities effectively.

The remaining concerns fall into five categories. Among them, 12 % of responses addressed issues related to “Reliability and accuracy” of the

data. Participants stressed the importance of ensuring trustworthy mechanisms in the data, whether derived from monitoring or models. As the GUI serves as a virtual gateway to real-world conditions or realistic scenarios, users expect it to deliver reliable data that supports their research, learning, or decision-making processes while clearly indicating potential issues and uncertainties in the data. Concerns about the “User accessibility and inclusivity” accounted for 9 % of responses, focusing on the inclusivity of diverse user backgrounds. The GUI should accommodate both specialists and casual users, enabling them to navigate the interface and understand the data with minimal learning requirements. Supportive materials or interactivity features (e.g., hovering panels) can enhance this inclusivity. However, designing and maintaining a single interface to meet the needs of such a broad audience is practically impossible and would require the GUI to have different interfaces for the user category. A potential alternative could involve creating dual interface architectures for a technical community and societal stakeholders. In the same context, another 9 % of responses highlighted “User goals and adoption” as a key concern. For the GUI to achieve regular and sustained use, it must align with the needs and expectations of its target audience. It is unlikely that a GUI tailored for monitoring activities will appeal to all user types, making it essential to clearly define the users’ categories. For ecological monitoring, the main target audience includes marine scientists and engineers, policymakers in ocean governance, and Non-Governmental Organizations (NGOs). Casual users, such as civil society, while less frequent, should still experience the same ease of access and quality as other user groups. Additionally, a frustrating user experience, stemming from the lack of desired functionalities or poor performance in data access, could deter users and limit the GUI’s appeal.

The last categories of concerns were about the “Compatibility with databases” (7 %) and “Efficient performance” of the GUI (5 %). Here, the concern about compatibility centred on accommodating future integrations of new and undefined data or functionalities by external systems (e.g., local users or a new data repository) and resources (e.g., new sensors). This concern is likely toward steps underneath the GUI, related to the DTO structure itself, at the phase of harmonization and standardization of data. Concerns about the performance of the GUI are associated with accessing and rendering large datasets in a smooth and fast way. Performance is a fundamental and technical asset that contributes to the user experience, while seen as the lowest concern for the GUI, it is a relatively highly challenging component (see section 4.2.2).

3.3.3. Challenges

Challenges referred to technical issues that might arise during the GUI development process. Of the 43 participants, 25 responses them were sufficiently detailed to be associated up to five out of eight thematic categories of challenges (Q4, Table S3). A total of 86 groups of text segments were used as justifications for classifying the answers into categories (Fig. 6). The main challenge identified was “integrating and handling data” (22 %). Ecological monitoring often involves large, diverse, and frequently updated datasets. Monitoring activities are characterized by a timestamp, a discrete location, and depth. Data

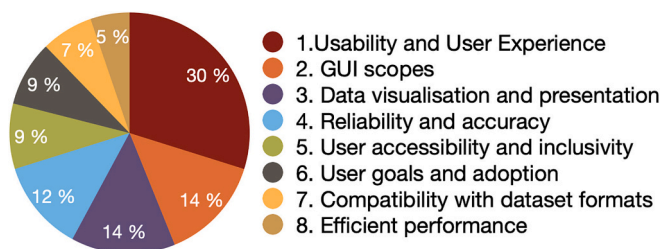


Fig. 5. Distribution of the 71 groups of text segments in 8 categories of concerns on the GUI. Information provided by responses of Q3 in the questionnaire and findable in Table S2.

