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Open Geospatial Consortium

OGC FEDERATED MARINE SPATIAL DATA INFRASTRUCTURE PILOT 2023 - CONNECTING LAND AND SEA FOR GLOBAL AWARENESS

ENGINEERING REPORT

PUBLISHED

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I EXECUTIVE SUMMARY

Rising sea levels together with increasing storm surges are amongst the most challenging issues for coastal communities in the context of global warming. The retreating ice sheets of the Circumpolar Arctic are a key contributor to sea level rise with consequences felt around the world.

The Federated Marine Spatial Data Infrastructure (FMSDI) initiative is a key component of OGC and the Marine Domain Working Group. The program is designed to engage with stakeholders from the marine dataspace to identify opportunities to assist, improve, and scale out core business processes complemented by the OGC suite of standards and best practices. The FMSDI-2023 pilot represents the fourth phase of the program with a focus on the interface between land and sea. A primary goal of this pilot is to advance the FMSDI concept to increasing threats posed by climate change.

The project is divided into three threads, each with application to distinct geographies.

- **Thread 1: Digital Twin of Land and Sea Interfaces — Singapore**

With approximately 30% of Singapore's land mass being less than 5m above sea level, the seamless integration of land and marine data is integral to Singapore's focus on coastal protection and climate resilience. The management of land and water is separated organizationally between the Singapore Land Authority (SLA) and the Maritime & Port Authority (MPA), respectively. Each agency is responsible for data assets specific to their jurisdiction presenting a challenge for cross-organizational concerns. This theme addresses the geospatial integration requirements through the development of a multi-dimensional Digital Twin of the Singapore coastline.

- **Thread 2: Digital Arctic Connecting Land and Sea — Canada**

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This thread addresses the data integration issues in the
context of Digital Twins for the Canadian Arctic. With the
loss of sea ice, continuing ocean warming, stronger winds
and currents, and accelerated shoreline erosion affecting
Arctic communities, efficient data usage and analysis is of
the utmost importance for Canada.
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Figure 1

- **Thread 3: Integrating Land & Sea for Various Use Cases — Caribbean**

This thread investigates how data developed primarily for navigation at sea can be used to better understand the opportunities in the Caribbean to support local capacity building and the application of marine data in expanded sea-land contexts.

Approach

The FMSDI 2023 pilot is managed through the OGC Collaborative Solutions and Innovation (COSI) Program. Each thread is a distinct project with a set of participants tackling specific use cases and scenarios important to the respective project sponsor.

Weekly project meetings are scheduled to encourage collaboration between the participants and sponsors and provide checkpoints to ensure the project scope meets the sponsor's expectations.

The FMSDI 2023 pilot also features a series of persistent demonstrators as one of its outputs. These demonstrators are workflows and applications that stakeholders can access for outreach, testing, and experimentation purposes. The demonstrators will be available even after the project is completed and are therefore referenced as persistent, but will only be available until December 2024. These demonstrators showcase how geospatial data can be used in an operational context or highlight the gaps in the resources available online, including data sources, metadata, access processes, and standards. As each participant has a unique solution platform, each has taken different approaches, all of which are available for review by stakeholders. Security concerns, such as authentication and authorization, are unique to each participant and have been communicated to stakeholders and participant contacts. For further details and access to the demonstrators, please refer to the link provided.

Common across the three threads is the application of the OGC FAIR principles — Findable, Accessible, Interoperable, and Reusable. Underpinning the use of the FAIR principles is the role of the core OGC Standards and Best Practices. Previous work products related to FMSDI form the core information model while the OGC standards, enhanced through the alignment and support of industry standards such as the IHO S-100 standard, address many of the requirements central to each thread.

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II KEYWORDS

The following are keywords to be used by search engines and document catalogues.

marine, msdi, marineDWG, climate, coastal resilience

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IV

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Maritime and Port Authority of Singapore (MPA)

Singapore Land Authority (SLA)

Natural Resources Canada (NRCan)

National Oceanic and Atmospheric Administration (NOAA)

UK Hydrographic Office (UKHO)

V

TERMS AND DEFINITIONS

Albedo	a reflection coefficient that describes the reflecting power of a surface
Data Cube	a multi-dimensional (“n-D”) array of values. Typically used in contexts where these arrays are massively larger than the hosting computer’s main memory
FAIR Climate Service	Climate resilience information system where the entire architecture is following FAIR principles

FAIR principles[1]	The approach of making digital assets Findable, Accessible, Interoperable, and Reusable.

Abbreviated terms

ArcticSDI	Arctic Spatial Data Infrastructure
ARD	Analysis Ready Dataset
AMSR	Advanced Microwave Scanning Radiometer
API	Application Programming Interface
ARD	Analysis Ready Dataset
ARDC	Analysis Ready Data Cube
ATLAS	Advanced Topographic Laser Altimeter System
C3S	Copernicus Climate Change Service
CAFF	Conservation of Arctic Flora and Fauna
CARRA	Copernicus Arctic Regional Reanalysis
CCI	Climate Change Initiative
CDR	Climate Data Record
CDS	Climate Data Store
CEOS	Committee on Earth Observation Satellites
CF	Climate and Forecast
CKAN	Comprehensive Knowledge Archive Network
CMIP	Coupled Model Intercomparison Project
COG	Cloud Optimized GeoTIFF
CRIS	Climate Resilience Information System
CSV	Comma-Separated Values

[1]further reading: https://www.go-fair.org/fair-principles/

CSW	Catalog Services for the Web
CWIC	CEOS WGISS Integrated Catalog
DEM	Digital Elevation Model
DGGS	Discrete Global Grid System
DTM	Digital Terrain Model
DWG	Domain Working Group
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EDR	Environmental Data Retrieval
EO	Earth Observation
EPSG	European Petroleum Survey Group
ER	Engineering Report
ERA5	fifth generation ECMWF atmospheric reanalysis of the global climate
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAIR	Findable, Accessible, Interoperable, Reusable
GADM	Database of Global Administrative Areas
GDAL	Geospatial Data Abstraction Library
GeoBON	Group on Earth Observations Biodiversity Observation Network
GDC	Geospatial Data Cube
GML	Geography Markup Language
GRIB	General Regularly-distributed Information in Binary form
HDF	Hierarchical Data Format
ICESAT-2	Ice, Cloud and Land Elevation Satellite
IGIF-H	Integrated Geospatial Information Framework — Hydro
IHO	International Hydrographic Organization

IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
ML/AI	Machine Learning / Artificial Intelligence
MPA	Maritime & Port Authority
MSDI	Marine Spatial Data Infrastructure
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NRCan	Natural Resources Canada
NSIDC	National Snow & Ice Data Center
OECD	Organization of Economic Cooperation and Development
OGC	Open Geospatial Consortium
OMSv3	OGC Observations, Measurements & Samples version 3.0
OPeNDAP	Open-source Project for a Network Data Access Protocol
OSM	OpenStreetMap
PAHO	Pan American Health Organization
PAME	Protected Areas of the Marine Environment
QGIS	Quantum Geographic Information System
RCI	Regional Climate Indicator
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
REST	Representational State Transfer

S3	Simple Storage Service
SDG	Sustainable Development Goal
SLA	Singapore Land Authority
STAC	SpatioTemporal Asset Catalogs
TIE	Technical Interoperability Experiments
UKHO	United Kingdom Hydrographic Office
UN-FCCC	United Nations Framework Convention on Climate Change
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
USGS	United States Geological Survey
WCS	Web Coverage Service
WCPS	Web Coverage Processing Service
WFS	Web Feature Service
WG Climate	Joint Working Group on Climate
WGISS	Working Group on Information Systems and Services
WMO	World Health Organization
WMS	Web Map Service
WMTS	Web Map Tile Service
WPS	Web Processing Service
XML	Extensible Markup Language

1 INTRODUCTION

1 INTRODUCTION

The FMSDI 2023 pilot focuses on the coastal domain representing arguably the most important realm on which billions of people depend each day. Yet, as a result of climate change, marine pollution, and population growth, coastlines around the world are being transformed through habitat loss, sea level rise, and a significant increase in micro-plastics entering local food chains.

A major challenge for all stakeholders with an interest in coastal environments is quantifying the rate of change to the environment affecting dependent ecosystem services. In the Arctic, important factors include identifying the rapidly changing characteristics of sea ice, anticipating the consequences of rising temperatures, changing habitats and biodiversity loss, and predicting the rate of thaw of permafrost with its diminishing role sequestering global greenhouse gases.

For the Caribbean, recent major weather events highlight the susceptibility of this region to warming oceans. Island economies are especially dependent on the ecosystem services provided by its coastal zones while coastal erosion poses a significant threat to local populations. Coastal and marine policies designed to mitigate the effects of climate change are impacted by a lack of extensive data connecting the coastal environment with the needs of stakeholders.

Singapore connects the major shipping routes of Southeast Asia and hosts one of the world's busiest seaports. Singapore is also one of the lowest-lying island countries with most of the island extending no more than 15m above sea level. As a result, Singapore is particularly susceptible to sea level rise, storm surge, and major coastal weather events. With a highly developed coastline, identifying the risk levels associated with coastal inundation is of the highest priority.

1.1. The role of the pilot

The FMSDI 2023 pilot is expressly designed to evaluate the key features and benefits of a standards-based approach to data discovery and application in support of stakeholders vested in the changing coastal environments of the Canadian Arctic, the Caribbean islands, and the Republic of Singapore. Of keen interest is the integration of distinct data products in a manner representing the coastal environment as a seamless transition from the ocean floor to the land surface. This transitional realm has its own unique organization and function as host to critical habitat and/or essential ecosystem services serving the needs of coastal communities.

One of the compelling challenges of this work is to overcome the disparity between marine and terrestrial data systems and define a digital twin representation of the coastal environment improving the 'time to decision' for stakeholders.

The FMSDI 2023 project required each participant to create persistent demonstrators. These demonstrators are essentially workflows and applications that can be accessed by stakeholders for outreach, testing, and experimentation purposes and made available until December 2024. Each persistent demonstrator resulting from this pilot has unique characteristics. Some demonstrate how geospatial data and information can be used in an operational context, while others showcase what is currently possible and what gaps exist with the resources that can be discovered on the internet. The demonstrators include various data sources, metadata, access processes to online data, and various standards used for data discovery, access, and processing interfaces. Due to the different solution platforms of each participant, various approaches were made available for review by stakeholders. Issues such as security (authentication and authorization) are unique to each participant and details are provided through outreach to stakeholders and participant contacts.

2

THREAD 1: DIGITAL TWIN OF LAND & SEA – SINGAPORE

2 THREAD 1: DIGITAL TWIN OF LAND & SEA — SINGAPORE

Singapore is an island-country with an industrialized coastline of roughly 131km with no point more than 15km from the coast. As a result, Singapore is extremely vulnerable to severe coastal events and, as such, maintains an extensive system of land-use and observation networks.

The Singapore Land Authority (SLA) is responsible for the effective use of land resources in support of the economic and social development of Singapore. As the gatekeeper of Singapore's land use, SLA focuses on the following three core principles.

- Developmental — the optimization of state land and properties
- Regulatory — registration and management of land and property transactions as a guarantor of all property rights
- Geospatial — development of the geospatial management strategy

Underpinning the core principles, the Survey & Geomatics Division is charged to uphold the national geospatial infrastructure for Singapore. The survey division maintains the national coordinate reference system and underlying control points while providing the GNSS Continuously Operating Reference System (CORS) infrastructure for positioning services.

Singapore's Maritime & Port Authority (MPA) acts as the central agency responsible for assuring the operational efficiencies of Singapore as a premier global port of call. Additionally, the Singapore MPA safeguards Singapore's strategic maritime interests with representation within the International Hydrographic Office (IHO) and the International Maritime Office (IMO). To facilitate these operational and strategic interests, MPA maintains Singapore's national MSDI platform — GeoSpace-sea — a single integrated platform providing seamless access to authoritative marine and coastal spatial data products. The platform serves the needs of a diverse set of stakeholders ranging from the sea port operations, shipping and navigation, marine biodiversity, submarine infrastructure, and waterfront use, including recreation and tourism.

Aside from the operational requirements for SLA and MPA, integration of the terrestrial, maritime, and cadastral data products is a priority for Singapore in its role within the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM). The development of a digital twin modeling Singapore's coastal area is integral to Singapore's commitment to meeting the UN's Sustainable Development Goals (SDG). Singapore is in a unique situation balancing the needs of continued economic development with the social and environmental constraints addressing food security, biodiversity protection, and a transition to clean energy. By integrating the national mapping, hydrographic surveys, and cadastral rights database with advanced systems and technologies, Singapore is well on its way to meet its strategic plan "Limited Land — Unlimited Space".

Key to this strategy is its investment in developing the vertical space *below* and *above* its land surface. Changes to the State Lands Act and Land Acquisition Act allow for the development of industrial spaces 30m below ground level (“Clarification of extent of underground ownership”). This change requires SLA to move from a 2D Cadastre model of its land registry to a 3D Cadastre model using the *Singapore Height Datum* (SHD) as its base vertical reference.

Integration between Land & Sea — Vertical Datum Relationships

The Singapore Height Datum is derived from the localized Mean Sea Level calibrated against a tide gauge previously located at Singapore’s Victoria Dock [1935-1937].

Figure 2 — Victoria Dock, Singapore - circa 1935

This vertical datum is the baseline for Singapore’s extensive *precise levelling network* and provides a common reference point for integration with Singapore’s bathymetric profile. Singapore’s multi-beam bathymetric surveys are based off the *Admiralty Chart Datum* which is offset from the Singapore Height Datum by a fixed vertical distance of ~1.56m. As a result, the bathymetry data product provided by MPA is adjusted by this vertical distance to align with the SLA provided terrain model.

A detailed review of the datum relationships and issues encountered processing the SLA terrain model is provided in Annex A.

2.1. Contributions

The following table summarizes the contributions of each Participant. Details for each contribution are provided in subsequent sections.

Table 1 — Singapore Theme Participant Contributions

ORGANIZATION	DELIVERABLE	SCENARIO
Wuhan University	D111	Analysis-Ready Datasets for Predictive Visualization of Storm Surge Events
Geomatys	D112	A Digital Twin framework for Advanced Visualization of Storm Surge Events
Ecere	D113	Modelling Storm Surge via a Multi-dimensional Geospatial Data Cube
Compusult	D114	Flood Modelling & Emergency Preparedness

2.1.1. D111: Analysis-Ready Datasets for Predictive Visualization of Storm Surge Events

The ongoing escalation of global climate change presents a significant challenge for Singapore, a coastal city-state surrounded by the sea on all sides. Greenhouse gas emissions are causing global warming, polar ice melting, and sea-level rise at an accelerated pace. Frequent extreme weather events, such as hurricanes and storms, further intensify the risk of coastal erosion. Consequently, there is a need to rely on sensor data and spatial analysis techniques to effectively assess potential risks and implement mitigation measures.

Background

Wuhan University (WHU) plays a role in researching and teaching all aspects of surveying and mapping, remote sensing, photogrammetry, and geospatial information sciences in China. The School of Remote Sensing and Information Engineering, WHU, is a university research center dedicated to developing standard-based geospatial information technology for applications in Earth science with a focus on geospatial interoperability, geoprocessing, disaster responses, and Machine Learning.

This project demonstrator extends previous work products integrating heterogeneous EO data for flood warning and impact assessment in storm analysis in Hainan Province, China. An assessment client that covers data discovery, integration, processing, and visualization is configured for the Singapore use-case. Refined models and methods are used for developing a demonstration client focusing on the analysis and visualization of storm surge data, addressing potential risks and assessing the impact of storm events.

2.1.1.1. Approach

The focus of this work product involves the following three major deliverables.

- **Integration of DTM and Marine Depth Data**

The first goal of this project involves integrating the digital terrain model for the research area in Singapore with marine depth data to establish a consistent elevation reference.

- **Data Integration and Management with GeoDataCube**

The second goal is to consolidate and manage data from various sources effectively. This will be achieved by utilizing the GeoDataCube framework to ensure data synergy and maintainability.

- **Simulation of Sea-Level Rise**

In the final goal, a flood model simulation tool is used to explore the potential range of coastal inundation resulting from sea-level rise. This step provides stakeholders with a view towards mitigating the challenges posed by rising sea levels.

The solution aims to provide a visual reference tool for coastal regions facing challenges from rising sea levels and coastal inundation due to global warming, natural disasters, and related factors. These organizations are eager to gain a clear understanding of the potential impacts on their communities, infrastructure, and residents as sea levels gradually rise and encroach upon critical infrastructure. The solution addresses this need by transforming complex data into intuitive visualizations, enabling users to vividly comprehend the potential scenarios that may unfold.

Against this background, the demonstrator platform is used to analyze various data related to sea level rise. The potential impact areas under different sea level rise scenarios are based on appropriate models and used to visualize coastal inundation providing decision-makers with a better understanding of possible consequences and challenges with appropriate measures to mitigate risk.

2.1.1.2. Solution Architecture

The project solution is based on the WHU implementation of the OGC GeoDataCube model extended to achieve the seamless integration of multi-dimensional datasets. The GeoDataCube framework represents the central data repository populated using an integration pipeline to successfully load and transform data from multiple sources, ensuring the unified management and analysis of data.

The WHU GeoDataCube schema comprises four fundamental dimensions: product, space, time, and variables. Within the product dimension, essential information is provided for each dataset, including the product name, data type, sensor, and satellite platform. Product names act as the primary data identifiers, usually combining data source and product type, while data types distinguish between raster and vector data. The spatial dimension employs a series of rule-based grids to precisely describe spatial location information, guaranteeing accurate geospatial referencing of the data. The temporal dimension encompasses the data acquisition time and the employed time standards, supporting the meticulous management and analysis of time-series data. The variable dimension directs attention to the granularity of raster data, facilitating the specific description of various variable attributes within remote sensing imagery, such as rainfall, temperature, and wind speed.

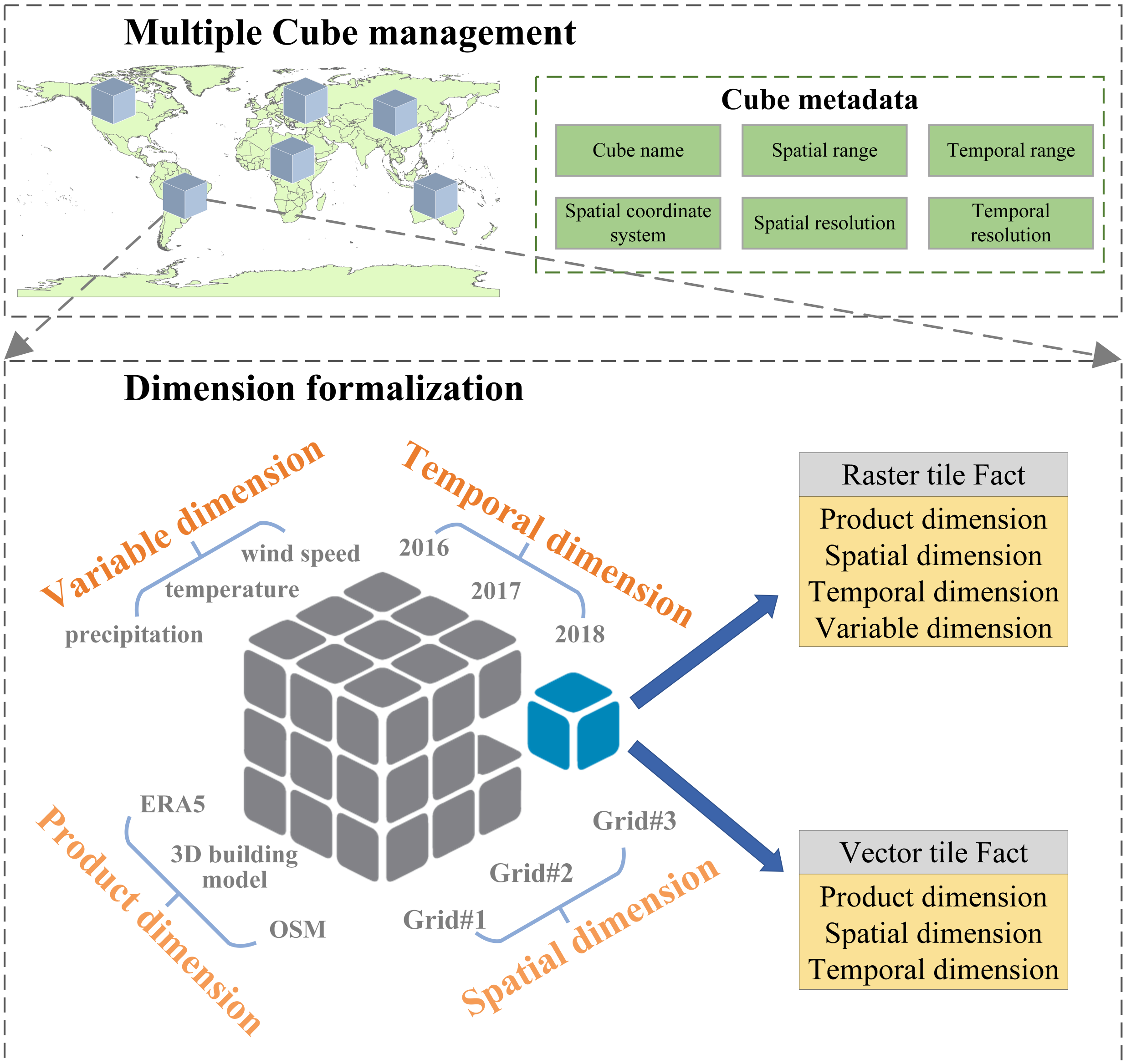


Figure 3 — WHU GeoDataCube Architecture

The WHU GeoDataCube provides a unified framework that maps raster and vector data to a common grid reference system, facilitating mapping relationships across diverse spatial data sources. It enables multi-dimensional and Spatial OLAP exploration of geospatial data. Within this framework, data is organized into tiles, which come in two main types: raster tiles, formed by physically partitioning raster data, and vector tiles, created by logically partitioning vector data.

