Articles

SINGAPORE'S NATIONAL MARINE SPATIAL DATA INFRASTRUCTURE "GEOSPACE-SEA" : Enabling Hydrospatial Context and Applications in a Changing Ocean and Seascape

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Abstract

The establishment of national Marine Spatial Data Infrastructures (MSDI) have been geographically uneven due to challenges such as funding, political will and human capital. Furthermore, actualising MSDI benefits; enabling and supporting hydrospatial applications, poses another set of challenges. Using Singapore's national MSDI – GeoSpace-Sea, this paper uncovers four catalysts of GeoSpace-Sea's development and describes three challenges an emerging national MSDI confronts when actualising its envisaged benefits. These challenges could vary over time, space and the MSDI's maturity. Along with integrated hydrospatial and geospatial management, MSDIs would foreseeably continue to be key to unlocking the value of spatial data and in revealing insights into the past, present and future.

Résumé

La mise en place d'infrastructures de données spatiales maritimes (MSDI) nationales a été inégale sur le plan géographique en raison de défis tels que le financement, la volonté politique et les ressources humaines. En outre, l'actualisation des avantages des MSDI, la facilitation et le soutien d'applications hydrospatiales, représentent un autre défi. En utilisant la MSDI nationale de Singapour – GeoSpace-Sea, cet article dévoile quatre catalyseurs du développement de GeoSpace-Sea et décrit trois défis auxquels est confrontée une MSDI nationale émergente lors de l'actualisation de ses avantages envisagés. Ces défis peuvent varier dans le temps, l'espace et selon la maturité de la MSDI. Parallèlement à la gestion hydrospatiale et géospatiale intégrée, les MSDI continueraient probablement à être essentielles en vue de libérer la valeur des données spatiales et de révéler des perspectives passées, présentes et futures.

Resumen

El establecimiento de las Infraestructuras Nacionales de Datos Espaciales Marinos (MSDIs) ha sido geográficamente desigual debido a desafíos como la financiación, la voluntad política y el capital humano. Además, la actualización de los beneficios de las MSDIs; la activación y el apoyo a las aplicaciones hidroespaciales, plantean otra serie de desafíos. Al utilizar la MSDI nacional de Singapur - *GeoSpace-Sea*, este documento revela cuatro catalizadores del desarrollo de *GeoSpace-Sea* y describe tres retos a los que se enfrenta una MSDI nacional emergente a la hora de actualizar sus beneficios esperados. Estos desafíos podrían variar con el tiempo, el espacio y la madurez de la MSDI. Junto con la gestión hidroespacial y geoespacial integrada, es previsible que las MSDIs sigan siendo fundamentales para desentrañar el valor de los datos espaciales y para desbloquear el valor de los datos espaciales y revelar perspectivas sobre el pasado, el presente y el futuro.

1. Introduction

At Singapore's World Hydrography Day celebrations in June 2019, the Maritime and Port Authority of Singapore (MPA) officially announced the setting up of our national Marine Spatial Data Infrastructure (MSDI) initiative, called 'GeoSpace-Sea' (Maritime and Port Authority of Singapore, 2019a). This initiative complements Singapore's terrestrial-based spatial data infrastructure (SDI). The MPA collaborated with 11 other government agencies and academic representatives to deliver the marine component of the national SDI, and in doing so, bridge the land-and-sea information gap through data harmonisation and interoperable standards, in particular those that are Open Geospatial Consortium (OGC) approved.

At the national level it was agreed that a continuous land to sea surface model would be fundamental to addressing issues such as sea level rise and coastal adaptation. The first phase of GeoSpace-Sea aimed to establish partnerships, implement the Geographic Information System (GIS) infrastructure and provide access to government stakeholders. The next phase is expected to create access for institutes of higher learnings and public end-user groups, enhance the repository with the integration of near real-time data, and enable hydrospatial end-user applications.

MSDIs are an embodiment and enabler of hydrospatial applications; harmonising and distributing marine and coastal spatial data and information to support a wide range of applications beyond safety and efficiency of navigation, such as marine and coastal spatial planning, marine science research and development, climate change research, and disaster response. 'Hydrospatial' is a new proposed branch of applied science to study the evolving marine and coastal spatial objects in the ocean and sea space, and how they are applied to serve agendas like a sustainable Blue Economy (Ponce, 2019; Hains, 2020). A key advantage of geospatial data is providing the geographical context to observations, likewise, hydrospatial data will emphasise the geography of the oceans and seas in the marine and coastal data and information acquired.

