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ORIGINAL RESEARCH ARTICLE

A Marine Spatial Data Infrastructure to manage multidisciplinary, inhomogeneous and fragmented geodata in a FAIR perspective — the Adriatic Sea experience

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Adriatic Sea

Abstract The Institute of Marine Sciences (ISMAR) and the Institute of Polar Sciences (ISP) of the Italian National Research Council (CNR) have gathered a substantial amount of heterogeneous geodata through the years in the Adriatic Sea, with different methodologies and for multiple scopes regarding geological, oceanographic, biological, anthropogenic aspects, and their interactions.

To overcome challenges in datasets heterogeneity and fragmentation, a Marine Spatial Data Infrastructure (MSDI) has been set up, with the aim to integrate and preserve geodata, foster their reuse (e.g. the generation of scenarios for geological past and future developments by the application of numerical models), and ensure a good degree of FAIRness (FAIR: Findable, Accessible, Interoperable, and Reusable). The MSDI consists of a Spatial Relational Database Management System (RDBMS) based on specific data models designed following in part the INSPIRE Directive data specifications, a WebGIS, a metadata catalogue, and a cloud system. This paper shows the potentialities of this MSDI and discusses the main implementation steps, the elements that make up the infrastructure, the level of FAIRness reached, the main elements promoting FAIRness, and the gaps to be covered.

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Compliance with the FAIR principles represents a fundamental step to developing interoperability with European and international marine data management infrastructures for handling and exchanging multidisciplinary data.

1. Introduction

Deep-time geoscience data, allowing a global understanding of the entire Earth system linking the surface to the hydrosphere and atmosphere, demands harmonization and integration of multidisciplinary datasets and their international accessibility (Sinha et al., 2013; Wang et al., 2021). The comparative studies of marginal seas (from mapping to process modelling), including both historical reconstruction and future projection, require fast and convenient access to databases containing necessary geological, oceanographic, bathymetric, ecological and climate data characterized by specific data resolution and scale, satisfactory quality and easy accessibility (Sievers et al., 2021 and references therein, Wilson et al., 2018).

Despite the great effort of ongoing European/international projects and infrastructures, such as GEBCO (https://www.gebco.net), EMODnet (https://emodnet.ec.europa.eu/en), ENVRI-FAIR (https://envri.eu/about-envri-fair/), EUROARGO (https://www.euro-argo.eu/), EMSO (https://emso.eu), and ICOS (https://www.icos-cp.eu), there is still a lack of accessibility to local high-resolution datasets with the adequate time frame for ocean modelling of marginal seas (Sievers et al., 2021). Databases of different sizes and disciplines are often hosted, generated and administered by various institutes in the world with dissimilar data policies, and mostly not following the FAIR data principles (Stall et al., 2019). These principles have been discussed and launched for the first time at the Data FAIRPORT Lorentz workshop in 2014 (https://www.datafairport.org/), then referenced in the FORCE11 webpage (https://www.force11.org), and described by Wilkinson et al. (2016). In concrete, FAIR data means that a dataset can be easily searched and discovered, downloaded and reused making results and methodology fully transparent (Koymans et al., 2020). In recent years, given the increasing volume of data collected, the geoscience and the biodiversity communities are recognising the importance of achieving “FAIRness” (Lannom et al., 2020).

Several tools have been developed for conducting FAIRness evaluations, ranging from questionnaires to checklists, and semi-automated evaluators (de Miranda Azevedo and Dumontier, 2020 and references therein). The FAIRsharing group (https://fairsharing.org) has released the FAIRassist.org website, providing a summary of these different tools according to execution type, key features, organization, target objects and reading materials. A detailed analysis of the existing FAIR assessment tools was recently published by the FAIR Data Maturity Model Working Group (DMM WG) of the Research Data Alliance (RDA) established in January 2019 to remedy the proliferation of FAIRness measurements based on different interpretations of the principles. The aim was to develop a common set of core assessment criteria for the FAIRness evaluation, and the result was the first set of guidelines and a checklist related to the implementation of the indicators (FAIR Data Maturity Model Working Group, 2020).

This paper describes the components of the Marine Spatial Data Infrastructure (MSDI) designed and implemented to promote the findability, accessibility, interoperability, and reusability of multidisciplinary, inhomogeneous and fragmented datasets. Geodata were collected within the last 20 years in the Adriatic Sea for geological studies, habitat mapping and process modelling by the Institute of Marine Sciences (ISMAR) and the Institute of Polar Sciences (ISP) of the Italian National Research Council (CNR). The paper discusses the MSDI FAIRness level, the state of implementation and potentialities, pointing out the gaps still to be covered to fulfil all the FAIR requirements.

Finally, this work demonstrates how the integration and harmonization of these heterogeneous datasets are also key to foster interoperability with other marine data management infrastructures for handling and exchanging a high variety of multidisciplinary data (e.g. with the European Marine Observation and Data Network — EMODnet).

1.1. Geographical framework: the Adriatic Sea

The Adriatic Sea is a semi-landlocked basin of the marginal Mediterranean Sea (Figure 1) shaped during the Cenozoic build-up of the Alpine orogen, driven by the Africa-Eurasia plate convergence. The basin is relatively shallow, almost rectangular, bordered to the north by the Alps, to the west by the Apennines and to the east by the Dinaric mountain chain. This temperate warm sea is more than 800 km long in a NW-SE direction and has an average width of about 200 km. An anticlockwise oceanographic circulation (Artegiani et al., 1997) and multiple geo-biological facets characterize this basin.

The Adriatic Sea offers the opportunity to tackle key issues regarding the spatio-temporal seabed response to diverse forcing processes. For instance, it is suitable to investigate among others:

a) the sedimentary response to tectonic processes (Argnani et al., 2009; Maselli et al., 2010; Ridente and Trincardi, 2006);
b) expanded Late Quaternary sediment wedges (Cattaneo et al., 2003, 2004; Pellegrini et al., 2016, 2017, 2018, 2019, 2021; Verdicchio et al., 2007);
c) sea-level changes, submerged landscapes and their evolution (Correggiari et al., 2001, 2005; Del Bianco

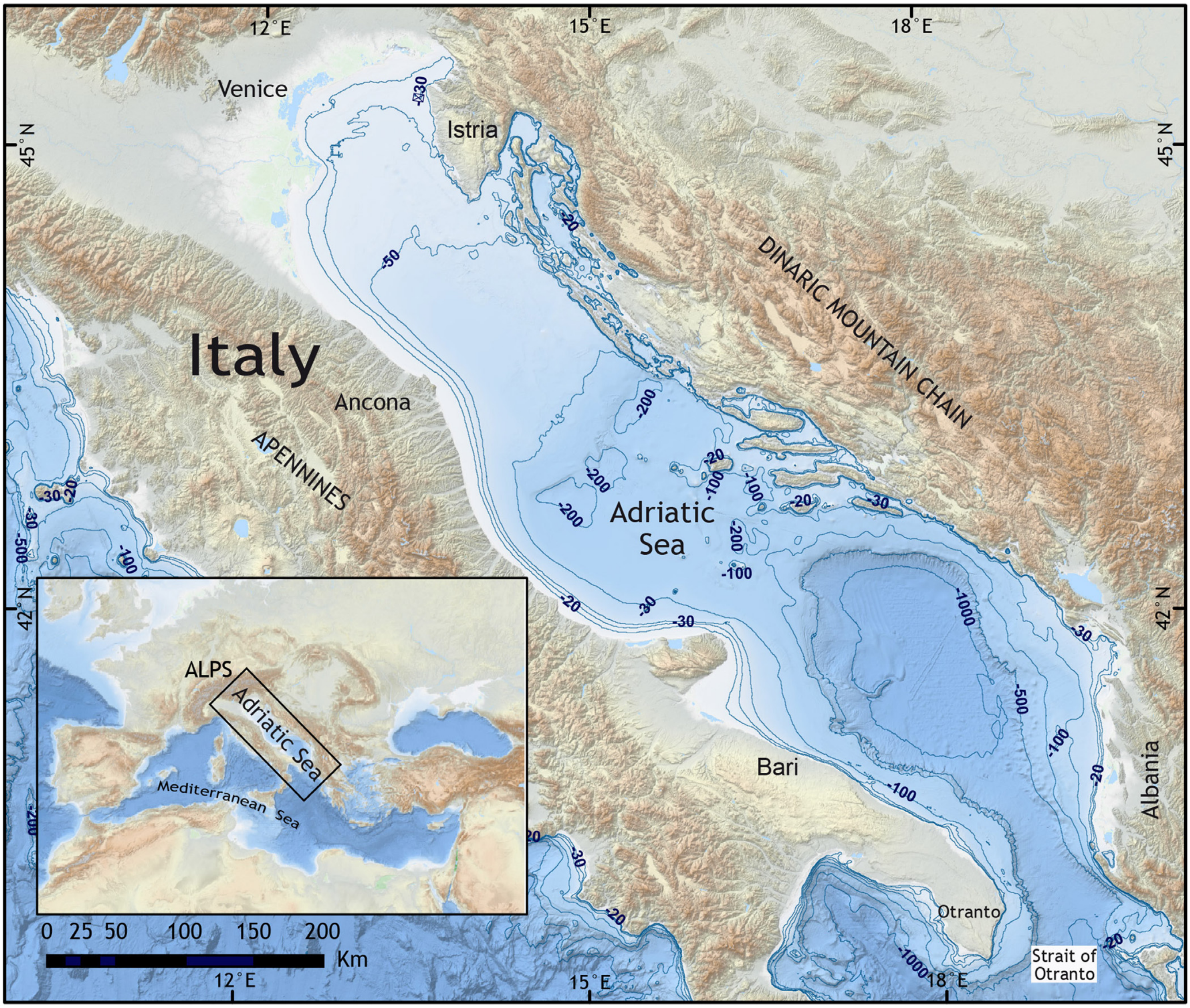

Figure 1 Geographical overview of the Adriatic Sea. Modified from Foglini et al. (2016).

