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Enhancing open science through ERDDAP™: use cases for data dissemination in marine science

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ABSTRACT Open science promotes a set of values, principles, and practices that collectively aim to make scientific research, across all disciplines, accessible to all and for the benefit of humanity as a whole. In this context, data becomes a strategic resource whose value depends on their quality, interoperability, and long-term accessibility. Applying the findable, accessible, interoperable, and reusable principles is, therefore, essential to enable effective data reuse across all disciplines. Data centres play a fundamental role in this process, ensuring the curation, preservation, standardisation, and dissemination of research data. The Italian National Oceanographic Data Centre exemplifies this role by managing extensive oceanographic archives and supporting national and international initiatives dedicated to environmental knowledge. This article presents concrete use cases for data dissemination based on the Environmental Research Division Data Access Program (ERDDAP™), an open-source platform that simplifies access, visualisation, and machine-to-machine interoperability of environmental datasets. Implementations conducted within European and national projects, such as European Marine Observation and Data Management Chemistry and the Italian Integrated Environmental Research Infrastructures System, demonstrate how ERDDAP™ improves the usability of curated datasets, supports validation workflows, enables interactive analysis, and facilitates integration into virtual research environments. These experiences highlight how the adoption of standardised tools for data dissemination contributes to the advancement of open science, improves scientific reproducibility, and strengthens collaborative and multidisciplinary research.

Key words: open science, open data, FAIR, ERDDAP™.

1. Introduction

European organisations produce large amounts of data, much of which is funded by public investment, particularly in scientific research. The European Union has adopted a series of policies to facilitate the return on investment of publicly funded data, emphasising that data should bring benefits to the European economy and society [Directive (EU) 2019/1024]. The rationale behind these regulations is to reduce barriers to the public use of data, especially publicly funded research data.

All data generated using public funding should be shared and there should be no restrictions on their reuse for any reason. It is in this context that the concept of open science has evolved.

In this paper we describe the different shades of open science during data lifecycle and showcase how the developments in funded research projects enable us to move towards open research science.

2. Open science

Open science is a broad and evolving concept, including multiple definitions and approaches to its implementation.

In 2021, UNESCO published the Recommendation on Open Science, which provided the first internationally recognised definition along with a set of shared values, guiding principles, and foundational pillars to guide the global Open Science future movement (UNESCO, 2021).

At its core, open science is a set of values, principles, and practices that collectively aim to make scientific research, across all disciplines, accessible to everyone, for the benefit of humanity.

It seeks to ensure that all aspects of scientific research are accessible to the public.

Beyond its core values, open science is also based on six guiding principles:

- quality and integrity: support high-quality research by bringing together multiple sources of knowledge;
- collective benefit: open science as a global public good belonging to humanity;
- equity and fairness: equity among researchers and equal access to scientific knowledge for both producers and consumers of knowledge;
- diversity and inclusiveness: diversity of knowledge, practices, workflows, languages, research outputs, and research topics.

UNESCO (2021) identifies four main pillars of open science, presented as the four pieces of a puzzle that fit together (Fig. 1):