Using Singapore's national MSDI – GeoSpace-Sea – as a case study, this paper aims to, firstly, uncover the catalysts for the development of a national MSDI in this time, and secondly, describe key challenges an emerging national MSDI would confront in order to actualise the benefit of enabling and supporting hydrospatial end-user applications.

2. Why the need for GeoSpace-Sea for Singapore?

Maritime, marine and coastal activities have significant socio-economic impact to Singapore. The maritime industry alone contributes 7% of Singapore's Gross Domestic Product (GDP) and employs over 170,000 people (Maritime and Port Authority of Singapore, 2018). Located at the crossroads of major shipping routes, Singapore's sea space is one of the world's busiest. At any one time, there are about 1,000 vessels in the Singapore port and every 2 to 3 minutes, a ship arrives or leaves Singapore.

Despite the busy waters, Singapore's sea space is home to about a third of the world's hermatypic coral species and at least 994 marine intertidal species (Chou, et al., 2012; Lim, et al., 2020). In 2014, southern islands Small Sister's Island and Big Sister's Island, and the western reefs of St John's Island and *Pulau Tekukor*, were officially designated as Singapore's first Marine Park (Koh, 2015). Recently, Singapore also announced its expansion of aquaculture to the southern waters (Tan, 2020). Other uses and needs of Singapore's sea space include recreational activities and coastal development. In the future, Singapore residents could even be living in floating apartments (Paulo & Mak, 2019).

Singapore is not spared from the potential impacts of climate change and is at risk from more frequent and extreme rainfall events, storm surges, and sea level rise, which is projected to continue beyond 2100, even if global warming is limited to 1.5°C in the 21st century (*high confidence*) (National Environment Agency, 2018; IPCC, 2018). As a densely populated, low-lying, small island city-state with limited resources, sustainable development and science-based climate change adaptation and mitigation strategies continue to be a focal point of Singapore's story.

3. Catalysts of a national MSDI

While the benefits of MSDIs are endless, the implementation of government-led MSDIs have been geographically uneven due to challenges such as funding, political will and human capital. However, countries and governmental bodies have shown heightened interest in MSDIs, especially in recent years. This is evident from the growing IHO MSDI WG Member States' membership from 2008 to 2020 which has grown from 22 to 29. The total number of participants inclusive of Member States, IHO secretariat and expert contributors has also steadily increased from 14 in 2008, to 35 in 2019, and 58 in 2020.

Due to increased interests in the marine domain, the OGC in 2016 established a Marine Domain Working Group (OGC Marine DWG). With support from IHO Member States, the United Nations Global Geospatial Information Management Working Group on Marine Geospatial Information (UN-GGIM MGI WG) was also established in 2017 and held its inaugural face-to-face meeting in Busan, Republic of Korea, in 2019. Singapore's timely establishment of a national MSDI is in line with these positive international trends.

This section describes four catalysts that led to the establishment of GeoSpace-Sea: the changing ocean and seascape, regional and global agendas, the role of the national hydrographic office, and the advancements and availability of standards and frameworks.

3.1 Changing ocean and seascape

The changing local seascape coupled with threats of climate change impacts were drivers for Singapore's GeoSpace-Sea initiative. Our seascape involves diverse stakeholders that can be categorised to government, industry, academia and public users, and further broken down into diverse use-cases and activities (***Figure 1***). Although most of Singapore's sea space are port waters, with its expanding users and uses, policymakers recognised the need to move beyond port planning and to produce a more comprehensive marine spatial plan and integrated urban coastal zone management. Mr Khoo Teng Chye, Executive Director, Centre for Liveable Cities, highlighted that planning requires an inventory of historical and present information and Professor Lui Pao Chuen, adviser to the Ministry of National Development and National Research Foundation, supported that "GeoSpace-Sea would be the source for integrated knowledge-based planning and development of Singapore, and the instrument for the modelling of Singapore for various applications" (Maritime and Port Authority of Singapore, 2019b). The local scientists and community have also recommended, through 'The Singapore Blue Plan 2018', that a coordinated marine database for Singapore is required for the sustainable management of Singapore's sea space (Jaafar, et al., 2018)