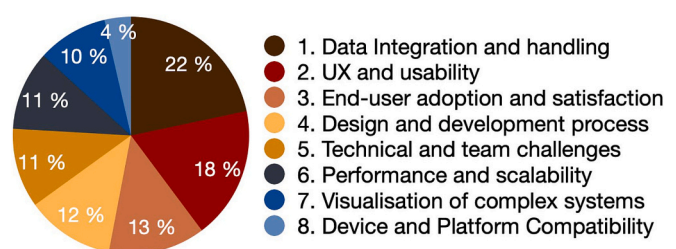


Fig. 6. Distribution of the 83 groups of text segments into the 8 categories of challenges identified in developing the GUI. Information provided by responses of Q4 in the questionnaire and findable in Table S3.

collected via monitoring activities often exhibit irregularities and discontinuities across these dimensions. For example, data might be only available at certain time periods, collected at different time intervals, and at different locations/depths. These inconsistencies pose a challenge for the GUI design, with the additional complication that datasets are relevant at different time and spatial scales. For example, to understand species behaviours, proper time scales may cover circadian rhythms, seasons, years, and periods of specific extreme events (marine heat waves, storms) (Aguzzi et al., 2023; Capotondi et al., 2024). However, other types of data such as seawater temperature anomalies due to climate change, may only be meaningful on a yearly or decadal scale. Summarising different datasets of the GUI is particularly relevant for societal stakeholders - provided that the summary includes contextual information, as these users often lack the expertise to synthesize data into accessible insights. To ensure smooth handling of large and multi-parametric datasets within the GUI, it is essential that data undergo standardization and quality assurance in accordance with established protocols prior to the GUI's design phase. Notably, the Darwin Core protocol, widely adopted for species observations, can be highlighted as an example of such standards. The "user experience (UX) and usability" category was the second most frequently mentioned challenge (18 %). Creating an intuitive, easy/friendly, and inclusive design that meets the expectations of users with varying technical expertise was highlighted as critical but complex. This overlaps with previously discussed concerns in this same category, showing the importance of maintain user/centred design principles across all expertise levels.

For the six remaining categories, varying between 4 % and 13 % of responses, the challenges were:

- The "challenge of end-user adoption and satisfaction" category (13 %) was overlapping with a concern (see section 3.3.2). Participants also mention the importance of complying with legal requirements such as GDPR and cybersecurity regulations.

- The "design and development process" category (12 %) encompasses challenges related to following a structured approach to GUI development. Pre-conception of the GUI, equivalent to a "Customer/Market research" phase for a minimum viable product, was approached in the survey to define the scope, select functionalities, and identify a common design framework. Participants stressed the importance of maintaining a clear scope, ensuring consistency across the GUI, and conducting regular testing. Testing is critical for identifying technical issues and gathering general feedback (e.g., on scope and consistency). Such measures ensure a smooth, structured, and relatively autonomous development process while addressing elements that could compromise the user experience.

- The "technical and team challenges" category (11 %) for the capacity to sustain efficient maintenance and updates for a GUI with dynamic data (i.e., new integrations, real-time updates) and reactive functionalities, which require repository accesses, adequate computational capacity, and sufficient storage space.

- The "performance and scalability" category (11 %), notably for managing large data volumes, which ensure responsive and efficient operation of the GUI.

- The "visualisation of complex systems" category (10 %), associated with the design of interactive and intuitive data visualizations for multidimensional data, particularly in 3D and 4D. This includes addressing the complexity of interactions within ecosystems and creating an immersive yet comprehensible user experience.

- The "device and platform compatibility" category (4 %), commonly referred to as "interoperability", remains a significant challenge when designing a web-based GUI accessible via various systems, browsers, and devices. For GUIs that are not fully interoperable, clear information about compatibility and the systems that offer the best user experience should be provided.

### 3.4. Biological priorities

This section deals with three questions related to the display of biological data, namely the selection of species (Q8), use of ecological functions (Q6), and upscaling of ecological monitoring information (Q7, Q10) in the GUI.

#### 3.4.1. Selection of species to be displayed

The question Q8 focused on selecting species for indicator computing and display in GUIs (see Section 3.2). The responses distributed in three key categories: a) targeted species, which are of primary interest for monitoring projects; b) prevalent species, observed in high number at monitoring sites; and c) commercial species, valued for their economic interest. A significant portion of answers (47.4 %) prioritised targeted species, while 38.6 % preferred displaying only prevalent species. Only a small fraction (1.8 %) proposed prioritizing on commercial species.