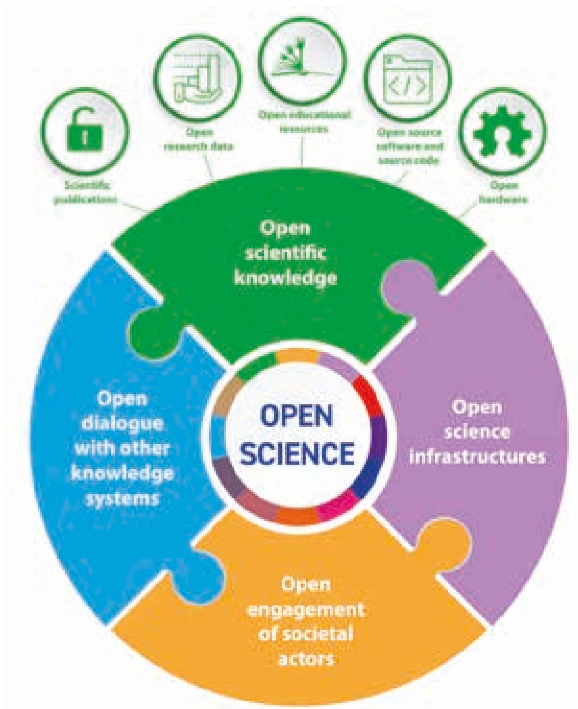

Fig. 1 - Pillars of open science, with focus on the Open scientific knowledge pillar (UNESCO, 2021).

1. open scientific knowledge;
2. open scientific infrastructures, enabling the generation of scientific knowledge;
3. open engagement of societal actors, including both qualified scientists and other groups;
4. open dialogue with other knowledge systems.

Together, these pillars form the foundation for a more transparent, collaborative, and inclusive scientific ecosystem.

Among the four pillars of open science, two are particularly relevant for data management: Open scientific knowledge and Open science infrastructures.

The first pillar, Open scientific knowledge, encompasses the open access publication of scientific articles, open research data and metadata as well as open educational resources. However, it also includes open source software and research codes as well as open hardware, all of which are essential components to promote open scientific knowledge.

Open science also relies on Open science infrastructures (Fig. 2), which include virtual and physical infrastructures that enable scientific research. The infrastructures include spaces, equipment, tools, workflows, and other supporting structures and processes without which research could not take place.

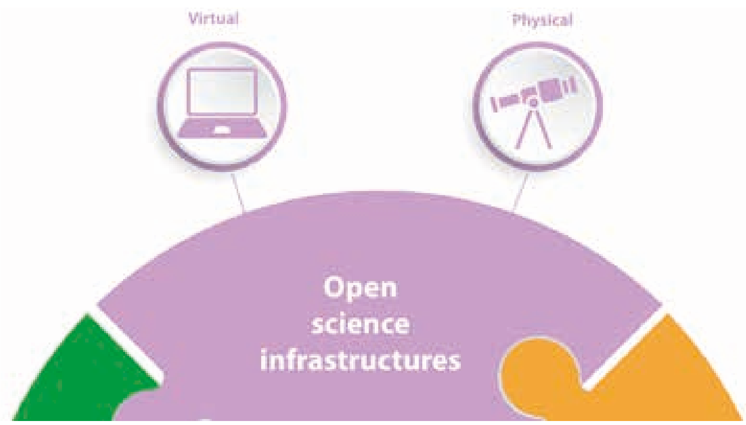

Fig. 2 - The Open science infrastructures pillar (UNESCO, 2021).

In the context of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) (UNESCO, n.d.), one of the challenges identified in the 2030 Vision is the sustainable expansion of the Global Ocean Observing System (Miloslavich *et al.*, 2024), where long term observations benefit almost all the targets of Sustainable Development Goal 14 - Life Below Water. FAIR (findable, accessible, interoperable, reusable) information from closed data silos or from new observations are needed to generate fit-to-purpose knowledge, useful to multiple stakeholders, for taking advantage of the investments and avoiding the duplication of efforts.

3. The strategic role of data in open science

In open science, data are a strategic cornerstone that ensures the transparency, accessibility, and reusability of scientific knowledge. Research data are not merely a by-product, but a central resource that enable the verification, reproducibility, and advancement of knowledge. This approach accelerates research and reduces duplication of effort. Data are not just a technical tool, but a strategic element for transforming how research is conducted, shared, and leveraged.

For an effective reuse in new studies, including interdisciplinary ones, data must be well documented and structured according to the FAIR principles (Wilkinson *et al*., 2016).

In short, the FAIR data principles are useful as they enhance the accessibility of research data. However, FAIR does not imply that all data must be openly available without restrictions; rather, it emphasises making data reusable under clear conditions, thereby promoting open science in a more general sense.