et al., 2014; Ridente et al., 2008; Rovere et al., 2019; Trincardi et al., 2014, 2020);

d) geohazards with a focus on mass wasting and fluid escape processes (Argnani et al., 2011; Dalla Valle et al., 2015; Minisini et al., 2006);
e) biotic and abiotic resources, and remediation strategies to coastal erosion (Correggiari et al., 2011, 2012);
f) charismatic habitats, their biodiversity, controlling factors and evolution (Angeletti et al., 2015, 2019, 2020a, 2020b; Corriero et al., 2019; Freiwald et al., 2009; Prampolini et al., 2020; Taviani et al., 2012, 2016);
g) palaeoceanographic and palaeoclimatic reconstructions, like the role of organic matter flux for the budget of carbon cycle (Asioli et al., 2001; Pellegrini et al., 2021; Piva et al., 2008; Tesi et al., 2013);
h) oceanographic modelling of a major Mediterranean sector for dense cold water production with regional and global implications (Benetazzo et al., 2014; Chiggiato et al., 2016; Cushman-Roisin et al., 2001; Turchetto et al., 2007; Vilibić and Orlić, 2002; Vilibić and Supić, 2005);
i) impact of direct and indirect human activities in the marine system, from coastal lagoons (Madricardo et al., 2019) to the deep sea;
j) heritage of a prominent natural and historical maritime region (Madricardo et al., 2021); and
k) multi-objective spatial tools for maritime spatial planning (Depellegrin et al., 2017). Against that background, the Adriatic Sea is ideal to promote the integration, sharing, curation and reuse of data achieved over the years from different sources and for multiple scopes.

2. Material and methods

2.1. Datasets description

A substantial amount of geodata regarding geological, oceanographic, biological, and anthropogenic aspects and their interaction has been gathered through the last 20 years by the ISMAR and ISP researchers. These multidisciplinary datasets include sampling features, data and products. The sampling features are grouped as follows: 1) *Stations* including boreholes for geological studies and ocean observing systems (e.g. mooring stations, monitoring platforms, multiparametric buoys); 2) *Samples* representing cores, seafloor samples (e.g. box corers, grabs, dredges, videos), and water column sampling (e.g. CTD profiles, water samples); and 3) *Geophysical data* with seismic profiles (multichannel data, chirp and sparker), and acoustic datasets showing both navigation tracklines and surveyed areas (singlebeam, multibeam and backscatter swaths). The geoscience data and products consist of four thematic groups: 1) *Geology* (geological units, geological structures and geomorphological features); 2) *Geophysics* (bathymetric and reflectivity surfaces); 3) *Habitat mapping* (Remotely Operated Vehicle (ROV) description, benthic habitat maps and habitat suitability models); and 4) *Oceanography* (hydrodynamic models).

2.2. Marine Spatial Data Infrastructure (MSDI) implementation

Starting from 2005, the first three components of the MSDI: i) data model, ii) File Geodatabase, and iii) Relational Database Management System (RDMS), were developed to manage data collected on board oceanographic vessels in different years with different instruments to produce the 1:250.000 scale geological map of the Adriatic Sea (http://www.ismar.cnr.it/products/thematic-mapping/the-carg-geological-cartography). Specific data models, following in part the data specification technical guidelines of the INSPIRE Directive (https://inspire.ec.europa.eu), were designed to harmonize all collected data and derived products. Full compliance with the INSPIRE Data models was not reached, because the models were adapted according to the scientific community's needs, mostly for what concerns the physical sampling and the related results. The UML structures were implemented by means of Enterprise Architect software (© Sparx Systems Pty Ltd) inside a standards-based modelling environment with defined mappings between UML 2 and ArcGIS concepts (https://sparxsystems.us), and automatically imported into File Geodatabases (© Esri) using the export capability for ArcGIS geodatabase schemas of the Enterprise Architect. Successively, all the data stored within the File Geodatabases were loaded in an RDBMS based on an Oracle spatial database managed through ArcSDE (Spatial Database Engine) and ArcGIS desktop. Since 2005, the RDBMS has been constantly updated.

Starting from 2012, the data models were enriched and extended to include habitat mapping and oceanography in the context of the CoCoNet Project (Boero et al., 2016). The WebGIS component was added concurrently in order to ensure accessibility to the spatial database given the requirements of the high number of project partners from 39 different countries. To this aim, the data was transformed into layers with specific portrayal rules (e.g. symbologies, scales, labels), and catalogued in cartographies, themes, legends, groups and tables using the Moka Content Management System (CMS) (© Semenda srl). All these elements were organized in thematic web applications published with ArcGIS Server as Web Map Services (WMS) in a geoportal (WebGIS).

A step forward was done in the framework of the AMAre Project (2016) (https://amare.interreg-med.eu/) to describe the layers within the WebGIS adding metadata published by means of the Esri Geoportal. This component linked to the Moka CMS allows users to visualize the metadata of the layers directly in the WebGIS.

From 2018, the need emerged to make the data findable and interoperable with other Spatial Data Infrastructure (SDI) implemented for different purposes and within different projects (e.g. EVER-EST (https://ever-est.eu), RITMARE, ADRIPLAN (http://adriplan.eudriplan)). To fulfil this demand, the digital resources managed in the RDBMS and published in the WebGIS were described in a GeoNetwork metadata catalogue using the standard ISO19115 for spatial datasets, ISO 19115-2 for Imagery and gridded data, ISO19119 for web services, Dublin Core for a non-spatial resource (such as web applications, figures, tables, cruises, and projects). Periodically (once a month), a harvesting procedure using a Catalogue Service for the Web (CSW) integrates the metadata of the layers hosted by the Esri Geoportal in the Geonetwork, so that the catalogue includes the entire set of metadata (datasets, layers and any other digital object) and represents a unified user interface for searching and exploring metadata in the web. Today, we are working on the inclusion of standardized vocabularies (ISO and INSPIRE codelists) in the metadata schemas and in the data models.

Integration with other GIS platforms is also possible by using the Open Geospatial Consortium (OGC) web services, in particular: Web Map Services (WMS), Web Feature Services (WFS), Web Coverage Services (WCS), and the Catalogue Service for the Web (CSW).

The cloud system is the last component implemented in the MSDI. It enables data providers to store digital resources in an organized file system reachable by the web using credentials and, to associate a URL and password for sharing them. The users searching for the data in the metadata catalogue can download the resources through the link in the metadata form according to the specific data policy. The system consists in a NAS-QNAP (Network Attached Storage — Quality Network Appliance Provider) that is a storage device with QTS as the operating system and myQNAPcloud for the remote access.

2.3. FAIRness evaluation

The indicators proposed by the FAIR DMM WG specifications and guidelines (2020) are used in this work to measure the state or level of digital resources with regard to a specific FAIR principle. In the analysis, we also took into account the context of data-related tools, workflows, protocols and other data-related services that are produced or managed as digital objects, as suggested by the FAIR DMM WG. These indicators derive from the FAIR principles and permit to measure the compliance of a digital object with regard to each specific principle. Each indicator is classified with three levels of importance: 1) *Essential*, 2) *Important*, and 3) *Useful*. The FAIRness progress per indicator is an