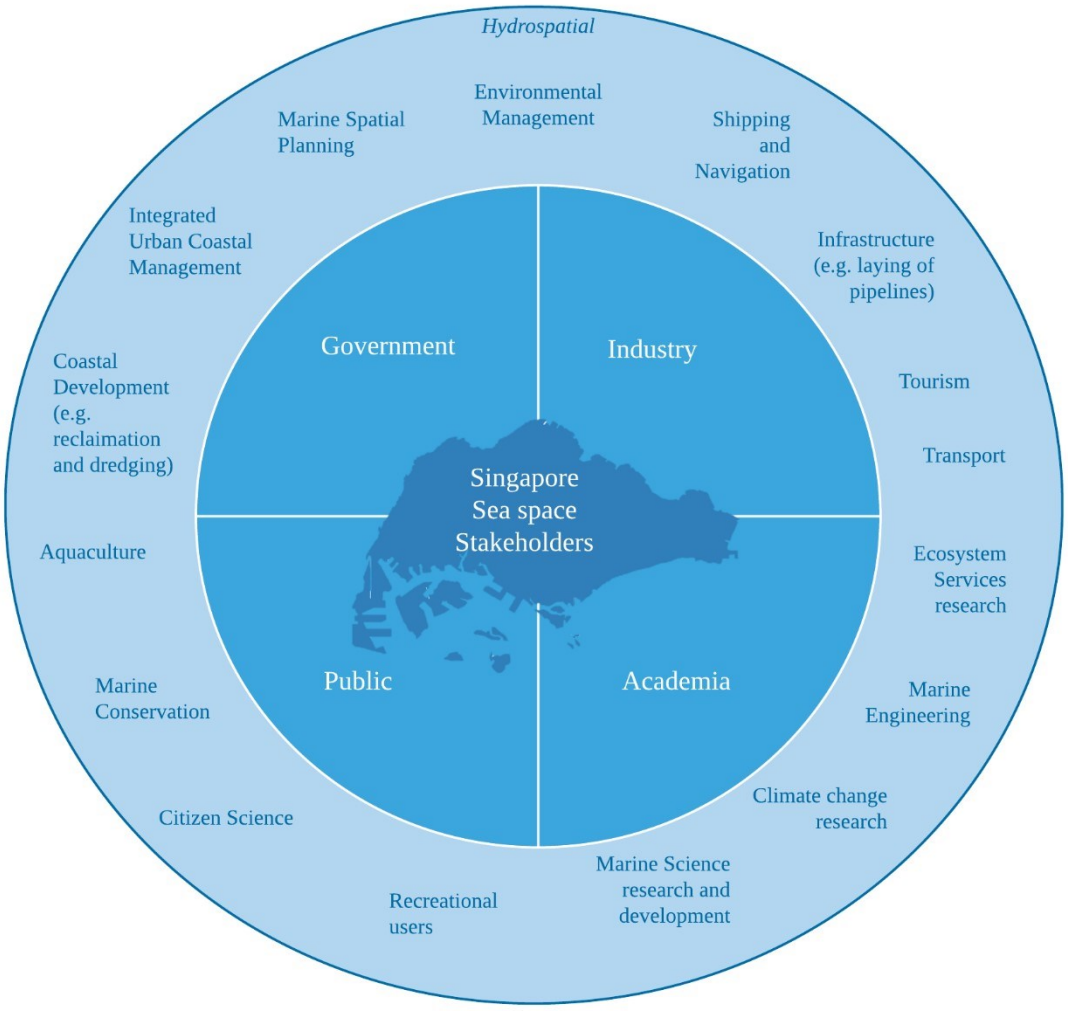

Figure 1: *Singapore's sea space stakeholders*

The threat and experience of climate change impacts were also push-factors for GeoSpace-Sea. Prolonged sea surface warming caused major coral bleaching events in 1998, 2010 and 2016 whereby 60% to 90% of surveyed corals were bleached (Chou, et al., 2019), and the absence of coral reefs could consequently have dire impact on ecosystem services such as food (fish) security (Friess, 2017). Furthermore, sea level rise and the more frequent and intense climate-change extreme events are expected to be a strong external physical stressor on Singapore's resilience (Chow, 2018). In the worst case scenario of 0.87m sea level rise, adaptation strategies (construction and maintenance) are projected to cost US$ 5.7 million and US$ 16.8 million by 2050 and 2100, respectively (Ng & Mendelsohn, 2005). Data is needed to study how local extreme events are related to global-scale climate change, monitor regional hydro-climate phenomena (e.g. ocean acidification, ocean warming and tropical cyclones) and local geographical changes (e.g. tidal heights and coastal development). Monitoring and understanding the risks of hydro-climate hazards, such as storm surge impacts, would contribute to the knowledge production chain and produce more robust science-based adaptation, mitigation and response strategies.

3.2 Regional and global agendas

Singapore's commitment to global agendas, such as the Paris Climate Agreement and United Nations (UN) 2030 Agenda, including the UN Decade of Ocean Science 2030 complemented by The Nippon Foundation-General Bathymetric Chart of the Oceans (GEBCO) Seabed 2030 Project, and membership to regional and international organisations, such as East Asia Hydrographic Commission (EAHC) and International Hydrographic Organization (IHO), were also catalysts to the establishment of GeoSpace-Sea.