The four FAIR data principles are summarised below [as defined by Wilkinson *et al*. (2016)].

The first principle is FINDABLE. This means that the data should be easy to find for both humans and computer tools thanks to detailed metadata and a unique, persistent identifier.

The second principle is ACCESSIBLE. This means that the data must be stored in such a way that they can be easily accessed and downloaded.

The third principle is INTEROPERABILITY. This means that the data must be available in a format that can be easily used, combined with other data, and processed by both humans and machines. In technical terms, the principle of interoperability requires that data and metadata use a formal, common, and widely applicable language to represent knowledge, including consolidated vocabularies and references.

Ultimately, the fourth principle, REUSABILITY, means that data should be available for reuse with detailed and accurate documentation and a clear license to use. Essentially, interoperable means that data files should be easy to access, work with, combine with other datasets, and analyse. No special proprietary software or file formats should be required and there should be no further technical barriers to the processing of the data once found and retrieved.

This is the most important FAIR principle, as the reuse of research data is the focus. The other three principles, data findability, accessibility, and interoperability, help to make reuse easier and more likely. To be reusable, data and metadata must, therefore, be described in detail, with multiple, accurate, and relevant attributes. It is also important that data and metadata are accompanied by a clear license for use. This should clearly describe how the data and metadata may be used, what terms of use apply, and the requirements established, e.g. naming the original authors. Licenses should be understandable by both humans and machines to facilitate automated workflows and compliance.

4. The role of data centres in open science

Data centres play an important role in ensuring data FAIRness. For open science, these centres are indispensable, as they often serve as national or international nodes, ensuring the preservation of measurements, possibly spanning decades or more, which is valuable for time series studies (Tanhua *et al*., 2019). To make data reusable, standards for formats, metadata, validation procedures, and quality control are required. These data centres often implement such procedures, making data more reliable by applying FAIR principles, with well-documented metadata, access interfaces, and clear sharing policies. This is essential for opening up research, promoting reproducibility, and enabling interdisciplinary use.

A concrete example of an oceanographic data centre that serves as a fundamental pillar for implementing open science in the marine field is the Italian National Oceanographic Data Centre managed by the National Institute of Oceanography and Experimental Geophysics (NODC-OGS). The NODC-OGS plays a key role in collecting, storing, validating, and making national oceanographic data accessible. Officially accredited as an oceanographic data centre by the International Oceanographic Data and Information Exchange programme of the UNESCO Intergovernmental Oceanographic Commission, the NODC-OGS fully adheres to the FAIR principles and promotes open access, reproducibility, and interoperability policies. Its archive holds over 460 million measurements, including more than 300,000 water column observations, collected through an extensive network of *in situ* monitoring systems, European projects, and international collaborations. These data are crucial for climate change research, improving marine and oceanographic modelling, supporting sustainable management of marine resources, and informing evidence-based environmental policies. The NODC-OGS also actively participates in initiatives such as SeaDataNet, the European Marine Observation and Data Network (EMODnet) and the European Open Science Cloud, strengthening the link between national science and European infrastructures. In a context of growing demand for transparency and open access to knowledge, data centres not only facilitate the dissemination of scientific knowledge but also strengthen the country's ability to contribute to global challenges related to ocean health and environmental sustainability.

Fig. 3 shows the data life cycle proposed by the Harvard Longwood Medical Area Research Data Management Working Group (Cioffi *et al.*, 2023), with the NODC-OGS involved in every phase, starting from Plan & Design. In this phase, the overall research plan is discussed and documented through the drafting of the Data Management Plan. An example is the version published by the EU Commission (European Commission, 2022). Specifications and agreements are defined, the system architecture and life cycle development are initiated, the necessary toolsets, infrastructure, and standards are agreed upon, and arrangements are made for their implementation.