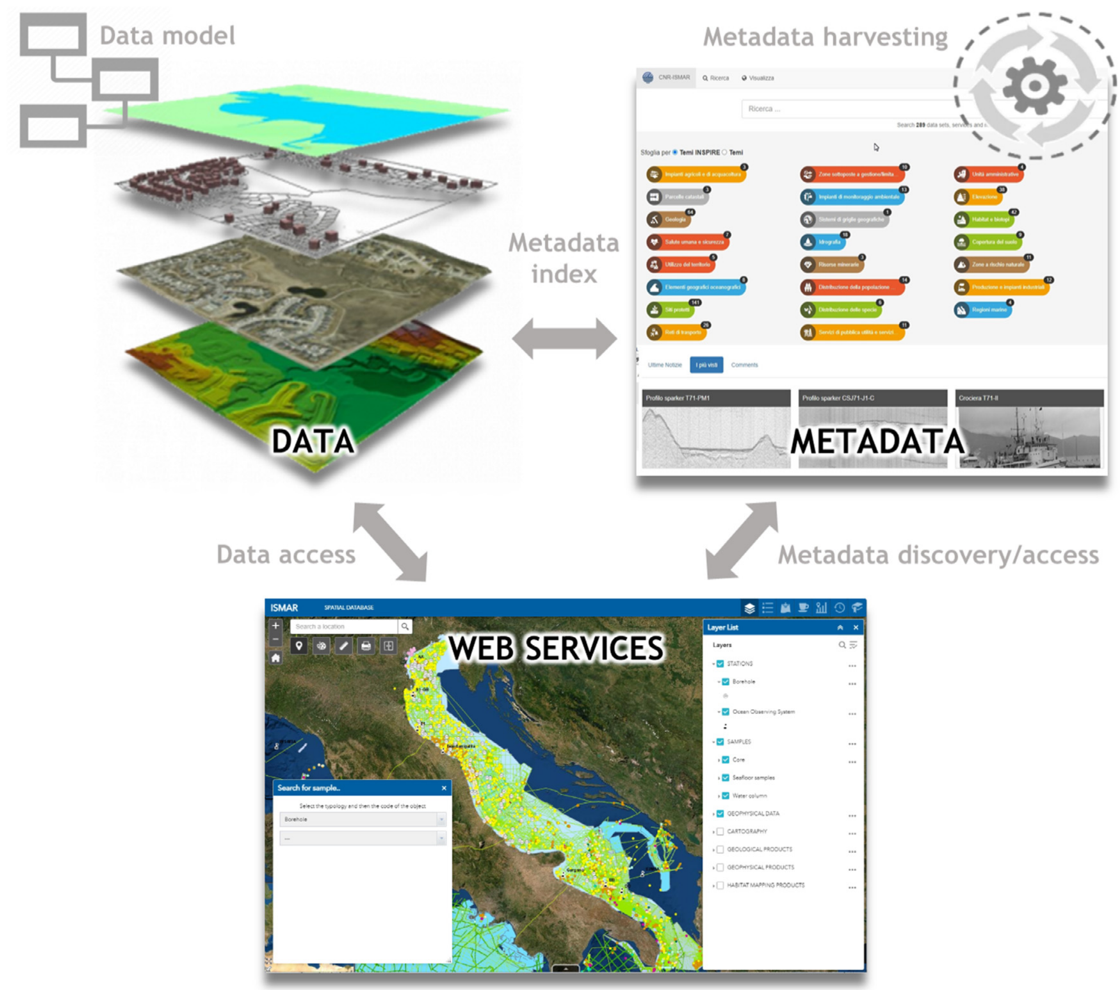

Figure 2 The three main components of the MSDI: Data, Metadata and Web services.

evaluation of each indicator against five maturity levels of compliance from *not applicable* to *fully implemented*. This approach is focused on the extent to which a resource under evaluation meets the requirement of the indicator, and the results of this evaluation method for the four FAIR areas: Findability, Accessibility, Interoperability and Reusability.

3. Results

3.1. Marine Spatial Database Infrastructure (MSDI)

The MSDI is made of three main components as shown in Figure 2: 1) the data organized in data models and stored in Geodatabase/Oracle, 2) the metadata managed through a catalogue, and 3) the OGC web services (WMS, WFS, WCS, CSW) making the digital resources in the MSDI available in an open and internationally known format.

3.1.1. Data

Geodata are managed by means of an RDBMS, stored in an Oracle database and archived according to specific data models designed starting from the data specifications defined by the INSPIRE Directive (see Table 1 to check correspondences). In particular, five INSPIRE themes have been taken into account: Elevation, Environmental Monitoring Facilities, Geology (Geophysics), Observation, and Oceanographic geographical features (https://inspire.ec.europa.eu/data-specifications/2892). Some fields, classes and relationships have been customised or added, with the aim to reach the marine scientific community requirements, and manage all the geoscience data and products. So far, we produced four data models: Geology, Geophysics, Seafloor mapping, and Water column (available as images and XML files in the Research Object at the link: https://w3id.org/ro-id/97985638-81ed-42b1-ae48-ab432f14db52).

The RDBMS stores the spatial information published as layers in the geoportal; these geodata included in the Oracle spatial databases are not publicly accessible, but only for internal use. A spatial relational database allows us to visualize spatial data (feature classes and raster datasets) and related information (object classes) through the geoportal, to query the information and to build charts.

3.1.2. Metadata

The GeoNetwork metadata catalogue is the main user interface for searching, navigating and creating metadata, available at the link: http://www.ismar.cnr.it/products/

Table 1 Typology and name of the objects making up the four thematic data models. For each element, the table indicates the correspondence with the INSPIRE Data models themes and objects.

Data model	Typology	Geometry	Name	INSPIRE Theme	INSPIRE Object
Geology	Feature dataset	Abstract	Sampling features	Geophysics	SF Spatial Sampling Feature
	Feature class	Points	Core	None	None
	Feature class	Points	Borehole	Geology	Borehole
	Feature class	Points	Sample	None	None
	Feature dataset	Abstract	Geologic units and structures	Geology	Geologic Unit Geologic Structure
	Feature class	Polygons	Geologic Unit	Geology	Geologic Unit
	Feature class	Polygons	Geologic Unit Contour	Elevation	Elevation Vector Elements
	Feature class	Polylines	Geologic Unit Interval	None	None
	Feature class	Points Polyline Polygons	Geologic Structure	Geology	Geologic Structure
	Feature class	Points Polyline Polygons	Geomorphologic Feature	Geology	Geomorphologic Features
	Object class	None	Grain Size Distribution	None	None
	Object class	None	Granulometric Indices	None	None
	Object class	None	Organic Matter	None	None
	Object class	None	Process	Observation	Process
	Object class	None	Radioactive Isotopes	None	None
	Object class	None	Related Resources	None	None
	Object class	None	Results	None	None
Geophysics	Feature class	Points	Geoph Station	Geophysics	Geoph. Station
	Feature class	Polylines	Geoph Profile	Geophysics	Geoph. Profile
	Feature class	Polygons	Geoph Swath	Geophysics	Geoph. Swath
	Feature class	Polylines	Swath Line	None	None
	Feature class	Points	Profile Mark	None	None
	Feature class	Points	SVP	None	None
	Object class	None	Process	Observation	Process
	Object class	None	Related Resources	None	None
	Raster catalogue	None	Bathymetry	Elevation	Elevation Grid Coverage
	Raster catalogue	None	Derivatives	Elevation	Elevation Grid Coverage
	Raster catalogue	None	Reflectivity	Elevation	Elevation Grid Coverage
Seafloor mapping	Feature datasets	Abstract	ROVs	None	None
	Feature class	Polyline	Habitat	None	None
	Feature class	Point	Heading	None	None
	Feature class	Polygon	Positioning error	None	None
	Feature class	Point	Sample	None	None
	Feature class	Polyline	Transect	None	None
	Feature class	Point	Video frame	None	None
	Feature datasets	None	Seafloor Maps	None	None
	Feature class	Polygon	Habitat map	None	None
	Feature class	Polygon	Cartography	None	None
	Feature datasets	Abstract	Seafloor Samples	None	None
	Feature class	Point Polyline	Sample	None	None
	Raster catalogue	None	Habitat Suitability Maps	None	None
	Object class	None	Indicators	None	None
Water column	Feature class	Points	Monitoring Facility	Environmental Monitoring Facilities	Environmental Monitoring Facility
	Feature class	Points	Monitoring Activity	Environmental Monitoring Facilities	Environmental Monitoring Activity
	Object class	None	Observations	Observations	Observation
	Object class	None	Process	Observations	Process
	Object class	None	Related Resources	None	None

Table 2 List of principles and indicators for the four FAIR areas (*F — Findability, A — Accessibility, I — Interoperability,* and *R — Reusability*) with the relative score. The priority of the indicator is classified as *E — Essential, I — Important*, and *U — Useful*. The score reached by the indicator is expressed as *1 — not being considered yet, 2 — under consideration or in planning phase, 3 — in implementation phase*, and *4 — fully implemented*.

