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The Value of Marine Spatial Open Data Infrastructures—Potentials of IHO S-100 Standard to Become the Universal Marine Data Model

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Abstract: Marine spatial "open" data infrastructures (MSDI) have a significant economic and societal potential for coastal nations and their realization is driven by the evolution of the International Hydrographic Organization's (IHO) S-100 data model for facilitating marine domain interoperability and the World Wide Web Consortium's (W3C) best practices for spatial data publishing on the Web. The recent European directive on open data and the re-use of public sector information, known as the "Open Data Directive" is a key driver towards the establishment of "open" MSDIs among other spatial data infrastructures. The paper discusses possible data architectures for the MSDIs, examines the maturity of open data platforms that they could be built upon and compares the most prominent marine spatial data models for their applicability in relation to three marine information domains. MSDIs can facilitate the continuous data capturing of spatial-temporal physical phenomena and human activities at sea and coastal areas, the corresponding data analysis and the decision-making for achieving continual improvement in the marine planning and management processes. MSDIs could play a key role in digital government transformation (DGT) for effective data sharing and offering marine services across various stakeholders. The information provided through a MSDI can be used for safe and efficient operation of maritime traffic, exploration and exploitation of marine resources, marine spatial planning (MSP), integrated coastal zone management (ICZM), environmental protection, and naval and maritime security.

Keywords: open data platforms; spatial data on web; marine spatial data infrastructure (MSDI); universal marine data model (S-100); digital government transformation (DGT)

1. Introduction

1.1. Marine Activity Domains

While life on earth depends on the sea as it covers 71% of our planet and 90% of the biosphere [1], people have different interests from the sea. Generations of fisherman have been living from fishing and lately from sea farming; containership captains need deep water and direct access to the ports by the shortest route, and environmental conservationists are committed to protecting the sea. The situation gets more complicated when minerals are found that the energy industry wants to extract and investors plan to build wind farms. Competition for the different establishments, activities and sectors of economic development requires effective and integrated management, in order not only to avoid potential conflicts, but also to create synergies among different activities. Recently, marine planning has been driven by national policies to develop offshore wind energy [2]. These policies are a result of many countries having ambitious renewable energy-generation targets associated with international climate change mitigation agreements. Many countries in Western and Central Europe and many States in the US have developed and implemented marine plans that incorporated substantial consideration of offshore wind energy [3].

1.1.1. Managing Human Activities at Coastal Areas and Sea

Marine spatial planning (MSP) is a relatively new way of managing human activities that take place in the sea. It is a long term and strategic process that guides when, where and how human use takes place. MSP can be useful where there are opportunities for new uses with possible impacts on nature, to balance competing interests, making sure society benefits while protecting the marine environment. According to [2] marine spatial planning should be:

1. integrated and multi-objective, including all important economic sectors; economic and social objectives as well as ecological ones,
2. strategic and future-oriented, considering alternative means to achieve a vision,
3. continuing and adaptive, with an emphasis on performance monitoring and learning by doing,
4. participatory, building a broad base of stakeholders to ensure long-term support for management,
5. ecosystem-based, with a focus on maintaining ecosystem services over time,
6. place-based, with a focus on marine spaces that people can understand, relate to, and care for.

1.1.2. Protection of the Marine Environment

Dealing with demands for marine space use, government officials face many challenges in how to satisfy all potential stakeholders and their interests as well as how to balance use and protection of the same marine space. Marine planning is possible to accommodate multiple uses of a different nature, as the design can be carried out simultaneously on all three dimensions of the marine area, namely, the bottom, the water column and the surface, and allow the same marine area to be exploited for the development of more than one use. Similarly to the Earth's atmosphere, the water column is divided into different layers, called "pelagic zones" [4], as depicted in Figure 1. The word "pelagos" in ancient Greek means "open sea". Conditions in the water column change with distance from the surface, for example, the pressure increases, while the temperature and the amount of light decrease.

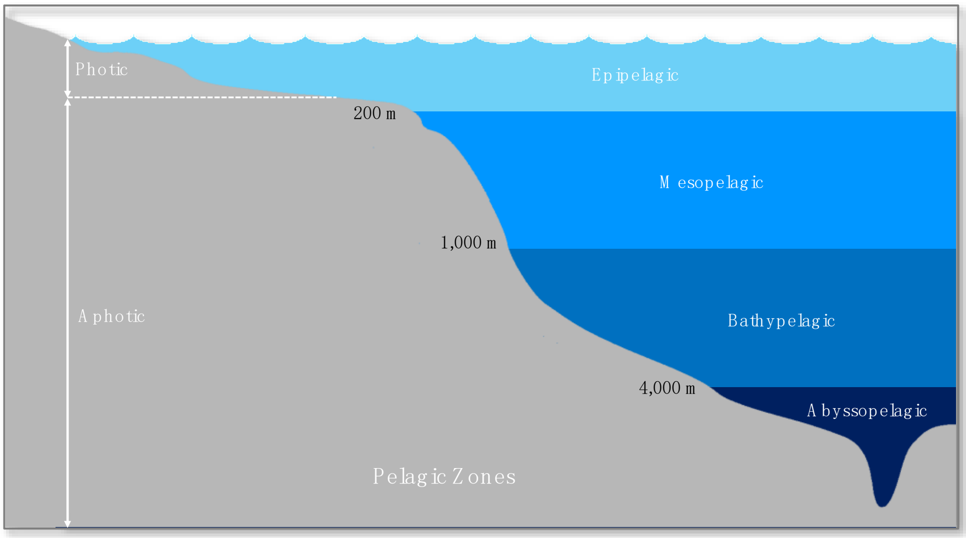

Figure 1. Oceanographic pelagic zones.

Some areas of the ocean may be considered more important than others from both ecological and socio-economic perspectives [5]. Species, habitats, populations of animals, oil and gas deposits, sand and gravel deposits, sustained winds or waves are all distributed unequally in space and over time [6].

Successful marine management needs planners and managers who understand how to work with the spatial and temporal diversity of marine resources. Understanding these spatial and temporal distributions and mapping them are essential components of effective marine spatial planning. Impacts due to climate change and other long-term pressures (e.g., overfishing and habitat loss) on marine systems is another important challenge for marine spatial planning.

1.1.3. Maritime Transport

Shipping is perhaps the most important marine activity that enables trade between states and provides the main vehicle for imports and exports of goods [7]. Moreover, the quality of life on islands depends on good maritime transport services and maritime industries are an important source of employment for world economies. According to the International Maritime Organization (IMO), shipping is on one hand the most international and on the other hand one of the most dangerous industries [8]. It has been recognized that the best way to improve safety at sea is by developing international regulations that are followed by all shipping nations. In that context, e-navigation is a strategy developed by the IMO for improving maritime safety through better organization of information, easier data exchange and communication between ships and shore operational centers.

1.2. Marine Information Domains

Related to the three main activity domains introduced so far, respective information domains exist that relate to the data being captured for each domain. Among these domains there are information entities common to between either two or all three, such as the coastlines as illustrated in Figure 2.

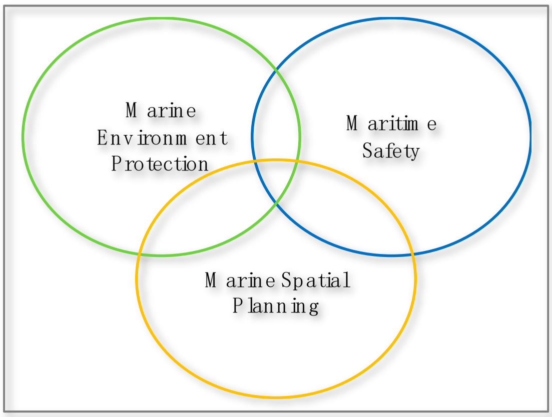

Figure 2. Marine information domains.

Need for the Best Available Data

In order to ensure that marine activities are based on reliable data and to avoid additional administrative burden, it is necessary for states to use the best available data and information by encouraging stakeholders to share data and information as well as exploit existing data and data collection tools, such as those developed under the "Marine Knowledge 2020" green paper of the European Commission [9]. The initiative brings together marine data from different sources with the aim of helping maritime industry, public authorities and researchers to find the data and make more effective use of them in order to develop new products and services.

1.3. Paper Objectives

The paper's objectives are to assess the maturity of the policy and technological advances related to open spatial data platforms and their applicability to coastal states' projects to establish a national marine spatial data infrastructure (MSDI). Section 1 provides a brief introduction of the marine information domains and the need for the best available data. Section 2 reviews the economic value of open data and the relevant EU directive that will drive their growth in the following years. Section 3 discusses the spatial data on Web best practices, as well as the most relevant data architectures for spatial data infrastructures (SDIs). Section 4 provides a comparative matrix of the available open data platforms (ODPs) that an SDI could be built upon. Section 5 presents the main categories of marine spatial data (MSD) and the most important marine-related spatial data model standards as well as discuss the benefits of the IHO S-100 standard, the relevant geospatial registry and the validity of the S-100 product specifications. Section 6 provides a comparative analysis among the most prominent standards, that are the International Hydrographic Organization's (IHO) S-57 and S-100 and the EU's Infrastructure for Spatial Information in the European Community (INSPIRE). The analysis concludes that S-100 could be considered as a universal MSD model.