SLA/MPA Ingestion Pipeline

The project deliverable focuses on the data transformation pipeline incorporating the SLA Digital Terrain Model with the MPA bathymetric model to produce a seamless georeferenced view of Singapore's coastal area. In the integration process of the land terrestrial data and ocean bathymetry data, the following adjustments are applied.
⇒ a basic transformation is applied to the bathymetry data to adjust its pixel values to positive values for compatibility with terrestrial data.
⇒ the bathymetry data is matched with the terrestrial data to identify overlapping areas, which were then resampled.
⇒ bathymetry data is re-fitted to the reference plane of the terrestrial data to ensure alignment with the reference plane of the land data.

This workflow generates the final image output completing the integration of the two datasets.

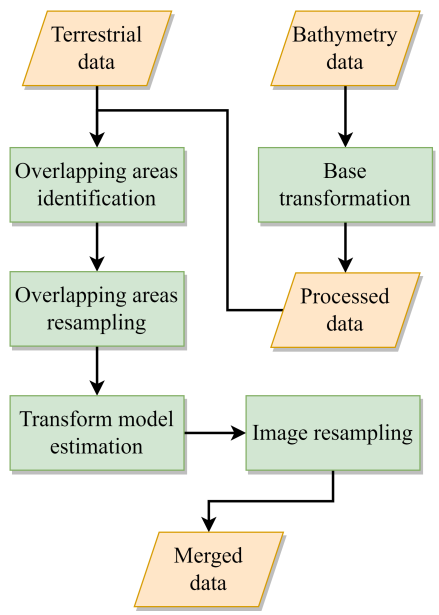


Figure 4 — Integration workflow for DTM and Bathymetry

In simulating the process of coastal inundation and inland erosion due to rising sea levels, the flood model aims to determine a set of grid cells that meet predefined water level conditions while satisfying geographical connectivity requirements. These grid cells constitute the desired flooded area. Grid cells that do not meet the geographical connectivity requirements, even if they meet the water level conditions, are excluded from the collection.

The core steps of the model are based on a specified water level threshold. The ocean side is considered the source of flooding and the model simulates the spread of water in four directions across the grid cells to identify grid cells with water levels below the given threshold and connected to the ocean. These grid cells are designated as the flooded area and are colored blue to represent the inundation extent. The workflow of the model is illustrated in the diagram below.

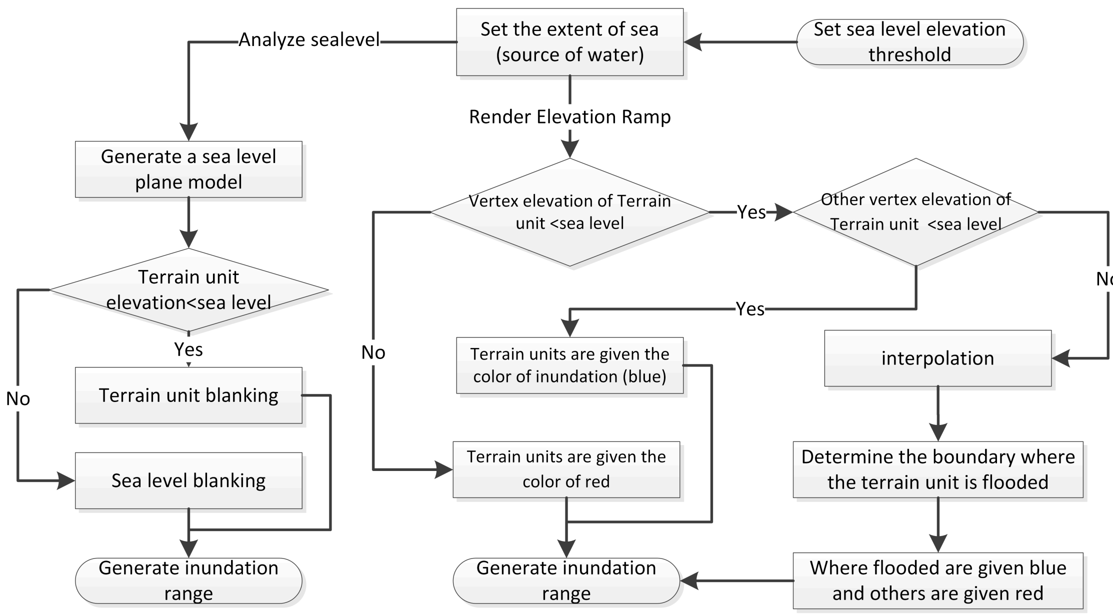


Figure 5 — Flood model simulation workflow

The resulting transformation is published as an analysis-ready dataset (ARD) modeled as a multi-source isomerized cube providing operations such as reprojection and resampling. Attribute data and metadata reside in relational databases while original vector and raster data are stored in non-relational databases and distributed file systems.

A data service module provides a standardized view of the ARD through the effective use of OGC APIs — Features and Coverages. This service endpoint facilitates the access and management of geospatial data and analysis services.

3D Visualization and Interactive Operations on the OGE Platform

The WHU Open Geospatial Engine (OGE) provides three-dimensional data visualization enabling a user-friendly interactive workflow to explore and analyze data.

Temporal Coverage

On April 17-18, 2021, Singapore was hit by heavy rainfall. To accurately reflect this time period of interest, the WHU platform ingested data based on the temporal period of April 1 to May 31, 2021.

Data and Platforms

The WHU GeoDataCube is composed of data integrated from the ERA5 land daily mean temperature and precipitation data from April to May 2021; temperature, precipitation, and wind speed data from Singapore's meteorological stations; terrain data derived from the SLA-provided CityGML TINRelief feature model; and marine depth data from MPA.

- **ECMWF ERA5_hourly_data_on_single_levels_from_1940_to_present_Reanalysis**
    - 10m_v_component_of_wind

    - 10m_u_component_of_wind
    - 2m_temperature
    - total_precipitation

- **Meteorological Service Singapore**
    - total_precipitation
    - mean_temperature
    - mean_wind_speed

- **CityGML**

WHU uses the CityGML format data provided by SLA to visualize the building and uses the universal model slicing tool provided by Cesiumlab to convert .gML files into Cesium loadable 3d tiles.

- **Terrain Data**

For terrain data, WHU uses the grid horizontal resolution of 2m DEM (GeoTIFF format) provided by SLA, and the terrain slicing tool provided by Cesiumlab converts the .tif file into a Cesium loadable terrain file.

Standards & Interoperable Technologies

The consolidated data products processed into the WHU GeoDataCube are published through a set of OGC APIs.

Table 2 — WHU GeoDataCube support for OGC standards

OGC API	URI	DESCRIPTION
OGC Coverages	http://oge.whu.edu.cn/ogcapi/coverages_api	ERA5 land daily mean temperature and precipitation data from April to May 2021; temperature, precipitation, and wind speed data from Singapore meteorological stations; terrain data provided by SLA; and marine depth data from MPA
OGC Features	http://oge.whu.edu.cn/ogcapi/features_api	WHU integrates vector data of the research area, organized according to the the structure of the GeoDataCube, along with raster data, into a unified data cube

2.1.1.3. Challenges & Future Work

- **Accuracy of meteorological data**

To enhance the accuracy of meteorological data within a limited spatial range, historical meteorological station data provided by the Singapore government can be utilized. These meteorological stations are strategically located to offer more representative meteorological observations.

+ By employing interpolation techniques such as Kriging and Inverse Distance Weighting (IDW), it is possible to estimate meteorological values at unobserved locations based on existing data points from meteorological stations, thereby generating more continuous and precise meteorological surfaces.

+ However, the reliability of interpolation is influenced by extrapolation errors and the quality of the original data, necessitating adjustments to data point weights and consideration of spatial distribution constraints.

- **Flood Model Limitations**

In actual flood events, water levels typically fluctuate over time due to various factors such as rainfall and tidal events. The current implementation of the Singapore digital thread may be enhanced by accounting for the time-variable water levels, resulting in an improved flood propagation model and assisting in addressing the multifaceted risks associated with floods.

- **Flow vectors**

The current model accounts for water diffusion in the four cardinal directions overlooking the intricacies of water flow paths. To enhance flood simulation accuracy, the model may be enhanced to incorporate hydrodynamic elements such as flow velocities, water depths, and flow directions.

- **External forcings**

The model does not account for external forcings due to interactions with features such as buildings. Flood propagation, especially in dense urban areas, is influenced by available pathways and structural elevations. Future improvements will benefit by incorporating key building characteristics, for example, into the model to determine how the height, shape, and pathways apply forcings to the water propagation model.

2.1.2. D112: A Digital Twin framework for Advanced Visualization of Storm Surge Events

As Singapore is surrounded by the ocean, it is especially vulnerable to severe weather events. In order to address the operational planning around Singapore's coastal infrastructure, predicting the coastal inundation of storm surges with advanced visualization technology is key to climate resilience planning.

Background

Geomatys is a geospatial intelligence company delivering a cloud-based data lake architecture aligned closely with the norms and standards defined by the Open Geospatial Consortium and

ISO. Geomatys' platform development is directed by four fundamental principles — Innovation, Interoperability, User Experience, and Quality Control — transforming large volumes of disparate data into innovative visualization products for Data Science.

The Geomatys digital twin product is based on advanced gaming technology able to merge different kinds of elevation data into a quantized mesh format with raster imagery wrapped to create realistic textures. The Geomatys server is specifically designed to model environmental issues, maritime surveillance solutions, and defense theater management operations.

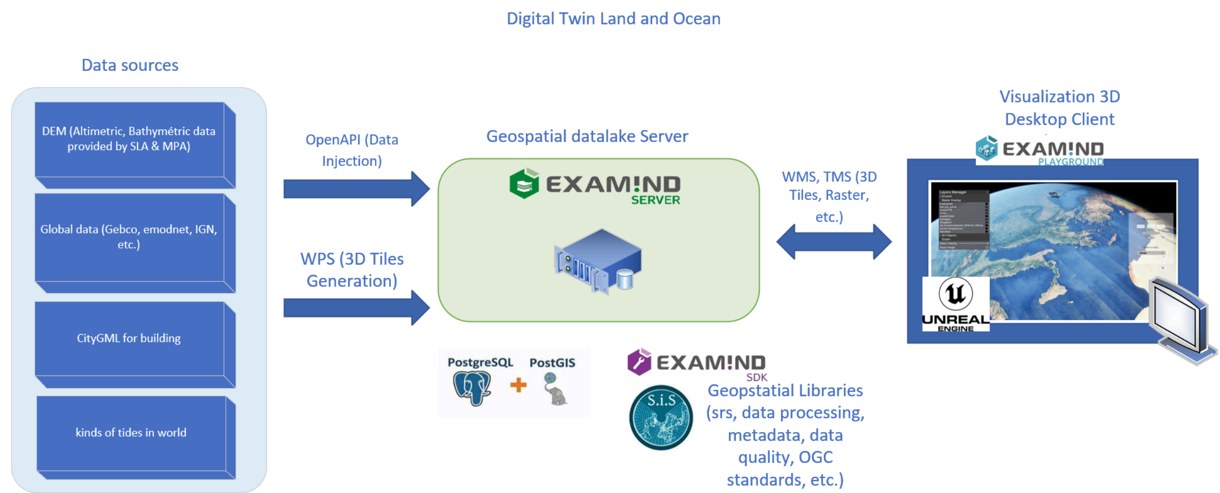


Figure 6 — Geomatys Digital Twin Framework

2.1.2.1. Approach

The Geomatys demonstrator focuses on ocean submersion on the land of Singapore. The platform simulates changes in ocean level in a 3 dimensional environment affected by the coefficient of local tidal events together with bathymetric, elevation, and building models to assess the impact on the city infrastructure.

2.1.2.2. Solution Architecture

Terrain elevation and bathymetric data are modelled based on the Singapore regional datum. This workflow provides a 3-dimensional feature model representing the footprint of water spread over land with different variations of sea level based on the tides coefficient and sea level height. The simulation model represents the flood areas on the land with coverage of storm surge impacts to infrastructure.

The approach for waves is based on research provided by Tessendorf-2004 to simulate ocean water. The height of wind-waves in the open ocean is decomposed into a sum of sine and cosine waves. Given a set of frequencies and sampling points, the height is calculated using Discrete Fourier Transform (DFT). Fast Fourier Transform (FFT) is an efficient way to calculate height. Technically, the method implemented uses an Inverse FFT, as it creates wave heights from frequencies. Different parameters such as wind speed, wind direction, repeat period, wind tighten, and amplitude adjust the model for a more realistic representation.

A cartographic service provides the core component to the demonstrator platform into which the digital terrain model, bathymetric profile, and CityGML data products are ingested. The elevation and bathymetric data are aggregated into a 3-dimensional quantized mesh with a watermask area to locate the ocean vertices.

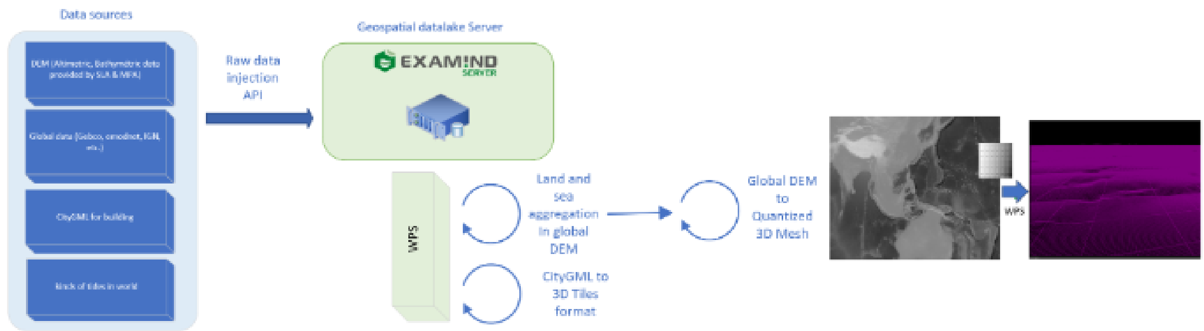


Figure 7 — 3-dimensional quantized mesh with watermask

Raster imagery derived from Sentinel 2 earth observation datasets is streamed to the cartographic server and draped over the quantized mesh data providing a realistic view of the coastal zone.

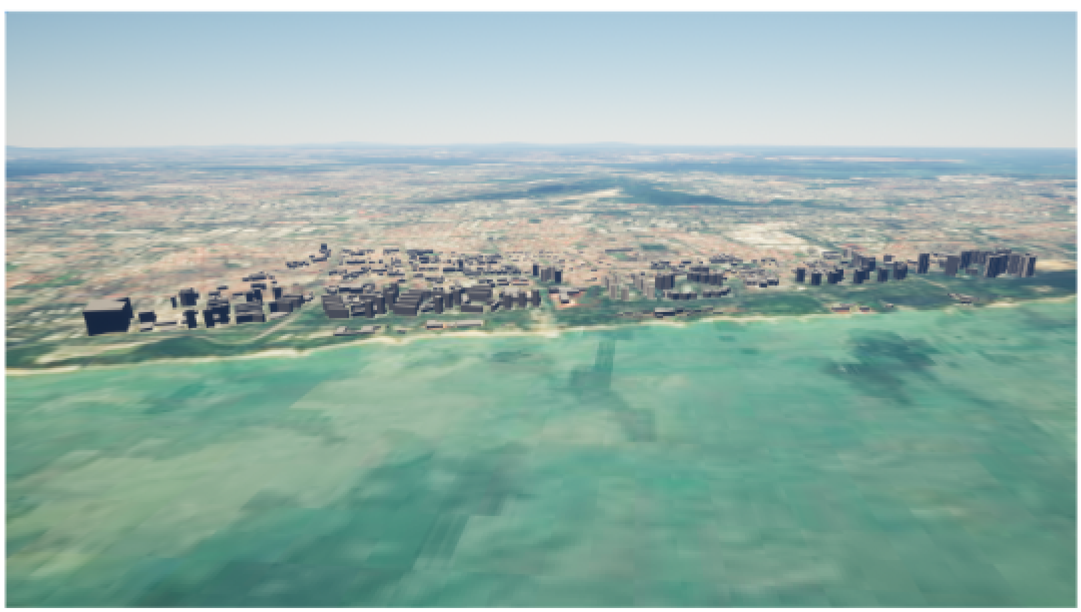


Figure 8 — Elevation, Bathymetry and Building Footprints of the Singapore Coastline

Simulating the storm surge event combines the terrain and bathymetric mesh with the water mask based on the tidal coefficient at mean sea level and range using the low-water mark (LWM) and high-water mark (HWM). Adjusting for the simulated height of sea level, ray tracing identifies the affected terrain features and applies an extended water mask over land based on elevation.

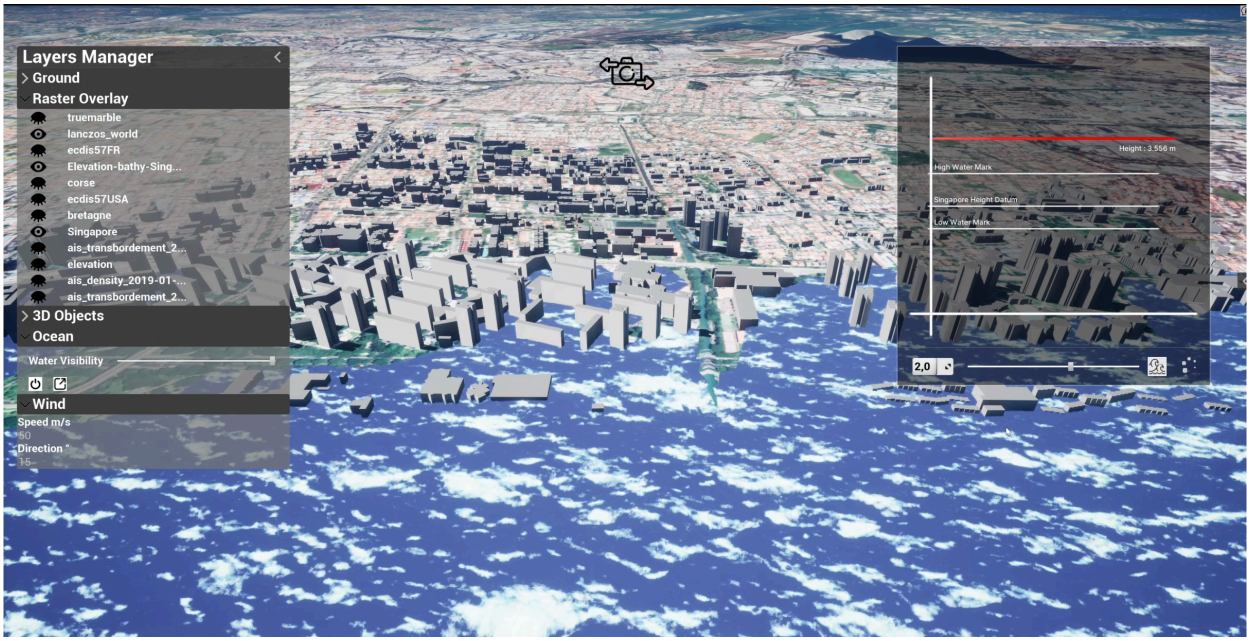


Figure 9 — Simulation of Coastal Inundation due to Storm Surge

Data and Platforms

- **Service hydrographique et océanographique de la Marine**

Tidal information is sourced from the Service hydrographique et océanographique de la Marine (SHOM) and provides the periodicity of tides to simulate the theoretical sea level within a specific spatial and temporal extent. This variable determines the water level mask applied to the simulation adjusted in relation to other hydrographic and meteorological datasets.

- **CityGML Feature Collection**

The CityGML building dataset provided by MPA and SLA is converted to the 3DTiles format by the following tools.

- citygml-to-3dtiles to convert CityGML dataset to 3DTiles format (https://github.com/njam/citygml-to-3dtiles)
- 3d-tiles-tools to upgrade 3DTiles dataset to version 1.1 (https://github.com/CesiumGS/3d-tiles-tools)
  - **Digital Terrain Model**

The terrain model is based on the SRTM Digital Elevation Model with 1 arcsecond resolution.

- **Bathymetry Profile**

Bathymetry data was sourced from the GEBCO data repository.

- **Satellite Imagery**

Satellite imagery was sourced from the Sentinel-2 data repository and used for raster overlay.

Standards & Interoperable Technologies

The demonstrator platform provides interfaces compliant with the OGC API — Coverages, Features, Processes, and 3D Tiles. Additionally, an OGC WMS service endpoint is configured to provide imagery to client environments based on the simulation results.

2.1.2.3. Challenges & Future Work

- **Coastal Wave Models**

The sea level and sea state representation applies a simulated wind speed and direction as an external forcing to derive the extent of coastal inundation to Singapore's coastal area. Future work will benefit from integrating with real-time and forecasted meteorological data to improve the accuracy of results.

+ The Geomatys coastal wave model currently does not incorporate the bathymetric profile of the Singapore extent. Future work would provide improved the wave energy model by accounting for the physical effects of MPAs bathymetric dataset. Wave energy is enhanced or diminished by the effects of wind, breaking waves, and energy exchanges between the various physical components of the local environment.

- **Spatial Resolution**

Higher spatial resolution for the digital model elevation would improve the water spread algorithm and provide a more realistic footprint of water over land. Tidal data provided by SHOM provides the periodicity of tides to simulate the sea level of the specific region and date. An issue was identified during the processing of the aggregated terrain model resulting in a gap between the Singapore DTM and global SRTM likely due to an inconsistent elevation reference for each data product.