ID		PRINCIPLE	INDICATOR_ID	INDICATORS	PRIORITY	SCORE
1	FINDABILITY	F1	RDA-F1-01M	Metadata is identified by a persistent identifier	E	4
2		F1	RDA-F1-01D	Data is identified by a persistent identifier	E	2
3		F1	RDA-F1-02M	Metadata is identified by a globally unique identifier	E	4
4		F1	RDA-F1-02D	Data is identified by a globally unique identifier	E	2
5		F2	RDA-F2-01M	Rich metadata is provided to allow discovery	E	4
6		F3	RDA-F3-01M	Metadata includes the identifier for the data	E	4
7		F4	RDA-F4-01M	Metadata is offered in such a way that it can be harvested and indexed	E	4
8	ACCESSIBILITY	A1	RDA-A1-01M	Metadata contains information to enable the user to get access to the data	I	4
9		A1	RDA-A1-02M	Metadata can be accessed manually (i.e. with human intervention)	E	4
10		A1	RDA-A1-02D	Data can be accessed manually (i.e. with human intervention)	E	4
11		A1	RDA-A1-03M	Metadata identifier resolves to a metadata record	E	4
12		A1	RDA-A1-03D	Data identifier resolves to a digital object	E	4
13		A1	RDA-A1-04M	Metadata is accessed through standardised protocol	E	4
14		A1	RDA-A1-04D	Data is accessible through standardised protocol	E	4
15		A1	RDA-A1-05D	Data can be accessed automatically (i.e. by a computer program)	I	2
16		A1.1	RDA-A1.1-01M	Metadata is accessible through a free access protocol	E	4
17		A1.1	RDA-A1.1-01D	Data is accessible through a free access protocol	I	4
18		A1.2	RDA-A1.2-01D	Data is accessible through an access protocol that supports authentication and authorization	U	4
19		A2	RDA-A2-01M	Metadata is guaranteed to remain available after data is no longer available	E	4
20	INTEROPERABILITY	I1	RDA-I1-01M	Metadata uses knowledge representation expressed in standardised format	I	3
21		I1	RDA-I1-01D	Data uses knowledge representation expressed in standardised format	I	3
22		I1	RDA-I1-02M	Metadata uses machine-understandable knowledge representation	I	4
23		I1	RDA-I1-02D	Data uses machine-understandable knowledge representation	I	4
24		I2	RDA-I2-01M	Metadata uses FAIR-compliant vocabularies	I	3
25		I2	RDA-I2-01D	Data uses FAIR-compliant vocabularies	U	3
26		I3	RDA-I3-01M	Metadata includes references to other metadata	I	4
27		I3	RDA-I3-01D	Data includes references to other data	U	4
28		I3	RDA-I3-02M	Metadata includes references to other data	U	4
29		I3	RDA-I3-02D	Data includes qualified references to other data	U	4
30		I3	RDA-I3-03M	Metadata includes qualified references to other metadata	I	4
31		I3	RDA-I3-04M	Metadata include qualified references to other data	U	4
32	REUSABILITY	R1	RDA-R1-01M	Plurality of accurate and relevant attributes are provided to allow reuse	E	4
33		R1.1	RDA-R1.1-01M	Metadata includes information about the license under which the data can be reused	E	4
34		R1.1	RDA-R1.1-02M	Metadata refers to a standard reuse license	I	4
35		R1.1	RDA-R1.1-03M	Metadata refers to a machine-understandable reuse license	I	1

(*continued on next page*)

Table 2 (*continued*)

ID	PRINCIPLE	INDICATOR_ID	INDICATORS	PRIORITY	SCORE
36	R1.2	RDA-R1.2-01M	Metadata includes provenance information according to community-specific standards	I	4
37	R1.2	RDA-R1.2-02M	Metadata includes provenance information according to a cross-community language	U	4
38	R1.3	RDA-R1.3-01M	Metadata complies with a community standard	E	4
39	R1.3	RDA-R1.3-01D	Data complies with a community standard	E	4
40	R1.3	RDA-R1.3-02M	Metadata is expressed in compliance with a machine-understandable community standard	E	4
41	R1.3	RDA-R1.3-02D	Data is expressed in compliance with a machine-understandable community standard	I	4

data-sharing/geonetwork. Metadata describe spatial data and services in terms of access and use rights, conformity with implementing rules, quality, validity, geographic location, responsible authorities, and online resources. The catalogue enables the preservation of spatial information and the discovery of geospatial resources using the standards ISO for spatial data (ISO19115 for spatial datasets, ISO19115-2 for Imagery and gridded data, and ISO19119 for web services), and Dublin Core for other digital resources. Periodically (once a month), it harvests the metadata records stored in the Esri Geoportal dedicated to the layers published in the WebGIS, but also from external metadata services, such as the high-resolution bathymetric products provided by the EMODnet Products Catalogue (https://emodnet.ec.europa.eu/geonetwork/emodnet/eng/catalog.search#/home). The metadata catalogue makes the resources searchable, findable and reusable, answering to the increasingly widespread demand of FAIRness for scientific data, especially if produced with public funds. Direct access to the digital resources through the metadata records is possible thanks to the cloud component (https://qlink.to/GISMARcloud), enabling data providers to link the resources to the metadata record in the GeoNetwork (as demonstrated in Figure 3), manage the access requests, and provide credentials to download the data. The users can access the resources from the metadata form based on the license indicated.

3.1.3. Web services

The WebGIS is accessible at the link http://www.ismar.cnr.it/products/data-sharing/webgis. It integrates sampling features, data and products organized in layers managed by a dynamic Table of Contents (TOC) allowing users to search and explore the contents. The WebGIS provides user-friendly tools to navigate through the datasets, make simple queries, and access the metadata (Figure 4).

Through the TOC, it is possible to access the metadata describing every single layer containing information useful to understand its content (e.g. abstract, lineage, point of contact) and to access the relative WMS (Figure 5). In the attribute table of the layer, users find the link to the metadata of each digital object, hosted in the GeoNetwork metadata catalogue or in any other external repository, such as the EMODnet portal for Bathymetries (https://www.emodnet-bathymetry.eu) or SESAR (https://www.geosamples.org).

The WebGIS displays also information produced in other projects preserving them, as in the case of the CROP database (Bernabini and Manetti, 2003, http://www.crop.cnr.it), already integrated in the ViDEPI Project (https://www.videpi.com) with the aim to make technical documents relating to oil exploration in Italy easily accessible, but never included in a multidisciplinary platform. Through the WebGIS, users can see the seismic profiles collected, explore the map or filter the attribute table according to the field *Larger Work* (Figure 6). The field *Image* stores an overview of the digital resource (as in the example in Figure 6: https://www.videpi.com/deposito/videpi/crop/F_08_M5.pdf), while the field *Metadata* hosts the link to the relative GeoNetwork form (as in the example in Figure 6: http://libeccio.bo.ismar.cnr.it:8080/geonetwork/srv/eng/catalog.search#/metadata/1d12b137-91e4-4f3b-af1d-a0748c581780). The metadata of the digital resource may contain information about: i) source and relative public documentation, ii) data access, iii) survey (e.g. cruise report) and/or to project during which it was collected (e.g. CORDIS or project webpage), iv) people (e.g. ORCID), v) link to external databases and vi) scientific papers (e.g. DOI).

The WebGIS allows users to visualize WMS from other infrastructures using the function *Add data* avoiding data duplication (Figure 7). In that case, the layer is added temporarily in the TOC and available only for the current working section.

The interoperability between systems is guaranteed by the publication of WMS permitting the integration of the geodata (stored in the Oracle database and published as thematic layers through the WebGIS) in other platforms. In some cases, the WMS are available in the metadata records allowing the users to visualize the layer directly on your desktop.

3.2. Degree of FAIRness

How FAIR is the implemented MSDI? The digital objects managed by the MSDI, described in this work and evaluated according to the guidelines of the DMM WG (2020), reached 80% of FAIRness. Table 2 shows the score per indicator, while Table S1 of the supplemen-