In the last two sections of the paper the focus is on governance issues of marine spatial data infrastructures (MSDIs) and challenges for their establishment. Section 7 relates the various stakeholders to potential uses and discusses indicators for evaluating their success in relation to the four MSDI pillars. Section 8 discusses limitations and further innovative research needed to improve continuous data capturing and quality of the marine data. The paper concludes with Section 9 which emphasizes the important role of MSDIs for the digital transformation of the public sector services for marine planning and maritime support, as well as the principal role that the International Hydrographic Organization (IHO) aims to play the next decade towards the openness and the better utilization of the marine spatial data.

1.4. Methodology

The methodology of the conducted research comprises the following stages:

- determination of the marine information domains (maritime safety, marine environment, marine spatial planning)
- identification of the international organizations involved (Open Geospatial Consortium—OGC, World Wide Web Consortium—W3C, International Hydrographic Organization—IHO, European Union—EU associations)
- monitoring the activities of relevant working groups
- extensive review of the working groups' reports
- identification of challenges and limitations
- determination of assessment criteria from the common challenges or limitations for two comparative analysis (open data platforms—ODP and marine spatial data models—MSDM standards)
- functional review of national organizations use cases that have implemented ODP technologies
- design of comparative matrices
- population of the comparative matrices with data from the conducted assessment
- extraction of results and conclusions

2. Open Data Potential

2.1. Economic Value of Open Data

Numerous studies [10–13] have measured the impact of data for economic, political and societal development, pinpointing the importance of open data for economic growth. According to McKinsey [10], a global management consulting firm, making data more "liquid" (open, widely available and in shareable formats) has the potential to unlock large amounts of economic value, by improving the efficiency and effectiveness of existing processes, making possible new products, services and markets, as well as creating value for individuals and enterprises. Open data, meaning the release of information by governments and private institutions and sharing the data across industries, extends the power of data and makes entirely new services and applications possible. This research [10] highlights that open data could help unlock more than $3 trillion in value every year in seven domains of the global economy.

At [11], recognizing the importance of the overall data economy, the report specifically focuses on open government data, which should be considered in relation to what is happening in the overall data landscape and understood in the broader context of what is referred to as big data. Big data is a popular term to describe the exponential growth and availability of data, both structured and unstructured [12].

Figure 3 provides a conceptual overview of five different data categories that fall under the broader umbrella of big data:

- Public sector information is information generated, created, collected, processed, preserved, maintained, disseminated or funded by or for the Government or public institutions.
- Private sector information is the data collected, produced and owned by either private natural or legal entities.
- Open data refer to data that is open in terms of: access, redistribution, reuse, absence of technological restriction, attribution, integrity and no discrimination.
- Open government data are data produced or commissioned by public bodies or government controlled entities that are made accessible, can be freely used, reused and redistributed by anyone.
- Open private data, as in the context of open government data, the license will specify their terms of use.

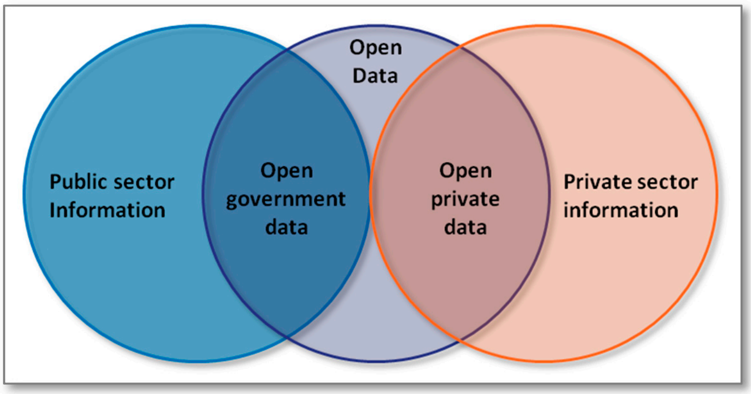

Figure 3. Open data in the big data economy. Reproduced from reference [11], with permission from European Data Portal, 2017.

2.1.1. Open Data Value Chain

In the context of this EU study [13], open data are information that can be freely used, modified and shared by anyone for any purpose. It must be available under an open license and provided in a convenient and modifiable form that is machine-readable. The steps for value creation of open data are depicted in Figure 4.

The first step is for data to be created, commonly a public task. Then data need to be validated and aggregated. When data are released via a portal or bought by a private company, they can be analyzed. Analyzing the data will make it possible to combine different information or make visualizations. This will lead to the creation of data services and products. These services can be aggregated one step further. During this entire process, data need to be stored and preserved.

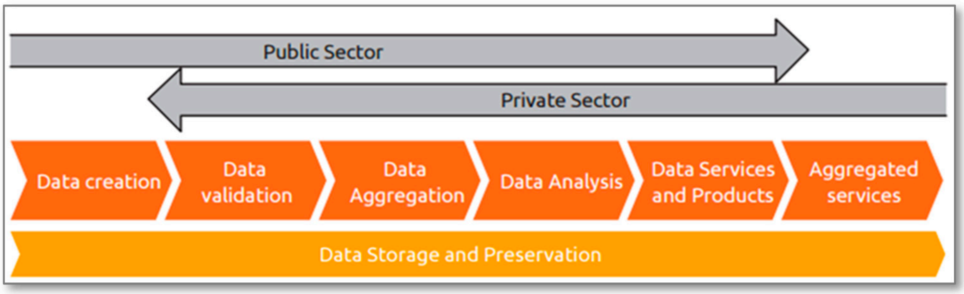

Figure 4. Open data value chain. Reproduced from reference [13], with permission from the European Union, 2015.

2.1.2. From Data to Information and Knowledge

The principle of data being the foundation of knowledge is well known [14]. In essence, knowledge is only of value if conveyed, and as the pyramid shows (Figure 5) with a broad base of data required to extract a smaller volume of knowledge. What is less commonly expressed is the amount of complexity in many information systems, where much more data are retained than actually converted into knowledge.

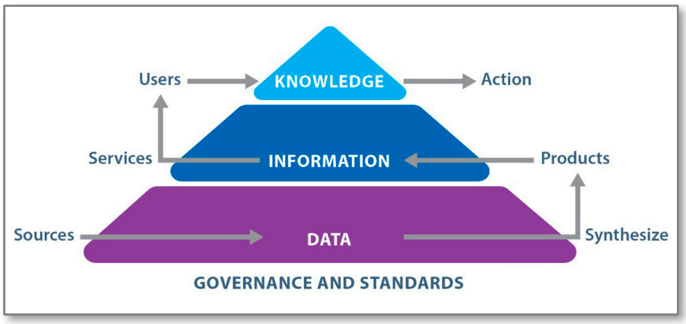

Figure 5. The data information knowledge triangle. Reproduced with the permission of the International Hydrographic Organization (IHO) Secretariat (Permission No 05/2020) acting for the International Hydrographic Organization (IHO), which does not accept responsibility for the correctness of the material as reproduced: in case of doubt, the IHO's authentic text shall prevail. The incorporation of material sourced from IHO shall not be construed as constituting an endorsement by IHO of this product. Permission No 05/2020 Material from IHO publication C-17 Figure 3–"The Data Information Knowledge triangle" reference [14].

Often, open data are thought of as unprocessed raw public data that are easy to transfer and re-use by the private sector. However, this is an oversimplification according to [15]. Open data exist in many forms and degrees. Three forms of open data can be distinguished and are related to the data value chain:

- Raw data, that corresponds to quantities or other quantitative or qualitative attributes derived from observation, experiment, measurement or computation. The data are not structured, contextualized nor commented.
- Information that corresponds to a set of contextualized and structured data, the producer's intention being to make them meaningful.
- Knowledge corresponds to the cognitive appropriation of the information by an individual who organizes, synthesizes or summarizes it to make it more readily understandable.

Organizations and businesses use data across the data value chain. Different actors are involved in the process, from data creation to data services and products as shown in Figure 6, as distinguished by the World Bank [16]. Data creation and data validation is done by the suppliers. The organizations that collect and aggregate the open data are called the aggregators. Individuals or companies that analyze the data and create services and products can be divided into developers and enrichers. Developers use the data for the development of new applications, while enrichers use data to gain new or better insights from the analysis of the data.