The Plan & Design phase is followed by the Collect & Create phase, during which the data centre is involved in the actual acquisition of data and provides researchers with support in the correct documentation of metadata, as data without appropriate metadata can be completely

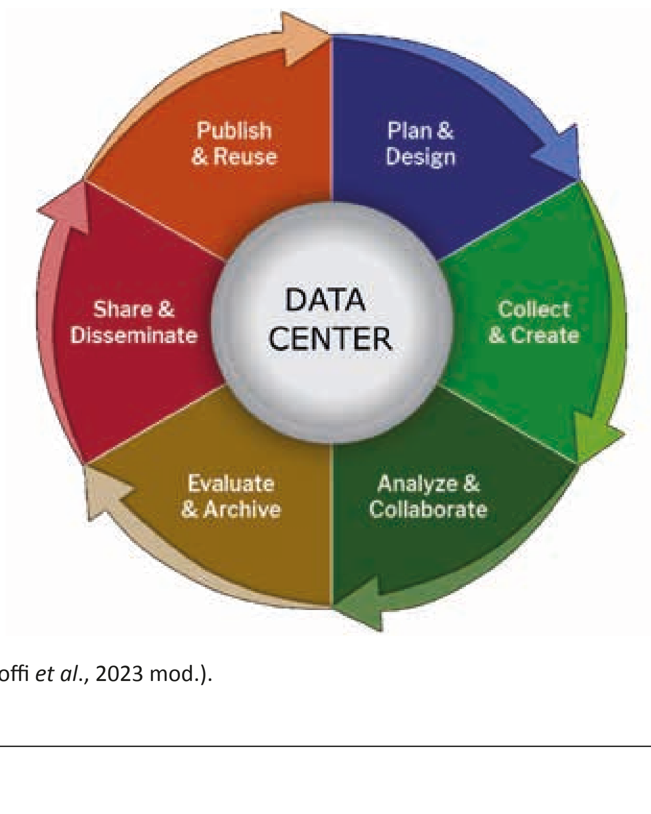

Fig. 3 - Data life cycle (Cioffi *et al.*, 2023 mod.).

worthless. In the Analyze & Collaborate phase, the complete organisation and standardisation of data and metadata takes place. During this phase, data may be cleaned and transformed, while specific quality control procedures may be applied. The data and results must be stored for the long term. Although the objective of the Evaluate & Archive phase is to ensure that data remain available even after the end of the research project, it also aims to preserve data in the very short term, minimising the risk of data loss. Preservation activities may include ensuring data quality, converting file formats, creating metadata records, assigning digital object identifiers to datasets, licensing dataset reuse, and implementing access controls.

Once processed and placed in the appropriate repository, the data flow continues with the Share & Disseminate phase to make them available online. The data can, then, be reused by other researchers, both to corroborate the results of original research and to generate new insights through further queries and analysis. This phase also introduces other researchers to the next phase of data reuse (Publish & Reuse), enables them to answer new research questions or to use existing datasets for training purposes, giving science students and new researchers the opportunity to practise and improve their research skills.

Data reuse also promotes collaboration and mutual trust among researchers within a discipline and can serve as a bridge to initiate interdisciplinary collaborations. By redistributing research data for reuse, researchers can maximise the scientific, economic, and social benefits of their work.

5. Use cases

Data dissemination in open science is a strategic component of the scientific process, aimed at making research data accessible, reusable, and visible. In this context, data centres play a crucial role as infrastructures dedicated to the storage, management, and distribution of data, ensuring their integrity and availability over time.

Disseminating data does not simply mean publishing final results, but involves making raw data, metadata, and protocols available so that they can be verified, reused, and integrated by other researchers, in accordance with the FAIR principles. Often defined as data wrangling, making data useful is probably the most tedious and time-consuming aspect of analysis (Kandel *et al.*, 2011).