The two first categories often overlap, as targeted species are often among the most prevalent ones identified through long-term datasets. These responses align with findings from the review of ecological GUI contents (see Table 2), which tend to display a curated list of species rather than the full set of available biological data. The limited diversity of responses may be partly due to the closed-question format, which could have constrained participants' input. Nonetheless, it is noteworthy that targeted species can span across multiple categories, including commercial, iconic, and recreative groups. Here, the results also likely reflect the narrow career demographics of survey participants. Including policymakers, fishers, non-governmental organizations, and citizens may have led to different priorities and higher percentage favouring other species categories like endangered, commercial, invasive, and iconic species. If greater emphasis were placed on commercial species, this could provide an opportunity to enhance GUI features relevant to policymakers – for example, cross-checking the status of the monitored population with fisheries statistics. Likewise, displaying ecologically and conservation-relevant iconic species (e.g., sharks, mammals, and turtles) could increase public engagement and raise awareness among non-governmental organizations.

#### 3.4.2. Ecological functions

An advanced GUI should not only visualize ecological indicators as seen in Section 3.2.2, but also allow users to understand how external events, activities, or stressors impact them. This approach aligns with the concept of a Digital Twin of the Ocean, which virtually represents the past, current, and future status of oceans using data and models. Understanding ecological indicators can range from simple statistical summaries to complex modelling predictions. In that regard, all survey participants agreed in question Q6 that basic statistical summaries are essential in the GUI, although in regard to the GUI's expectation (Q2), modelling capacities had more mentions ( $N = 10$ ) than basic analysis ( $N = 6$ ).

Basic statistical summaries provide multidisciplinary insights over selected time intervals (e.g., last data reading, previous days, etc.) at a glance. In Q19, the option to display that summary in the dashboard was graded 7.8 out of 10. Applying "event-based" scenarios is another useful simple feature for observing changes in ecological indicators. We defined event-based scenarios as data bifurcation based on real and recorded events. Bifurcations can be characterized by preset thresholds (e.g., maximum water temperature), experiments (e.g., deployment of a dolphin carcass; Francescangeli et al., 2023; or an artificial reef; del Rio et al., 2024), time intervals (e.g., storms), or policy decisions (e.g., fishery closure). Event-based scenarios are valuable for presenting clear evidence of ecological shifts to non-experts, provided that the data representation is intuitive. Qualitative comparisons enable side-by-side visualizations, such as the change of species composition in catches with belt charts in ICATMAR. Quantitative analyses, on the other hand, can highlight temporal or extreme event changes or shift in comparison to a selected reference. Ecological anomalies were not identified in the

reviewed GUIs (Table 2, Table 3), in contrast to the visualization of physical data.

Modelling is a powerful approach to ecological data analysis and upscaling information over spatiotemporal dimensions. Modelling encompasses various stochastic techniques (e.g., Machine Learning, regression models) and deterministic methods (e.g., ecosystem models, individual-based models). These approaches allow the users to identify relationships among variables, calculate new indicators, and predict values for data gaps or under “what-if” scenario implementations. We defined “what-if scenarios” as computational setup models trained on existing data to predict changes under different conditions (Börjeson et al., 2006). For example, a what-if scenario might assess the response of the marine resource indicators to variations in water temperature (e.g., Corrales et al., 2018). Modelling also facilitates linking ecological indicators with biological, environmental, economic, and societal components. For a cabled observatory, the modelling concept is limited to approaches trained using data sourced directly from the monitoring site itself. In this context, ecological modelling focuses on characterising the relationship between ecological patterns and stressors, predicting spatial distributions using scattered data collected by mobile platforms near the monitoring site, and projecting time series, such as scenarios of global warming impacts on ecological indicators (Cooley et al., 2022).