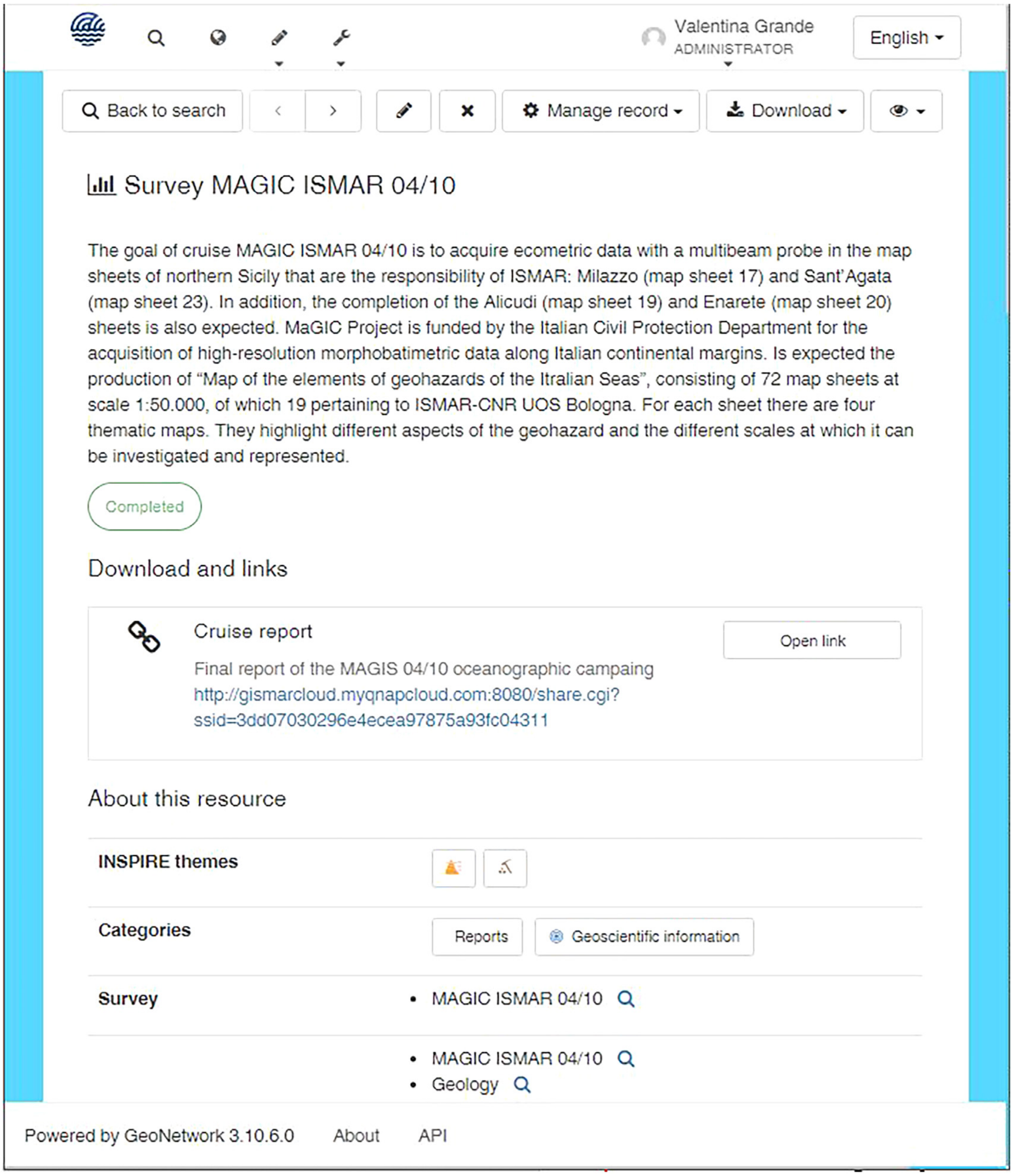

Figure 3 The example shows how to download directly the cruise report of the oceanographic cruise MAGIC 04/10 stored in the cloud system through the metadata record in the GeoNetwork catalogue.

tary materials contains the complete evaluation (also available in the Research Object: https://w3id.org/ro-id/97985638-81ed-42b1-ae48-ab432f14db52).

Thirty-three of forty-one (33/41) indicators are fully implemented (Table 3): 90% of the *Essential* principles, 64% of the *Important* principles, and 86% of the *Useful* principles. Only two of the *Essential* principles are not fully implemented, both referring to data identifiers, essential to make datasets findable (RDA-F1-01D and RDA-F1-02D). The MSDI achieved more than half of the principles labelled as *Important*: the presence of metadata information to access the data (RDA-A1-01M); the usage of free access protocol to access the data (RDA-A1.1.01D); the inclusion in the metadata of qualified references to other metadata (RDA-I3-01M, RDA-I3-03M) and to a standard reuse license (RDA-R1.1-02M); the presence of the provenance information according to community-specific standards (RDA-R1.2-01M, RDA-R1.3-01M); and finally, the compliance of the data format with a machine-understandable knowledge representation (RDA-I1-02D) contextually to community standards (RDA-R1.3-02D). About *Useful* principles, six of them (6/7) are fully implemented, four concerning the *Interoperability* area, one the *Accessibility* area and, the last one the *Reusable* area. The only one under implementation yet is RDA-I2-01D — Data uses FAIR-compliant vocabularies.

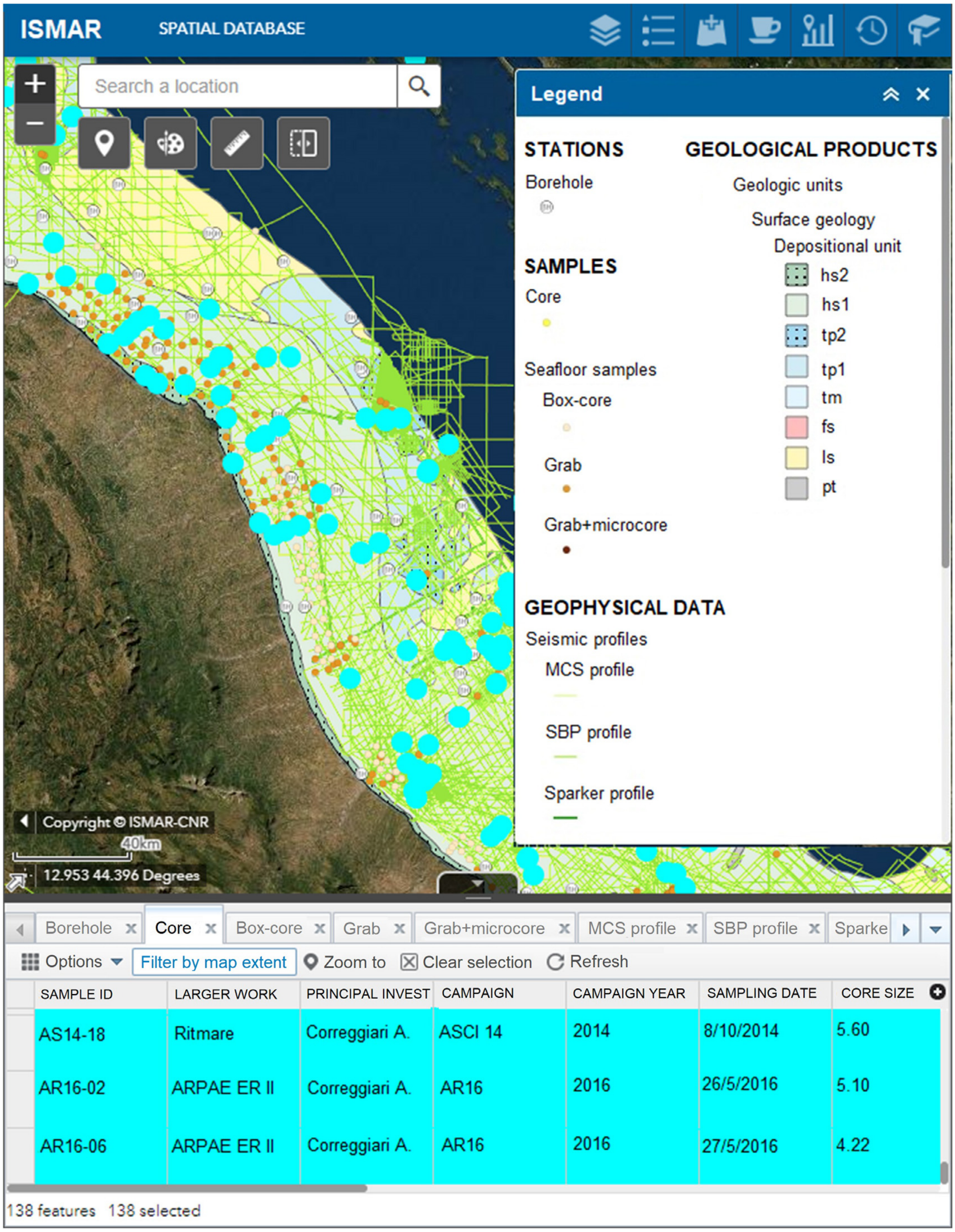

Figure 4 WebGIS interactive map to visualize and identify data and products in an integrated manner. Using the attribute tables and the filter function, the user can select the digital objects of interest. In this example, the selected rows in the table and the corresponding points highlighted in cyan colour on the maps represent the cores longer than 4 meters collected in the map extent.

FAIRness was not fully achieved for any of the four FAIR areas (as shown in Figures 8 and 9). The level of findability and reusability is 0, because the data identifiers are missing (RDA-F1-01D and RDA-F1-02D), and the reuse licenses are not yet machine-understandable (RDA-R1.1-03M). Accessibility of digital resources and the interoperability of the system reached level 2, which means that 100% of the *Essential* criteria and almost 50% of the *Important* criteria have been satisfied.