2.1.3. D113: Modeling Storm Surge via a Multi-dimensional Geospatial Data Cube

The complex challenges of a rapidly transforming world are prompting stakeholders to investigate standards for efficiently accessing and exchanging geospatial data addressing the predictive impact of severe weather events. Answering questions pertaining to these challenges requires the integration of multiple, very large high resolution, global datasets in order to perform spatial analysis.

Interoperability, accessibility, and open data policies greatly facilitate finding solutions to global issues of the marine domain effectively and rapidly.

Background

Ecere Corporation develops high performance geospatial software for 2D/3D visualization and large-scale data distribution using open standards. The company provides cutting-edge features as part of its GNOSIS Software Development Kit (SDK) and GNOSIS Cartographer GIS tool/visualization client with integrated support for Discrete Global Grid Systems (DGGS) and GeoDataCubes (GDC). Ecere is an active contributor to several OGC Standard Working Groups (SWG) with a number of co-chair and co-editor roles including the OGC API — Coverages and OGC API — DGGS SWGs.

The Singapore thread benefits from the multi-dimensional/multi-resolution datacube capabilities of the GNOSIS platform to highlight the impact of storm surge and sea level rise to the Singapore coastal infrastructure. The solution builds on previous work products provided as part of the OGC Testbeds 17, 18, and 19, the Climate Resilience and Disaster Pilots, and FMSDI-3. In particular, support for the Singapore CityGML datasets is provided through an OGC API — 3D GeoVolumes extension developed in compliance with the OGC 3D Container & Tiles Pilot and Testbed 18 Building Energy thread.

The Federated Marine SDI (FMSDI) 2023 Pilot provides an opportunity to highlight the multidimensional/multiresolution capabilities of the GNOSIS platform to visualize coastal flooding scenarios integrated with multispectral ESA sentinel-2 Level 2A observation datasets and Copernicus CDS climate projection forecasts.

2.1.3.1. Approach

Quantifying the impact of storm surge scenarios requires the ingestion and transformation of multiple data products aligned with the regional coordinate system and temporal range.

The land elevation and the bathymetric profile data products are transformed from CityGML Triangulated Irregular Network (TIN) and Comma-Separated Values (CSV) depths, and combined into a set of GeoTIFF gridded coverage files. The coverages are then optimized into a multi-resolution tiled data store served through the OGC API — Coverages interface of the GNOSIS Map Server. The bathymetry data transformation applies the necessary vertical datum adjustment to merge these two datasets into a common datum.

The land cadastre polygonal features and CityGML 3D buildings are imported into optimized data stores with 3D buildings exposed as 3D Tiles through the OGC API — 3D GeoVolumes interface. The 3D Tiles collection is used as the basis for integration experiments in the Compusult client demonstrator (D114).

Once imported into a GNOSIS Data Store, the GNOSIS Map Server provides multidimensional/multiresolution datacube capabilities extended for the multi-spectral ESA sentinel-2 Level 2A observation datasets and climate projection datasets from the Copernicus Climate Data Store.

The GNOSIS Map Server provides support for Discrete Global Grid Systems (DGGS) through its OGC API — DGGS interface providing a convenient way to explore the datasets through hierarchical DGGS zones. The GNOSIS Map Server supports two specific discrete global grids which are also 2D Tile Matrix Sets: the GNOSIS Global Grid; and the Icosahedral Snyder Equal Area aperture 9 Rhombus (ISEA9R) grid.

Figure 10 — Exploring Combined Land Elevation from Singapore Land Authority and Bathymetry from Singapore Maritime and Port Authority through GNOSIS Map Server DGGS API

2.1.3.2. Solution Architecture

A deployment of Ecere's GNOSIS Map Server hosted the various datasets for the scenario, including data provided specifically for the Singapore scenario as well as global data products.

The rising water level scenario is demonstrated using the GNOSIS Cartographer client for visualizing the hosted data collections. The GNOSIS Cartographer client relies on the GNOSIS library to request OGC compliant data products for visualization at specified extents, with the ability to configure visual styles and optional data filtering.

A key feature of the GNOSIS Cartographer software is 3D projection. The Singapore land and marine data products are rendered to a 3-Dimensional Globe representing sea level heights against the terrain model. New functionality was developed to allow rendering water separately from the 3D terrain representing the land and marine elevation datasets. The datasets are styled and visualized together in the client viewport, allowing the end-user to assess the impact of coastal inundation on Singapore's land-based features.

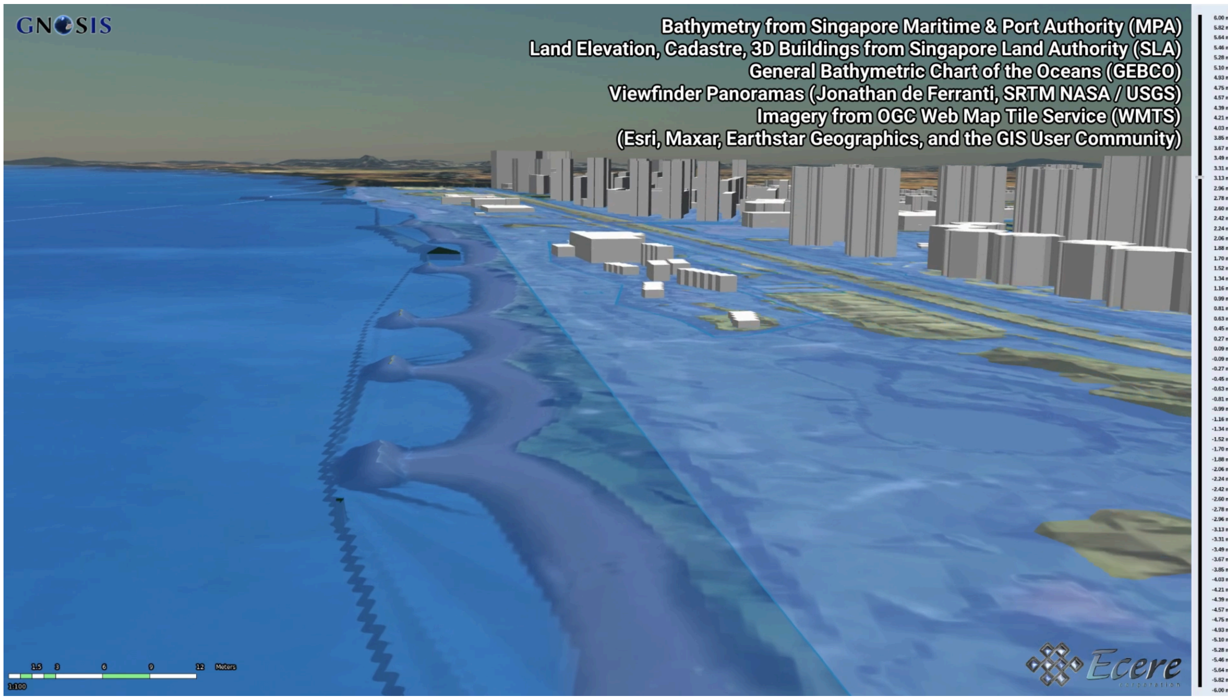


Figure 11 — Close-up view of the Singapore coastline during storm surge scenario visualized in GNOSIS Cartographer

Data and Platforms

The Singapore Land Authority (SLA) and Singapore Maritime and Port Authority (MPA) provided multiple datasets used for the experiments:

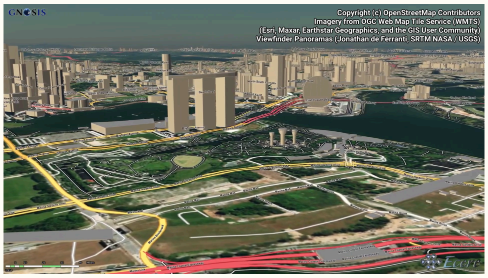
- bathymetry in the form of 3D geospatial coordinates with depth values (MPA);
- land elevation, provided as CityGML TIN data (SLA), which was converted by Safe Software to gridded coverage in GeoTIFF format;
- 3D Buildings, as CityGML (SLA); and
- cadastre land lots polygon features (SLA).

Figure 12 — Visualizing the impact of rising sea level
on the Singapore coastline in GNOSIS Cartographer

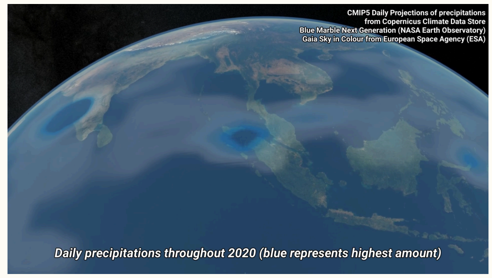
Additional datasets were used to complement the Singapore storm surge scenario:

- a visualization of CMIP5 climate variable daily projections from the Copernicus Climate Data Store, including wind speed and precipitation, were visualized in GNOSIS Cartographer, as potential inputs to storm surge predictions;
- the Blue Marble Next Generation from the NASA Earth Observatory was used as a lower resolution base imagery layer;
- the Viewfinder Panoramas 3 arc-seconds (90m) global digital elevation model from Jonathan de Ferranti, based on the NASA / USGS SRTM and additional elevation datasets;
- Sentinel-2 Level 2A data from the European Space Agency (ESA) to provide higher resolution Earth Observation imagery as well as for a year-long time lapse visualization;
- the *Gaia Sky in Colour* from ESA was used to provide a starry background to the 3D virtual globe; and
- OpenStreetMap (OSM) data for all of Singapore as an alternative 3D buildings dataset, extruded from footprints based on the OSM Simple 3D Buildings.

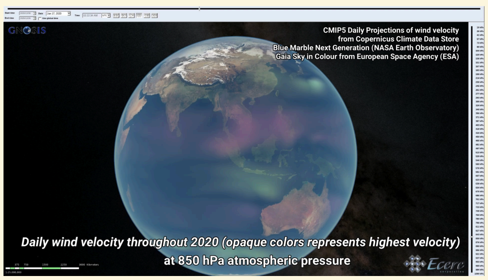
The platform for the demonstration consisted of Ecere's GNOSIS Map Server and GNOSIS Cartographer visualization client, both built on top of the GNOSIS Software Development Kit, which was built using Ecere's open-source cross-platform Software Development Kit and eC programming language. The GNOSIS products implement OGC API standards which provide a framework for interoperability with other geospatial products, including those of other pilot participants.



OpenStreetMap data visualized in GNOSIS Cartographer



CMIP5 Precipitations visualized in GNOSIS Cartographer



CMIP5 Wind velocity visualized in GNOSIS Cartographer

ESA sentinel-2 and OpenStreetMap Dataset over Singapore accessed from GNOSIS Map Server

Standards & Interoperable Technologies

The GNOSIS Map Server demonstration endpoint at https://maps.gnosis.earth/ogcapi/collections/fmsdi4-singapore provides access to the various georeferenced datasets, including the gridded coverage of the Singapore coastal area integrating marine and land elevation.

The data can be accessed using the OGC API — Coverages, OGC API — Tiles, OGC API — Features, OGC API — 3D GeoVolumes, OGC API — DGGS, and OGC API — Maps standards.

GNOSIS **GNOSIS Map Server** ecere.ca Ecere

fmsdi4-singapore

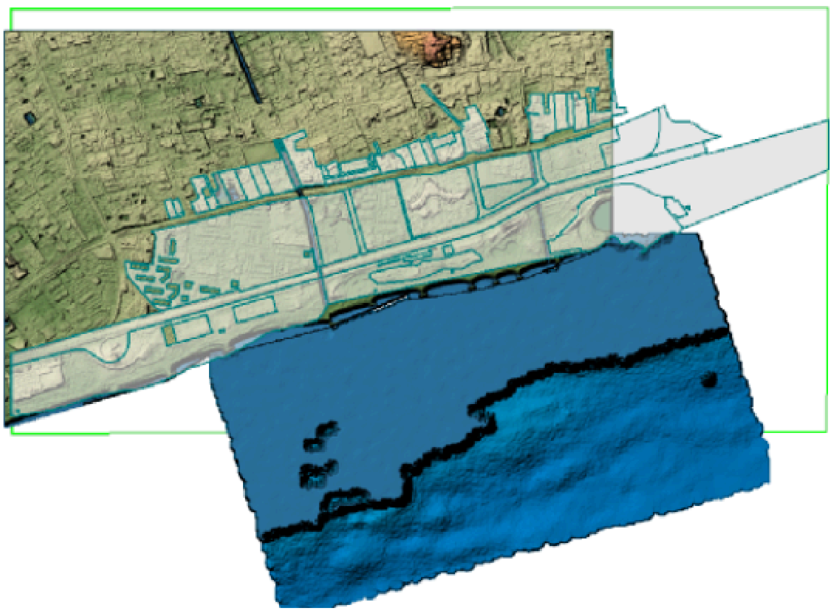
(View JSON or ECON representation)

Back to list of data collections

Multi-layer vector tiles for this data collection

Map for this data collection

Map tiles for this data collection



Component data collections

Singapore CityGML Buildings
Cadastre_Landlots_LADM
Combined Elevation from SLA and Bathymetry from MPA (including 1.556m datum adjustment)
ProposedECPArea_SVY21

Figure 13 — Datasets provided by Singapore Land Authority and Singapore Maritime and Port Authority hosted on GNOSIS Map Server demonstration end-point

2.1.3.3. Challenges & Future Work

High Resolution Data

The main challenge faced during the initiative was the limited access to high resolution data.

For future work, Ecere could attempt to more accurately simulate the spread of water as a result of a storm surge scenario. Having access to higher resolution elevation datasets, for example by working directly from the high resolution point cloud data, would be useful for this purpose.

Presenting the simulation results as a number and/or area of affected buildings would also be an interesting outcome.

Using a larger spatial extent for the scenario would better illustrate the advantages of multiresolution datacubes.

The representation of elevation datasets relative to the Singapore Height Datum on the virtual globe could likely be more accurately referenced in relation to the WGS84 ellipsoid.

Using high resolution weather and/or water current datasets to calculate the water level at different areas, as opposed to simply uniformly rising the water level, could also result in a more compelling storm surge scenario.

2.1.4. D114: Flood Modeling & Emergency Preparedness

Emergency preparedness requires the integration of multiple data sources into a seamless application platform to allow stakeholders to identify, plan, and predict catastrophic scenarios. Floods are one of the most recurrent natural disasters worldwide with estimates of global damage exceeding $40 billion annually. Ensuring the right information reaches the right individuals at the right time is key to ensuring the safety of affected communities.

Background

Compusult is a diversified information technology (ICT) company based in Mount Pearl, Newfoundland, Canada with offices in Den Hague, Netherlands and Virginia, USA. Compusult provides platforms and services focusing on Geospatial Data Discovery and Management Systems; Mobile Applications & Services; Asset Tracking & Inventory Control; Custom and Commercial Software and Electronics; and Assistive Technology for Persons with Disabilities.

The FMSDI Singapore theme leverages the Compusult Web Enterprise Suite (WES). WES components are based on OGC and ISO standards and is compliant with many commercial/open-source tools and products. Compusult is a long-standing member of the OGC and active supporter of the Web Map Service (WMS), Catalog Service for the Web (CSW), and OGC GeoPackage specifications.

2.1.4.1. Approach

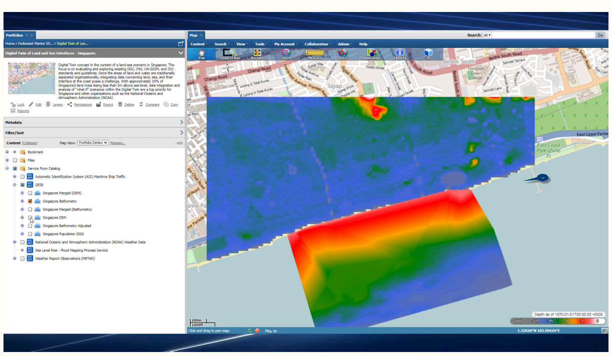
In WES, scenarios are managed by creating an associated Portfolio. A Portfolio provides the ability to manage, organize, and track information associated with incidents and events. The Portfolio component has been optimized to support display and management of Common Operating Pictures (COPs) and the creation of situational views that organize and visualize content from disparate data sources and applications for a particular area of interest or topic.

Each dataset of interest for the Singapore thread is registered with a centralized Catalog Service and exposed using the OGC Records API service providing a single service endpoint to discover datasets for analysis and processing. These data collections are managed as a Common Operating Picture and published as a Portfolio representing the Singapore flood modeling scenario.

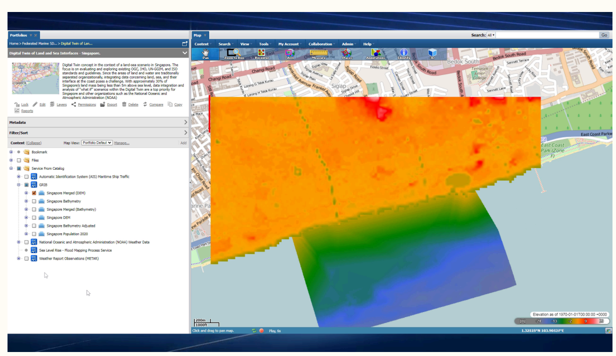
2.1.4.2. Solution Architecture

The Singapore flood modeling scenario is implemented using the WES application platform. The client application provides both a 2-dimensional and 3-dimensional view of the Singapore coastscape together with representation of the city infrastructure. The client application provides the user the ability to configure various flood models with the appropriate visualization highlighting the coastal inundation of increasing flood levels.

A catalog service is implemented based on the OGC Catalog Service standard (CSW) and extended to provide a compliant OGC Records API service documenting the data products used in the Singapore evaluation. The SLA and MPA datasets are processed into a seamless topological mesh in order to avoid gaps in terrain data. Using the GDAL libraries gdal_calc and gdalwarp, the bathymetry dataset is inverted and adjusted to conform to the Singapore Height Datum. The dataset is then merged with the SLA digital elevation model and persisted as a GeoTIFF. This merged dataset is registered with the Catalog Service and published as a Coverage Service for client use.



SLA & MPA datasets with gap



Merged SLA & MPA datasets with no gap

An OGC API Process layer allows clients to register content to the Catalog Service while an OGC API Coverages layer allows clients to query and discover data layers used within the Singapore scenario.

Visualization

The WES client provides a simulation model to represent various scenarios of coastal inundation. The client accounts for estimates of sea level rise and tide levels and initiates the flood model simulation through an OGC Processes service interface. The resulting coverage dataset is visualized as a separate layer and supports both a 2-dimensional map representation and 3-dimensional view highlighting the extent of the coastal sea level relative to the SLA terrain. OpenStreetMap feature layers are included and overlaid with the Singapore merged dataset to facilitate decision-making policies.

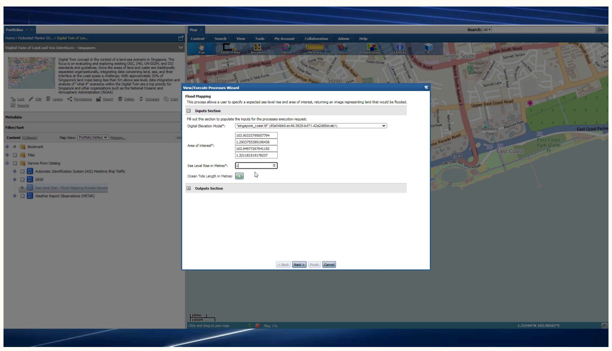


Figure 14 — Flood model Configuration

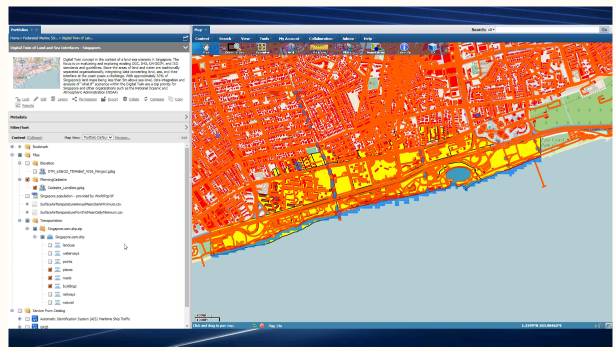


Figure 15 — Coastal Inundation

OGC GeoDataCube

The flood model analysis is based on work within OGC for multi-dimensional spatial data cubes (GeoDataCubes). The merged topological dataset is integrated with external datasets harvested from the Copernicus Climate Data Store (CDS) and SentinelHub into a GeoDataCube.

A flood modeling service abstracts the GeoDataCube behind an OGC Map Service and OGC Coverage Service. These service layers produce data based on the flood modeling scenario and rendered in the WES client for visualization.

Integration with OGC Tile Service

The WES 3D Client is configured to integrate with the Ecere Gnosis OGC Tile Service to render the Singapore cityscape as a 3-dimensional model highlighting vulnerabilities to higher storm surge levels.

Figure 16 — WES 3-D client flood model

Standards & Interoperable Technologies

The Singapore flood modeling scenario is based on the OGC suite of standards including the following.

- OGC API Records: provides the interface to the WES Catalog
- OGC API Processes: provides an interface to publish content to the WES Catalog
- OGC API Coverages: provides access to various data sources including
  - Geo Data Cubes
  - GRIB files
  - NetCDF
  - External sources such as sentinel hub

2.1.4.3. Challenges & Future Work

- **Visualization**

The 3-D client implementation of the Services API does not have well-defined styles and is not supported by OGC or other relative standards. This is addressed by looking at various metadata and holding local models for the OGC Features API although similar issues exist for OGC Coverages. This issue is fundamental to any 3D application and is recommended as an issue to be raised to the OGC API Styles SWG. Either a new styles format specific to 3D is required or an extension to the specification to accommodate various 3D data models (gLTF, Obj, etc.)