Within the GUI, users should have three practical possibilities for implementing these modelling techniques. However, in practice, model training is more effective when performed locally after exporting data, i.e., in an external software. Exporting ecological data was 30 % of the answers of Q7 to upscale the ecological variables and one of the most highly anticipated functionalities of the GUI (see Category 3 in Fig. 4). Training a model from scratch requires a certain level of expertise, computational resources, and time, making it impractical to perform within the GUI. To optimize its performance, the selection of models and scenarios to be run inside the GUI should be limited to a few predefined options, unless the GUI integrates a computational server or a prompt (e.g., Python prompt in QGIS). Including a pre-trained model stored within the GUI, offers a more efficient approach. Users can call these models to make predictions within a specific scope but allowing them to explore scenarios and manipulate data with relative freedom. Existing thin-client interfaces (e.g., Shiny apps, Jupyter based tools) permit these runs, calling external services with high computing capacity (e.g., High

Performance Computing clusters, cloud-based APIs) to fetch results dynamically. However, the assumptions and limitations of these predefined models should be clearly disclosed, and models should be fed with quality/controlled, validated datasets to avoid propagating errors, as incorrect scenario conditions can lead to inaccurate extrapolations. Ultimately, incorporating model predictions within the GUI is a practical solution that minimises user errors and misinterpretations of outputs while maintaining control over the modelling process. Some GUIs designed for ecological data have adopted the approach of directly visualizing model predictions, as seen in systems that integrate physical gridded conditions as map layers or predictions developed within specific frameworks (e.g., EMODnet Biology, AquaMaps of Fishbase - Kaschner et al., 2019).

#### 4. Roadmap for GUI development: guidelines and future work

Based on the survey results and the review of existing GUIs, the development of a GUI for exploring and integrating ecological data should align with both general users’ needs and technical functionalities. Below and schemed in Fig. 7, we detailed steps that should be considered when designing a GUI including biological data from continuous ecological monitoring.

##### 4.1. Setting the GUI objectives, priorities, and scopes

Before developing a GUI for ecological data, it is critical that developers and stakeholders jointly identify expectations, define requirements, align on a primary scope and agree on a mock-up GUI (“Mock-up” 1 in Fig. 7). This initial agreement lays the ground for selecting appropriate functionalities and delivering a coherent narrative user experience throughout the GUI. Survey responses reflected a wide range of expectations for the GUI from the expert point of view, with the most common being the desire for a modern and intuitive interface that offers responsive interactions to enhance the user experience and engagement. However, developers must carefully balance these expectations against the inherent complexity of ecological data and the limitation of display capabilities. A GUI cannot present all data collected at monitoring sites; instead, its content must reflect the objectives of the monitoring program. This necessitates thoughtful selection of ecological