4. Discussions

Multidisciplinary geoscience data should be managed by means of an interoperable system of systems, which allows datasets to be easily findable, accessible, interoperable, and reusable for thematic integrated data, products and services. Local and interoperable discovery and access, together with secure archiving, guarantee a long-term preservation of the data. Effective data management is based on

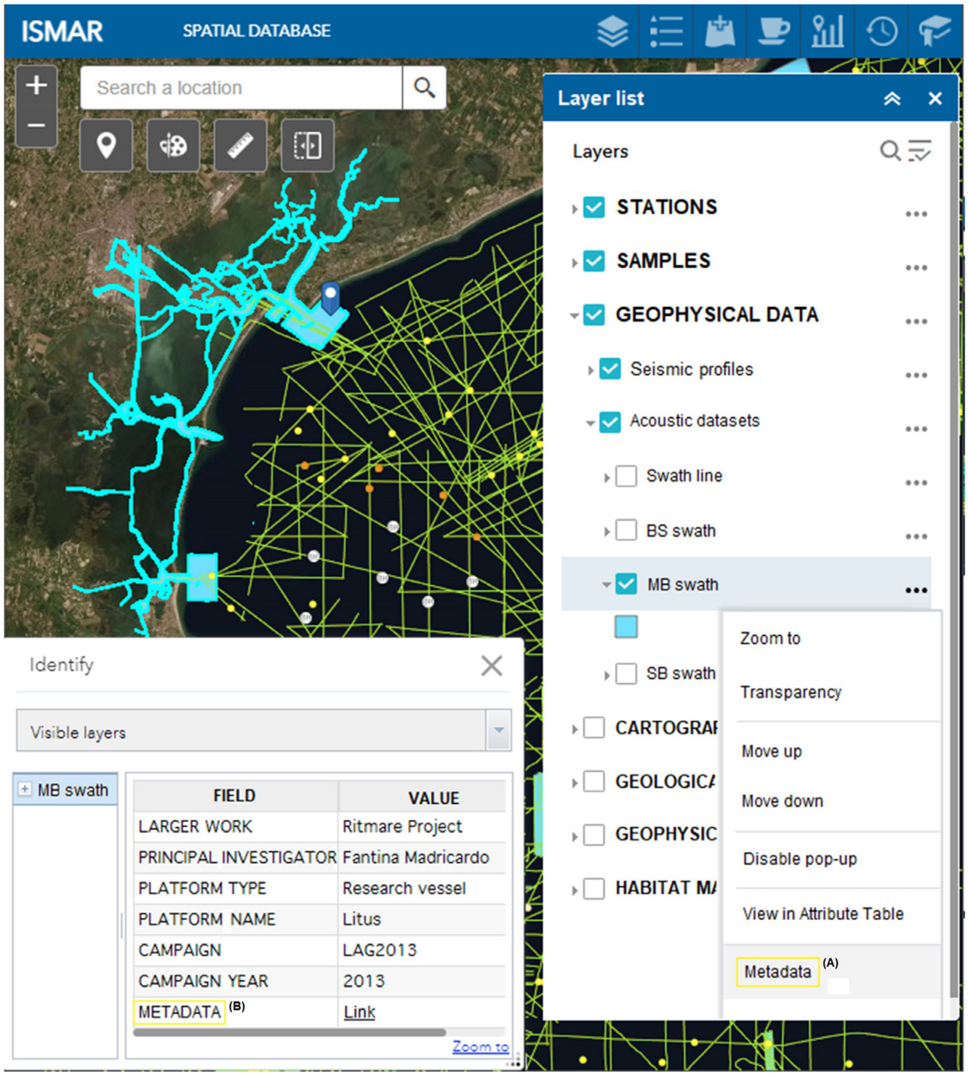

Figure 5 Two ways to access metadata through WebGIS. In the layer list (TOC), the user can access the metadata of the entire thematic layer (A). Opening the attributes table or clicking a feature on the map, the user finds the link to the metadata of the specific digital object (B).

Table 3 Number of Essential, Important and Useful principles achieved for the four FAIR areas: Findability, Accessibility, Interoperability and Reusability.

	Principle				
Priority	Findability	Accessibility	Interoperability	Reusability	Total
Essential	5/**7**	8/8	0/0	5/**5**	18/20
Important	0/0	2/3	4/**7**	3/4	9/14
Useful	0/0	1/1	4/**5**	1/1	6/**7**
Total	5/**7**	11/12	8/12	9/10	33/41

collaboration across activities including observations, metadata and data assembly, quality assurance and control, and data publication (Tanhua et al., 2019).

Tanhua et al. (2019) summarise the challenges to make data and services FAIR in the following points: i) wide diversity of oceanographic data, ii) generating data that follow FAIR principles can be expensive, iii) multitude of disparate data management structures, iv) increased volume of data, v) new devices and software creating new formats, vi) widely used formats not universally applicable, vii) gap between data-producing scientists and downstream users of the data, viii) development of common protocols takes time, and ix) best practices poorly defined.

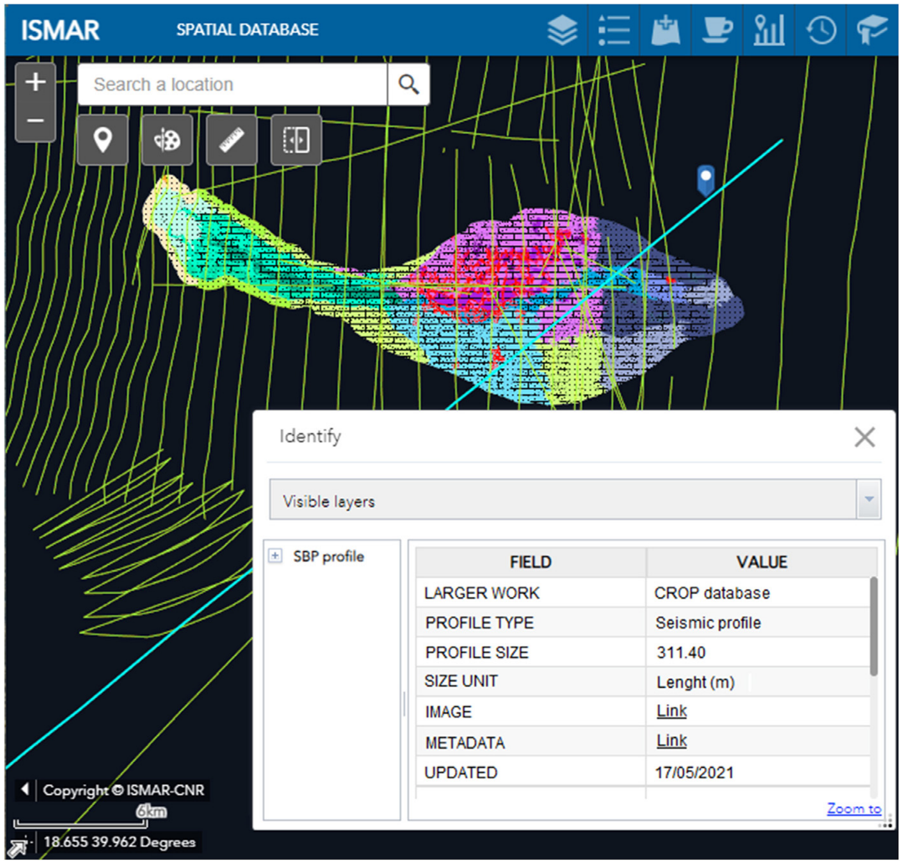

Figure 6 In this example, the user identified a seismic profile intersecting the Tricase Canyon benthic habitat map. The attribute table provides some basic information according to the data model, such as the link to the profile's image stored in the ViDEPI database, and the link to the metadata record describing the CROP Project and hosting the relative website where the user can ask for the data.

In the case of the Adriatic Sea, the datasets were fragmented and multidisciplinary, collected for decades without specific and coordinated data management by different research groups and with different devices, formats and scopes. In the last years, ISMAR and ISP were involved in several projects — aiming at collecting and storing data in common and thematic platforms — and led the data management of national and international projects, where the objective was the creation of an infrastructure for spatial data for conservation and management of the coastal and marine environment. All these efforts were fragmented and not suitable in a long perspective. The need was to integrate all this information in a common infrastructure, i) homogenizing the datasets in a standard data model ensuring a quality assessment and control of the input data, ii) enabling us to find, explore, access and possibly share and reuse data and products for different purposes, and iii) providing web services interoperable with other platforms. For these reasons, a Marine Spatial Data Infrastructure (MSDI) based on a Relational Database Management System (RDMS) integrated with a metadata catalogue and providing web services was successfully implemented.

The MSDI so far reached a good level of FAIRness (80% of the total score with 33/41 principles fulfilled), allowing users to search, visualize and access information in an integrated manner and increase the collaboration with national and international marine data infrastructures.