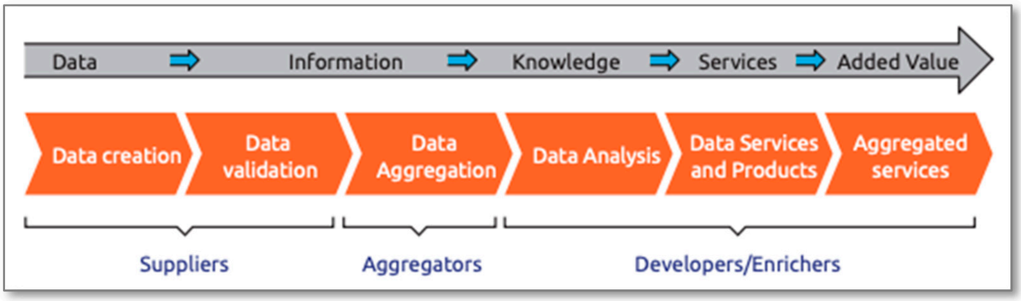

Figure 6. The data value chain and data value chain archetypes. Reproduced from reference [17], with permission from European Data Portal, 2017.

2.1.3. Data Economy Population

In this EuDEco (Modelling the European Data Economy Project) publication [18] on modeling the data economy, data holders (suppliers), data users and data distributors constitute the core of the data economy population (Figure 7). Enablers facilitate the supply or use of open data for the other archetypes, by providing platforms from which the data can be extracted and solution providers offer technologies and services supporting data-related activities, including data generation, acquisition, processing, aggregation, analytics, visualization and distribution.

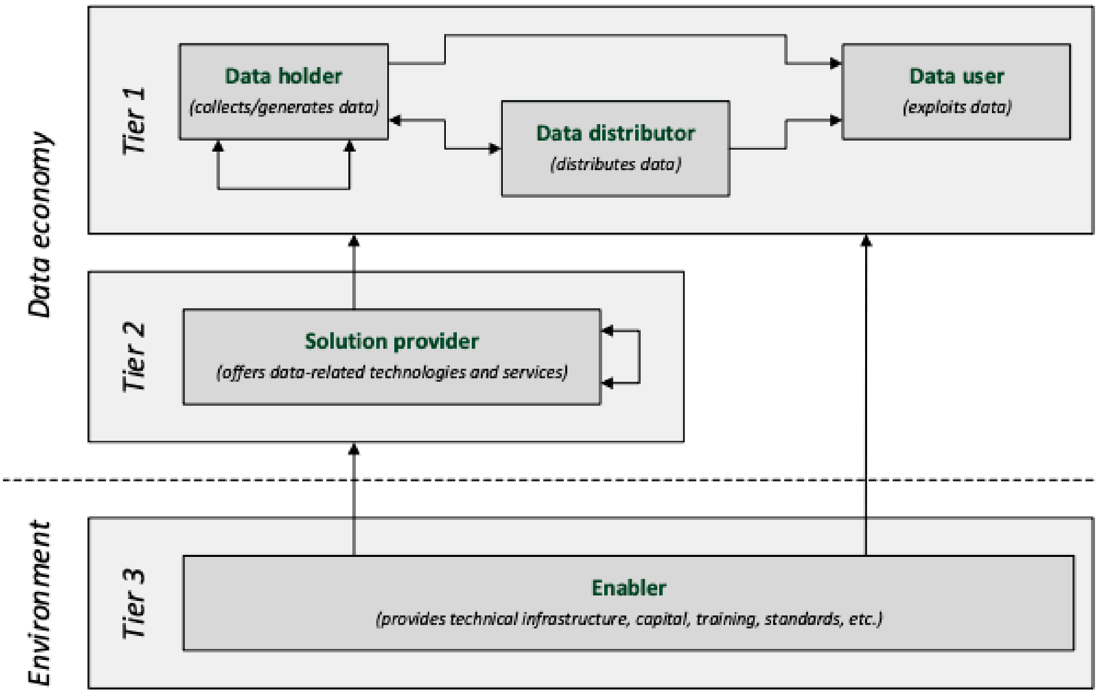

Figure 7. Data economy population. Reproduced from reference [18], with permission from European Union, 2017.

The first four activities describe what data holders might request. Data processing and aggregation as well as data analytics and visualization are of interest to data users. Data distributors rely particularly on data distribution technologies and services, but they may also request support regarding data processing and aggregation.

2.2. Open Data Directive

The recent European Directive on open data and the re-use of public sector information, also known as the "Open Data Directive" (Directive (EU) 2019/1024) entered into force on 16 July 2019 [19]. It replaces the Public Sector Information Directive, also known as the "PSI Directive" (Directive 2003/98/EC). The new directive, which member states are required to harmonize by 16/7/2021, introduces a number of changes to the institutional framework governing the re-use of public sector information. The directive provides a common legal framework for a European market for government-held data. It is built around two key pillars of the internal market, transparency and fair competition.

The directive focuses on the economic aspects of the re-use of information rather than on the access to information by citizens. It encourages the member states to make as much information available for re-use as possible. It addresses material held by the public sector, at national, regional and local levels, such as ministries, state agencies and municipalities, as well as organizations funded mostly by, or under the control of, public authorities (e.g., meteorological institutes).

2.2.1. High-Value Datasets

The directive introduces the concept of high value datasets, defined as documents, the re-use of which is associated with important benefits for the society and economy. They are subject to a separate set of rules ensuring their availability free of charge, in machine readable formats, provided via application programming interfaces (APIs) and, where relevant, as bulk download. The thematic categories of high-value datasets, as referred to in Article 13(1) of the directive, are:

- geospatial
- earth observation and environment
- meteorological
- statistics
- companies and company ownership
- mobility

2.2.2. Publishing Principles

Public enterprises in the utilities and transport sectors generate valuable data when providing services in the general interest that will enter into the scope of the directive. They will have to comply with the principles of transparency, non-discrimination and non-exclusivity set out in the directive and ensure the use of appropriate data formats and methods of dissemination. They will be able to set reasonable charges to recover the costs of producing the data and of making it available for re-use. With this directive, public sector bodies are not being able to charge more than the marginal cost for the reuse of their data.

2.2.3. Publicly-Funded Research Data

The directive includes any research data that should be openly accessible and re-useable. Member states are required to develop policies for open access to publicly-funded research data while harmonized rules on re-use will be applied to all publicly-funded research data which are made accessible via repositories.

2.3. Publishing Open Data

Open data, when published, should be discoverable and understandable both by humans and machines. The World Wide Web Consortium (W3C) is an international community that develops open standards to ensure the long-term growth of the Web. Several working groups of the W3C develop recommendation documents for the open data ecosystem to provide guidance to publishers to improve consistency in the way data shall be managed, as well as to promote the reuse of data. In 2006, Tim Berners-Lee, the Director of W3C and the inventor of the World Wide Web, suggested a 5-star deployment scheme for open data [20]:

1. make it available on the web (whatever format) but with an open license
2. make it available as machine-readable structured data
3. as (2) plus non-proprietary format (e.g., CSV instead of excel)
4. all the above, plus use semantic standards (RDF and SPARQL) to identify things, so that people can point at your data
5. all the above, plus link your data to other people's data to provide context

2.3.1. Open Data Principles

Similarly, the Sunlight Foundation [21] has published key principles for the datasets that the governments shall open for public use. The principles refer to completeness, being originals, having immediacy, ease of physical and electronic access, machine readability, no discrimination, use of open standards, licensing, timelessness and cost of use.

2.3.2. Open Data Licensing

Open data is a concept that describes the freedom of using the data, as anyone can use, share, redistribute or republish it. The data should be legally open published under public domain to be used with minimal restrictions, and technically open as it should be published in open technical formats available for download. The open data license is used to set the legal foundation of the use of the published data. Their license must permit people to use the data freely, including data transformation, redistribution, republishing and even commercially. Common open data licenses are [22]:

- Creative Commons: CC-By and CC0 (Public Domain Dedication)
- Open Database License/Open Data Commons Open Database License (ODbL)
- Open Data Commons Public Domain Dedication and License (PDDL)

Sometimes governmental and international organizations have released their own open data licenses like the World Bank, the French Open, and the UK Government Data Licenses.

3. Spatial Data on the Web

3.1. Data on the Web Best Practices

The growth in online sharing of open data by governments across the world, the increasing online publication of research data, the harvesting, analysis and online publishing of social media data, the crowd-sourcing of information and the increasing presence on the Web of important cultural heritage collections, provide some examples of this growth in the use of Web for publishing data. This W3C document [23] provides best practices related to the publication and usage of data on the Web designed to help support a self-sustaining ecosystem. The 35 best practices described in the document have been developed to encourage and enable the continued expansion of the Web as a medium for the exchange of data. The data on the Web best practices (DWBP) provide a set of recommendations that are applicable to the publication of all types of data on the Web and cover aspects including data formats, data access, data identifiers, metadata, licensing and provenance.