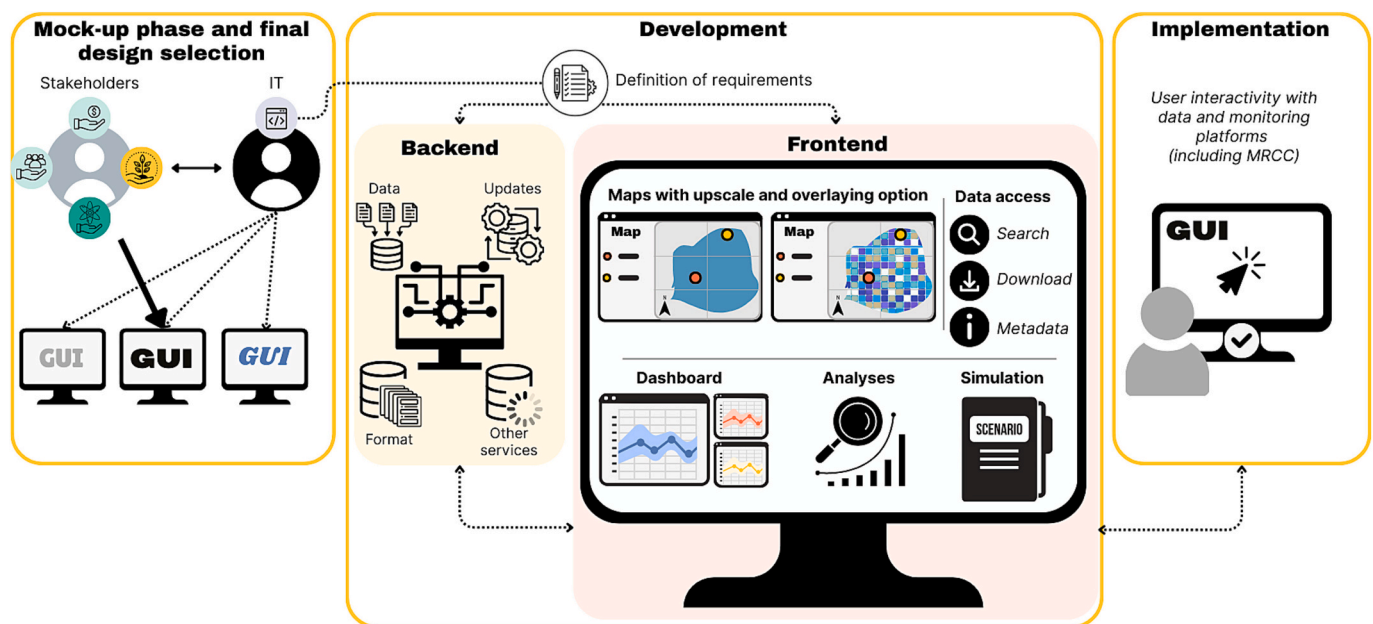


Fig. 7. Schematic processes for developing a GUI from stakeholder consultations to the implementation of the final product. Features in the frontend development block are developed in the text and correspond to listed services based on the review of GUIs and survey. MRCC: Mission Remote Control Center.

indicators, often including the need to specify taxa and define the most effective methods of visualization.

As continuous influx of new data evolves, the GUI must be routinely maintained and updated to keep pace with data inputs, advances in software, and ensure long-term usability. While the development of GUIs and DTOs can be supported by research and development (R&D) projects, these projects are by nature time-limited, and therefore cannot guarantee long-term continuity (Ducklow et al., 2009). To ensure stable operation, everyday maintenance should instead rely on constant funding streams and cover personnel, material, and operational costs. These costs encompass several critical areas: (i) sustained data collection supported by structured monitoring plans; (ii) data curation and treatment, requiring permanent staff such as data managers and technicians; (iii) continuous data analysis to update models, extract information, and generate usable ecological insights; (iv) technical maintenance of DTO and GUI architectures, supported by software engineers and IT specialists; (v) dissemination, communication, and training activities to improve DTO/GUI literacy and perception among local communities; and (vi) material and infrastructure upkeep to meet computational demands (Urbano et al., 2023; Vander Naald et al., 2019). In addition to public support, the private sector, particularly those involved with the monitoring product, could contribute by providing data, expertise, or targeted financial support for specific components of the GUI (Lindenmayer et al., 2022; Sergeant et al., 2012).

Finally, brainstorming sessions help gather user requirements and ensure GUI development is guided by a clear understanding of the target users, stakeholders, and their needs. In the scope of ecological monitoring, we identified four key target groups: technicians and engineers responsible for the monitoring stations, marine and oceanographic researchers, policymakers, and civil society. Each group requires different levels of data complexity, visualization depth, and interactivity, which should be considered in the interface design. Technicians and engineers need to get real-time updates on the status of the monitoring equipment, such as battery levels, data quality indicators, or on-site needs of maintenance operations (for e.g., biofouling on sensors; Delgado et al., 2021). Academia requires that data are traceable and that its processing and collection methodologies are clearly stated. This target group often demands an in-depth GUI where different data sources can be crossed and tuned to be able to test and create new hypotheses. The last two groups were not represented in the questionnaire, as technical and innovative mentions about DTOs and monitoring equipment require a level of literacy. Their consultation is an added value for the GUI pre-design, development feedback, and sustainability of the GUI (Mackenzie et al., 2019). Governmental agencies and policymakers could typically expect a GUI to provide services for comprehensive overview of the data context and limitation along clear evidence to support decision-making (Crosby et al., 2023). In contrast, civil society uses may seek the GUI as enthusiasts about marine life, support educational purposes, or even contribute to data collection through citizen-science initiatives (Crosby et al., 2023; del Rio et al., 2013). Although GUI design often targets a specific user group, it is possible to create a multi-interface system that accommodate varying levels of expertise and aspects of accessibility, thereby serving diverse audiences effectively. Creating a GUI that fits all is a challenge, often leading data providers to create multiple GUIs to access the same data from a different scope. For example, the CMEMS provides three different GUIs (MYOCEAN LEARN, MYOCEAN LIGHT, and MYOCEAN PRO), each adjusted in terms of complexity and content to different levels of user expertise. A simple approach to adaptive GUI is to let users select their role, which will subsequently customize the UI layouts into streamlined and advanced settings. First-time users would benefit from an interactive help option for navigation and data interpretation (see e.g., Reef Life Survey in Table 2), or with the interpretation of displayed data, indicators, and maps. Alternatively, the GUI can use progressive disclosure settings that first show the most important settings and provide advanced options upon requests. Finally, more complex approaches could use machine-