The ocean is one giant conveyor belt of dynamic ocean currents, nutrients, including pollutants, therefore, global and regional action and data is required to address marine environmental management, especially for confined and busy waterways used for international navigation like the Singapore and Malacca Straits. GeoSpace-Sea is envisaged to ultimately contribute to the global marine and coastal data ecosystem for sustainable development. Singapore updated its climate pledge under the Paris Agreement and reaffirmed its commitment to the UN 2030 Agenda through a voluntary national review report at the UN High-Level Political Forum on Sustainable Development (Ministry of Foreign Affairs, 2018; Ministry of the Environment and Water Resources, 2019). The UN 2030 Agenda is a global development framework adopted by World Leaders, including Singapore, at the UN Sustainable Development Summit in September 2015. The 2030 Agenda comprises 17 Sustainable Development Goals (SDG). Open hydrographic and marine spatial information is expected to contribute to not only hydro-related SDG 14 (Life below water) and SDG 6 (Ensure availability and sustainable management of water and sanitation for all), but also others like SDG 13 (Climate action), SDG 11 (Sustainable Cities and Communities), and SDG 15 (Life on land).

Regionally, Singapore is also an active member of the EAHC MSDI WG which includes a total of 10 Member States and 1 observer from the region: Brunei Darussalam, China, DPRK, Japan, Indonesia, Malaysia, Philippines, Republic of Korea, Singapore, Thailand and Vietnam. One of EAHC MSDI WG's key tasks is to implement a regional EAHC MSDI in order to share and exchange marine spatial data.

A national MSDI is now almost necessary for countries to address, demonstrate and fulfil its regional and global commitments for sustainable development and climate action. The list of MSDIs have been growing and as of 31 March 2020, 66 MSDI/SDI portals, across 41 countries have been reportedly established (International Hydrographic Organization, 2020a).

3.3 The role of Singapore's hydrographic division

Hydrographic offices (HO) play an important role in driving the development of a national MSDI and in being national custodians of marine and coastal data. Having been an integral part of Singapore's marine and coastal spatial data life cycle, the MPA's Hydrographic Division is spearheading this national initiative. Over the years, the difficulties in ocean data acquisition, big 3D marine data processing and enabling marine GIS applications has diminished alongside advancements in technology and digitalisation of the hydrospace (Li & Saxena, 1993). Today, HOs like Singapore's which have been acquiring, processing and distributing navigational products have become valuable sources of high quality, long-term, fundamental marine and coastal spatial data such as bathymetry, coastline and tidal heights (International Hydrographic Organization, 2017a; Ponce, 2019). Being custodians of most of the fundamental marine and coastal data and having the experience of handling these spatial data formed the foundation of the GeoSpace-Sea initiative.

Before 2018, Singapore Hydrographic Division's role and core functions like many of HOs remained largely to support safety of life at sea (SOLAS): (1) conduct hydrographic surveys; (2) publication of nautical charts; (3) provide, install and maintain aids to navigation (Oei,1991).

However, the changing local, regional and global ocean and seascape has served as impetus for the Singapore's Hydrographic Division to expand its role and core functions.

In July 2018, the 'GeoSpace-Sea' section of Singapore's Hydrographic Department was set up to dedicate resources to the development of GeoSpace-Sea, and on 1 April 2019, the Hydrographic Division was upgraded to a Division. Presently, Singapore's Hydrographic Division consists of four departments: Survey, Cartographic, Aids to Navigation and GeoSpace-Sea. Its role now encompasses serving a wider range of applications and users beyond safety of navigation and mariners. Its additional functions include maintenance of data and marine GIS, namely Singapore's Integrated Hydrographic Management System (IHMS) and GeoSpace-Sea. By supporting safe navigation, and preventing collisions and oil spills, Singapore's Hydrographic Division has been protecting the marine environment (Oei, 2010), but it is now taking the next step to enable more to contribute to this mission.

In May 2020, the co-author and author accepted to join the volunteer "Hydrospatial Movement Club and Community (HMCC)", as the Asian Node; to be the voice of Hydrospatial as the foundation of any activity in the oceans, seas, lakes and rivers with emphasis on the Blue Economy for Sustainable Development.

3.4 Advancements and availability of standards and frameworks

The advancements and availability of MSDI standards and frameworks was also a driver for the timely establishing the GeoSpace-Sea. The IHO MSDI WG, OGC Marine DWG and UN-GGIM MGI WG have been providing technical guidance and standards on MSDIs and supporting the development of innovative solutions to MSDI challenges, most notably, data interoperability.