4.1. Findability

In the MSDI, users can assign a persistent identifier (PID) and a global unique identifier (GUID) to the metadata through the GeoNetwork metadata catalogue, in the metadata elements *Unique resource identifier* and *File identifier*. For this reason, the indicators RDA-F1-01M and RDA-F1-02M are fully implemented. On the other hand, RDA-F1-01D and RDA-F1-02D are currently under consideration; the system does not allow users to associate an identifier with the datasets. To be fully findable, the data should have a long-lasting reference (PID) ensuring that the data will remain findable over time and reduces the risk of broken links, and a globally unique string consisting of 36 characters of hexadecimal digits and hyphens (GUID) avoiding the use of the same identifier for two different digital objects (FAIR DMM WG, 2020). To this aim, we could: 1) choose a repository providing PID and GUID for each digital resource, such as Zenodo (https://zenodo.org), Figshare (https://figshare.com), and Pangaea (https://www.pangaea.de); or 2) foster the implementation of an institutional repository (such as the NSD — Norwegian Centre for Research Data) able to pro-

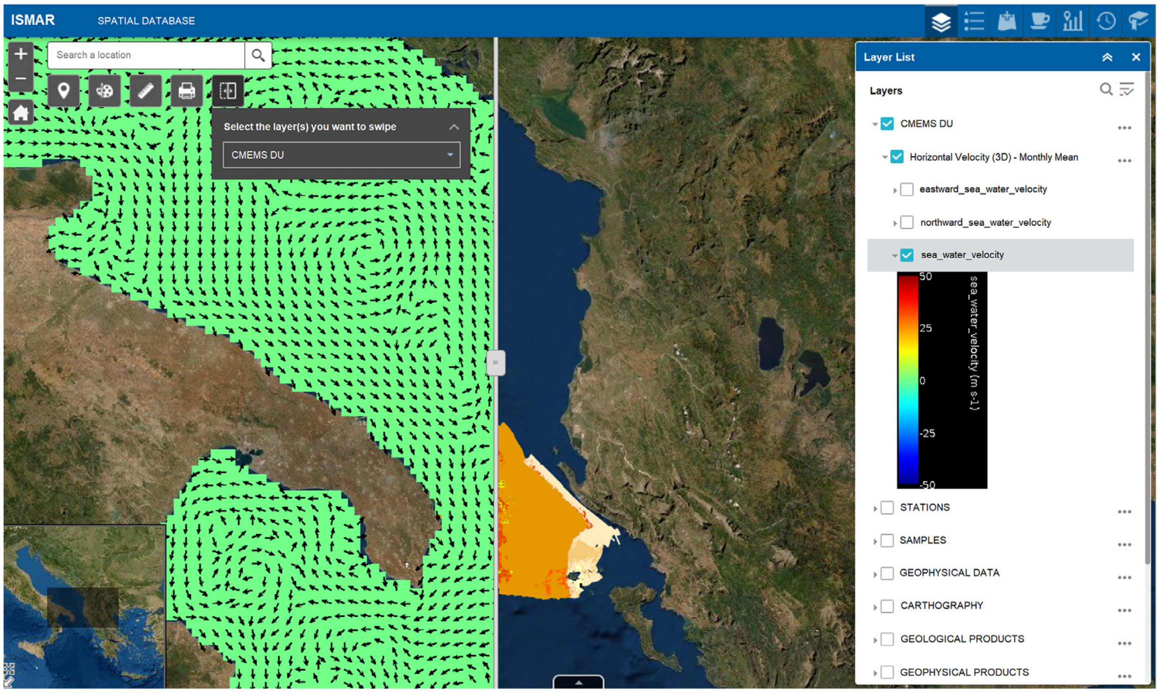

Figure 7 Layer produced by CMCC and provided by Marine Copernicus (CMEMS) as WMS (https://doi.org/10.25423/CMCC/MEDSEA_ANALYSISFORECAST_PHY_006_013_EAS6) representing the seawater velocity and direction, superimposed on the south Adriatic benthic habitat map in the WebGIS. The *Swipe* function allows users to slide from one layer to another facilitating the visualization of overlapped multidisciplinary data.

vide PIDs and GUIDs to the datasets, and to archive, store and license research data avoiding fragmentation.

The other three indicators addressing the findability of the system are: RDA-F2-01M that refers to metadata richness, guaranteed by the inclusion in the GeoNetwork forms of all the items considered mandatory (ISO and INSPIRE rules), and by a validation process provided by the catalogue to evaluate the degree of the form completion; RDA-F3-01M that refers to the inclusion of data identifier, implemented including the element *Citation identifier* in the metadata forms allowing the user to insert multiple identifiers to access the digital objects; and RDA-F4-01M about the possibility of the metadata to be harvested and indexed, ensured by the GeoNetwork user interface and by the CSW provided by the catalogue.

4.2. Accessibility

Metadata include elements containing all human-readable information to access the data: *Resource constraints*, *Legal constraints* and *Contact for the resource* (RDA-A1-01M). Metadata can be accessed and downloaded through the GeoNetwork user interface (RDA-A1-02M), while the digital objects can be visualised in the WebGIS and accessed through the metadata (RDA-A1-02D). If the license of the data is open, the requester can directly access the data by clicking on a link in the relative metadata form, while if the data are password protected, the requester can send an e-mail to the metadata owner/point of contact, or calling by telephone to receive instructions. The data links are managed using cloud storage (NAS-QNAP) where the data provider can store the digital resources obtaining a free or password-protected URL (Uniform Resource Locator) to be included in the metadata record. The digital resources are downloadable according to a case-specific data policy described in the metadata record, for example, indicated by the research institute, agreed inside a project or decided by the data provider. The indicators RDA-A1-03M, RDA-A1-04M and RDA-A1.1-01M are fully implemented because the identifier assigned to the metadata enables access to the metadata record through the standard free access protocol HTTP. Regarding the data (RDA-A1-03D, RDA-A1-04D and RDA-A1.1-01D), the URLs produced by using the cloud service resolve to a digital object accessible through the standard free access protocol HTTP. The automatic accessibility of the data by a computer program (RDA-A1-05D) is an option under consideration because the data policies are too specific and change case by case, a CNR institutional data policy is still not signed and agreed. The data provider is free to manage the data requests by himself through human intervention, using the cloud storage supporting authentication and authorisation (RDA-A1.2-01D). The last indicator dealing with accessibility (RDA-A2-01M) is fully implemented, metadata records are guaranteed to remain accessible after data is no longer available, and the status of the data is described in the metadata element *Lineage*.

4.3. Interoperability

Interoperability is the principle with the greater number of indicators under implementation (4/12). The indicator RDA-I1-01M referring to the usage of standardised

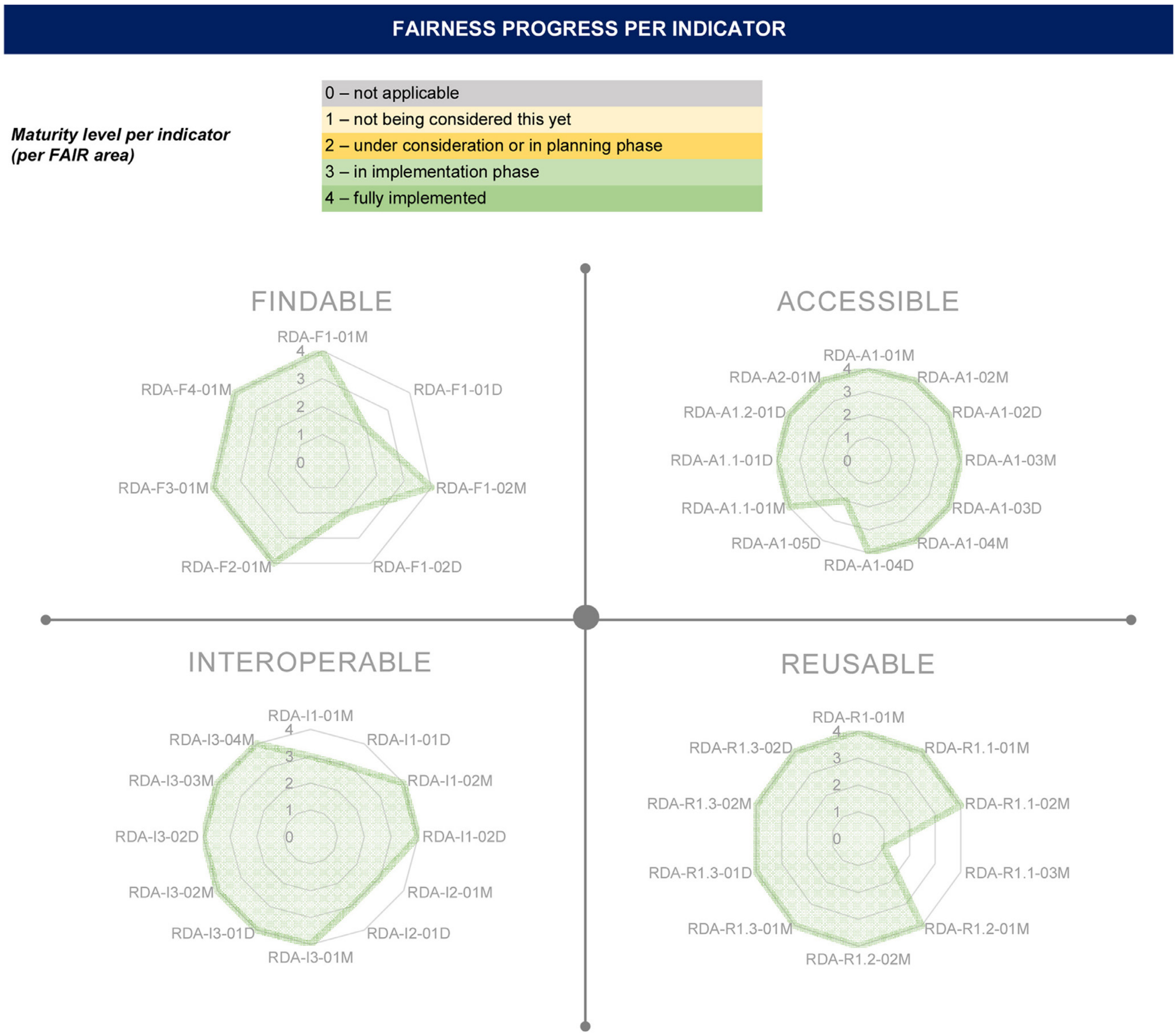

Figure 8 'Measuring progress' visualisation per indicator per FAIR area. Modified from the FAIR DMM WG specification and guidelines (2020).