learning reinforcement techniques to automatically tailor the GUI to the user's expertise (e.g., Todi et al., 2021).

#### 4.2. Autonomous and remote biological data management

An efficient GUI depends on a well-understood workflow, from data collection at the sensor level to storage in repositories, resulting in harmonized datasets that support visualization and analysis features ("Data pipeline" in Fig. 7). Ensuring dataflow is a key service happening before the GUI development and requires protocols to homogenise and standardise data (Aguzzi et al., 2025). Beyond these foundational elements, the adoption and attractiveness of the GUI are closely tied to its innovation and regular updates. Like any product, a new GUI must respond to "market demands", appealing to users through novelty, smooth navigation, and rapid access to new information. Demonstrating active development and delivering timely, informative content increase the likelihood that users return and remain engaged. The questionnaire identified two innovative priorities to advance the features of an ecological monitoring GUI: enabling near-instant processing of biological data upon collection and facilitating the coordination of targeted monitoring activities.

##### 4.2.1. Incorporation of near-real time biological data

Near-real-time integration of faunal data through the GUI with environmental data – such as time series - and merging with historical datasets, provided that data collection methods are standardized to ensure comparability and interoperability. With the ongoing advancements in AI, there is a growing opportunity to automatically extract species information from video footage in near-real time. This includes generating annotation tables linked to biological indicators and assessing the identification quality/errors (referred to F1 score and mean Average Precision in Stavelin et al., 2021 and applied in e.g., Catalán et al., 2023). Although this AI-driven approach is gradually being incorporated into monitoring workflows (e.g., Baños Castelló et al., 2025), expert taxonomic validation remains essential to ensure accuracy, which introduces delays due to the time and expertise required. Conversely, near-real-time data from long-term and frequent physical sampling remains a significant challenge. Nonetheless, thanks to technological advancements facilitating miniaturization and portability of DNA sequencing instruments, eDNA metabarcoding workflows are becoming increasingly time- and cost-effective, with promising applications especially in fish community profiling (e.g. Tibone et al., 2024). Autonomous systems capable of collecting and fixing in situ marine eDNA samples are already in use (Yamahara et al., 2019), while autonomous systems capable of processing eDNA data in situ are in development, showing promising results for species-specific detection (e.g. Hansen et al., 2020). However, real-time processing (both in data generation and bioinformatics), as well as hardware maintenance requirements, continue to be major obstacles for eDNA data integration, especially in the marine environment (Scholin et al., 2017). Currently, efforts in integrating eDNA data in multidisciplinary studies carried out at cabled observatories have focused on sample acquisition, with downstream sample processing and data acquisition performed a posteriori in suitable laboratory conditions (e.g. Tibone, 2023; Tibone et al., 2025).