In this work, concrete examples of data dissemination carried out by the NODC-OGS through the use of environmental research division data access program (ERDDAP™) servers are presented. These have been implemented in the framework of different research projects facilitating the distribution of data once enriched and curated. Data sharing is a fundamental phase in the life cycle of scientific research which takes full advantage of the low hanging fruits obtained thanks to the work in the previous phases of the data flow and enables data lifecycle to continue through data reuse for different purposes.

ERDDAP™ is an open-source platform developed by the National Oceanic and Atmospheric Administration's Southwest Fisheries Science Center to simplify data access and use. It addresses key data management challenges, such as diverse formats, download protocols, and automated access, by providing a unified interface for aggregating gridded and tabular datasets from local and remote sources. Users can easily select data subsets and download them in standard formats, thus facilitating analysis and integration across a variety of contexts. Thanks to an intuitive web interface, ERDDAP™ enables to explore environmental events through customisable maps and graphs. It also provides direct data access via representational state transfer (RESTful) web services, supporting machine-to-machine applications. These features make ERDDAP™ a powerful tool for expanding the use of remote sensing data in multidisciplinary settings, including research and education. ERDDAP™ is widely used by marine data publishers around the world, for example the Irish Marine Institute (n.d.), IFREMER (n.d.), and the British Oceanographic Data Centre (n.d.).

Following, some use cases of the platform's key features, including examples of its visualisation capabilities, are presented.

The first use case was developed in the context of the framework of European projects where open science is a fundamental asset. European and global institutions are working hard to collect, format, archive, and share high quality environmental data and information. The ocean knows no borders and data sharing is necessary to draw up environmental policies based on knowledge that is informed by extensive data.

Fifteen years ago, the European Commission Directorate-General for Maritime Affairs and Fisheries (EC DG MARE) launched the EMODnet data infrastructure, which today provides a consolidated framework for open access to marine data, products, and services. The institutions behind it work together in scientific thematic areas to offer FAIR information.

The thematic discipline of EMODnet Chemistry focuses on data and information relevant to eutrophication, pollution by hazardous substances, and litter. Each year, regional aggregated datasets on these themes, containing validated unrestricted data in a single format described with common semantics, are published.

The aggregated data collections are available through various access points; direct download (https://emodnet.ec.europa.eu/en/chemistry#chemistry-data) or visualisation and subsetting (https://emodnet-chemistry.webodv.awi.de/) have been possible for a long time. Yet, neither of these distribution procedures were machine readable; the implementation of an ERDDAP™ (Fig. 4) instance for the EMODnet Chemistry aggregated data collections (https://erddap.emodnet-chemistry.eu/erddap/index.html) has provided additional interoperability to data dissemination, promoting the interaction with other systems (e.g. software, applications) and contributing to data integration, enriching the digital landscape. The choice of ERDDAP™ was based on its main features: being an open-source, simple, and user-friendly tool that enables the downloading of data in different formats. In addition, the automation of requests and the chainability to other ERDDAP™ servers are important assets.

EMODnet has a central ERDDAP server that can potentially host the data products for all thematics. However, the deployment of a specific EMODnet Chemistry ERDDAP server has different advantages which significantly improve the quality of the service. In this sense, it is worth noting that domain knowledge is fundamental to provide meaningful scientific content during the publication of data in ERDDAP. The chainability to other ERDDAP instances enables the harvesting of the thematic server from EMODnet central ERDDAP, maintaining the whole information management in the chemistry lot. Technical research and development work has been carried out to implement a sustainable workflow that can be annually reused with the release of each new version of the collections. The various thematic datasets differ in their structure, so each type of collection requires a specific development. By using a series of Python scripts, data is uploaded to ERDDAP™.