Frameworks are useful to establish and periodically assess the state of a national MSDI. MSDIs must be reliable in order to enable and support the broader hydrospatial context and its applications. Two complementary conceptual frameworks have been adopted for GeoSpace-Sea. The first, is the IHO MSDI WG recommended 'Four Pillars of MSDI': (1) Policy and Governance (People); (2) Technical Standards (Standards); (3) Geographic Content (Data); and (4) Information Systems (ICT) (***Figure 2***). The four pillars of MSDI have been useful in organising the resources required to establish and monitor the progress of GeoSpace-Sea.

Figure 2: *The Four Pillars of MSDI (International Hydrographic Organization, 2017b, p. 6)*

The second framework adopted is the UN-GGIM Integrated Geographic Information Framework (IGIF) and its nine strategic pathways, which could be useful particularly for long-term strategic plans (***Figure 3***). The four pillars of MSDI is complementary and can be easily mapped to the nine strategic pathways (***Table 1***). It is noteworthy that the 'innovation' centre puzzle piece is intended to be applied across all other pieces.

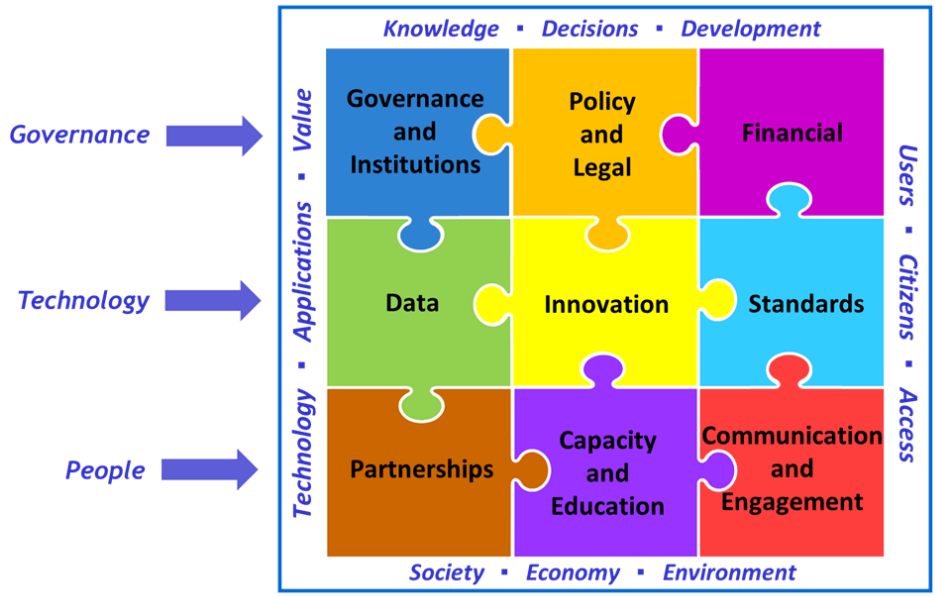

Figure 3: *UN-GGIM IGIF Nine Strategic Pathways (UN-GGIM, 2018, p. 21)*

Table 1: How the four pillars of MSDI and IGIF nine strategic pathways are complementary

The Four Pillars of MSDI	UN-GGIM IGIF Nine Strategic Pathways
Technical Standards (Standards)	Standards
Geographic Content (Data)	Data
Information Systems (ICT)	Innovation (particularly for ICT)
Policy and Governance (People)	Governance and Institutions Policy and Legal Financial Partnerships Capacity and Education Communication and Engagement

Open standards that MSDIs could adopt are also available to ensure data and system interoperability, for instance those approved by OGC. The marine and maritime community is currently working towards producing and implementing a suite of product specifications to promote data standardisation and interoperability for hydrospatial services such as e-navigation (***Table 2***). At present, it appears that MSDIs could be both at the receiving end and producers of these products. The adoption of these advancing common standards and technology could enhance the mission of MSDIs in enabling a wider range of hydrospatial applications.

Table 2: List of Planned Marine Data Product Specifications (International Hydrographic Organization, 2020b)