formats for metadata is in the implementation phase because controlled vocabularies have been used only partially and for specific domains (e.g. https://standards.iso.org/iso/19139/resources/gmxCodelists.xml). Missing vocabularies will be formalized and included in the GeoNetwork with the relative documentation (RDA-I2-01M). Today, not all the vocabularies used are documented and resolvable using globally unique and persistent identifiers. Concerning the data (RDA-I1-01D, RDA-I2-01D), the knowledge is managed by the RDBMS according to specific data models following, when possible, the INSPIRE Data Specification for spatial data (including codelists). Standardised formats are used for the representation of the data, that is, OGC geospatial services (WMS, WFS and WCS) allowing requests for geographical features across the web using platform-independent calls (RDA-I1-02D). Metadata are readable and thus interoperable for machines without any requirements thanks to the usage of standards (RDA-I1-02M). The geospatial records are exposed as XML (Extensible Markup Language) on the Internet (over HTTP) by a CSW. The last six indicators about interoperability (RDA-I3-01M/D, RDA-I3-02M/D, RDA-I3-02M/D) are fully implemented, meta(data) can be connected to other online resources through links to people (ORCIDs), scientific papers (DOIs), projects (webpages), or other meta(data) catalogues. In addition, metadata records can be connected to other digital objects described in the GeoNetwork through the element *Associated resources* defining also the role of the relationship (parent, service, source dataset, source catalogue, other resource).

4.4. Reusability

Concerning the quantity and the quality of metadata provided in order to enhance data reusability (RDA-R1-01, RDA-R1.1-01M), license information can be included in the metadata form using the metadata ele-

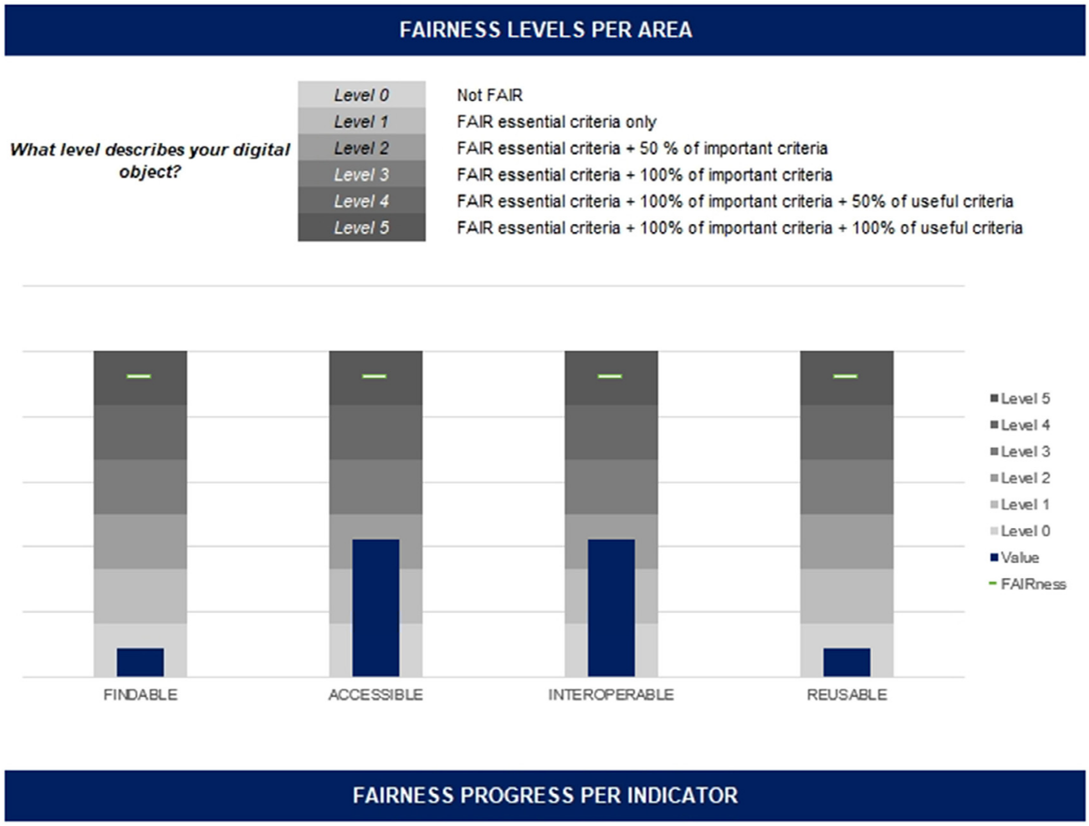

Figure 9 'Measuring pass or fail' visualisation. Modified from the FAIR DMM WG specification and guidelines (2020).

ments: *Classification*, *Use constraints*, *Access constraints*, *Other constraints* and *Credits*. The reuse license (RDA-R1.1-02M) is expressed as a human-readable text applying the ISO19139 codelists *MD_ClassificationCode* and *MD_RestrictionCode* (https://standards.iso.org/iso/19139/resources/gmxCodelists.xml) within the *MD_Constraints* element (https://wiki.esipfed.org/ISO_Constraints). It is not recognized automatically by machines without human intervention, because the ISO19115 standard does not provide a field dedicated to the "license" with dedicated vocabularies (such as the RDF expression of Creative Commons licenses, or the Open Data Rights Language serializations); the Dublin Core provides it, but currently without any standard vocabulary. RDA-R1.1-03M is the only indicator of reusability not yet implemented. Metadata include information about the provenance of the data, such as origin, history and workflow in the *Quality* section, in particular in the metadata elements *Format*, *Lineage* and *Process step* (RDA-R1.2-01M). To ensure a cross-community understanding (RDA-R1.2-02M), most of the metadata records are filled in Italian and English (as reported in the metadata element *Metadata language*). The standards used for metadata indicated in the elements *Metadata standard* name and *Metadata standard version* are compliant with community standards (RDA-R1.3-01M/D) and machine-understandable (RDA-R1.3-02M/D). The metadata records are exposed as XML with the HTTP protocol and the CSW allows other infrastructures to automatically harvest them. The OGC geospatial services for the representation of the data in the geoportal, in other infrastructures or in desktop environments (e.g. ArcGIS, QGIS) are compliant with machine-understandable community standards (WMS, WFS, WCS) and available in the section *Distribution* of the metadata form.

5. Conclusions

In this paper, we presented and discussed the Marine Spatial Data Infrastructure (MSDI) implemented to guarantee the findability, accessibility, interoperability, and reusability of local multidisciplinary, inhomogeneous and fragmented datasets collected in the last 20 years for geological, habitat mapping and process modelling by ISMAR and ISP in the semi-landlocked Adriatic Sea (Mediterranean Sea).

This challenging effort represents one of the few examples of successful integration of geological, oceanographic, bathymetric, ecological data and products with satisfactory quality and easy accessibility, contributing to make possible comparative studies of marginal seas (from mapping to process modelling). The MSDI reached so far a good level of FAIRness (80%) with 33/41 FAIR principles implemented, in particular 90% of the *Essential* principles, 64% of the *Important* principles, and 86% of the *Useful* principles. This result makes it possible to i) preserve geodata and products and ii) share them at the local and global scale, iii) avoid wasting time and money, iv) foster cross-disciplinary work, v) reuse existing data, and vi) increase collaboration with national and international marine data infrastructures through a good level of interoperability.

The main gaps are currently related to the lack of data identifiers, to the full implementation of standardised and FAIR-compliant vocabularies, and to the lack of a machine-understandable reuse license under consideration yet (linked to the lack of a CNR data policy). The cloud component and the metadata catalogue are running and filled, but a complete description and archiving of all digital resources represented in the WebGIS will likely take years. Our next efforts will focus on reaching a full FAIRness of the MSDI, recovering all previous datasets, digital products and physical samples collected by ISMAR and ISP through the years all over the world, and fostering the integration in the MSDI of new data and products from different countries. In this perspective, we will go forward coordinate investments for a long-term sustainability of the implemented MSDI.

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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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.oceano.2022.11.002.

Data models implemented for the themes *Geophysics, Geology, Habitat mapping* and *Water column* are available as images and XML files in the research object at the link: https://w3id.org/ro-id/97985638-81ed-42b1-ae48-ab432f14db52. The complete list of indicators used for the FAIRness evaluation and the relative answers are shown in Table S1 of supplementary materials. The excel file produced by the FAIR Data Maturity Model (FAIR DMM WG, 2020) and used in this work is available at the link: https://zenodo.org/record/3909563#.YP_k3o77Q2y.

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