Metadata in ERDDAP™ is quite rich. Global dataset attributes (https://erddap.github.io/docs/server-admin/datasets#global-attributes) and variable attributes (https://erddap.github.io/docs/server-admin/datasets#variable-addattributes) enable the provision of the necessary information to describe the dataset. The inclusion of meta-information is encouraged. For the first datasets, it requires a considerable effort, but afterwards the process becomes easier due

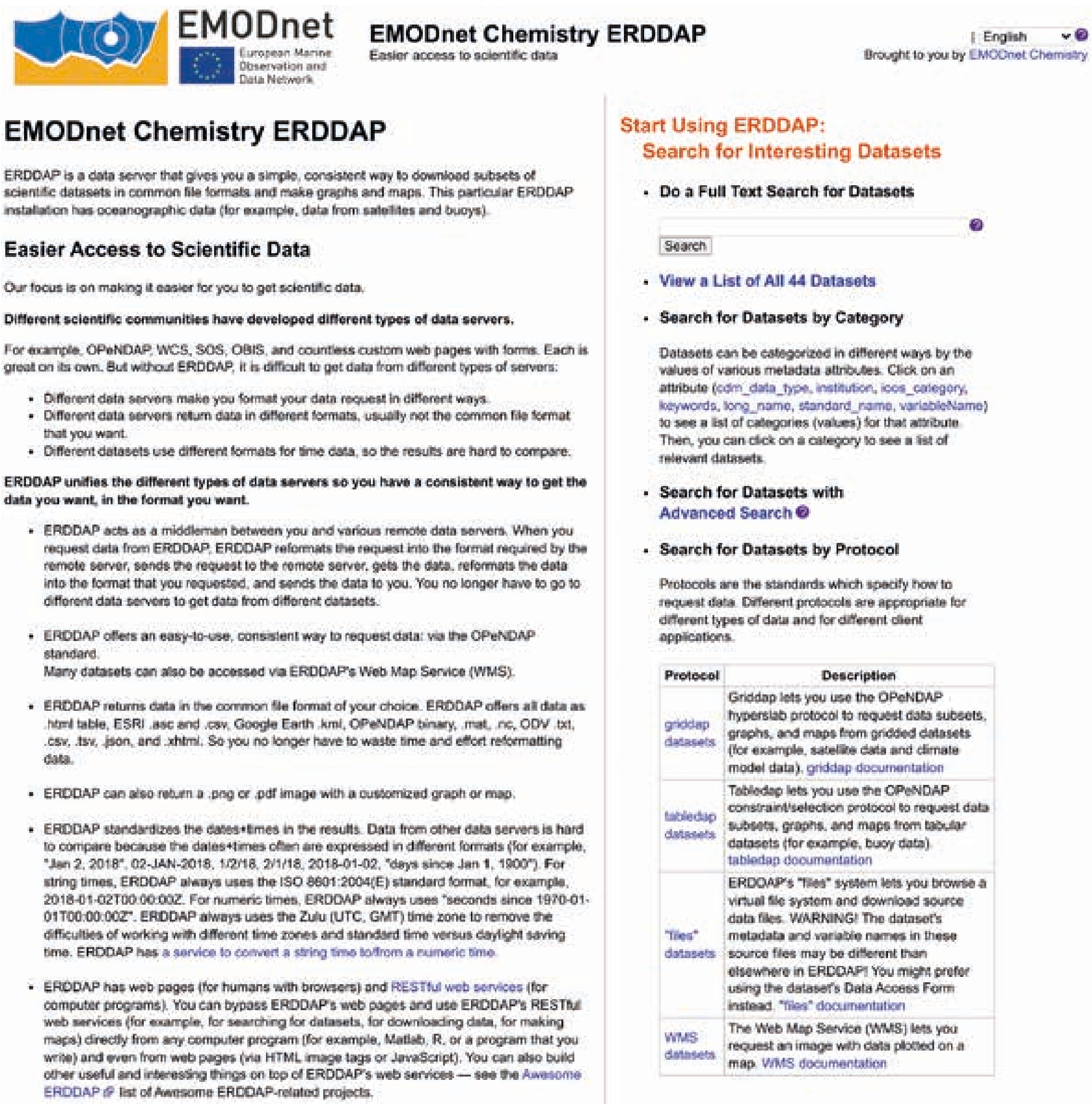

Fig. 4 - EMODnet Chemistry aggregated data collection ERDDAP™.

to the possibility of re-using work previously carried out. The metadata are compiled using the newly developed erddapcfg tool (Plehan, 2024) and a SQLite database, ensuring that all metadata and data fields are given appropriate scientific meaning. A complementary GeoServer web service provides a Web Map Service (WMS) of the data stations.