- **UX/UI**

Certain coverage datasets are quite large and introduce issues of latency in the processing framework. This leads to long network request times and may affect client usability. Alternative strategies were investigated to improve on the client processing workflow. Requesting entire datasets initially allows for more seamless user experience at the cost of load times. Requesting small amounts of data at lower resolutions can have similar benefits to performance but come at the cost of a large number of requests which can lead to scalability issues. Caching certain requests is also an option that was implemented but this still leads to a first request duration that is longer than preferred.

- **GeoDataCubes**

The GeoDataCube storage model provides fast and efficient access to multi-dimensional datasets. The main benefit is that the GeoDataCubes are very flexible in the types of data stored. The multidimensional storage model is very similar to OGC API coverages format and lends itself to seamless conversions. The models have defined axes on which data is stored that allow for querying and filtering on dimensions of interest that are directly applicable to coverage areas.

+ The GeoDataCube standard is currently in development and is evolving to meet the core requirements of the OGC suite of standards. An emphasis of the GeoDataCube initiative focuses on extending the OGC Coverages and Web Coverages Processing Service to incorporate the multi-dimensional storage model. Use of the GeoDataCube storage model introduced issues of scale for the processing framework and issues of latency for client frameworks designed for low-latency communications protocols.

2.2. Thread Summary & Future Work

The Singapore Land Authority and the Singapore Maritime & Port Authority agencies cooperatively support Singapore's geospatial infrastructure strategy of "Limited Land — Unlimited Space". A key aspect supporting this strategy is the ability to apply coastal simulation models and external data products in the context of Singapore's infrastructure and biodiversity initiatives.

Each contributing participant was charged to independently research the problem domain and design a demonstration platform incorporating the unique requirements of the Singapore data space. A common scenario evolved highlighting the effects of extreme sea levels on Singapore's coastal environment based on the provided terrain, cadastre and bathymetric datasets.

Each of the solutions applied a similar design pattern in which the data products provided by SLA and MPA were transformed and loaded into a core datastore at which point external data products were used to simulate the effects of sea level rise. The initial transformation projected the MPA bathymetry dataset to EPSG: 6927 (SVY21 + SHD) adjusting for the difference between the Admiralty Chart Datum and the Singapore Height Datum. Conflicts between the terrain and bathymetry feature sets were addressed to produce a seamless georeferenced view of Singapore's coastal area.

2.2.1. Summary of Results

Results of the project successfully addressed the visualization component of the project through a multi-dimensional view of the SLA terrain and cadastre information together with representation of sea level as a height varying body of water. The client environments provide time-instant 2-dimensional and 3-dimensional views of coastal inundation using information derived from external data sources such as tidal events coincident with storm surge simulations. Factors such as the bathymetric profile and other forcings on the water body were not taken into account which would provide a truer representation of the vulnerability of Singapore's cityscape to severe weather events.

Visualization of coastal inundation as a result of storm surge and sea rise simulations produced an effective workflow to communicate the vulnerabilities of the Singapore coastal area. The coastal inundation models provided their analysis in a global context in order to benefit from integrating with external data products such as the SRTM Digital Elevation Models and/or IHO derived tidal event predictions.

2.2.2. Future Work

A major component of interest to the Singapore Land Authority is the identification of specific features directly impacted. To benefit from such predictive models, the Singapore Land Authority and Maritime Port Authority require the simulations to be represented in the local coordinate reference system as an integrated analysis workflow extending day-to-day planning and management processes. With consideration of SLA's role as the gatekeeper of Singapore's land information, and their strategic position accounting for the vertical development of infrastructure and climate resilience policy, the results of simulating coastal inundation need to be provided in the native cadastre coordinate reference system — with particular consideration for the Singapore Height Datum as the system of record.

Vertical Datum Relationships
Future considerations need to account for inaccuracies introduced as a result of projecting terrain and bathymetry datasets from the Singapore Height Datum to the WGS84 vertical datum. The Singapore Height Datum, being a local coordinate system statically referenced against a historic tidal gauge, is independent of any considerations of the global geodetic datum. A complex algorithm is available to project the Singapore vertical datum to Singapore's regional geoid — SGeoid09 — which in turn, may be projected to the WGS84 vertical datum for simulation trials. Each step, however, exposes some level of approximation of vertical height relative to a reference elevation model which, in turn, may compound the inaccuracies of simulation models should the result be re-projected back to the Singapore Height Datum. Considering the level of accuracy of the Singapore Land Authority to +/- 5mm vertical for its cadastre information system, further analysis is required to assure any policy driven from coastal simulations maintains its accuracy to the same degree.

Testbed-19 GeoDataCube / Analysis Ready Data

In parallel to the FMSDI 2023 pilot, the OGC Testbed-19 initiative is evaluating certain concepts that may benefit future work related to this project. In particular, discussions on the role of the OGC GeoDataCube and OGC Analysis Ready Data (ARD) work products are relevant to addressing concerns of scale and positioning accuracy. The FMSDI pilot demonstrates the use of the GeoDataCube architecture as a core component of the Singapore solution framework. The Ecere Gnosis platform and WHU Datacube platform both implement a reference system for Testbed-19 extended with Singapore's coverage model with compliance of the OGC Coverages and OGC Coverage Processing Service. The OGC ARD initiative is designed to identify and promote further capabilities of multi-dimensional analysis by abstracting the complexities of earth observation monitoring systems and producing satellite derived data products aligned with regional concerns. This approach represents an opportunity to address SLA's requirements through the use of analysis ready datasets for Singapore's regional extent and strategically aligns with a Digital Earth model for the Republic of Singapore.

OGC Building Blocks

A formal conceptual model of the SLA and MPA processing requirements aligned with the OGC Building Blocks initiative would be of benefit to SLA and MPA. The Building Blocks initiative is developing a set of best practices for developing standards-based APIs for location-aware application frameworks. A building block is a reusable component that may implement a complete OGC API standard, one part of a multi-part standard, or more granular functionality within a standard.

3

THREAD 2: THE DIGITAL ARCTIC — CONNECTING LAND AND SEA — CANADA

3 THREAD 2: THE DIGITAL ARCTIC — CONNECTING LAND AND SEA — CANADA

Natural Resources Canada (NRCan) is responsible for the GeoConnections Program, a national program with the mandate to design and manage Canada's Spatial Data Infrastructure. This program provides the key components of a National Spatial Data Infrastructure facilitating the sharing and interoperability of geospatial information across federal agencies including the Department of Fisheries and Oceans (DFO) and the Canadian Hydrographic Service and Surveyor General Branch.

NRCan also leads Canada's involvement in the Arctic Council, a multi-national forum promoting cooperation in the Arctic. Established in 1996 through the Ottawa Declaration, eight member states with territories within the Arctic were invited to act as members of the Arctic Council. Together with six designated Permanent Participants representing the Indigenous Peoples of the Arctic, the Arctic Council is responsible for various working and expert groups aligned with its overall mission to establish a "region of peace, stability and constructive cooperation, that is a vibrant, prosperous, sustainable and secure home for all its inhabitants, including Indigenous Peoples, and where their rights and wellbeing are respected."

The Arctic Council maintains six working groups covering a broad range of subjects, each grounded on science and data. To support this mandate, the Arctic Spatial Data Infrastructure (Arctic-SDI) program was established to provide open access to geospatial information in support of policy and related decision making processes affecting Arctic communities.

Key challenges of maintaining an Arctic SDI program center around the generation and sharing of geospatial data pipelines. This involves the topics of *Discovery* and the *Digital integration of geospatial information* across jurisdictions and feature domains. Of particular interest is the ability to support the mandates of the core Arctic Council working groups by demonstrating the capabilities of a federated geospatial infrastructure based on OGC standards and best practices.

- **D101: Discovery**

The Digital Arctic Discovery requirements are designed to evaluate the set of best practices and standards aligned with the OGC suite of protocols. The goal is to demonstrate an enhanced methodology for discovery and integration of land and marine geospatial information in support of analysis services from multiple sources. Satellite and in-situ observation data is a primary focus of the initiative.

- **D102: Demonstrator Program**

The Digital Arctic demonstrator is designed to address Canadian research interests in the context of its role within the Arctic SDI program with a particular focus on information derived from satellite and in-situ sensor data. The Arctic SDI program incorporates the concept of a 6-dimensional information model integrating spatial extent (x,y) with vertical dimensions (z), temporal dimensions (t), vectors of flow (v), and scientific research lifecycle management (s). These dimensions are designed to support predictive insights into change over time in a fluid Arctic ecosystem affected by climate change.

The scope of the demonstrator program is divided across various areas of study ranging from the impact of climate change to inland waters and permafrost through to identifying changes in habitats extending into Arctic waters. Each demonstrator project focuses on a specific area of interest over a variable temporal extent demonstrating the 6-dimensional concept aligned with the operational requirements of the Arctic SDI.

A core objective is to evaluate and position core OGC standards as a means to supplement existing in-situ monitoring programs of the Arctic Council with external platforms that complement the critical areas of research associated with the Arctic SDI program.

3.1. Contributions

The following table summarizes the contributions of each Participant. Details for each contribution are provided in subsequent sections.

Table 3 — Arctic Theme Participant Contributions

ORGANIZATION	DELIVERABLE	SCENARIO
Compusult	D131	Impact of Sea Ice Loss and the Migratory Patterns of Arctic Fauna
Esri Canada	D132	Interoperability of Geospatial Information across Land & Sea
HSR.Health	D133	Health Risk Indicators of microplastics in the environment and the effect on coastal communities
Pelagis Data Solutions	D134	Satellite-derived Essential Climate Variables with application to Large Marine Ecosystems and Protected Areas

3.1.1. D131: Impact of Sea Ice Loss and the Migratory Patterns of Arctic Fauna

Changes in ice conditions in the Arctic profoundly affect conditions experienced by animals, including food availability, inter-species competition, predation, and increased human disturbances. Impacts of climate change on Arctic vertebrates, especially in regions affected by the loss of sea ice, can have a profound effect on migration patterns.

Background

Compusult is a diversified information technology (ICT) company based in Mount Pearl, Newfoundland, Canada with offices in Den Hague, Netherlands and Virginia, USA.

Compusult provides platforms and services focusing on Geospatial Data Discovery and Management Systems; Mobile Applications & Services; Asset Tracking & Inventory Control; Custom and Commercial Software and Electronics; and Assistive Technology for Persons with Disabilities.

The FMSDI Arctic theme leverages the Compusult Web Enterprise Suite (WES). WES components are based on OGC and ISO standards and are compliant with many commercial/open-source tools and products. Compusult is a long-standing member of OGC and an active supporter of the Web Map Service (WMS), Catalog Service for the Web (CSW), and OGC GeoPackage specifications.

3.1.1.1. Approach

This scenario makes use of a dataset of arctic sea ice concentrations with temporal bounds ranging from January 1979 to April 2023. There are three distinct processes which provide users with historical data, the trend of historical data between two dates, and a prediction of near-future ice concentrations.

Climate data is ingested into a GeoDataCube to manage the spatial and temporal dimensions of the Arctic Sea Ice concentrations. Complementary data products managing the locations and time periods of whales is incorporated into the WES portfolio to visualize the relationships between sea ice conditions and mammal migration patterns.

3.1.1.2. Methodology for Discovery and Integration of Data

Available data and sources of data are cataloged in the WES Catalog Service and exposed as an OGC API — Records service. This approach provides the application client with a single service to discover datasets for visualization. The data collections are processed into a *common operating picture* as a *WES Portfolio*, providing the ability to group subsets of data collections into scenarios addressing the needs of the Digital Arctic theme.

The use of the OGC API — Records service provides the discovery mechanism for the WES client to further manage the thematic data products with access mechanisms supporting collections implemented as OGC API — Features, OGC API — Coverages and OGC API — Processes. External data services conforming to the CKAN standard, such as the *Canadian Government Open API*, are also registered with the Catalog Service providing a central repository documenting the metadata model for larger repositories eventually ingested into the WES client environment.

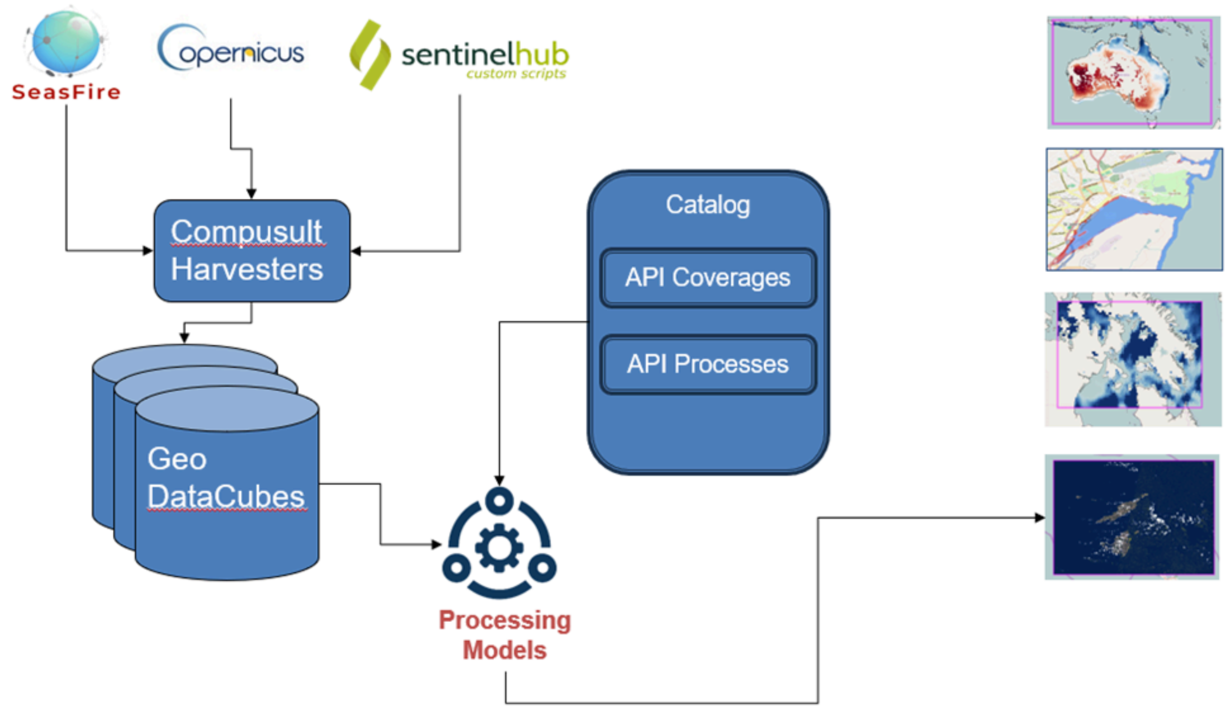


Figure 17 — Compusult WES Catalog Service Architecture

3.1.1.3. Solution Architecture

The digital arctic theme is implemented as a repository of datasets registered in the WES Catalog Service. Service layers compliant with the OGC Features, Coverages, and Processes are configured for the WES client to consume the various data products as separate layers.

The general workflow for the client demonstrator is depicted below:

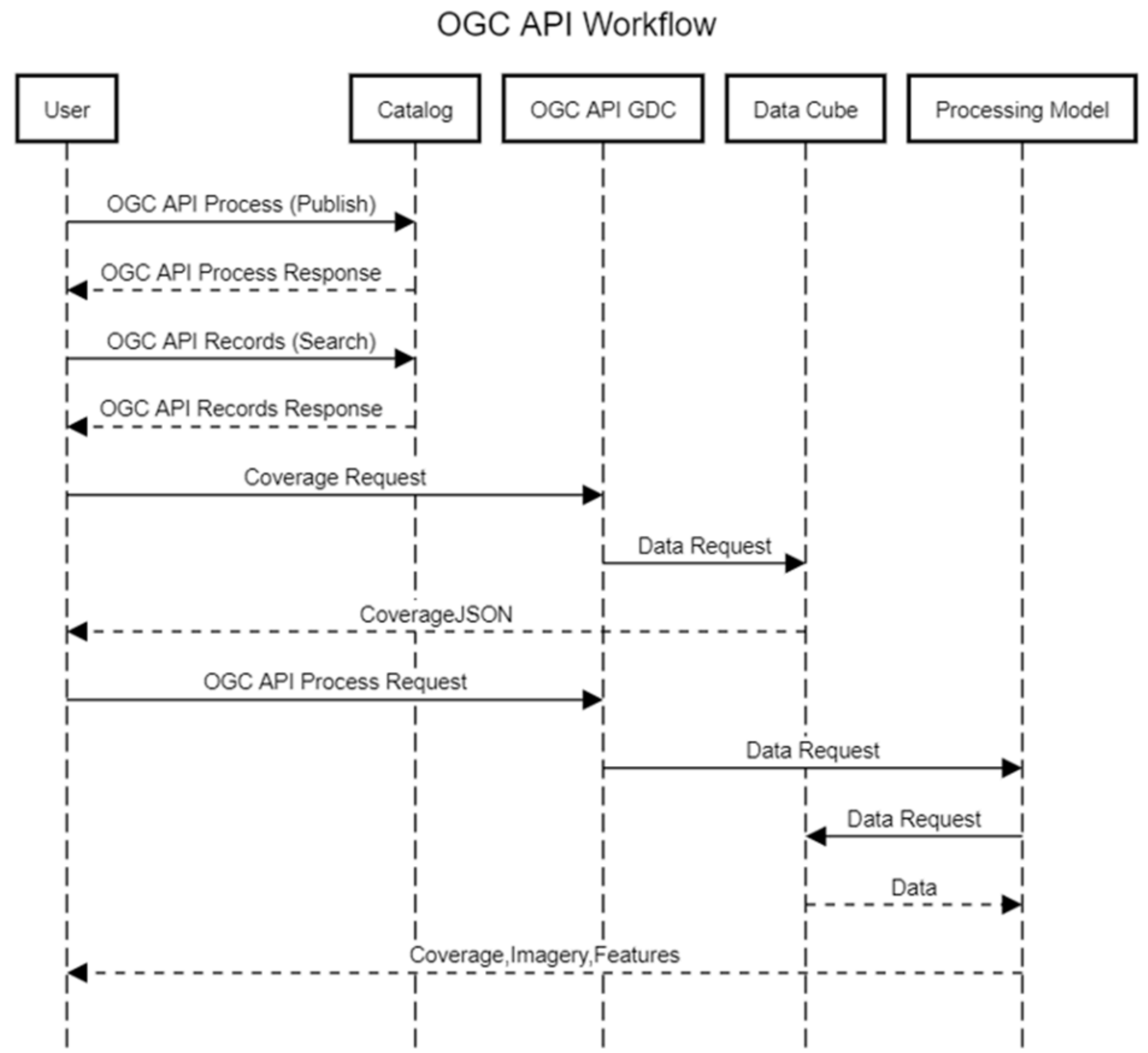


Figure 18 — Compusult Workflow

The Arctic Ice Concentrations are provisioned as an OGC Coverages service layer which abstracts a GeoDataCube data repository for the climate datasets. This thematic layer allows the client to visualize location specific data and analyze the change in sea ice concentration over time.

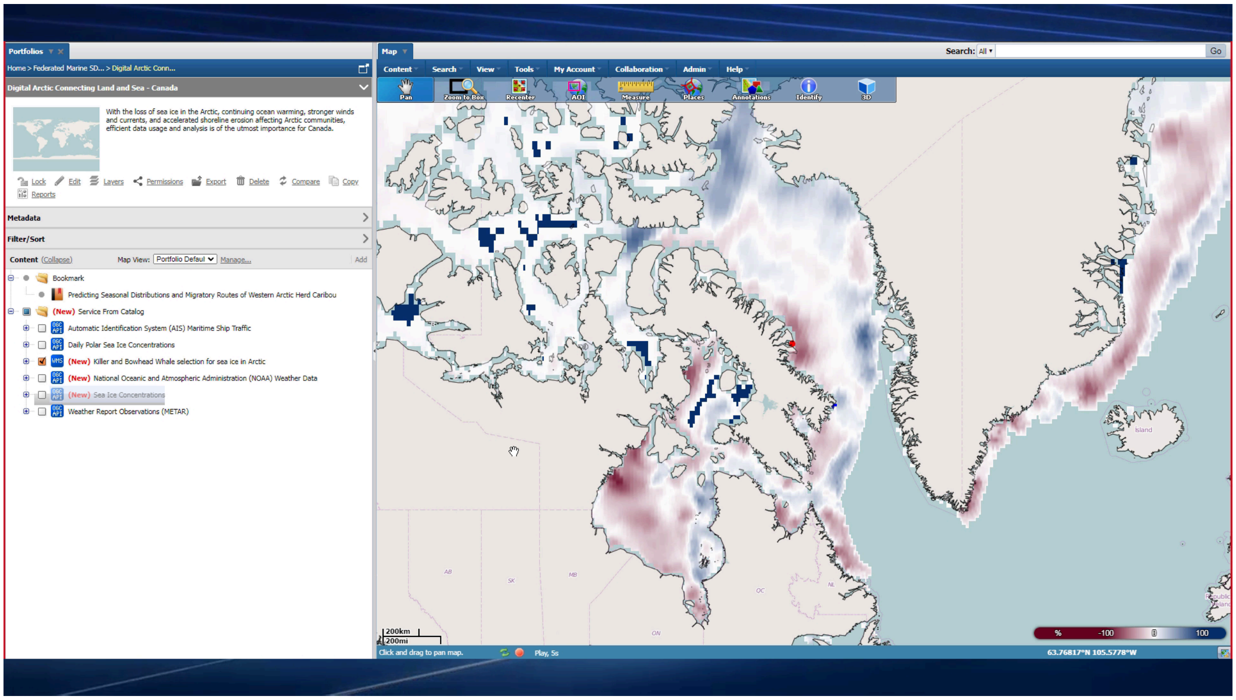


Figure 19 — Sea Ice Loss - June 2000, June 2022

An OGC Features service layer is responsible for provisioning the 'Whale Locations' based on an area of interest and time period.