3.1.1. Linked Open Data

This W3C document [24] sets best practices to facilitate the publishing of open government data as linked open data. The term "linked data" refers to data that are published on the Web and, apart from machine readable, they are also linked to other external datasets (Figure 8). Linking data is the process of connecting structured data on the Web and it is the final step in the five star deployment scheme for open data. Using linked data principles, developers can query the data from multiple sources at once and combine them without the need for a single common schema that all data share.

Linked open data make the World Wide Web into a global database, sometimes referred to as the "Web of Data". Linked data have principles and standards that enable data discoverability and usability. The principles are based on proven aspects of the Web such as resolvable identifiers, common representation formats and the rich interlinking of independently published information, but adds explicit vocabulary management and tooling that targets the development community [25].

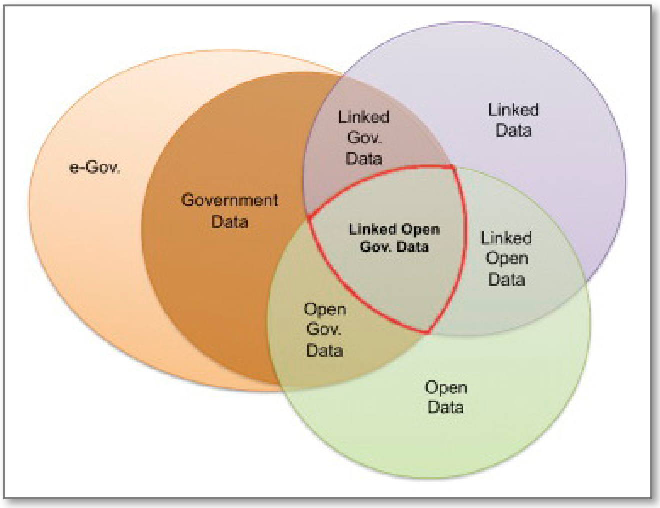

Figure 8. Relationship between open, government and linked data. Reproduced with permission from publisher of reference [26].

3.1.2. Linked Closed Data

Linked closed data [27] are semantic Web datasets which are published in accordance with linked data principles, but which include access and license restrictions. Linked closed data are likely to be the form of linked data publishing ultimately adopted by commercial linked data publishers when offering premium, paid access products, as they are likely to require some form of access restriction.

3.2. Spatial Data on the Web Best Practices

Nowadays spatial data are part of everyone's lives with the explosive growth in positioning technologies attached to mobile phones, sensors and IoT devices. They are useful for many convenient services like route planning, or for solving global challenges like climate change adaptation [28]. Historically, collecting, validating and using quality spatial data has largely been the role of military, government and scientific organizations. These organizations have long recognized the importance and benefits of sharing their own specialized data with others to achieve interoperability, increased usability and better spatial awareness, but did not manage to achieve the desired cross-community takeover.

Best practices for publishing and integrating spatial data on the Web (SDWBP) have been published as a W3C Note and as an OGC best practice [25]. These practices are guidance for application and website builders to address the needs of the consumer market. Furthermore, the best practices provide guidance for spatial data custodians. The SDWBP document [29] initially advises on the principles of the best practices related to the publication of spatial data on the Web. Then, it continues with several more in-depth introductions on spatial things and geometry, coverages, spatial relations, coordinate reference systems and linked data. After that, the following 14 best practices are described:

1. use globally unique persistent HTTP URIs for spatial things
2. make your spatial data indexable by search engines

3. link resources together to create the Web of data
4. use spatial data encodings that match your target audience
5. provide geometries on the Web in a usable way
6. provide geometries at the right level of accuracy, precision and size
7. choose coordinate reference systems to suit your user's applications
8. state how coordinate values are encoded
9. describe relative positioning
10. use appropriate relation types to link spatial things
11. provide information on the changing nature of spatial things
12. expose spatial data through "convenience APIs"
13. include spatial metadata in dataset metadata
14. describe the positional accuracy of spatial data

3.3. Spatial Data Infrastructures

Spatial data infrastructures (SDIs) as defined by the Global Spatial Data Infrastructure Association (GSDI) [30] are used to denote the relevant base collection of policies, institutional arrangements, standards and technologies that facilitate the availability of and access to spatial data. They are an ecosystem of geographic data, metadata, tools, applications, policies and users that are necessary to acquire, process, distribute, use, maintain and preserve spatial data. Due to their nature (size, cost and number of interactors) SDIs are often government-related.

The SDI provides a basis for spatial data discovery, evaluation and application for users and providers from all levels of government, the private sector, the non-profit sector, the academia and the citizens in general. SDIs are widely accepted as a way of enabling collaboration between various parties allowing sharing of data and services with each other [31]. SDIs can be realized as interoperable infrastructures, which enable government, private sector, academia and others to collaborate effectively. Collaboration is indispensable given the requirements such as the ones of the open data directive. SDIs are challenged [32] to become flexible and robust enough to absorb and embrace technological transformations and the accompanying societal and organizational implications.

Spatial data infrastructures [33] that typically employ international geospatial standards are now matured, but they have become part of the "deep Web", hidden from most web search engines and human knowledge seekers. The geospatial experts do not yet know where to begin looking for what they need or how to use it when they find it. The integration of spatial data from different sources offers possibilities to analyze them and gain new knowledge. However, spatial data on the Web are published in numerous formats and structures, with various granularities. This makes publishing, searching and viewing the spatial data on the Web a difficult task.

3.3.1. SDIs to the Web

Although, the SDWBP best practices suggest a significant change of emphasis from traditional spatial data infrastructures by adopting an approach based on general Web standards, spatial data infrastructures are a key component of the broader spatial data ecosystem. SDIs typically include policies, workflows and tools related to the management of spatial datasets, and provide mechanisms to support the rich set of capabilities required by the expert community. The goal is to help spatial data publishers build on these foundations to enable the spatial data from SDIs to be fully integrated with the Web of data. The following subset of SDWBP provides the most important steps that should be taken to make SDI data available on the Web:

- Best practice 1: Use globally unique persistent HTTP URIs for spatial things
- Best practice 2: Make spatial data indexable by search engines
- Best practice 3: Link resources together to create the Web of data

- Best practice 12: Expose spatial data through "convenience APIs"

The rest of the best practices provide more details on specific aspects of publishing spatial data on the Web, such as metadata, geometries, CRS (Coordinate Reference Systems) information, versioned data, et cetera.

3.3.2. SDI Architecture

As discussed in [34], spatial data infrastructures have been challenged by big data. For managing large volumes of data, a properly defined architecture is key for ensuring SDI remains healthy and growing. Data architecture acts as a framework of rules, policies, models and standards, which dictate how data are stored, managed and integrated. An important pillar of the data architecture is establishing what data model to use, how to store the data and where to store them. There are various options to consider and each has different pros and cons; the main ones are the 'data lake' and the 'data hub' [35] as depicted in Figures 9 and 10.

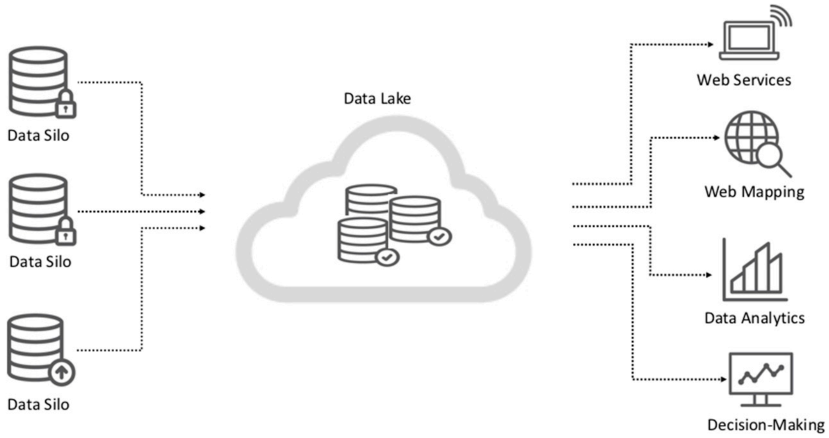

Figure 9. Data lake SDI architecture.