In the case of eutrophication datasets, the main challenge was related to the original ocean data view (ODV) file size. Specifically, the issue arose from the heavy resource requirements for reading and exporting data from the large ODV file; in our case, we were dealing with files of almost 60 GB, which are not optimised for ingestion into ERDDAP™. After some research and testing, we concluded that the optimal approach was to upload many smaller files (in our case, each no larger than 400 MB) in NetCDF format to ERDDAP.

To import the collections into ERDDAP, we developed a workflow to convert the large ODV files into many small NetCDF files. The pipeline (Fig. 5) begins with exporting the collections to a CSV file, which is, then, split into multiple CSV files. These are converted to NETCDF files and, finally, uploaded and published in ERDDAP.

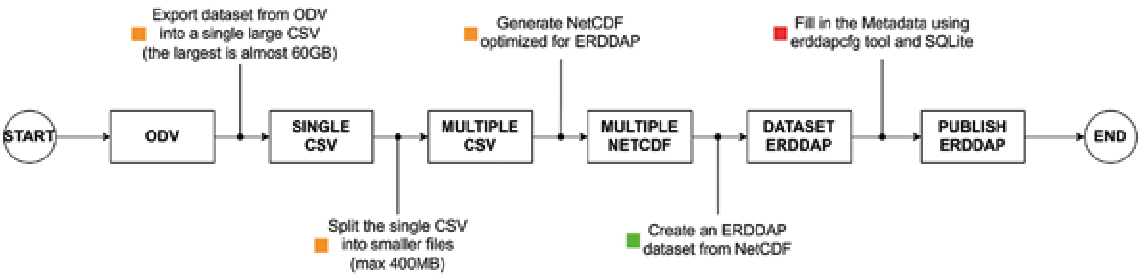

Fig. 5 - Workflow to publish EMODnet collections in ERDDAP™.

The second use case was developed within the Italian integrated environmental research infrastructures system (ITINERIS) project, funded by the NextGenerationEU program (2022–2025), which studies the impacts of climate and environmental change. The virtual research environment (VRE) on the downstream impacts of environmental change is dedicated to the use of research infrastructures that provide tools for data visualisation, analysis, and sharing. The downstream VRE (Franceschini *et al*., 2025), hosted by the D4Science infrastructure (Assante *et al*., 2019), and the toolboxes were developed for the marine and terrestrial domains (ITINERIS, n.d.). The VRE integrates a multidisciplinary analysis of environmental and climate data. By being hosted on a cloud-based environment, such as the D4Science infrastructure, it guarantees high interoperability and computing power.

ERDDAP™ plays a key role in this use case, thanks to its versatility and full alignment with the FAIR principles. In particular, the accessibility principle is addressed, as data can be retrieved using standardised and open protocols, often via RESTful services. One of ERDDAP™'s key strengths is its ability to provide access to data in multiple file formats (.csv, .netCDF, etc.), while also supporting machine-readable requests (e.g. OPeNDAP, WMS). This enables processing systems to access and integrate data with minimal human intervention.

The Marine Domain Toolbox leverages this functionality through the open-source web application ERDDAPNavigator (NODC-IT, n.d.) which enables the user to navigate across different ERDDAP™ servers. The application provides advanced capabilities for exploring, merging, uploading, editing, and manually managing datasets through the ERDDAP™ RESTful application programming interface. By building on this distributed architecture, the Marine Domain Toolbox facilitates the sharing of oceanographic datasets, strengthens collaboration among research institutions, and enhances the reproducibility of scientific studies, thus promoting true data interoperability.