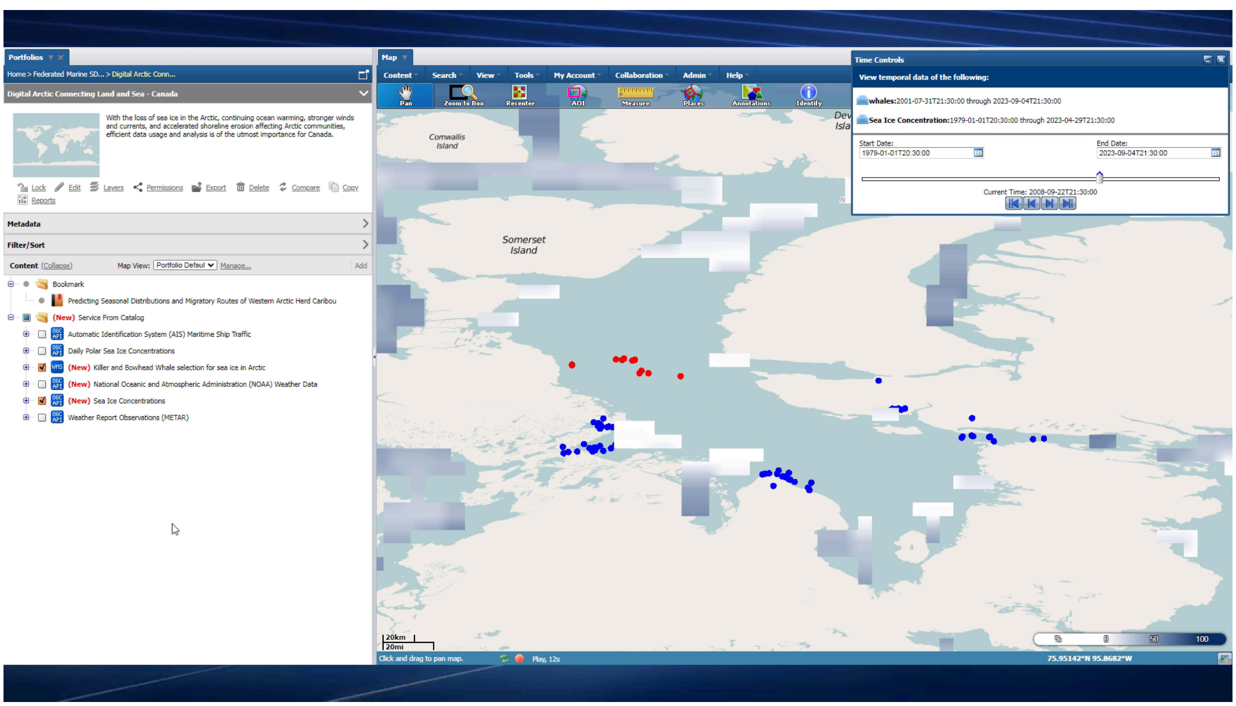


Figure 20 — Animal migration patterns within limited sea ice extents

Coverage Dimensions

Table 4 — D131 Coverage Dimensions

Spatial Coverage	Beaufort Sea
Temporal Coverage	January 1979 — April 2023

Data and Platforms

- **Copernicus Climate Data Store**

Sea Ice concentration is provisioned through the Copernicus Climate Data store for the identified spatial and temporal coverage. The Sea Ice concentration is encoded daily gridded data from 1979 to present.
The dataset consists of two products.

- The *Global Sea Ice Concentration Climate Data Record* produced by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Ocean and Sea Ice Satellite Application Facility (OSI SAF). This is a coarse-resolution product based on measurements from the following sensors: Scanning Multichannel Microwave Radiometer (SMMR; 1979–1987), Special Sensor Microwave/Imager (SSM/I; 1987–2006), and Special Sensor Microwave Imager/Sounder (SSMIS; 2005 onward). This product spans the period from 1979 to present and is updated daily. In the following, it is referred to as the SSMIS product.
- The *Global Sea Ice Concentration Climate Data Record* produced by the European Space Agency Climate Change Initiative Phase 2 project (ESA CCI). This is a medium-resolution product based on measurements from the Advanced Microwave Scanning Radiometer — Earth Observing System (AMSR-E) sensor (2002–2011) and its successor, AMSR2 (2012–2017). This product spans the 2002–2017 period and is not updated.
    - **Open.Canada.ca**

The Catalog Service layer is configured to provide access to external services that conform to the CKAN standard such as 'Canadian Government Open API,' This provides an access pattern to search for datasets from larger repositories and to ingest thematic datasets into the client environment for further analysis.

Standards & Interoperable Technologies

The Digital Arctic scenario is based on the OGC suite of standards including the following.

- OGC API Records: provides the interface to the WES Catalog
- OGC API Processes: provides an interface to publish content to the WES Catalog
- OGC API Coverages: provides access to various data sources including the following.
    - Geo Data Cubes

- GRIB files
- NetCDF
- External sources such as Sentinel Hub

3.1.1.4. Challenges & Future Work

- **Geospatial and Temporal Coverage**

Arctic data can be sparse with limited resolution affecting the extent of analysis available to clients.

- **UX/UI**

Certain coverage datasets are quite large and introduce issues of latency in the processing framework leading to long network request times and may affect client usability. Alternative strategies were investigated to improve the client processing workflow. Requesting entire datasets initially allows for more seamless user experience at the cost of load times. Requesting small amounts of data at lower resolutions can have similar benefits to performance but come at the cost of a large number of requests which can lead to scalability issues. Caching certain requests is also an option that was implemented but still leads to a first request duration that is longer than preferred.

3.1.2. D132: Interoperability of Geospatial Information across Land & Sea

Climate change in Canada's Arctic refers to the significant and ongoing shifts in the region's climatic conditions and ecosystems that have been observed over the past several decades and that are largely attributed to human activities, particularly the emission of greenhouse gases. The whole Arctic region, including Canada's Arctic, is experiencing some of the most rapid and pronounced effects of global warming, with temperatures rising at a rate about twice as fast as the global average. Key characteristics of climate change include increasing temperatures, melting sea ice, liquifying land glaciers, rising sea levels, thawing permafrost, ecosystem changes, and ocean acidification. Climate change most adversely impacts coastal regions where indigenous and wider communities have existed for some time, where human infrastructure has been built and where significant biodiversity exists.

Efforts to address climate change in Canada's Arctic involve a combination of global mitigation strategies to reduce greenhouse gas emissions and local adaptation measures to cope with the changes that are already underway. These local adaptation efforts must be targeted at areas of highest impact and greatest need.

Spatial data is key to studying, analyzing, visualizing, and researching climate change impacts in Canada's Arctic. Various topographic, hydrographic, ecographic, and geographic communities are continuing to investigate the use of Spatial Data Infrastructure (SDI) best practices for increasing the interoperability of GIS systems and streamlining the exchange of land and marine geospatial data assets for important coastal zone applications such as coastal zone erosion, climate change impacts, maritime navigation safety, and coastal infrastructure monitoring.

In particular, the Marine Spatial Data Infrastructure (MSDI) is the IHO initiative to develop the marine component of an SDI for data sharing. Specifically, the MSDI is a framework of suggested best practices and guidance for the management of marine geospatial data, underpinned by key principles such as standards, interoperability support, data integration, institutional collaboration, and data coordination. A Federated MSDI (FMSDI) adds the important dimension of a federated model as part of the overarching MSDI framework that will allow diverse organizations to share geospatial data from various SDIs for a common good. The FMSDI development will help improve the efficiency and quality of coastal area decision-making by supporting governments, agencies, NGOs, private companies, and citizens to unlock valuable investments in existing and recent spatial and observation data at national, regional, community, and local levels.

Many governments and organizations have recognized that spatial data and related information collected to produce navigational charts for supporting navigation safety are also useful for many other applications including the study and management of the ocean, marine, and coastal environments. In addition, many other valuable thematic land, maritime, coastal, marine, and oceans data layers are independently being collected but are not necessarily being widely used because access to them is limited and data integration is technically challenging meaning that the modern FMSDI must support the wider and less traditional base of marine data and maritime data users.

Background

Esri Canada is a private Canadian-owned company founded in 1984 that provides world-class enterprise GIS solutions. It is headquartered in Toronto and has 15 offices across the country serving 12,000+ customers. Esri Canada delivers geospatial solutions based on ArcGIS, the world's leading GIS software. Esri Canada solutions empower people in business, government, and education to make informed and timely decisions by leveraging the power of mapping and spatial analytics. Esri Canada provides expertise and solutions across many industries including: defense, security, government, public health, land, property, maritime, natural resources, public safety, transportation, and utilities.

The OGC FMSDI-23 project is important to Esri Canada as it will help show leadership in the use of modern geospatial technology, standards, and approaches to finding and combining land and marine spatial data across the Canadian Arctic regions. The goal of this work was to demonstrate how spatial data could be used to analyze and visualize the impacts of climate change on the environment, infrastructure, and inhabitants of Arctic coastal regions.

3.1.2.1. Approach

This project implements a complete end-to-end demonstration of a climate change scenario for the Canadian Arctic coast. The project demonstration website demonstrates how geospatial data/information can be used in an operational context within the parameters of the Arctic coastal sensitivity to climate change use case through modern geospatial interoperability approaches.

This task leverages Arctic data portals to create a seamless multidimensional “Digital Arctic” that links the land, atmosphere, and marine Arctic domains within an integrated platform. The concept of a Digital Arctic occurs over multiple dimensions of space and time. The dimensions comprise location (X, Y, or other coordinates), elevation/bathymetry/altitude, time, and flows to measure pathways and directions (e.g., currents, migration, icebergs, ice flows, etc.). This work relates to and builds on other ongoing emerging technologies such as metaverse and digital twin.

3.1.2.2. Methodology for Discovery and Integration of Data

The data discovery portal builds on previous work efforts supporting the Government of Canada and its Spatial Data Infrastructure. In particular, this work effort leverages the following.

- OGC FMSDI-23 Pilot Project, Thread 2 -Arctic GitLab Data Resources Site
- Arctic Data Committee Portal
- NWT Geospatial Data Discovery Portal
- GeoYukon Data Discovery Portal
- Arctic SDI GeoPortal
- NRCan Earth Observation Data Management System (EODMS)
- Conservation of Arctic Flora and Fauna (CAFF) Data Portal
- NRCan Geospatial Web Services Harvester for the CGDI
- OGC FMSDI Compusult Catalog

3.1.2.3. Solution Architecture

The Digital Arctic demonstration site provides access to existing catalog portals that contain Arctic climate change related data. Data or web services can be searched, evaluated, and accessed by users that incorporate disparate sources of information applicable to the Arctic SDI use cases.

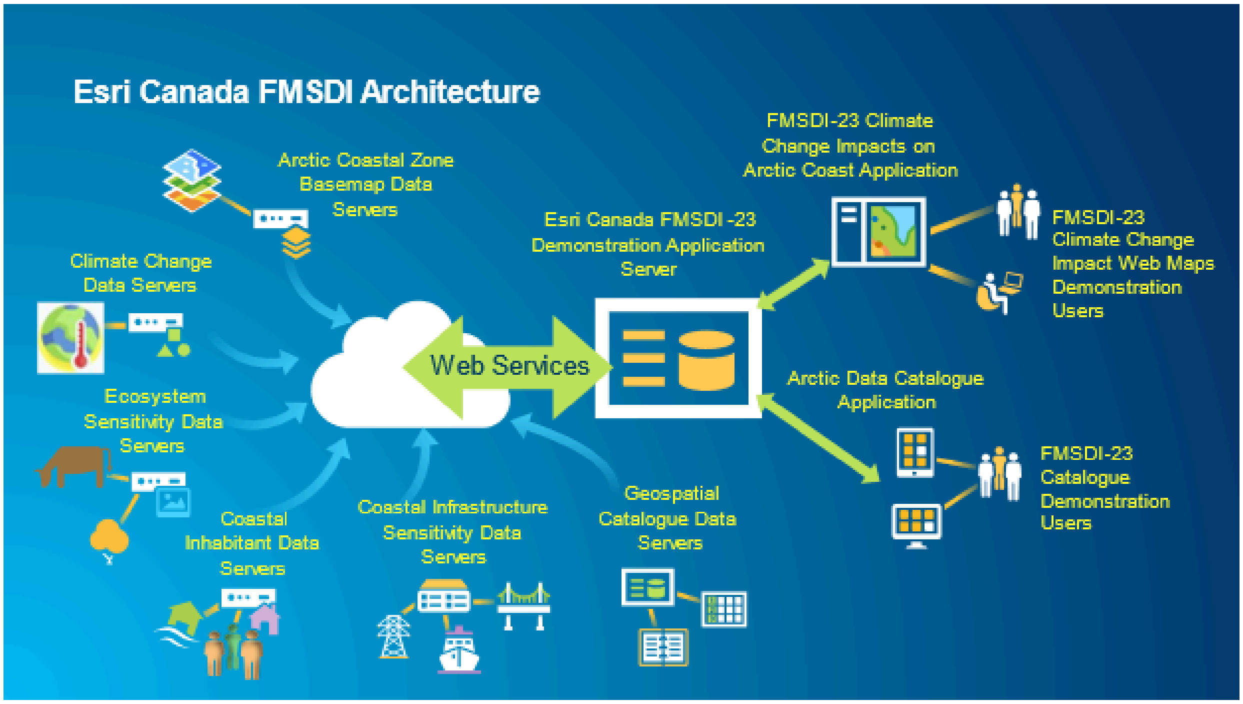


Figure 21 — ESRI Demonstrator Solution Architecture

A 12nm (22.2 km) buffer zone is calculated on water and on shore representing the coastal zone used for visualization and analysis. The coastline is noted in reddish brown; the 22.2 km landward coastal zone is noted as pink; and the 22.2 km marine seaward coastal zone is noted as blue.

Figure 22 — Visualization of Canadian Arctic Coastal Zone

The resultant platform provides a series of online maps that can be used for Arctic climate change studies and includes services with the following capabilities.

- A persistent public demonstration group site is available on ArcGIS Online entitled "FMSDI 2023 Public Demonstration group" at https://esrica-ncr.maps.arcgis.com/home/group.html?id=5c69123818b94b4ebf85370a75e6b404#overview.
- A bilingual FMSDI data discovery portal for searching and finding Arctic geospatial data.
- An Arctic coastal zone base map showing the coastline, coastal areas, topographic, hydrographic, and imagery base maps, including NRCan's CanCoast 2.0 data.
- A Web map showing the sensitivity level to climate change of the entire Canadian Arctic coastline. Supporting layers include sea level change, ground ice, and wave height.
- A Web map showing locations of human dwellings and residential infrastructures in the Canadian Arctic in reference to the 12 Nautical Mile coastal zone on land and in the water as defined for this application.
- A Web Map showing locations of transportation and infrastructure features in the Canadian Arctic in reference to the 12 Nautical Mile coastal zone.
- A Web map showing Canada's marine protected and conserved areas and five bioclimatic subzones based on climate and vegetation in the lowlands.

- A coastal ecosystem sensitivity map based on selected data from the Conservation of Arctic Flora and Fauna (CAFF) web services.
- A map of Tuktoyaktuk, Northwest Territories displaying a 3D sea level change feature layer with the sea level increase value extruded from the average elevation of each line segment.

Coverage Dimensions

Table 5 — D132 Coverage Dimensions

Spatial Coverage	The Canadian coastline from the Alaska border in the Western Arctic to the Quebec, Newfoundland and Labrador border in the East. It also included all the northern islands and the Hudson Bay coastline
Temporal Coverage	The majority of the data sets used in this demonstration contain data that represents current or near current conditions. However, the CanCoast data has two representations of sea level change, one for the time period 2006 to 2020 and the other for the time period 2006 to 2099. The Arctic Sea Ice Extent data covers the time period from 1978 to 2023.

Data and Platforms

The web maps build on the following data products and sites.

- Esri (Living Atlas):
  World Topographic Basemap; Imagery Basemap; Arctic Sea Ice Extent; OpenStreet 3D buildings; WorldElevation3D/Terrain3D
- CanCoast 2.0:
  Arctic Shoreline, Backshore Slope, Coastal Materials, Tidal Range, and 12 NM Coastal Zone Manson, G.K., Couture, N.J., and James, T.S., 2019. CanCoast Version 2.0: data and indices to describe the sensitivity of Canada's marine coasts to changing climate; Geological Survey of Canada, Open File 8551, 1
- Natural Resources Canada:
  Permafrost Atlas of Canada
- Fisheries and Oceans Canada:
  Canada's marine protected and conserved areas
- Government of Canada:
  First Nations map; Census Subdivisions 2016 map; CanVec Man-Made Features map; CanVec Transportation map; CanVec Resources map
- Conservation of Arctic Flora and Fauna (CAFF):
  Bioclimatic subzones of the Arctic territory map; Identification of Ecologically and Biologically Significant Areas map; Arctic Species Trend Index map; Arctic Protected Areas
- Arctic Research Mapping Application:
  Elevation and bathymetry

Standards & Interoperable Technologies

- OGC WMS — for displaying static map information
- OGC WFS — for displaying and analyzing map information
- ArcGIS REST — for displaying and analyzing map information
- OGC WMTS — for displaying basemaps
- Shapefile — for data files not available as a web service

3.1.2.4. Challenges & Future Work

- **Coastal Zone Analysis**

One of the dilemmas of performing spatial analysis of the coastal zone is that there is no common definition of what the coastal zone should be. The document published by Natural Resources Canada entitled "Canada's Marine Coasts in a Changing Climate" gives some specifics on the coastal zone in the section on defining coasts.

+ The document indicates "Derived predominantly from fisheries management and international marine law, the coast is often described as a zone or area along a shoreline, largely marine in focus, whose landward boundary is either determined by the highest anticipated inland intrusion of seawater or designated as a specified distance from the shore, and whose marine boundary extends to the limits of national territorial seas (i.e., 12 nautical miles [nm] seaward from the shore)." For simplicity this project expressed the coastal zone as 12nm seaward and 12nm landward.

+ image::esri-1.png[title='Coastal Zone Terms & Definitions: NRCan', role="center half-width", width=60%]

- **Usability**

The Arctic SDI WMTS topographic basemap orients topographic names fixed to certain projections limiting the user experience within an integrated mapping platform. This limitation may affect the use of and publishing of maps derived from multiple information pipelines in which certain basemaps may properly rotate annotations based on the map portrayal.

+ image::esri-4.png[title='Arctic SDI WMTS basemap', role="center half-width", width=60%]

3.1.3. D133: Health Risk Indicators of microplastics in the environment and the effect on coastal communities

Bioaccumulation of microplastics and toxins in marine organisms are increasing across the Arctic. These foreign materials are ingested by species at all levels of the food chain and ultimately accumulate to levels dangerous to human health. In the past decade, microplastics have been found in several marine ecosystems around the world and there have been samples of microplastic composition and concentration from Fram Strait and Central Arctic (Peeken et al. 2018).

Several studies have shown ingestion of microplastics in fish and shellfish (Hwang et al. 2020). These microplastics typically come from production contamination and contamination from plastic packaging. The microplastics that are less than 130 µm in diameter can potentially enter human tissues, which could release toxic chemicals that are added during plastic production (Cox et al., 2019). There are two types of microplastics, primary and secondary. Primary microplastics come from products that are directly made with microplastics, such as hand washing soaps, cleansers, or biomedical products (Hwang et al. 2020). Secondary microplastics are particles produced through the fragmentation of plastic litter. Secondary microplastics are particularly concerning because they could act as vectors for pathogens. Secondary microplastics have been referred to as “cocktail of contaminants” that are associated with persistent organic pollutants (POPs), heavy metals, and plastic additives.

After a human consumes fish or mammals that have ingested microplastics, it is possible that microplastics can enter the human’s bloodstream which could cause local inflammation or an allergic reaction in tissues. Digestive-level health effects could occur from microplastics, some colonic microbiota could adhere to microplastics, causing biofilms to form. To fully understand the effects of colonic microbiota, there are in vitro and in vivo approaches needed. The study reported by Tamargo et al., 2022 may be the first report of human colonic microbiota, as it has been seen that microplastics colonize in different human gut microbial species, such as Escherichia coli, Pseudomonas aeruginosa, and Staphylococcus epidermidis by sticking to and producing biofilms on diverse plastic material surfaces such as polyethylene, polypropylene, and polystyrene which is concerning as microbiota colonization could increase pro-inflammatory and disease-related bacterial groups, disrupting intestinal homeostasis.

Heavy metals, such as mercury, which is a neurotoxin, could also increasingly become an issue as climate change continues. A study from University of Alberta shows that caribou herds along the coast are eating lichen that are contaminated with mercury from the marine ecosystem (Wohlberg 2015).

Mercury can affect an individual’s health differently depending on several factors; what form the mercury is in, such as methylmercury versus elemental/metallic mercury, the amount of mercury in exposure, and age of exposure, for example unborn infants are the most vulnerable (United States Environmental Protection Agency, 2023b). Researchers have found permafrost is storing a substantial amount of methylmercury (Schuster et al. 2018). Permafrost is thawing due to climate change which is creating an increasing concern on the amount of methylmercury that could be released into the environment, as it could not only have an impact on human health, but also on local ecosystems.

Another type of toxin, POPs, have been found in Arctic animals. Consuming foods containing POPs increases the likelihood of developing respiratory illnesses, cancer, or birth defects (Robinson 2018). Highly toxic POPs are no longer allowed to be released in the environment, but levels of some POPs are still being measured in the Canadian Arctic (Boutet, 2023).