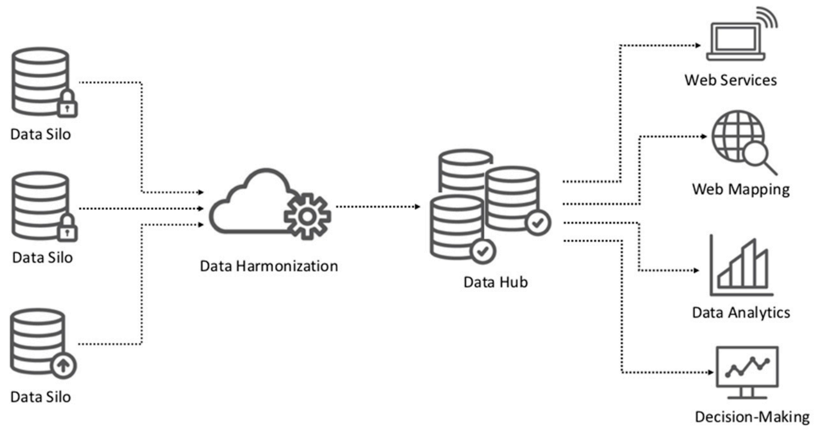

Figure 10. Data hub SDI architecture.

- Data lake, is a collection of data stored in its "natural" form. It is a catch-all area for any data and is typically built from a variety of different sources. It is optimized for quantity and is a place for data to sit untouched before they are cleaned, interpreted and transformed.

- Data hub, a hub-and-spoke approach to data integration where data is physically moved and re-indexed into the SDI. To be a data hub, the SDI would support discovery, indexing and analytics.

The choice of architecture between the above-mentioned could depend on the policy requirements for the protection of the raw data, as well as the licensing requirements of the data providers. The data hub is more adequate in the case that raw data need to be protected and implemented in conjunction with a common data model as the marine ones discussed in Section 5. A hybrid approach could also be considered as a viable option.

3.4. OGC API for Spatial Data

The Open Geospatial Consortium (OGC), an international, non-profit organization, which is comprised of members from government, companies and NGOs, has defined some of the most used network services for geospatial data [36], including:

- the web map service (WMS), that enables sharing of images
- the web feature service (WFS), that enables sharing of feature data with attributes
- the web coverage service (WCS), that enables sharing of raster data
- the web processing service (WPS), that enables sharing of algorithms to perform on data (for example coded in Python)

All these OGC web services are ISO-approved standards, which means that they are standards acknowledged by the International Organization for Standardization (ISO). Besides web services, other open technology options are developed and are gaining popularity around the globe at a fast pace. Within the geographic data sector, important examples are GeoServer and MapServer, which are servers for distributing web service, OpenLayers, which enables dynamic maps on web pages, the open source database postgreSQL with its spatial postGIS extension and the NetCDF software libraries that enable three-dimensional datasets, which is very important for marine ecosystem modeling.

4. Open Data Platforms (ODP)

4.1. ODP Types

An open data platform (ODP) consists mainly of web-based applications designed to publish data sets [37]. They are used by government organizations to publish data sets in order to provide transparency to their citizens. ODPs allow organizations to publish their data, organize them, tag/classify into categories and often come with data management tools with data reporting and visualization tools like maps and charts. There are many open source solutions that often come with more modules for application integration, and large scale use as they also have a community of users that are involved in production support and extensions/plugins development. The terms directory, platform and portal are sometimes used interchangeably. They are defined [38] as:

- Directory: is a catalogue of data sets that includes services for searching, metadata, clear licensing information and access to the data sets themselves.
- Platform: provides an online entrance for users to access available datasets to a geospatial data infrastructure. A platform includes the data directory along with other information and services that are part of the open data ecosystem. Data platform services are often implemented with a range of open data technologies.
- Portal: is a website that serves as a cyber door to the Internet in a particular area of interest or industry. A web portal usually provides specialized content, search engine capabilities and links to other relevant websites.

4.2. ODP Features

As described in [38], open data platforms may be relatively simple and standalone or sophisticated and interoperable with other systems. However, most of them share some common features such as:

- easy access
- search capabilities
- access to machine-readable data
- metadata

- reporting of data licenses
- preview/display data
- compliance with standards
- application programming interface (API)
- security

Table 1 summarizes facts and figures for the most common open data platforms found in the bibliography [38], as well as from the authors' research. From technological perspective the programming languages or frameworks used are included, as well as the existence of spatial extensions. An indication of maturity is the initiation year, while the major projects identified and reviewed indicate their applicability and maturity in regional, national and international use cases.

Table 1. Facts and figures of most common open data platforms.

Platform	Programming/Framework	License	Initiated	Spatial Extensions	Managed By	Major Projects
CKAN	Python	AGPL	2009	PostGIS, PyCSW, GeoJSON	Open Knowledge Foundation	data.gov open.canada.ca data.gov.au
DKAN	PHP, Drupal	GPLv2	2012		Open Community	data.ca.gov healthdata.gov
Socrata	Scala, Ruby, JavaScript, Python, Java	CC 3.0	2007	PostGIS, GeoJSON	Tyler Technologies	data.cityofchicago.org data.medicare.gov
Dataverse	Java	Apache	2007	-	Harvard	massopen.cloud dataverse.harvard.edu sshopencloud.eu
Swirrl-Publish MyData	-	-	2008	-	Swirrl IT Limited	statistics.data.gov.uk
The DataTank	PHP	AGPL	2011	-	Open Knowledge Belgium	data.beroads.com ewi.mmlab.be
GeoServer	Java	GPL	2006	OGC API	Boundless Spatial, GeoSolutions, Refractions Research	proba-v-mep.esa.int code-de.org dwd.de geodata.gov.gr
GeoNetwork	Java	GPLv2	2012	-	OSGeo	nationalgeoregister.nl geocat.ch geoportal.ypen.gr
Truedat	Elixir	GPLv3	2018	-	Bluetab Solutions	naturgy.com
Magda	JavaScript	Apache 2.0	2016	-	Magda.io	data.gov.au knowledgenet.co/
JKAN	Jekyll		2016	-	jkan.io	data.sandiego.gov opendata.riik.ee
GeoNode	Python, Django	OSGeo	2009	OGC API	OSGeo	ihp-wins.unesco.org worldmap.harvard.edu geonode.wfp.org mapsportal.ypen.gr caribbeanmarineatlas.net
Hue	Python	Apache2.0	2010	-	Cloudera	
Open Data Node	Java, Python, Groovy	-	2014	-	EEA	comsode.eu
Open Data Catalog	Django, Python	-	2011	PyCSW	Azavea	opendataphilly.org
Open Geoportal (OGP)	Java	GPL v3	2012	-	Tufts University	data.opengeoportal.org geodata.polimi.it
GetSDI	JavaScript	GPLv3	2014	PostGIS, GeoServer, GeoNetwork	Geospatial Enabling Technologies	getopendata.gr/bi/emy/ rae.gr/geo/ getmap.eu/live-apps/
Publica Mundi	Python, Javascript	-	2014	PyCSW, GeoServer	IMSI	geodata.gov.gr

4.3. Selecting and Implementing an ODP

From the matrix above, CKAN and GeoNode could be considered as the most promising ODPs. They are both implemented in major international projects and they are using open source stack based on mature and robust software frameworks with fully fledged spatial extensions. GeoNode particularly provides a large number of user-friendly capabilities, broad interoperability using Open Geospatial Consortium (OGC) standards, and a powerful authentication/authorization mechanism. It is an open source framework designed to build geospatial content management systems (GeoCMS) and spatial data infrastructure (SDI) nodes [39]. Its development initiated by the Global Facility for Disaster Reduction and Recovery (GFDRR) in 2009 and adopted by a large number of organizations in the following years. Supported by a global open source community, GeoNode is an official project of the Open Source Geospatial Foundation (OSGeo), an organization that incorporates mature open source projects.

Based on the review of geoportal designs and the theory of SDIs [40], it is important for geoportals that are used in national marine SDIs to ensure long-term strategies for data sharing and less redundant data displays. Recommendations for implementing an ODP may include:

- there should be only one single entry providing a clear overview of all data and download options available,
- data should be regularly updated in order to improve the usability of the data,
- metadata should be provided for the quality and resolution of the data,
- a clear strategy on how the data are published and updated,
- functionality to search for data based on resolution and time of origin,
- web services to allow viewing the data in users' own applications, improving interoperability,
- international, open technical standards should be used, ensuring interoperability between platforms in different countries,
- if any overlap between data in different portals exist, they are to be clearly communicated to the users,
- easy-to-read guides should be provided for how to use the portals.

Furthermore, strategies should be implemented to improve the data sharing of private data shareholders to expand the sources of open marine data.