Organisation In-charge	Product Specification Series	Planned Product Specifications
International Hydrographic Organization (IHO)	S-1xx	S-101 Electronic Navigational Chart (ENC) S-102 Bathymetric Surface S-103 Sub-surface Navigation S-104 Water Level Information for Surface Navigation S-111 Surface Currents S-112 Open - (See Decision HSSC9/38) S-121 Maritime Limits and Boundaries S-122 Marine Protected Areas S-123 Marine Radio Services S-124 Navigational Warnings S-125 Marine Navigational Services S-126 Marine Physical Environment S-127 Marine Traffic Management S-128 Catalogue of Nautical Products S-129 Under Keel Clearance Management (UKCM)
International Association of Light Authorities (IALA)	S-2xx	S-201 Aids to Navigation Information S-210 Inter-VTS Exchange Format S-211 Port Call Message Format S-230 Application Specific Messages S-240 DGNSS Station Almanac S-245 eLoran ASF Data S-246 eLoran Station Almanac S-247 Differential eLoran Reference Station Almanac
Intergovernmental Oceano-graphic Commission (IOC)	S-3xx	None proposed yet
Inland ENC Harmonization Group (IEHG)	S-401 to S-402	S-401 IEHG Inland ENC S-402 IEHG Bathymetric Inland ENC
Joint Technical Commission for Oceanography and Marine Meteorology (WMO/IOC JCOMM)	S-411 to S-421	S-411 JCOMM Ice Information S-412 JCOMM Weather Overlay S-413 Weather and Wave Conditions S-414 Weather and Wave Observations
International Electrotechnical Commission - Technical Committee 80 (IEC-TC80) Numbers	S-421 to S-430	S-421 Rout Exchange Format

4. MSDIs enabling hydrospatial context and applications

The MSDI road map does not stop at implementing policies, infrastructure and a portal for data consolidation, harmonisation and access. The process of actualising its anticipated benefits; enabling and supporting the hydrospatial context and wide-range of applications, poses another set of challenges MSDIs have to address. This section identifies and describes three key challenges GeoSpace-Sea has and would continue to confront in order to enable and support hydrospatial context and applications such as climate change research, marine spatial planning, coastal zone management, environmental impact assessments, incident reporting, environmental management, or maritime automated surface ships.

4.1 Partnerships

MSDI is a coordinated effort to collect, integrate, use and re-use marine and coastal spatial data. In order to establish and sustain the data lake of MSDIs, partnerships play a pivotal role in securing data sources and channels. Arguably, the biggest challenge of establishing GeoSpace-Sea was neither a technical one nor about data availability, it was about building partnerships and sharing of common goals. These partnerships extended across the national, regional and international scales. However, in order to enable and support hydrospatial context and applications, these partnerships would need to be sustainable, developmental and diversified.

At the national scale, a user-centric approach was adopted in the development of GeoSpace-Sea. A governance structure involving a steering committee, working committee and two technical committees were set up to support decision and policymaking. In its initial stages, an end-user application exercise was conducted between the government agencies to map out stakeholder user needs and commitment (***Figure 4***). Representatives from government agencies listed end-user applications and the data or resources required. At the same time, they stated data or resources they could offer to the rest of the stakeholders. The inputs were mapped and the outputs of the exercise were: (1) a base data inventory of data required and can be made accessible, and (2) a wish list of data that were presently neither available nor accessible. Ultimately, MSDI is a balancing act between user needs and concerns about data exchange and sharing, and its role is to maximise each user group's mission without compromising the strategic interest of another. An end-user application exercise makes this decision-making process transparent.