Animals that occupy the top of the food chain, such as polar bears, are exposed to contaminants such as POPs, mercury, and other heavy metals from their diet (Boutet, 2023). Polar bears are also a source of food for the Inuit. Ringed seals, a key source of food for polar bears, are known to accumulate POPs. There are several reasons why POPs and other contaminants are still found in the atmosphere. The POPs could be transported through short and long-range atmospheric transport, industrial activities such as petroleum extraction, and traveling due to major air currents (Boutet 2023). Biomonitoring can help track ongoing changes in an ecosystem.

Microplastics and toxins may continue to be seen in the environment unless drastic policy changes are implemented across the world. Microplastics monitoring of several fish species has recently occurred in the Arctic, including Canadian Arctic, and microplastics were found in Arctic char, which is a main source of food for the Inuit. There is a need to better understand the impact on the health of the Inuit and others who rely on fish as a primary food source.

Background

HSR.health is a company based in Rockville, Maryland, USA that has developed a novel GeoMD Platform that utilizes AI to draw conclusions from geospatial health data. HSR.health has created several Health Risk Indices (HRI) for public health initiatives associated with disaster and emergency response and social determinants of health. For this project, HSR.health utilizes Earth Observation imagery to identify plastic and microplastics in the Canadian Arctic and creates a risk index correlated to the indigenous populations and estimates of adverse health outcomes due to bioaccumulation which is especially important for Arctic communities which often rely on local fishing as a primary food source given the difficulty in transporting supplies and resources in and out of the Arctic.

The indicator provides several benefits. It identifies communities at-risk for adverse short and long-term health outcomes from bioaccumulation exposure; supports intervention policy makers responsible for monitoring health impacts; and provides the basis for the design of policies to better manage microplastics pollution, especially near regions with vulnerable populations. This indicator serves as a persistent health demonstrator for the Federated Marine Spatial Data Infrastructure (FMSDI).

3.1.3.1. Approach

To identify populations vulnerable to bioaccumulation, a weighted combination of factors influencing vulnerability is developed based on past and current public health research. Additionally, remote sensing techniques are used to identify the presence of surface plastics in the waters surrounding the study area.

Due to the sparse populations in the Canadian Arctic, the Risk Index is rasterized and merged with two and a half minute gridded populations to illustrate the degree of vulnerability of remote communities.

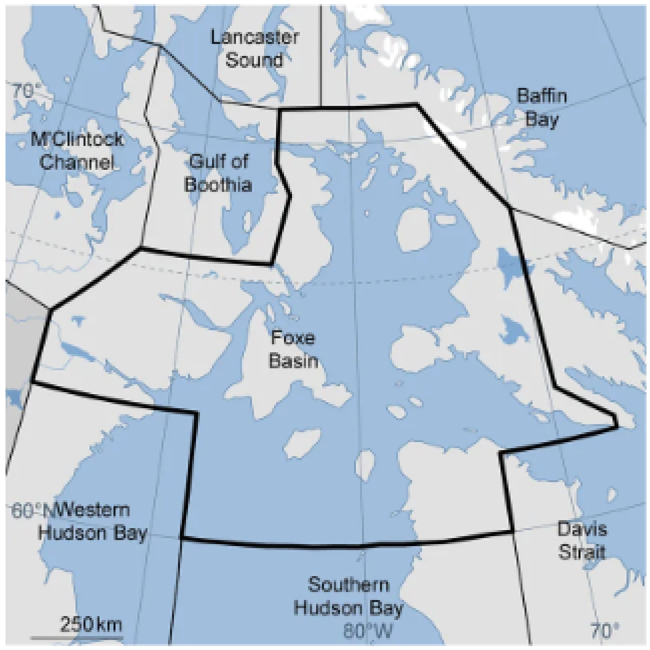


Figure 23 — HSR Coverage: Foxe Basin; 2021

3.1.3.2. Methodology for Discovery and Integration of Data

To initially discover the health and social data necessary for the calculation of the indicator, search engines like Google and queries to generative AIs such as ChatGPT are utilized to find the source organizations and repositories of the health and social data needed.

Social data for the Canadian Arctic is provisioned through multiple administrative levels available from Statistics Canada. Health data is sourced from the Canadian Chronic Disease Surveillance System albeit this information is only available at the national and provincial level.

There is often a limitation with the granularity of publicly available health outcomes data for privacy considerations which limits some of the explanatory power of the indicator at lower granularities than what is available for the health outcomes data which can be especially impactful for sparsely populated areas like the Canadian arctic.

The Bioaccumulation Risk Index and Plastic Presence analysis demonstrates a potential integration of EO data of marine environments with health and social data of land environments. Future additions to the indicator can incorporate fish migration patterns, fishing areas, and broad supply chain insights to directly tie the plastic presence to the at risk populations on land.

3.1.3.3. Solution Architecture

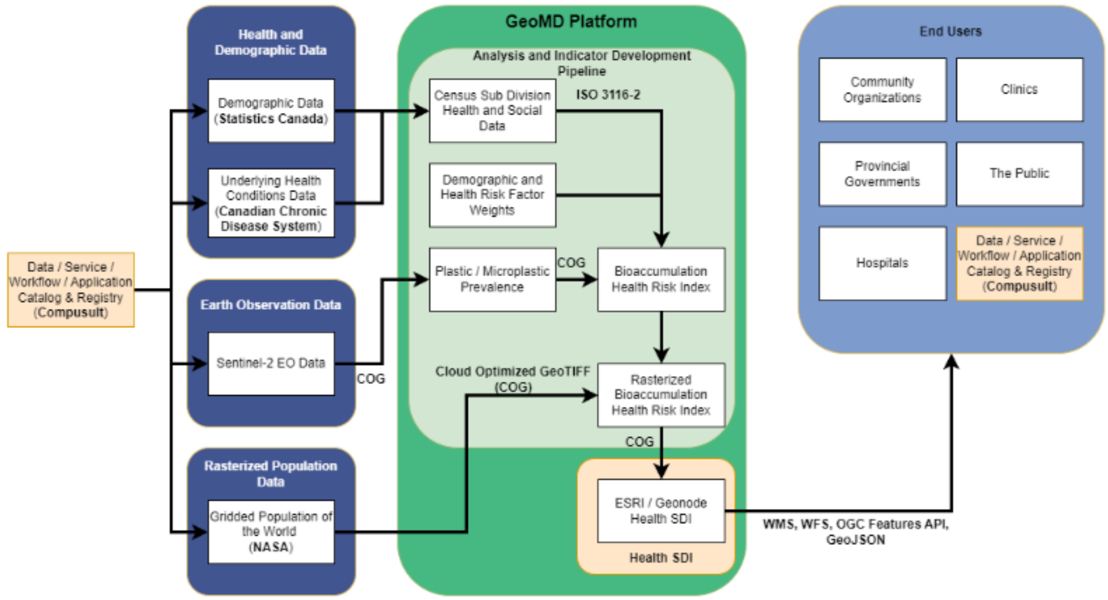


Figure 24 — HSR Solution Architecture

The Microplastic Bioaccumulation Health Risk Index is calculated through a weighted combination of the health and social characteristics of the population. Some of the primary indicators are the population under 10 years old and over 65 years old, as well as the prevalence of cancer, diabetes, and COPD. These indicators have been determined through reviewing several studies and finding consistent information on some of the health data included from the Canadian Chronic Disease Surveillance System are available for 2018 through Canada Open Data. The factors to include in the analysis and the weightings for each factor are determined through input from the HSR public health team based on published research. Sentinel-2 Imagery is processed through a map algebra process from published research to identify plastic and microplastic presence in the Canadian Arctic. The Health Risk Index and plastic prevalence indicators together provide the information for the end users to make a decision.

Within the Canadian Arctic, the populations that live in the region are sparse. To address this issue, the Bioaccumulation Health Risk Index is rasterized and combined with a two and a half minute gridded population of the world raster. In the following image, the black spots in the raster represent areas of population.

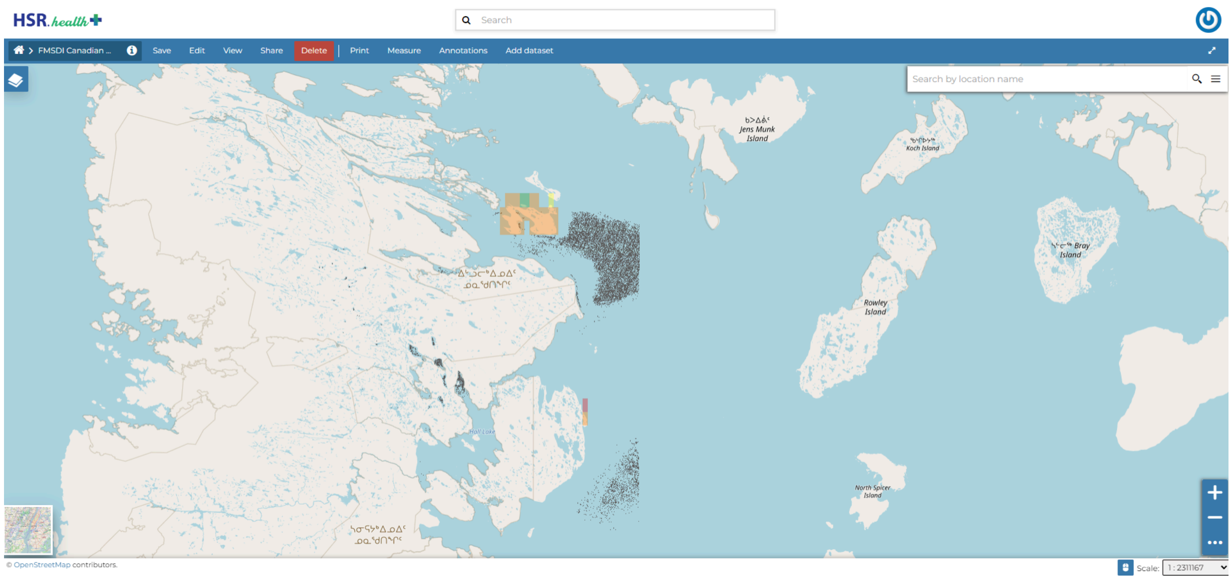


Figure 25 — HSR Bioaccumulation Health Risk Index

The Bioaccumulation Health Risk Index for the census subdivision level is published to the Health Spatial Data Infrastructure of the Open GeoMD Platform. The Open GeoMD Platform and the indicators that it hosts serve as the persistent demonstrator for the FMSDI pilot along with publishing of the indicators to the OGC Records catalog. The platform provides access to the indicators and persistent demonstrator through OGC open standards including the Web Mapping Service (WMS), the Web Feature Service (WFS), and the OGC Features API.

Data and Platforms
For the analysis of earth observation imagery for plastic and microplastic detection, the area of concern focused on the Foxe Basin. The data sources utilized for the analysis included Sentinel-2 Imagery, the Canadian Census Mapper API, the Canadian Census Bureau, and the Canadian Chronic Disease Surveillance System.

Standards & Interoperable Technologies

The Health Risk Index and associated data is published as a service hosted by the GeoMD Platform. Other spatial data infrastructures and data catalogs are made available through the pilot which will also be available through OGC API, Web Map Services, and Web Feature Services to be shared with stakeholders and participants.

3.1.3.4. Challenges & Future Work

- **Health Risk Indexes & Indicators**

Research on microplastics is relatively new and has not been studied thoroughly enough to know definitive health outcomes after exposure.

+ There is a need for more longitudinal studies that are done in vitro as well as in vivo to better understand the effects. Due to the novel nature of this topic, the hypothesized health outcomes are based on the research that is available to create a Health Risk Index. As more information is gathered and studies are released, this project may need to evolve and adapt.

- **Geospatial extensions to Health Standards**

Social and health data utilized for the health risk index are affected by a lack of accepted standards that align with the geospatial and temporal standards of OGC. Research continues to identify opportunities to extend such relevant standards as ISO 3166-2, ISO/TC 215 Health Informatics, and HL7 with the OGC Feature and Coverage model.

- **Health Data Granularity**

There is often a limitation with the granularity of publicly available health outcomes data for privacy considerations which limits some of the explanatory power of the indicator at lower granularities than what is available for the health outcomes data. More discussion is necessary across the geospatial, health, and security sectors to discuss how access to more granular, but anonymized and aggregated, health data can be made available for analysis.

3.1.4. D134: Satellite-derived Essential Climate Variables with application to Large Marine Ecosystems and Protected Areas

The Arctic region is home to a diverse population of species adapted to a cold and harsh environment, many of which directly support the traditional cultures of indigenous peoples. Directly affected by climate change, the environment on which these species depend is rapidly changing and has a profound effect on local populations and related ecosystem services. As habitats change, pressure increases for species to migrate to new areas or face increased competition from predatory and invasive species — described as the “conveyor belt of extinction” (Goedkoop, et al., 2022a).

Land cover change (LCC) affects the capacity of a defined ecosystem to support its native community. A rapidly warming Arctic is increasingly transitioning from multi-year ice cover to seasonal ice sheets dominated by younger and thinner ice cover. The extent and stability of sea ice is shrinking across seasons, but especially in the summer. The Arctic Ocean is projected to be virtually ice-free in the summer months within 30 years with the remaining multi-year ice persisting primarily between islands of the Canadian Arctic Archipelago and in the narrow straits between Canada and Greenland. Declining sea ice threatens some Arctic human societies, notably coastal Indigenous Peoples who depend on ice for harvesting and travel and whose cultures and food security are centered on sea ice and its biodiversity. Reduction of sea ice also accelerates new and expanded activities related to resource extraction, shipping, fisheries, and cruise-ship tourism — each of which carry substantive pressures to Arctic marine flora and fauna.(CAFF Life Linked to Sea Ice).

Protected areas are a key element for maintaining and conserving Arctic biodiversity and the functioning landscapes upon which species depend. Arctic protected areas are strategically important and represent those regions providing essential ecological features. However, with the rapid change to sea ice cover, especially in the transitional realms between land and sea, monitoring the ecosystem services dependent on sea ice takes on a new priority to protect migration routes and calving areas and the critical components of marine mammal habitats.

Background

Pelagis is an OceanTech venture located in Nova Scotia, Canada whose foundation focuses on the application of open geospatial technology and standards designed to promote the sustainable use of Earth's ocean resources. As a member of the Open Geospatial Consortium, Pelagis acts as co-chair the OGC Marine Domain Working Group (MarineDWG) responsible for developing a spatially-aware federated service model for marine and coastal ecosystems. Pelagis' immediate priority is the development of a federated marine reference model based on the core OGC standards in support of Nature-based Climate Resilience initiatives.

3.1.4.1. Approach

CAFF (Conservation of Arctic Flora and Fauna) is the biodiversity working group of the Arctic Council. CAFF's mandate is to address the conservation of Arctic biodiversity, and to communicate its findings to the governments and residents of the Arctic, helping to promote practices which ensure the sustainability of Arctic resources. It does so through various monitoring, assessment and expert group activities (CAFF-about).

Monitoring programs for Arctic biodiversity is a difficult challenge for observers to design and maintain. To facilitate targeted and consistent reporting, CAFF sponsors the Circumpolar Biodiversity Monitoring Programme (CBMP), a coordinating entity made up of a scientists, government, indigenous communities, and conservation groups. The CBMP is organized around the major ecosystems of the Arctic — marine, freshwater, terrestrial, and coastal and represents the official Arctic Biodiversity Observation Network (Arctic BON) of the Group on Earth Observations Biodiversity Observation Network (GEOBON). GEOBON is a global biodiversity observation network that coordinates observations to enhance management of the world's biodiversity and promote both the awareness and accounting of ecosystem services.

The CBMP has designed a set of indices and indicators that provide a comprehensive picture of Arctic biodiversity, from species and habitats to ecosystem processes and ecological services. The suite of indices and indicators are used to report on the current state of Arctic biodiversity at various scales and levels of detail (CAFF Strategy for Indices and Indicators). A summary of the CBMP biodiversity indices and indicators may be found in Annex D.

This project demonstrator explores the role of remote sensing to complement the set of in-situ monitoring programs to derive the essential variables that make up the CBMP suite of indices and indicators. Specifically, the project evaluates the use of the ICESat-2 Earth observation mission to enrich the view of land cover change related to the thinning sea ice extents of designated protected areas of the Canadian Arctic.

3.1.4.2. Discovery Methodology

The Arctic Council stresses the importance of an Ecosystem-based Management (EBM) approach to monitoring the relationship between human activities and the sustainable use of Arctic resources. An Ecosystem-based Management methodology involves the integrated management of human activities based on best available scientific and traditional knowledge about the ecosystem and its dynamics, in order to identify and take action on influences that are critical to the health of ecosystems, thereby achieving sustainable use of ecosystem goods and services and the maintenance of ecosystem integrity.

The emphasis of the Arctic Council EBM is on *monitoring* features and inherent relationships to the effects of human activities on regional ecosystems. The monitoring of spatial entities and related observations is central to the Observations, Measurements and Samples 3.0 standard and the OGC Connected Systems initiative. The former focuses on a *consumer* oriented approach to monitoring networks while the latter is focused on the *provider* centric approach.

Both of these specifications are evaluated as part of the Discovery process to abstract the EBM approach to ecosystem monitoring with a more generic *Observer ←→ Feature of Interest* model. Current work efforts within the OGC OMSv3 and OGC Connected Systems working groups are focused on the topic of discovery and catalog management. Of note, although outside the scope of this initiative, is the current OGC Testbed-19 workplan and the GeoDataCube (GDC), Analysis Ready Data (ARD), and Transfer Learning pilots. Each of these initiatives involves some aspects of Discovery that will be applicable to the Digital Arctic project.

Arctic BON Resources

The CAFF Circumpolar Biodiversity Monitoring Program maintains an open data portal publishing the observational results of each monitoring program. Using this framework, an observer model is developed to identify and define specific features of interest and related observation streams. Each CBMP service endpoint provides an OGC WFS capabilities interface to describe the metadata associated with the features and associated observable properties. Of interest to this project is the Arctic Biodiversity Data Service (ABDS) providing a collection of features designated as Protected Areas. The Canadian-managed protected areas are modeled as a *OMSv3::Feature of Interest* and provide context for the land cover change analysis.

Satellite Derived Observations

ICESat-2 observation data are managed through the National Snow & Ice Data Center (NSIDC) with its own specific discovery service. NSIDC publishes earth observation datasets based on the polar orbit of the ICESat-2 satellite separating each ground track revisit into separate data granules. There are 1387 reference ground tracks in the ICESat-2 repeat orbit. The reference ground track increments each time the spacecraft completes a full orbit of the Earth and resets to 1 each time the spacecraft completes a full cycle. Metadata specific to each polar orbit is maintained as a queryable and discoverable service identifying specific data granules based on spatial and temporal extents. A spatial query provides reference to the available data granules with reference ground tracks (RGTs) that intersect the extent of a feature of interest. Once established, temporal queries are available to isolate the set of data granules representing each ground track revisit.

The Copernicus Climate Data Store (CDS) is a funded program through member states of the European Commission and implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF). The service provides both an online toolbox and an application service to introspect climate data products based on product type, variable domain, spatial coverage, temporal coverage, sector, and provider. CDS datasets include observations, historical climate data records, derived Essential Climate Variables (ECVs), global and regional climate reanalysis of past observations, seasonal forecasts, and climate projections. Each data product is assigned a digital object identifier (DOI) and is accessible using the ISO-19115 metadata record standard and the OGC Catalogue Service protocol.

3.1.4.3. Solution Architecture

The Pelagis application service (AS) is a federated query service over a domain-specific information model. This approach obfuscates the complexity of multiple backend data services allowing analysts to focus on 'what' information and relationships are important to a subject and not requiring extensive development skill sets to access and combine multiple, provider-specific, data products.

The first stage of the Digital Arctic project provides for the seamless navigation between the CAFF monitoring programs and the earth observation data programs. The solution is implemented as a series of Jupyter notebooks with each breaking out query capabilities providing key variables supporting the set of CBMP Indices & Indicators for land cover change, protected areas, and trends in habitat change.

Extending this project is the effort to position the OGC GeoDataCube concept, and related OGC ARD initiative, to effectively create a *Digital Earth for Arctic* service providing an extensible and scalable platform for complex analysis of Arctic biodiversity. This stage of the project is aligned with the OGC Testbed-19 pilot and represents a collaborative effort between members of this initiative.