5. Marine Spatial Data and Data Models

5.1. Marine Spatial Data

Marine spatial data are seen as valuable resources that appear to have high acquisition costs. Large quantities of this data are collected and stored by various groups of public and private agencies all over the world for a wide variety of purposes. Due to their importance, marine data should be properly managed and made available to end users for a variety of uses, including policy and decision-making, marine management, marine spatial planning (MSP), scientific research as well as various economic activities [41]. Marine spatial data include:

- hydrographic data
- oceanographic data
- land and coast data
- vessel tracking data
- port information and data
- meteorology and climate data
- cryosphere data
- marine historical data

- real-time sensor data
- crowd-sourced data

Hydrographic data refer to measurements and descriptions of the physical features of oceans, seas, coastal areas, lakes and rivers within a given country or region. This would typically include seabed topography (bathymetry), marine infrastructure (e.g., offshore installations, pipelines and cables), hazards (e.g., wrecks, rocks and obstructions), aids to navigation, administrative and legal boundaries and areas of conservation, marine habitats and oceanography. They include also nautical charting and seabed data, possible crowd-sourced hydrographic data as collected by shipping, cruise ship companies and other stakeholders, as well as horizontal and vertical datum, maritime baselines, seabed characteristics, marine boundaries and shorelines.

Oceanographic data describe ocean currents, waves and tides. They include water properties including water temperature, salinity, fluorescence, turbidity, dissolved oxygen, chlorophyll, suspended material, chromophoric dissolved organic matter as well as geology, offshore minerals, oceanographic features and sea ice and iceberg presence, density and velocity. Land and coast data include topographic base maps (high and medium resolution digital elevation models (DEMs)) and coastal mapping. Moreover, land cover, offshore cadaster, land ownership, flood hazards and gazetteer, as well as optical and radar imagery with long-term historic imagery to provide valuable insights into changes and near real-time imagery to monitor the region.

Vessel tracking via AIS (automatic identification system) data refer mainly to continual near real-time monitoring of traffic via AIS or remote sensing together with historic data on vessels' voyages. Data include vessel position, velocity, voyage and historical track and position information. Port information data include port calls and vessel traffic monitoring data. Meteorology and climate data include wind velocity and direction, air temperature, humidity and atmospheric pressure as well as climate parameters and indices. Cryosphere data refer to areas of snow, ice and frozen ground to support research on warming permafrost, reduction in snow cover extent and duration, reduction in summer sea ice, increased loss of glaciers and the break-up of ice shelves. Marine historical data are used for marine spatial planning; a process that brings together multiple users of the marine environment to make informed and coordinated decisions. Real-time sensor data are received in real time from available marine sensor systems. Finally, crowd-sourced data that refer to advances in technologies and communications, coupled with the rapid rise and adoption of social media applications, have created a new category of data in the marine environment.

5.2. Marine Data Models

5.2.1. The IHO Transfer Standard for Digital Hydrographic Data—S-57

IHO (International Hydrographic Organization) is an intergovernmental scientific organization founded in 1921 to support the safety of navigation and the protection of marine environments. One of the IHO's primary roles is to establish and maintain appropriate standards to assist in the proper and efficient collection and use of hydrographic data and information. S-57 is the primary standard used for electronic navigation charts (ENC) production. The ENC product specification includes descriptions of objects, attributes, data encoding format and the product specification profile update. S-57 describes how ENCs should be produced [42].

The contents of this standard are organized into three parts. Part one provides a general introduction including a list of references and definitions of terms used in the rest of the standard. Part two describes the theoretical data model on which the entire standard is based. Part three defines the data structure or format that is used to implement the data model and defines the general rules for encoding data into that format. S-57 also has two appendixes with Appendix A being the object catalogue, that provides the official IHO approved data schema that can be used within an exchange set to describe entities in the real world. Appendix B contains the IHO approved product specifications. These are additional sets of rules applicable to specific applications.

5.2.2. The IHO Universal Hydrographic Data Model—S-100

IHO has defined the S-100 Universal Hydrographic Data Model as a versatile standard framework aligned with the International Organization for Standardization (ISO) 19100 Geographic Information/Geomatics series of standards. S-100 aims to support a wide range of users by developing digital products and transfer standards for the marine community beyond the core hydrographic applications of the IHO [43,44]. The first edition of the IHO publication of S-100—Universal Hydrographic Data Model—was published on January 2010 as an international standard for the marine geospatial information era, and till 2020 there are three more revisions of the standard.

To make hydrographic data accessible to users outside the maritime navigation community, it needs to be held in a universally recognized format. S-100 has been designed to address the limitations of its predecessor S-57, an established format for electronic navigational charts but limited only to hydrographic data, and extend its use to other marine GIS applications. S-100 provides the universal data model for holding a wide range of data in a widely recognized format. Moving to S-100 will provide the opportunity to remove duplication and ambiguity. The aim is to hold each feature once such that it is known to be authoritative. If scale dependent portrayal is required, this should be an attribute of the feature and not an excuse to hold the feature more than once.

The S-100 data model is also adopted by the United Nations' International Maritime Organization (IMO) to be the basis of IMO's common maritime data structure (CMDS) of e-navigation [45,46]. E-navigation covers strategies aimed at improving the sharing of marine information through the use of modern technology and includes marine data, such as electronic navigational charts, bathymetric data, tidal data, meteorology data, radar-image data and the radio-based AIS data.

The primary goal of S-100 is to support a greater variety of marine-related digital data sources, products and customers. This includes the use of imagery and gridded data, enhanced metadata specifications, unlimited encoding formats and a more flexible maintenance regime. This enables the development of new applications that go beyond the scope of traditional hydrography, for example, high-density bathymetry, seafloor classification, marine GIS (Geographic Information Systems) and maritime limits. S-100 is designed to be extensible so that future requirements, for example, 3D, time-varying data (x, y, z and time) and web-based services for acquiring, processing, analyzing, accessing and presenting marine data, can be easily incorporated.

S-100 Geospatial Information Registry

S-100 Geospatial Information Registry [47] contains several registers (online databases) that include items of information relevant to those communities developing S-100 based products and services. The main ones are:

- Feature concepts used to build feature catalogues
- Portrayal information
- Producers codes
- Product specifications

S-100 Based Product Specifications

S-100 enables the development of specifications for the provision of various digital products and marine GIS services. An S-100 based product specification defines a data product, and usually includes additional resources such as a machine-readable feature catalogue and portrayal catalogue, a data encoding guide and at least one data encoding format. The IHO S-100 working group (S-100WG) has developed draft guidance documents for developing product specifications. In order to manage the development of S-100 based products and with a view to minimizing duplication and encouraging conformity, the IHO Hydrographic Services and Standards Committee (HSSC) has allocated S-XXX numbers to be developed by:

- International Hydrographic Organization (IHO): numbers S-101 to S-199.

- International Association of Light Authorities (IALA): numbers S-201 to S-299.
- Intergovernmental Oceanographic Commission (IOC): numbers S-301 to S-399.
- Joint Technical Commission for Oceanography and Marine Meteorology (WMO/IOC JCOMM): numbers S-411 to S412.
- International Electrotechnical Commission - Technical Committee 80 (IEC-TC80): numbers S-421 to S-430.

The following table provides a list (Table 2) of S-100 based product specifications allocated by HSSC, which are either planned for development, currently under development or review or have already been published.

Specifications based on S-100 are now available for a range of thematic data resources such as S-121 for Maritime Limits and Boundaries (MLB) and S-122 for Marine Protected Areas (MPA).

Table 2. S-100 Product specifications allocated by IHO Hydrographic Services and Standards Committee (HSSC) and their status (February 2020).

Code	Name	Format	Status	Edition	Published
S-100	Universal Hydrographic Data Model	XML/UML	published	4.0.0	December 2018
S-101	Electronic Navigational Chart (ENC)	ISO 8211	published	1.0.0	December 2018
S-102	Bathymetric Surface	HDF5	published	2.0.0	October 2019
S-103	Sub-surface Navigation		planned		
S-104	Water Level Information for Surface Navigation		development		
S-111	Surface Currents	HDF5	published	1.0.0	December 2018
S-121	Maritime Limits and Boundaries	GML	published	1.0.0	October 2019
S-122	Marine Protected Areas	GML	published	1.0.0	January 2019
S-123	Marine Radio Services	GML	published	1.0.0	January 2019
S-124	Navigational Warnings		development		
S-125	Marine Navigational Services		development		
S-126	Marine Physical Environment		development		
S-127	Marine Traffic Management	GML	published	1.0.0	December 2018
S-128	Catalogue of Nautical Products		development		
S-129	Under Keel Clearance Management (UKCM)	GML	published	1.0.0	June 2019
S-1xx	Marine Services		planned		
S-1xx	Digital Mariner Routing Guide		planned		
S-1xx	Harbor Infrastructure		planned		
S-201	Aids to Navigation Information	GML	review	1.0.0	
S-211	Port Call Message Format	XML	review	1.0.0	
S-240	DGNSS Station Almanac	GML	review	1.0.0	
S-401	Inland ENC	ISO 8211	published	1.0.0	October 2019
S-402	Bathymetric Contour Overlay for Inland ENC		development		
S-411	Sea Ice Information		development		
S-412	Weather Overlay		development		