##### 4.2.2. Synergies with Mission remote control Centres for autonomous robotics operations

At present, most ecological data integrated into the DTO comes from fixed monitoring platforms, such as underwater observatories, smart buoys, and digitized fisheries records. However, marine robotic technologies are playing an increasingly significant role, enabling both routine and ad hoc surveys with diverse sensor payloads and the capability for physical sample collection. Autonomous marine robotic operations are typically supervised and coordinated by Mission Remote Control Centres (MRCCs), which serve as centralized hubs for mission

oversight (di Lillo, 2021; Vasilijevic et al., 2023). MRCCs provide real-time visualization and control, featuring map-based GUIs that display mission areas, vehicle locations, telemetry data, and sensor outputs -whether raw or pre-processed - depending on communication bandwidth constraints. These systems enable efficient management of the fleet of autonomous robots, adaptive mission planning, and human intervention. The implementation of MRCCs shares technological synergies with the data transfer, storage, and processing infrastructure required to support the DTO. Since both the DTO and MRCC rely on map-based GUIs, integrating their backend and frontend architectures could enable bidirectional data exchange. This would allow on one hand robot tracks and near real time survey data to be visualized within the DTO, while on the other, DTO-generated insights could be harnessed for mission simulations, AI-driven adaptive planning, and real-time decision-making in ecological monitoring. Such integration would enhance the ability of autonomous marine robots to dynamically respond to environmental changes, optimizing their efficiency and impact in long-term ocean observation.

### 4.3. Highlights on biological display in the GUI

Online interface represents the visible surface – the “tip of the iceberg” - of complex data infrastructures. Their primary role is to facilitate an accessible and intuitive overview of biological data, making ease of use and a gentle learning curve essential to design priorities. Responses from our questionnaire emphasized several key contents for ecological monitoring GUIs, including interactive mapping, diverse functionalities, and 3D visualizations (Steps 3–5 in Fig. 7). This section focuses on how to structure the access to biological data within the GUI to support such progressive exploration and analysis.

#### 4.3.1. Default home page: a map-based entry point”

For ecological and environmental data, the preferred home page when entering the GUI, was a map displaying key monitoring information including type and number of active monitoring platforms, from which a list of items can be filtered in and out. This idea follows the traditional information visualization mantra originally formulated by Shneiderman (1996): “Overview first, zoom in and filter, details on demand”, that is applied in almost every map-related data from environmental sciences to computer gaming. This initial map should be kept simple and should have option to add or modify spatial layers and scroll temporal features. Many of the reviewed GUI for continuous data stream (Table 3), display the spatial location of monitoring site network with a bathymetric map, allowing for a clear understanding on the geomorphological monitored environment (e.g., ONC and OOI in Table 3). Additionally, the ability to display the spatial distribution of sensors on a local map could be a valuable asset for establishing the spatial context of collected data. This feature enables users to understand the extent and positioning of both fixed and nearby mobile sensors, and to assess environmental conditions that may influence the observation, particularly when multiple cameras are deployed within the same area. Lastly, it is as well of specific interest for remote control functionalities when activating a mission to collect data over specific area.

After the home page, layouts can change with the user experience and activities in the GUI. For example, when selecting a monitoring site on a map, it is common to access a dashboard that provides a time series of data in widgets. For a first-time user, the goal is to explore further data availability and step visualization. For a regular user, being able to directly step into an advanced setup (i.e., without going through GUI exploration steps) is a great asset. The narrative of the GUI should trace consistent features while navigating through its components. It is essential to maintain the same experience through the functionalities (e.g., data access) or visualization despite changes in data sources, be they ecological or environmental. This consistency contributes to the efficiency of the virtual environment, ensuring the reuse of functions called for delivering an output to the users.