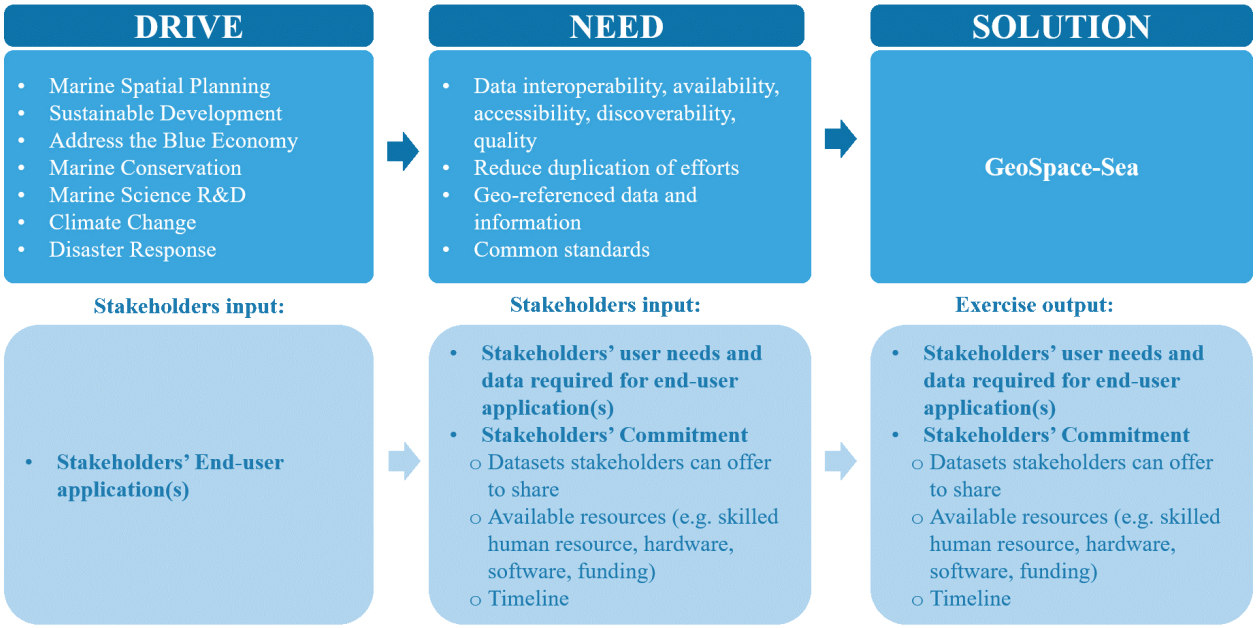

Figure 4: *GeoSpace-Sea end-user application exercise overview*

Apart from the technological infrastructure that has brought data together, GeoSpace-Sea has also formed a network of local sea space stakeholders. This network is expected to grow and become more diverse as GeoSpace-Sea continues engaging various groups and enabling more hydrospatial applications. The GeoSpace-Sea committees notably include representatives from academia too, and the stakeholder group would likely expand in the next phase which aims to create access for academia and public end-user groups. Government-academic-industry

partnerships have notable benefits of improving the quality of marine science research and development, increasing the efficiency of translating standards into industry-ready technologies or products, and potentially bridging the science and policy gap.

Partnerships beyond national scale are also required to build a regional and global marine and coastal data ecosystem. In its mission to promote safe navigation, the importance of international cooperation and exchange of best practices has been entrenched in the international hydrographic community. Since 2007, these principles have been extended to the IHO MSDI WG. IHO MSDI WG and regional MSDI working groups, such as the EAHC MSDI WG, have annual meetings to build these partnerships. At the meetings, sharing of national reports and discussions on common standards foster these connections.

4.2 Authoritative data and metadata

With data flows secured, another challenge is how MSDIs define and maintain the "authoritativeness" and quality of data for the hydrospatial context and wide range of applications it intends to enable and support. MSDIs, including GeoSpace-Sea, aim to promote the use and re-use of "authoritative" marine and coastal data. Authoritative data is often understood as data obtained with "formal quality assurance procedures", and traditionally, government agencies and reputable mapping companies have been sources of these data (Du, et al., 2016, p. 1). Presently, GeoSpace-Sea's base data inventory includes authoritative hydrographic, coastal geography, environmental, species distribution and habitat, meteorological and infrastructure data from government sources.

A dataset's quality can be assessed for either its internal characteristics (i.e. internal quality) or its 'fitness for use' (i.e. external quality). Typically, standardisation bodies develop internal quality assessments that consists of five to eight parameters, and users take these parameters to assess if the data is fit for use or purpose (Devillers, et al., 2005):

- Lineage/Source
- Spatial/Positional Accuracy
- Attribute Accuracy
- Semantic Accuracy
- Thematic Accuracy
- Completeness
- Logical Consistency
- Temporal Information/Accuracy.

HOs will be familiar with the production and distribution of authoritative data and information through Electronic Navigational Charts (ENCs) and paper nautical charts. For the production of these products, most marine GIS are equipped with IHO S-58 validation tools and marine cartographers are trained to ensure data quality from a mariner's perspective and for safe navigation. There are acceptable inaccuracies of data in charts, for instance, the generalisation of depth contours on the "safe side". For effective communication, spatial data and information are representations of reality, and are only as accurate as the elements selected to represent it. However, assessing data quality and 'fit for purpose' from a MSDI perspective is difficult because the use-cases and users are intentionally broad and diverse.

Instead of ensuring data is fit for purpose, MSDIs can focus on ensuring internal data quality is up to date. If the MSDI policy entails that data's 'fit for purpose'-ness should be determined by users, MSDIs have the responsibility of providing good quality and up-to-date metadata to support users' in this decision-making process. GeoSpace-Sea's metadata is aligned with its terrestrial

counterpart and both systems adopt a national 'GeospatialSG Data Standards' framework that is based on ISO 19100 standards.