5.2.3. The EU INSPIRE Directive and Data Model

INSPIRE (Infrastructure for Spatial Information in the European Community) is an EU initiative to create a spatial information network in Europe that is geared towards making spatial or geographical information more available and interoperable for a wide range of sustainable development purposes. The INSPIRE directive [48] aims to establish an infrastructure for spatial information in Europe that will help to make spatial or geographical information more accessible and interoperable for a wide range of purposes supporting sustainable development. The INSPIRE Directive entered into force on 15 May 2007 and provides a general framework for a spatial data infrastructure (SDI) for the purposes of European Community environmental policies. It is based on the infrastructures for spatial information established and operated by the member states of the European Union and addresses 34 spatial data themes of features needed for environmental applications. The following four may be considered as more closely related to marine data:

- Ocean geographic features (OF)

The ocean geographic features [49] include the measurable physical conditions of oceans, for example, salinity, oxygen, other chemical components and currents. Relevant observational data include:

- Remote-sensing of sea surface temperature, dynamic topography, synthetic aperture radar winds and ocean color
- Drifting buoys provide surface velocity, temperature and atmospheric pressure
- Ships-of-opportunity and regular voluntary observing ships provide temperature (bathythermograph) profiles
- Argo floats provide temperature and salinity profiles

- Sea regions (SR)

The sea regions features [50] include seas and saline water bodies divided into regions and sub-regions. Each region with common characteristics concerning water flow/circulation, adjacent river catchments, bio-chemical or temperature of water, based on scientific criteria. Both "Oceanographic geographical features" and "Sea-regions" are concerned with the physical conditions of marine water-masses.

- Atmospheric conditions and meteorological geographical (AC)

The meteorological geographical features [51] include weather conditions and their measurements; precipitation, temperature, evapotranspiration, wind speed and direction.

- Elevation (EL)

The elevation features [52] include terrestrial elevation, generally represented as the terrain data, ground surface topography, called digital terrain model (DTM) describing the three dimensional shape of the Earth's surface, the surface data, named digital elevation model (DEM), including the three dimensional shape of every feature placed on the soil (buildings, bridges, trees, etc.) and bathymetry, for example, a gridded bottom model.

6. Marine Data Models Comparative Analysis

6.1. Marine Data Models Capabilities

The comparative analysis of the marine data models is based on capabilities that a modern domain spatial data model should have. The capabilities were identified by extensive review of the IHO working groups and their project teams' activities to improve the S-100 data model and especially in the areas that the S-57 standard lags behind. They refer mainly on the interoperability of the standards, meaning the ability to cover multiple information domains as the ones introduced in Section 1. Both INSPIRE and S-100 are based on the ISO 19100 series of standards, while S-100 datasets have been designed to be interoperable across multiple marine product specifications with suitable features and portrayal catalogues and respective drawing rules.

The capabilities include the conceptual schema language that specifies tools and methods that the entities of the model shall be described. The information registers are dynamic lists of entities related to the models. The general feature model describes the internal architecture of the model entities. Metadata are used mainly to describe the information about the dataset including quality aspects, while the feature catalogue lists the identified entities of the model. The geographic coordinate system specifies the ability to include data in multiple systems and spatial schema primitives refer to the data types used to describe the spatial dimension. Imagery and gridded data indicate the ability to describe raster images and spatial grids. Portrayal refers to the ability to visualize the spatial data, usually incorporating cartographic rules. Multiple viewing layers mark the ability to easily switch the visualization between information layers of specific interest. Encoding formats refer to the internal representation and formatting of the exchange datasets. Product specifications refer to the ability to describe, based on specific methodology, multiple information domains. Maintenance regime specifies processes to incorporate improvements and changes. Data validation attributes to the rules defined to evaluate the correctness of the datasets. Interoperability indicates the ability to exchange data with heterogeneous information systems. Online data exchange attributes mainly to the well-known spatial data web services. Data protection refers to the ability to ensure the integrity of the datasets and in some cases, confidentiality. The 3D and time-dimensional data indicate the ability to describe phenomena in 3D space that change over time.

6.2. Marine Data Models Capabilities Matrix

The capabilities are listed in the first column of Table 3, where a comparative matrix is presented of the most important marine spatial data model discussed in Section 5, in other words, the S-57, the S-100 and the INSPIRE.

Table 3. Marine data model standards capabilities matrix.

Capabilities	S-57	INSPIRE	S-100
Geospatial Standards	-	ISO 19100 series	ISO 19100 series
Conceptual Schema Language	-	UML	UML
Information Registers	Part A: Object catalogue	Online (10 Registers) inspire.ec.europa.eu/registry	Online (6 Registers) registry.iho.int
General Feature Model (GFM)	composite and simple objects, attributes	features, complex and simple attributes	features, complex and simple attributes
Metadata-Data Quality	No	ISO 19115	S-100–Part 4c
Feature Catalogue	No	4 related themes	378 marine related features
Geographic Coordinate System	WGS84	Multiple	Multiple
Spatial Schema Primitives	node, edge, face	point, curve, surface	point, pointset, curve, surface, coverage
Imagery and Gridded Data	Partly	Supported	Supported
Portrayal	S-52	No	XML and Scripting based (Lua) mechanism
Viewing Layers	not defined	8	28
Encoding Formats	ISO8211	GML	ISO8211, GML, HDF5
Product Specifications	No	domain based	domain based
Maintenance Regime	S-65	MIWP	S-99
Data Validation	S-58	ARE3NA and ELISE Actions	S-98 Annex B
Interoperability	-	ISO 19131	S-100 Part 16 and S-98
Online Data Exchange	-	CSW, WMS and WFS	S-100 Part 15
Data Protection	S-63	GDPR	S-100 Part 13
Three-dimensional Data	Partly	Supported	Supported
Time-dimensional Data	-	Point Time Series Observation	Extension under evaluation

6.3. Marine Data Models Relation to Information Domains

The relevance of the assessed marine data model standards to the marine information domains, is empirically assessed in Table 4, and resulted mainly from the evaluation of their development goals, meaning the purpose they were initially introduced, as well as the comparison of their capability for feature catalogue coverage of the respective domains. S-100 has an extensive and open to additions—online—features catalogue register that is capable of covering all three marine information domains in adequate detail. This capability, in addition to all other modern capabilities that it incorporates, could potentially nominate it as the most prominent one to use in marine related SDIs and become the de-facto universal marine spatial data model.

Table 4. Marine data model standards relevance to the marine information domains.

Information Domain	S-57	INSPIRE	S-100
Marine Environment Protection	low	high	medium
Maritime Safety Information	high	low	high
Marine Spatial Planning	low	high	high

7. Marine Spatial Data Infrastructure (MSDI)

7.1. MSDI Purpose

MSDI is the component of an SDI that encompasses marine geographic and business information in its widest sense [32]. Typical data content includes marine boundaries and limits, protected areas, marine habitats, oceanography, bathymetry, geology, marine infrastructure, wrecks, offshore installations, pipelines, cables and many others. Moreover, along the coastline, there are measurements related to climate change that indicate sea level change, incidence of storm events, higher wave energy and surges that have an impact on fixed structures, and significant beach erosion and flooding inundation. Controllable and equitable use of coastal resources for urban planning, renewable energy, tourism, conservation and preservation of natural habitat, are within the scope of an MSDI developed framework.

A definition [14] by the International Hydrographic Organization (IHO) provides a succinct interpretation: "A Marine SDI is the component of an SDI that encompasses marine and coastal geographic and business information in its widest sense and would typically include information on seabed bathymetry (elevation), geology, infrastructure (e.g., wrecks, offshore installations, pipelines, cables); administrative and legal boundaries, areas of conservation and marine habitats and oceanography."

As discussed in [53], the information provided through a MSDI can be used for safe and efficient operation of maritime traffic, exploration and exploitation of marine resources, marine spatial planning, integrated coastal zone management (ICZM), environmental protection, naval and maritime security. MSDI could provide benefits such as promoting data and information sharing and exchange, enabling the wider use of field data and information, facilitating development of new products and services, improving organizational decision-making and reducing duplication of activities.

MSDI Stakeholders

Although the MSDI stakeholders (Table 5) vary considerably [41,54], there are substantial overlaps in terms of the needs of the majority, such as, the aspects of easy discovery, access, download and analysis of marine spatial data. For the data producer, provider and processor, needs include the ability to publish, integrate, aggregate and analyze geospatial data and related non-geospatial data. The focus should be on ease-of-use and effectiveness. Integrated systems, possibly in a system-of-systems or network-of-networks approach, with the ability to harvest data from existing solutions in a secure, reliable manner, should be supported. In addition, there is a need for further requirements in real-time or archived availability, data and system intellectual property rights (IPR), reuse and indemnification rules and regulations, security and privacy settings, as well as financial costs.