#### 4.3.2. Data access and traceability

Data from monitoring activities or generated by numerical calculations is the core item of the GUI and was the principal challenge according to the survey’s answers (Fig. 4). Handling them requires a list of functionalities that were detected in reviewed GUIs: metadata, data access, data export. Metadata should be easily found, ideally following the best practice guides and protocols available (European Commission, 2023) for data flows in international data infrastructures (e.g., EMODnet), or at least with a consistent vocabulary and structure among data of the same GUI. Data access is about retrieving data from the repositories in which monitoring data are stored or from local datasets, providing their format have been standardized to the GUI’s requirements. It is important to optimize and maintain the performance of the GUI in that regards, and cutting-edge technology developed for modern Internet of Things applications in the GUI back-end is crucial to the GUI functioning. Notably, the micro service architecture within which the GUI interacts with services can call one or more separated services to operate the user demand. This kind of architecture limits risks of blockage due to programming and system errors and facilitates data access and updates of the GUI over time. Data export, finally, is an important functionality, complying with the Findability, Accessibility, Interoperability, and Reusability (FAIR) principles of digital scientific assets (Wilkinson et al., 2016). Datasets are often stored in public repositories per mandates of funding agencies and exportable from these portals. Most GUIs that were explored in this paper also provide a data downloading service, but levels of services to be added can include downloading a subset of the dataset using filters, dataset beneath plots, or plots themselves.

#### 4.3.3. Digitalization perspectives for cabled observatory

Cabled observatories, being or becoming a large spatially distributed scientific network of robotic platforms, can be presented in an innovative 3D GUI, with immersive experiences that include interactions with the platforms themselves or with the collected data (Fig. 7). This type of experience is an innovative feature integrating into a DTO framework (e.g., EDITO). The vision for a digital twin of a cabled observatory would be an equivalent to be a gamer in a virtual water tank with simulated 3D fauna and seabed structure, “missions” across the robotic and sensors platforms present in the tank, extending in the surface area of the deployed platforms, and offering a new way to experience ocean observation. Instead of a virtual reality, in which permanent and heavy payload of equipment would be costly and facing latency issues, virtual and simulated 3D environment provide a more constant continuity of digitalised data, that only depends on one spatial entry source of data: the cost-effective cabled observatories. Virtual 3D simulated environments already exist, bounding the possibility of simulating changes in the environment (e.g., OBSEA 3D simulations, Llorach-Tó et al., 2023) and interacting with the platforms to visualize a real stream of data (e.g., SmartBay 360 Tour). Steps about integrating mobile fauna features and other sessile specimens should be developed, such as when a species is observed and identified, a chain of functions can trigger the appearance of a 3D fish in the virtual tank. A suggested option for the whole monitored area consists in hybridizing constant pre-rendering systems of static (e.g., platforms, and seabed topography and coverage) and dynamic (e.g., biota and environmental changes) elements. At the end, the user can access to a default 3D environment and overlay the dynamic elements based on collected data, scenario cases, or model runs by inquiries.

## 5. Conclusion

The collection of biological information on marine life, from individual species to entire ecosystems, is essential for understanding and managing ocean health. In the face of accelerating marine biodiversity loss and the degradation of key habitats, there is an urgent need to strengthen long-term marine monitoring. Advances in autonomous monitoring technologies, including underwater observatories, network

sensor platforms, and automated ecological data acquisition systems, have enabled the digitalisation and modelling of biological conditions in real time. Accordingly, a GUI serves as a critical operational representation of a DTO. A well-designed GUI not only classifies and visualises biological and environmental datasets but also enhances accessibility for users by integrating real-time and historical data streams into an interactive, user-friendly virtual space. This study focused on defining GUI design guidelines for the integration of ecological and environmental data. To this end, we developed a virtual ecological space, incorporating expert perspectives collected through an online survey targeting specialists from various marine science fields. The results provide a structured foundation for a GUI development, ensuring that future GUIs effectively balance usability, functionality and ecological representation. The insights from this study will be valuable for multiple stakeholders, including scientists, managers, and policymakers, by improving their ability to interpret and utilise ecological data for conservation, management, and decision-making. By defining the GUI guidelines for DTOs, this study lays groundwork for more accessible and interactive ocean monitoring. Future work should focus on further refining GUI functionalities, integrating machine learning models for ecological forecasting, and enhancing interoperability with global DTO initiatives such as EDITO.

### CRedit authorship contribution statement

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### 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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### Data availability

This review/synthesis paper did not generate any primary data nor did it create any codes that could be shared with the readership of the journal.

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