3.1.4.3.1. Overview

Validation of the first stage of development focuses on the Canadian set of protected areas. Testbed scenarios are developed specific to the Ninginganiq National Wildlife Area over the temporal period of 2015 through 2023. The period of sea ice observations are seasonal and correlated to the northward equinox to provide sea ice height measurements prior to summer warming. Of note is that summer ice observations are prone to error as sea ice melt affects the determination of sea ice freeboards. For reference, see Lu, P., Li, Z. (2014)

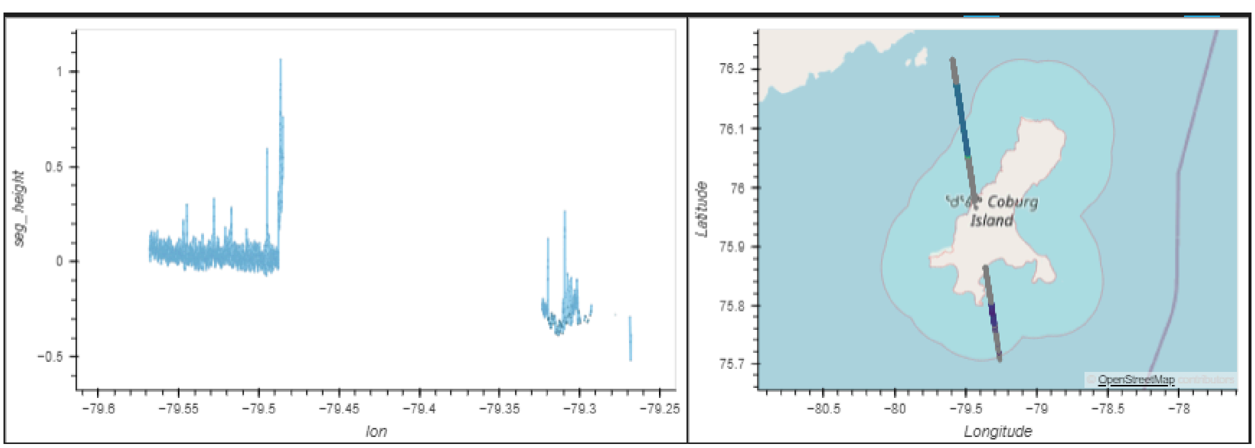


Figure 26 — Sea Ice Height Observations over the Ninginganiq National Wildlife Area - April 2022

3.1.4.3.2. Coverage Dimensions

Table 6 — D134 Coverage Dimensions for Ninginganiq National Wildlife Area

Spatial Coverage	Ninginganiq National Wildlife Area
Temporal Coverage	Seasonal [vernal equinox: 2018 — present]
Vertical Datum	Sea Ice Height relative to the tide-free mean sea surface
Scientific Research Lifecycle Management	The use of a GeoDataCube framework based on Testbed-19 provides a named and immutable analysis ready dataset (ARD) produced through a WCPS service endpoint.
Flow Vectors	For the purpose of this experiment, a 'vector of flow' is liberally defined as the rate of change in sea ice height above MSS relative to the geo-position (lat, lon, crs=WGS84, epsg:4326) of the along-track observation. See OGC Moving Features for more information.

3.1.4.3.3. Data and Platforms

- **PAME**

The Protected Areas of the Marine Environment service endpoint provides the designated protected areas of the Arctic region. Canadian-designated protected areas are filtered from the service endpoint representing the feature of interest for further analysis.

- **ICESat-2 ATLAS**

The ICESat-2 mission carries the Advanced Topographic Laser Altimeter System, or ATLAS sensor, which times the travel of laser pulses to measure the elevation of Earth's surface ICESAT-2 Mission Information Portal. The raw observation data is processed into a suite of Analysis Ready Dataset (ARD) products beginning with the ATLAS/ICESat-2 L2A Global Geolocated Photon Data data product. This dataset processes the raw observation data into a geo-corrected data product containing the height observations above the WGS84 ellipsoid.

The ATLAS/ICESat-2 L3A Sea Ice Height data product contains along-track heights for sea ice and open water leads relative to the WGS84 ellipsoid after adjustment for geoidal and tidal variations and inverted barometer effects. Height statistics and apparent reflectance are also provided to determine the category of sea ice.

- **Copernicus C3S Arctic Regional Reanalysis (CARRA) West**

The CARRA West dataset contains 3-hourly analyses and hourly short term forecasts of atmospheric and surface meteorological variables (surface and near-surface temperature, surface and top of atmosphere fluxes, precipitation, cloud, humidity, wind, pressure, snow, and sea variables) at 2.5 km resolution. Additionally, forecasts up to 30 hours initialized from the analyses at 00 and 12 UTC are available. The CARRA West domain covers Greenland, the Labrador Sea, Davis Strait, Baffin Bay, Denmark Strait, Iceland, Jan Mayen, the Greenland Sea, and parts of Svalbard.

In this use case, the CARRA West dataset is loaded into a GeoDataCube environment and processed to visualize the change in albedo for the region extending around the Ninginganiq National Wildlife Area. As apparent, the change in albedo between the period of May 2020 and April 2023 is substantial in the southern extent while the changes specific to the Ninginganiq National Wildlife Area have remained relatively stable.

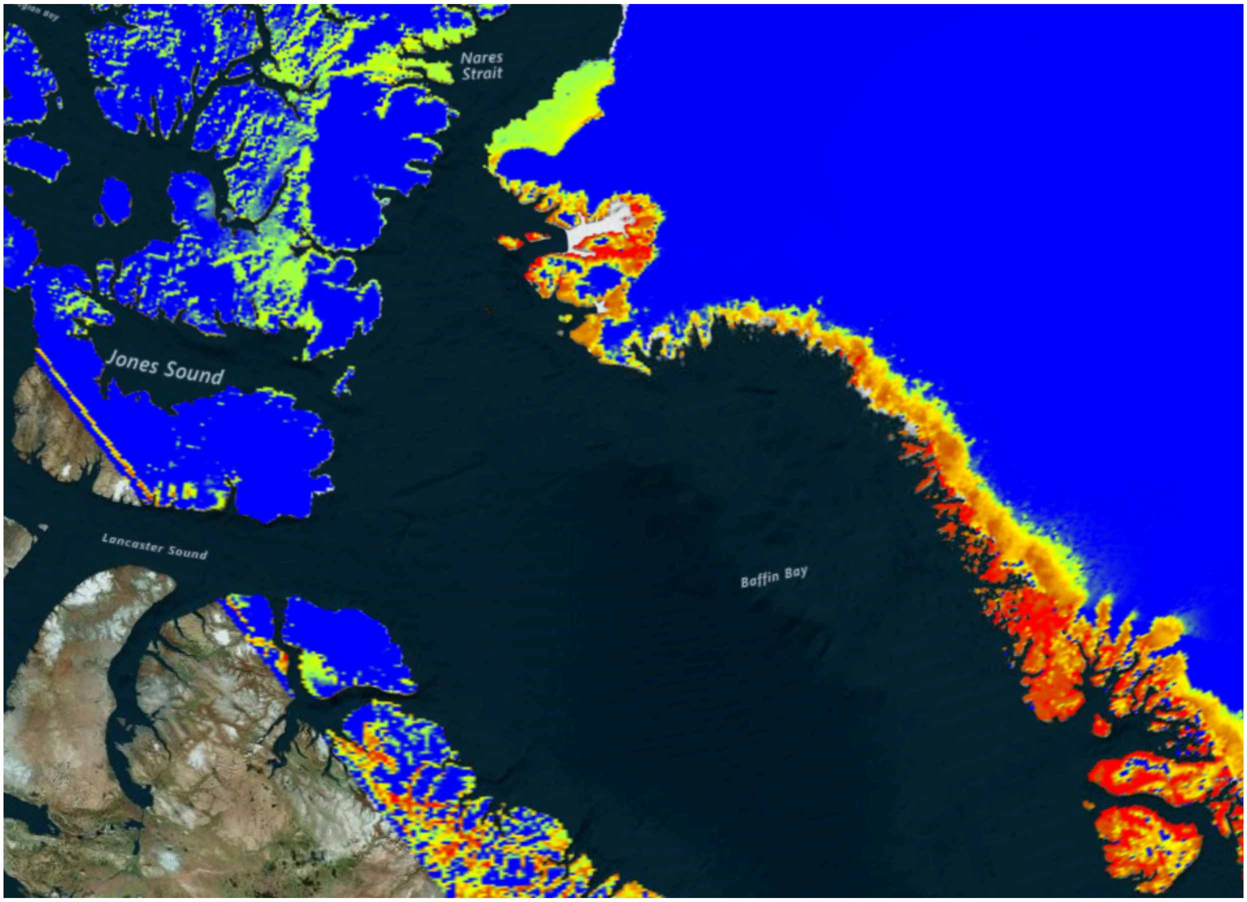


Figure 27 — Albedo as an Essential Variable of the Arctic

3.1.4.3.4. Standards & Interoperable Technologies

The following standards and interoperable technologies were evaluated as part of the Digital Arctic theme.

- **OGC Moving Features**

The OGC Moving Features specification defines a standard encoding for features in motion. Testbed-18 extended this model to include observation collections made along a trajectory by an observer. Continuing to extend the principles of the Moving Features specification, this project uses terms defined by OGC Connected Systems to model the ICESat-2 satellite as a *platform* hosting the ATLAS sensor. The *Reference Ground Track* represents the movement of a 'virtual' observer traveling along the earth surface providing height *observations* against a *Feature of Interest* with *observable property* 'sea ice height.'

Leveraging the Moving Features model to encode the sea ice height observations of ATL07 allows client applications to ingest the surface height trajectory and apply trajectory based analysis directly against the observation collection. For example, the ATL07 revisit to the Ninginganiq National Wildlife Area may be down-sampled to intervals of 1/10th of a second with the Moving Pandas Python library.

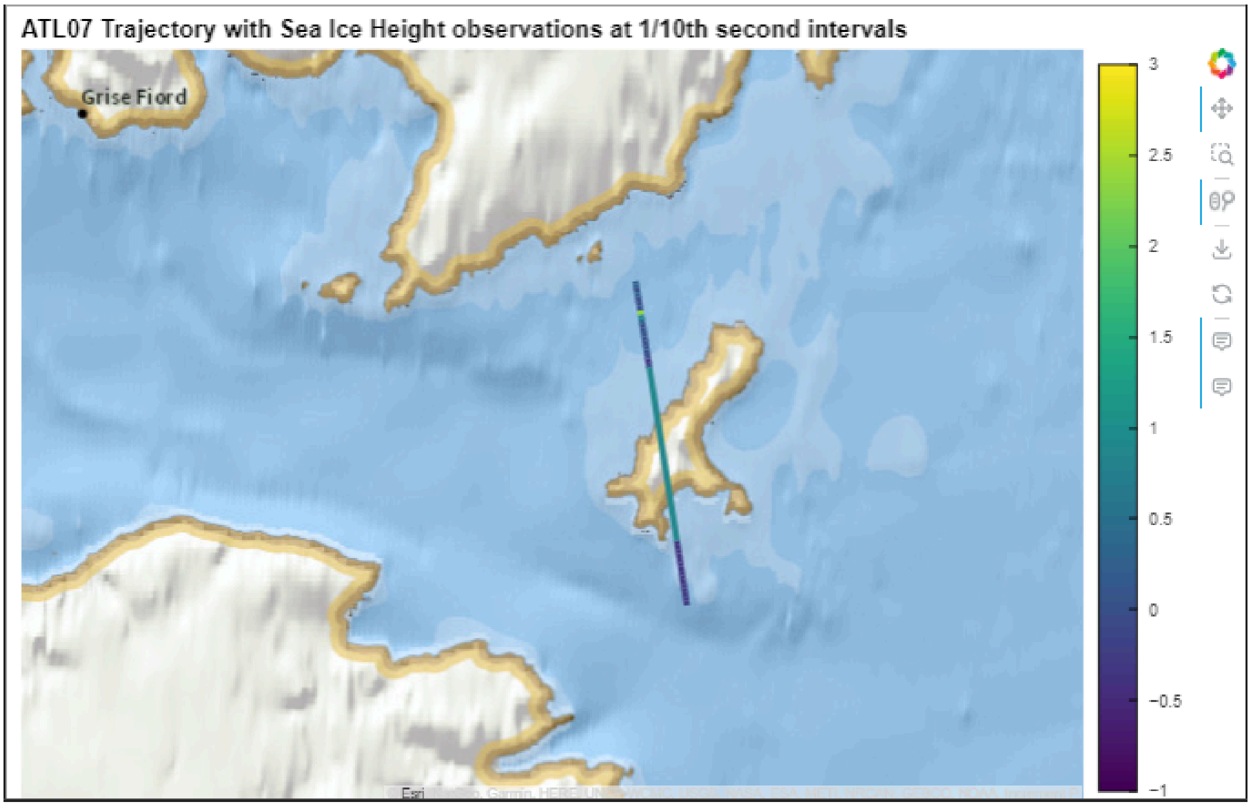


Figure 28 — Downsampled Sea Ice Height Observations over the Ninginganiq National Wildlife Area - May 2019

3.1.4.4. Challenges & Future Work

- **Spatial Resolution**

Analysis of regional biodiversity indices and indicators requires a finer resolution of processed satellite-derived observation datasets. Level 3 processed earth observation data products tend to lose their fidelity to offset exponential storage costs. As an example, the Copernicus ERA5 global reanalysis data product is provided as a 31km gridded coverage. Arguably, this resolution

is not useful as a regional monitoring program for studying the localized habitats of dependent species. The Copernicus CARRA data product provides a horizontal resolution of 2.5km albeit with a significantly reduced coverage area while the ICESat-2 ATLAS sensor provides raw, geolocated observations at a spatial resolution of 70cm x 70cm.
Current work efforts related to Testbed-19 are designed to evaluate the effectiveness of regionally specific ARDs that maintain finer spatial resolution without incurring storage costs associated with a global coverage model.

- **Temporal Resolutions**

Satellite observations are periodic relative to a reference feature of interest. The ICESat-2 mission, for example, revisits the same reference ground track on a 91-day schedule resulting in sea ice observations that may not overlap with a specific event or period of interest. Inferring observations along a temporal coverage is required not only at time instant of an observation event but for relevant periods of observations to infer causal analysis.

- **GeoDataCubes & Analysis Ready Datasets**

The concept of multi-dimensional arrays and their use supporting earth observation missions are well established. However, as per the OGC initiatives related to GeoDataCubes and Analysis Ready Datasets, further development to enhance the concept along a spatial and temporal coverage is required to support a scalable framework for climate observations and biodiversity.

- **IHO S-122**

The IHO S-122 standard provides the core information model for marine protected areas. Previous work products from the OGC MSDI-3 pilot provides an OGC-compliant feature model for the Baltic and North Sea. In contrast, the features extracted from the PAME service endpoint for protected areas represent both terrestrial and marine protected areas with minimal attributes. Protected Area features do have a designation type for 'marine' but with limited attribution to allow the feature encoding to be translated to the S-122 model.

Refactoring the PAME model to align with the IHO S-122 specification and leveraging the federated design pattern from MSDI-3 would allow the information lifecycle for marine protected areas to be tightly coupled to the respective IHO agencies for the circumpolar arctic region.

- **Protected Areas**

The information model for protected areas is inconsistent between the IUCN WCPA and IHO S-122 specification and is based on stakeholder interests. It is unclear which agency has the jurisdiction for managing the Protected Area information model albeit the IHO agencies do have provenance over access restrictions and regulations for marine protected areas. It is unclear how the concepts of restrictions and regulations overlap with similar governance of terrestrial and marine transitional protected areas.

- **Ecosystem Models**

The CBMP is predicated on the use of an Ecosystems-based Management model.

The concept of an ecosystem is well-defined as a biological community of interacting organisms and the physical environment in which they exist. Attempts to translate this definition to an OGC compliant feature model highlighted inconsistencies between the feature model adopted through the CBMP and the IUCN Global Typology of Earth's Ecosystems.

As the concept of an ecosystem is central to the CBMP monitoring program, future work efforts would benefit from a gap analysis between the CBMP model and the IUCN model to ensure the concept of *coastscapes* as defined by CAFF may take advantage of external bodies of work from the IUCN related to protected areas and the Red List of Threatened Species.

- **Security**

A federated approach to the Digital Arctic program requires accessors to external platforms for relevant data products. These accessors have license and security restrictions that are not easily enforced in an isolated environment as required for the FMSDI Demonstrator platform.

3.2. Thread Summary & Future Work

The Digital Arctic pilot emphasized the need to establish a standards-based approach for monitoring the effects of climate change to the Arctic region. The requirements were designed to encourage participants to evaluate existing processes developed in support of the Arctic Council mission and to design solutions that further extend the reach of the Arctic SDI program as a foundational spatial data infrastructure.

Each contributing participant was charged to independently research the problem domain and design a demonstration platform incorporating the unique requirements of the Arctic SDI program. For each platform, the issue of *Discoverability* was addressed to ensure the accurate application of various data products to the Digital Arctic theme.

3.2.1. Summary of Results

Discovery

Standards such as ISO 19115:2003 and the OGC Catalog Services for the Web (CSW) have been integrated into several Spatial Data Infrastructure (SDI) initiatives at national and international levels and is a basis for the existing NRCan Arctic SDI program. The uptake of cloud-provided resources, especially as they concern earth observation and climate data, has necessitated the modernization of existing metadata and catalog approaches. OGC leads the investigation harmonizing Spatio-Temporal Asset Catalogs (STAC) with the ISO 19115 metadata standard through initiatives such as the OGC API — Records, OGC Features and Geometries JSON (JSON-FG), and extended support for the OGC Coverages catalog services.

The pilot focused on the use of the OGC API — Records candidate standard to evaluate its effectiveness managing the feature resources applied within the Digital Arctic domain. The draft

OGC API — Records standard defines an API with two goals: * provide modern API patterns and encodings to facilitate further lowering the barrier to finding the existence of spatial resources on the Web; and * provide metadata discovery and retrieval functionality that is comparable to that of the OGC Catalog Service (CSW) standard.

Results of the investigation were generally positive as resource collections were registered with the catalog service abstracting the feature collection from its implementation details.

Arctic SDI

NRCan plays a central role within the Arctic Council's CAFF program with focus on monitoring the state of biodiversity within the Arctic region. The Arctic SDI program incorporates the concept of a 6-dimensional information model integrating spatial extent (x,y) with vertical dimensions (z), temporal dimensions (t), vectors of flow (v), and scientific research lifecycle management (s).

Each participant demonstrated the core capabilities of managing feature collections along the horizontal (x,y) axis with most solutions demonstrating support along the vertical dimension. The results leveraged existing Arctic data portals to create a multidimensional view of the Arctic linking the land, atmosphere, and marine Arctic domains. In most cases, the integrated platform effectively communicated the visual relationships between the Arctic feature collections as a means of highlighting interdependencies between species and habitat.

The temporal dimension provided further enhancements to the visualization components through a multi-dimensional view of a digital Arctic product. The client environments demonstrate time-instant 2-dimensional and 3-dimensional views of the Arctic features providing visual cues as to the extent of the changing environment.

Vectors of flow contributed to the visualization of meteorological effects and migratory patterns on the Arctic environment with extended models demonstrating the use of the OGC Features and OGC Moving Features specifications to model movement. Vectors of flow, as defined within the context of the pilot program, identify changes in location over time and is of importance when modeling the effects of ecosystem change on the behavioral properties of the Arctic flora and fauna. Concerns of migration pathways as a "conveyor belt to extinction" highlight the priority of modeling the rate of change to biodiversity and ecosystems and the pace of species adaptation. The core capabilities of the OGC Moving Features initiative, extended to model observation collections consistent with the OGC OMSv3 standard, demonstrated an effective approach to encoding vectors of flow for the ecosystems of the Arctic region.

3.2.2. Future Work

A review of the applied OGC standards reinforced the role of the OGC Features and OGC Coverages specifications with further investigation highlighting the role of the OGC Web Coverages Processing Service as an interface to the evolving OGC GeoDataCube initiative.

Testbed-19 GeoDataCube / Analysis Ready Data

In parallel to the FMSDI 2023 pilot, the OGC Testbed-19 initiative is evaluating certain concepts that may benefit future work related to this project. In particular, discussions on the role of the OGC GeoDataCube and OGC Analysis Ready Data (ARD) work products are relevant to addressing concerns of scale and latency when leveraging earth observation systems.

Testbed-19 ARD will continue to investigate the use of Analysis Ready Datasets to provide a high-performance compute environment for biodiversity indicators and satellite-derived variables. The inherent model across multiple dimensions provides key capabilities to address the 6-dimensions of freedom required of the Arctic SDI program.

OGC Building Blocks

A formal reference model of the Digital Arctic aligned with the OGC Building Blocks initiative would be of benefit. The Building Blocks initiative is developing a set of best practices for developing standards based APIs for location-based application frameworks. A building block is a reusable component that may implement a complete OGC API standard, one part of a multi-part standard, or more granular functionality within a standard.

This effort aligns with strategic recommendations to expand the use of OGC Standards within the Arctic SDI program. Analysis based on the CAFF Arctic Biodiversity Data Service (ABDS) provides subject matter information as discrete collections of features. These service portals implement the OGC Web Feature Service and OGC Web Mapping Services interfaces which allow client environments access to feature specific data and/or georeferenced map images. This is an effective means to support the visualization of features as layers to communicate the spatial relationships between collections. However, extending the framework to align with OGC's investments modeling observation networks as *connected systems* would further enhance the capabilities of the Arctic SDI incorporating near-real time monitoring, in-situ observation strategies, an integrated approach to leveraging earth observation systems, and support further investments in community based biodiversity monitoring.

4

THREAD 3: INTEGRATING LAND & SEA — CARIBBEAN

4 THREAD 3: INTEGRATING LAND & SEA — CARIBBEAN

Shipping is making great strides towards a future characterized by digital innovations, improved connectivity at sea, and optimized data solutions. These not only herald the next generation of navigation, but also enable multiple uses of data beyond their original reason for collection through new data integration capabilities.

Current use cases for integrating marine data in the Caribbean include targeting the commercial shipping industry, ensuring Safety of Life at Sea (SOLAS), and supporting the efficiency of global trade using digital charts.

This pilot looks at the use and integration of navigation data in various application scenarios with focus on the *Blue Economy* and *Climate Resilience*. The pilot aims to demonstrate an extended MSDI framework that complements an emerging global geospatial information framework using a data-driven approach towards coastal sustainability and economic growth.

4.1. Request for Information & Online Survey

The FMSDI 2023 Caribbean thread surveyed stakeholders to qualify the current state of the regions' Marine Spatial Data Infrastructure. The survey, as detailed in *Annex B*, is designed to assess the availability of marine and land data products that may be applied to the Caribbean region and the inherent relationships to coastal resilience policy and economic growth.

The survey was made available online on August 17, 2023 with the results finalized by October of the same year. Questions and the related analysis regarding the organization and individual information was omitted to maintain anonymity.