Table 5. Marine SDI stakeholders and potential uses. Adapted from reference [41].

MSDI Stakeholders	Policy Makers	Data Producers	Data Processors	Data Handlers	End Users
Academic and educational institutions		✓	✓	✓	✓
Archaeology, marine, hydrology, ecology science					✓
Authorities: Port Authority, Marine Transportation	✓	✓		✓	✓
Commercial data/analytic providers		✓	✓		
Diplomatic and national security officials	✓				✓
Environmental Protection Agencies	✓				
Federal, state, provincial government agencies	✓	✓	✓	✓	✓
Fishing companies					✓
GIS and Information Technology		✓			
Insurance companies	✓	✓	✓		✓
Internet and Social Media Providers		✓		✓	
International Intergovernmental Organizations	✓				
Local Government Agencies	✓			✓	
Mapping and GIS experts			✓		
Marine and Oceanographic boards and groups	✓	✓	✓	✓	✓
Military Organizations	✓	✓	✓	✓	✓
Mining companies					✓
NGO Service Providers					✓
Port managers and harbormasters					✓
Public Authorities	✓				
Public Works	✓				✓
Researchers for climate conservation					✓
Search and rescue officials					✓
Shipping and cruise ship companies					✓
Software developers			✓		
Standards Developing Organizations	✓				
The General Public		✓			✓
Transportation			✓		✓
Utility companies/organizations: Oil and Gas, Power		✓			✓

7.2. MSDI Governance

Some states are characterized by a very strong stakeholder representation and openness towards inputs from the academia and the private sector [55–57]. In some other countries, stakeholder participation is very limited, where SDI related discussions are mainly among the public authorities and minor involvement of others. There are also cases where there is no representation of lower levels of governments either. In that respect, Table 6 depicts SDI pillars [25] indicators for evaluating their maturity, stimulating the importance of the stakeholders' participation among other factors.

Although technological advances discussed in previous sections are important for MSDIs successful implementations, Table 6 highlights the importance of the policy and governance pillar and its interaction with the other three pillars. In this context, Table 7 provides a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis of the governance pillar.

Table 6. Indicators for evaluating SDIs. Adapted from reference [55].

Pillar	Area	Indicators
Policy and Governance	Policy Level	- existence of a government policy for SDI - handling of intellectual property rights, privacy issues - objectives for acquisition and use of spatial data
Domain Standards	Management Level (**Standards**)	- arrangements for data providers - arrangements for data dissemination and access - coordination of spatial data - definition of core datasets and data modeling - web interoperability
Policy and Governance Information Systems	Management Level (**Access Network**)	- access pricing - delivery mechanism and procedure - access privileges - value-adding arrangements
Information Systems	Operational Level (**Access Network**)	- type of network - data volume - response time
Geographic Content	Operational Level (**Data**)	- data format - data capture method - data maintenance - data quality and accuracy
Policy and Governance	Other Influencing Factors (**People**)	- number of organizations and people involved - opportunities for training - market maturity for data providers, data integrators, end users
Policy and Governance	Performance Assessment	- degree of satisfying the objectives and strategies - user satisfaction - diffusion and use of spatial data and information - turnover and reliability

Table 7. SWOT analysis of marine spatial "open" data infrastructures (MSDI) governance. Adapted from reference [55].

Strengths	Weaknesses
Regular review of marine information strategy Government appointed organization is responsible for marine spatial data, imposing strong leadership and decision-making Strong academic sector Good cooperation among providers and operators	Strategy does not consider cadastral issues No promotion of data modeling and interoperability and hence freedom (mesh) of systems and methods No independent board which could promote and coordinate spatial information
Opportunities	**Threats**
Vision of spatial information being crucial for good governance Strengthen political support	Not being able to bring the diverging interest groups together Losing political support

8. Discussion

Open data exploitation promises to create value for the private sector in a variety of operations, from the optimization of value chains in manufacturing and services to more efficient use of labor and tailored customer relationships. Moreover, the public sector is both an important data user and a key source of data and more effective use of public-sector information can generate benefits across the economy. However, greater access and use of open data creates a wide array of policy issues, such as privacy and consumer protection, appropriate data access methods, necessary user skills and many others.

On the other hand, the marine environment is constantly changing, whether due to variations in the climate, extreme environmental events or simply the natural movement of tides and currents. Up-to-date marine information will enable states to measure and adapt to these changes. To develop marine renewable energy projects, operators need information not only related to the topography of the seabed, but also the strength and regularity of currents. Industries like fishing and aquaculture are also dependent upon environmental factors such as temperature, salinity and currents, information which is recorded in hydrographic surveys. All of these activities will be impacted and will need to adapt if the marine environment changes, as trends seem to indicate.

As examined in Section 5, the most prominent data model to facilitate continuous data capturing and development of innovative services for the marine domain is IHOs S-100. S-57 has been used successfully for more than 20 years, though it is primarily targeted at the maritime safety domain. INSPIRE with over a decade of experience has great potential for inland waters and coastal areas and could be used in cases where environment protection has the highest priority. S-100, even its official adoption has been delayed for almost a decade from the initial target of IHO, is the most versatile, focused on interoperability and remains the most promising of the two, to cover the future needs of all three main marine activity domains.

Further innovative research and developments in marine standards will be made in order to cover strategic goals for sustainable marine spatial planning and e-navigation, in conjunction with improving the quality and certifying, where necessary, the marine data available for use. The intergovernmental organization governing the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Commission—HELCOM), proposes ten principles as valuable guidance for achieving better coherence in the development of the region [58] and the quality of data available is highlighted. The proposed principles are:

1. Sustainable management
2. Ecosystem approach
3. Long term perspective and objectives
4. Precautionary principle
5. Participation and transparency
6. High quality data and information basis
7. Transnational coordination and consultation
8. Coherent terrestrial and maritime spatial planning
9. Planning adapted to the characteristics and special conditions in different areas
10. Continuous planning

9. Conclusions

Open data holds a tremendous societal and economic potential, as when disclosed can stimulate growth, better decision-making, more transparency and efficiency of governments, as well as higher quality of life and more inclusive societies. They are seen as a driver for economic growth and an enabler for transparency and accountability, as well as innovation and knowledge. According to an OECD (Organisation for Economic Co-operation and Development) report [59], data-driven innovation forms a key pillar in the 21st century sources of growth. The confluence of several trends, including the increasing migration of socio-economic activities to the Internet and the decline in the cost of data collection, storage and processing, is leading to the generation and use of huge volumes of data—commonly referred to as "big data". These large data sets are becoming a core asset in the economy, fostering new industries, processes and products and creating significant competitive advantages.

Moreover, the increased rate of adoption of linked data best practices has led the Web to evolve into a global information space containing billions of assertions, where both documents and data are linked. The evolution of the Web enables the exploration of new relationships between data and the ensuing development of new applications.

At the same pace, the use of spatial technologies is increasing rapidly, with the proliferation of sensor devices and the rise of location-based services. The existing geospatial data, online maps combined with new forms of dynamic location-based data and services, create an opportunity for various new applications and services. Considering that location is often the common factor across multiple data sets, spatial data is a valuable addition to the Web of data. However, the particularity and the complexity of spatial data, such as the use of miscellaneous coordinate reference systems, make it difficult for users and developers to discover, interpret and use the information on the Web. In order to make spatial data more effectively available, a set of common practices are required to determine how spatial data can be published, discovered, queried and integrated with other data on the Web.

The best practices for publishing and integrating spatial data on the Web (SDWBP), published by W3C, provide a comprehensive set of guidelines for publishing spatial data on the Web. The best practices are intended for practitioners and geospatial experts, and are compiled based on evidence of real-world application. Based on these practices, marine spatial "open" data infrastructures (MSDIs or MSODIs) could play a key role in digital transformation of governments (DGT) related to marine space management [60], as they constitute the main building blocks for effective data sharing across not only the public sector, but also the private sector and academia. Their development has stressed the importance of collaboration across sectors, centricity of users' needs as well as the usefulness of platforms and proliferation of application programming interfaces (APIs).

The S-100 standard of the International Hydrographic Organization (IHO) has the potential to become the de facto marine data model for future MSDI implementations. Hydrography can be considered the basis for all activities involving the sea, as it focuses on the physics of the marine environment, as well as the measuring and charting of seabed topography. Up-to-date marine data and nautical charts, made according to international standards, enable states to monitor changes and adapt their marine management activities. In this direction, IHO is helping its member states to improve their marine data and to facilitate the sharing of hydrographic information globally. IHO is determined to play a key role in the next decade towards the openness and utilization of marine spatial data, through its support for industry operational products and services based on the S-100 standard [61], as well as through its partnership in the "GEBCO Seabed 2030" project, which will enhance the available bathymetric data and produce a complete map of the ocean floor by 2030.

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