A crucial added value of ERDDAPNavigator, beyond what a single, federated ERDDAP™ instance could provide, is the offering of a unified discovery and comparison environment not available in the standard ERDDAP™ interface. While federating endpoints would centralise access, it would still inherit limitations related to dataset discoverability, cross-server searches, and metadata inconsistencies. ERDDAPNavigator addresses these gaps by providing intelligent filters, interactive previews, and an integrated workspace for multi-server operations, thereby significantly reducing the effort required to identify, evaluate, and prepare datasets for analysis.

Once a dataset is selected from the federated catalogue of ERDDAP™ endpoints, data validation, quality control, and merging can be performed directly within ERDDAPNavigator. Its intuitive interface enables users to visually inspect variables, assign quality control flags, analyse temporal or spatial coverage, and merge datasets into cohesive collections (Reyes *et al.*, 2025). The resulting integrated datasets can, then, be used to generate climate-relevant indicators, including ocean acidification metrics and ocean carbon cycle balance assessments.

An illustrative example of the toolbox capabilities is the integration of the EMODnet Chemistry ERDDAP™ server. Using ERDDAPNavigator, the time series of the EUT_MED_TIMESERIES_2024 dataset (Fig. 6) for the Mediterranean Sea, eutrophication and aggregated acidity, can be explored. This case study highlights the versatility of ERDDAP™, demonstrating how it can be used to visualise and analyse complex data, significantly contributing to the improvement of scientific research and the understanding of environmental phenomena.

Fig. 6 - ERDDAP Navigator example using dataset: EUT_MED_TIMESERIES_2024 (HCMR/HNODC and OGS, 2025).

6. Conclusions

In conclusion, open science is the better science. It is more transparent, more rigorous and accountable, more diverse and inclusive, and it is more collaborative. It is a science that provides more confidence in its results, so as to move more quickly from new knowledge to new applications. And the world needs robust and trustworthy science more than ever, so as to use scientific knowledge to address and solve the complex global problems that are being faced.

Open science provides immediate access to research resources such as publications, datasets, and software tools, as well as infrastructure. This accessibility enables researchers to contribute more effectively to scientific progress. By making research methods and results publicly available, open science improves the transparency and reproducibility of scientific research. Other researchers can verify and build on existing studies, ensuring the trustworthiness of scientific findings.

Open science enables policy makers to base their decisions on sound scientific evidence, contributing to better informed and more effective policies. It also fosters engagement between researchers and policy makers, dialogue, and collaboration to address pressing societal challenges with evidence-based solutions.

ERDDAP™ provides simple, consistent, and flexible access to complex scientific data, facilitating interoperability and visualisation. The standardised interface enables unified access to heterogeneous data. It also allows users to download data subsets in common formats (CSV, NetCDF, JSON, etc.), supporting integration with analysis tools such as charts and maps through flexible formats and visualisations. Standardising content also ensures interoperability, making ERDDAP™ a key tool for disseminating data according to the FAIR principles within the scientific community. A practical example is illustrated by the catalogue of global ERDDAP servers (ERDDAP, n.d.), which provides access to hundreds of ERDDAP™ servers around the world, facilitating the search for environmental scientific data by aggregating datasets from different institutions and offering standardised formats and developer tools for downloading and visualising oceanographic information.

In summary, ERDDAP™ is ideal for those working with large volumes of scientific data (especially oceanographic and environmental data) and seeking a powerful yet accessible tool to explore, visualise, and share information. For these reasons, the NODC-OGS has chosen to use ERDDAP™ in various scientific contexts, highlighting its clear advantages as a strategic tool for achieving the objectives of Open Science and making research more transparent, collaborative, equitable, accessible, and reproducible.

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