In the near future, MSDIs may also have to consider the "authoritativeness" of crowd-sourced data. The data collected through volunteer GIS, mobile applications or as a bi-product of other processes could contribute to policy-making (Goodchild, 2007; Du, et al., 2016). For instance, as a bi-product of shipping and navigation, crowd-sourced bathymetry data are being contributed to The Nippon Foundation-GEBCO Seabed 2030 Project. There are also researcher-validated crowd-sourced biodiversity records, such as those in the 'Wild book for Whale Sharks' available in the International Union for Conservation of Nature (IUCN) open-source database (Morales-Ramirez & Pang, 2018). GeoSpace-Sea could also in future consider incorporating researcher-validated citizen science biodiversity records. These data, albeit not from traditional sources of authoritative data, could meet a data quality criterion and be approved for sharing in MSDIs.

4.3 Funding and operational sustainability

A MSDI questionnaire completed by IHO Member States revealed that majority of MSDIs are funded by 'task of an organisation'. The ownership and willingness to fund MSDIs is a recognition of the benefits of MSDIs, however, it is important to quantify its benefits, and translate them into cost-benefit analysis so as to justify its longer-term funding and operational sustainability. To enable and support the hydrospatial context and various applications, the MSDI itself needs to be sustainable and reliable.

While the direct costs of MSDIs and, fundamentally, sharing of open data could be justified with qualitative potential benefits (Johnson, et al., 2017), quantification of potential and actualised benefits is a challenge to overcome. These benefits include operational cost-savings, such as reduction in duplication of data collection and improved decision-making, and socio-economic and environmental benefits both in the short term and long term. Griffin, Coote and Crompvoets (2019) found that direct costs of MSDIs could result in a net benefit; for every US dollar invested, it is predicted that 2 to 18 US dollars would be returned. However, the authors also highlighted that these are projected figures and the evaluation of the actual effectiveness of MSDIs remain a knowledge gap.

Data being the currency of MSDI has value and MSDI could become a source of revenue too. Value-added data could be produced in the process of harmonising data from various sources. Encouraging the re-use of data also serves to maximise the lifespan of data collected and enhances its value when a wider range of applications depend on it. The higher value of this data eventually asserts the mandate of the data source and its acquiring cost (Garavelli, 2018). The United Kingdom (UK) Hydrographic Office Admiralty Marine Data Portal has 'paid Admiralty data services' which currently includes five data layers: 'offshore infrastructure', 'Vertical Offshore Reference Frames (VORF)', 'wrecks and obstructions', 'seabed composition' and 'HMNAO Astronomical and Calendar Information' (UK Hydrographic Office, 2019). In order to do so, pricing mechanisms and models are required to quantify and assign a monetary value to data, possibly by the 'age' of the dataset or the 'demand' for it.

5. Conclusion: Looking ahead

This paper has described the four catalysts that led to the establishment of Singapore's GeoSpace-Sea. It has also identified three key challenges that an emerging national MSDI may confront in the process of actualising its envisaged benefits. Catalysts and ease of establishing a national MSDI could vary over time and space depending on the country's funding priorities and the spatial data policies enacted. For instance, countries without an open geospatial data policy

or with restricted funding opportunities may have to seek more commercially driven catalysts. This is especially so with the economic impacts arising from the global pandemic, funding could surface as a more immediate challenge in the establishment of a national MSDI.

Similarly, MSDIs could face additional challenges in enabling hydrospatial context and applications depending on its maturity. For example, mature MSDIs may be required to upgrade and be kept up to date with the latest S-100, S-200, S-300 and S-400 standards. There are various challenges in implementing these standards that would involve standards organisations who are producing these standards, the industry translating these standards into operational tools for production, and the HOs which must seek an opportune time and source of funding to upgrade the specifications of their MSDI. For HO-led MSDIs, partnerships remain essential in the implementation of these S-100 product standards too because the process could involve transforming data and workflows beyond the hydrographic domain. Looking ahead, identifying MSDI-relevant product specifications, an implementation roadmap for MSDI and continued exchange of tangible benefits from MSDIs to justify investments would be needed.

In an increasingly digital hydrospace, MSDIs would foreseeably continue to play a key role in unlocking the value of hydrospatial data, and reveal insights through data integration, hydrospatial analysis and applications. To sustain MSDIs and enable it to support the hydrospatial context and wide-range of applications in the medium and long-run require integrated hydrospatial (geospatial) information management that strategically considers data, metadata, people (partnerships and capacity building), governance, and how to exploit opportunities arising from present crises and disruptive future technological and non-technological trends, for instance, Artificial Intelligence (AI) and the demand for digitalisation. Ultimately, when national MSDIs, regional MSDIs and other domain SDIs agree to better cooperation and collaboration on data sharing and exchange, we could develop and visualise a more holistic view of water movements and impact on our earth. This would enable functions akin to the development of a time machine where users can dynamically and more accurately model the past, present and future. In other words, we could be more proactive than reactive in managing our marine environment.

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