4.1.1. Summary of Findings

A total of six questions were asked in four categories. A summary of the RFI is provided in the following sections.

Question 5: *Is your organization a data user, data broker, data producer/owner, or do you work with geospatial data related to Marine or Coastal areas in the Caribbean region?*

Out of 18 responses, 89% were from individuals who use, broker, produce/own, or work with geospatial data related to Marine or Coastal areas in the Caribbean region, while only 11% were not.

Question 6: *What type of data do you have or work with?*

The majority of participants in the study were those who utilized data, with the most popular type (80%) being Depth data models and bathymetric surfaces. A smaller percentage of participants were data producers, with 40% owning or producing Depth data models among other data types. Data brokers/enablers made up the smallest portion of participants with the Marine Protected (30%) being the highest. Habitat mapping was not listed as a data type; also one participant mentioned using land use/land planning, ocean color, chlorophyll, and temperature data.

Unfortunately, the summary on openly available data lacks significance as only 2 participants provided their response. Based on the responses provided, it was suggested that Depth data models, Bathymetric Surface, Electronic Navigational Charts (ENC) products, and Raster Navigational Chart (RNC) products should be openly available. However, only one of the participants suggested that Marine Protected Area data, Weather and Wave, Marine Harbour Infrastructure, Catalogs of Nautical Products, and Seafloor Backscatter should be openly available. Maritime Limits, Surface Currents, and Continental Shelf were not mentioned as being openly available.

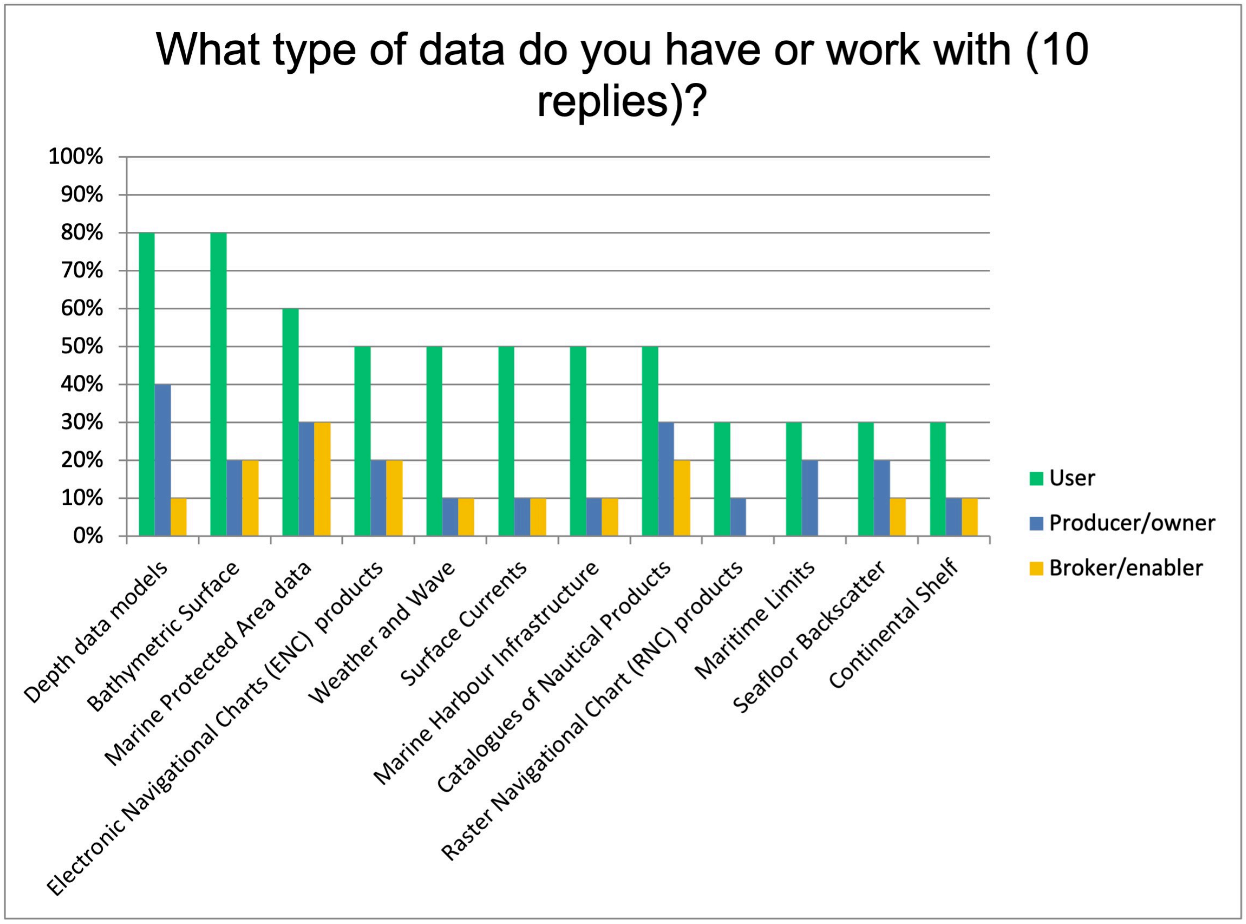


Figure 29 — The summary of the answers for the organization's role in the marine ecosystem and the type of data they handle.

Question 7: *Please indicate the format(s) of the data. You may select multiple options if applicable.*

The most commonly used format was Shapefiles, with 75% of the 12 responses. This was followed by OGC's GeoTIFF and ESRI's Geodatabase, at 58%.

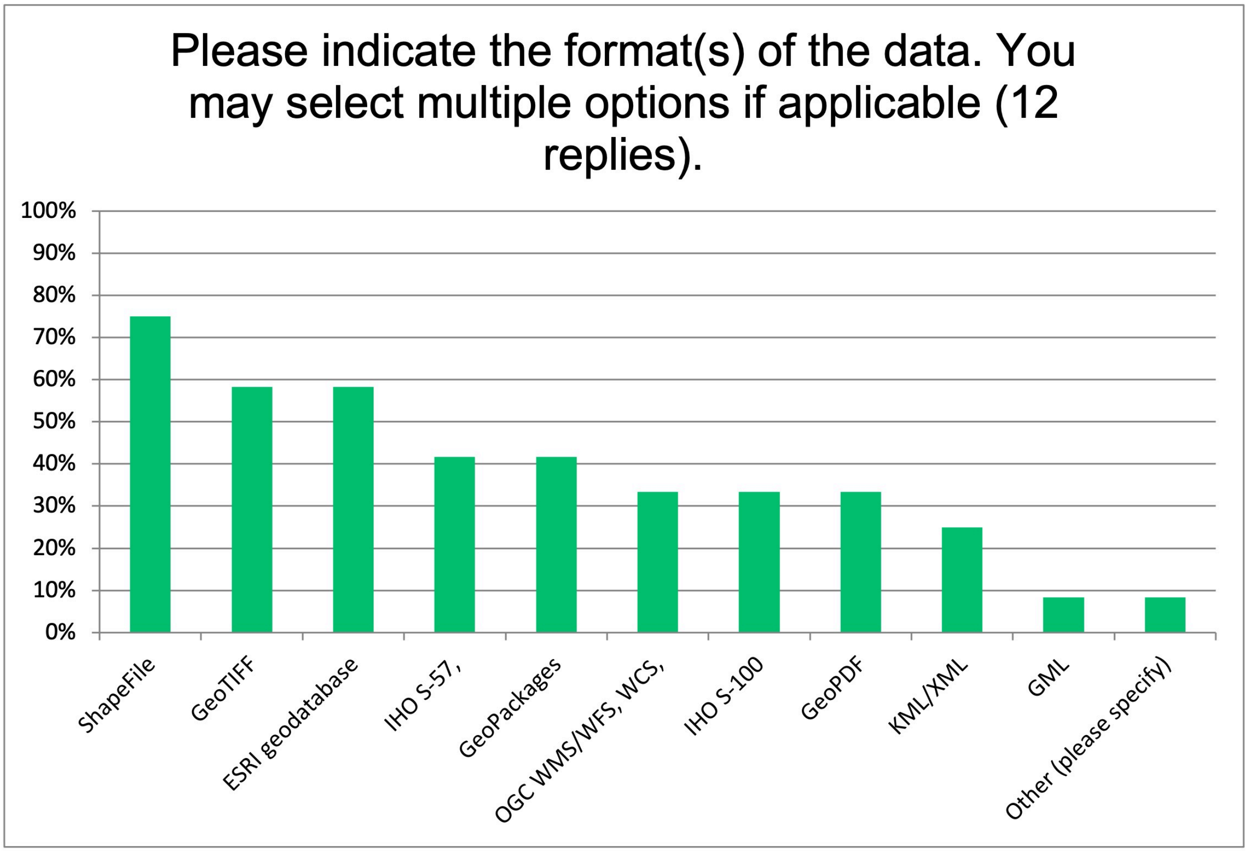


Figure 30 — Data formats for marine geospatial features

Question 8: *Do you currently use geospatial standards to access data and services? If so, what are the key geospatial standards you use?*

Out of the 12 responses received, it was found that the Wxx (WMS/WFS/WCS/WPS) series of OGC standards and the IHO S-xx (S-57/S-52/S-63) series of standards were the most commonly used by our participants. Interestingly, 25% of participants did not use any standards at all.

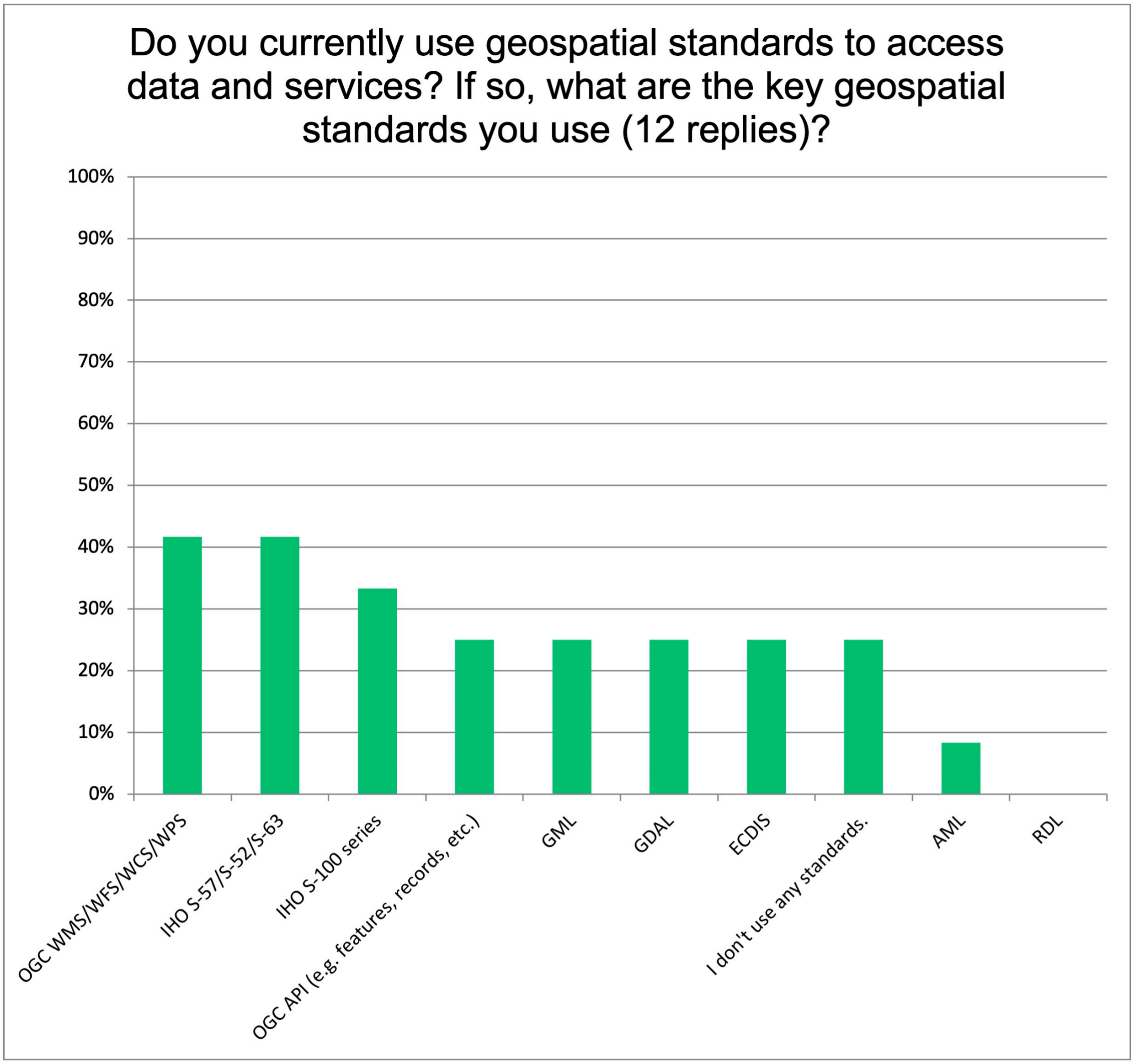


Figure 31 — Geospatial standards utilized by participants to access data and services.

Question 9: *Are you involved in any sustainable activities related to the blue economy?*

Only 33% of the participants did not engage in any such activities, while the majority, 67%, were focused on improving livelihoods and social inclusion by protecting biodiversity and ecosystems. One participant highlighted the importance of informed decision-making in the water quality realm to benefit society, which was not included in the list of activities.

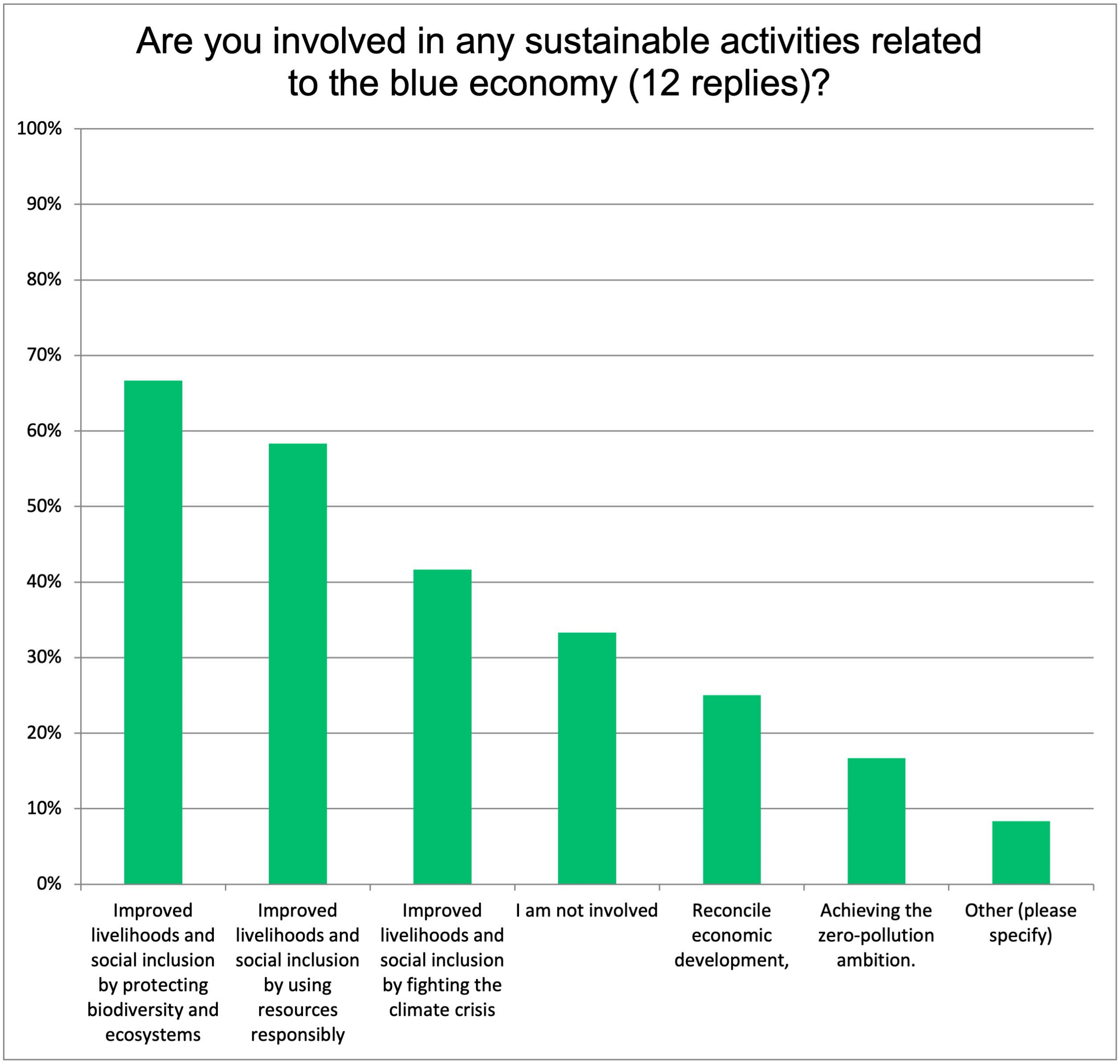


Figure 32 — Sustainable activities related to the blue economy.

Question 10: *Please rank the industries you believe contribute to the future of the blue economy.*

Several industries were presented to the participants. The results found that participants considered the traditional sectors, such as fishing, oil and gas, tourism, transport, and recreation, to be the highest contributors to the future of the blue economy at 76%. Ocean renewable energy, including tidal current and wave energy, followed closely at 70%. The blue bio-economy, which utilizes renewable biological resources from the sea, such as fish, animals, and micro-organisms, to produce food, health, materials, products, textiles, and energy, was at 64%. Industries connected to the on-land economy, such as supply chains, were at a lesser level of 33%, while desalination only contributed 3%. It is important to note that the percentages were calculated using a weighted average formula ((3*high+medium-low)/3).

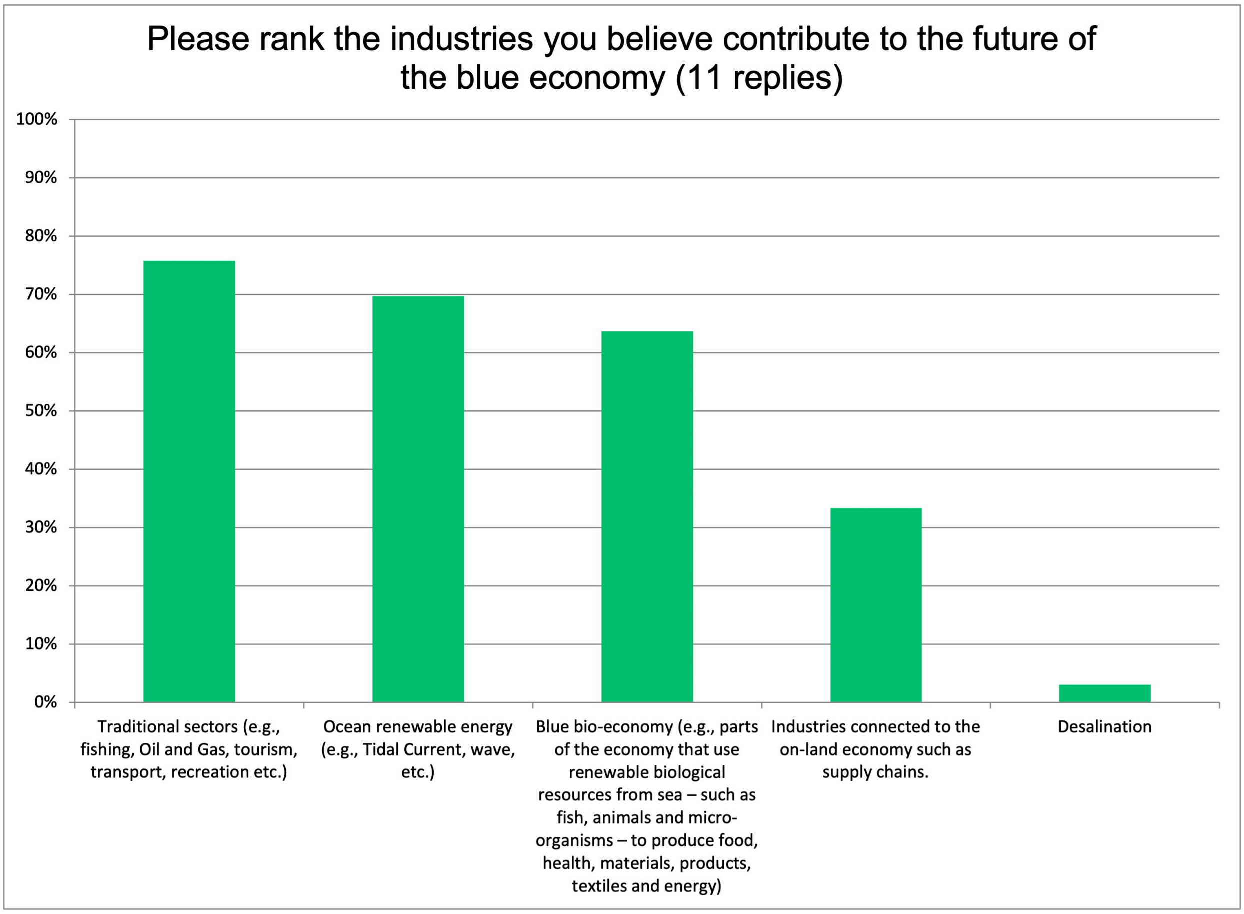


Figure 33 — Ranking of industries contributing to the blue economy

Question 11: *What is your assessment of the geolocation technology that will have the most significant influence on the blue economy?*

Out of the 11 participants who were part of the RFI survey, 82% believed that Underwater data gathering holds the most significant influence as a geolocation technology on the blue economy in the Caribbean region. Other popular options included more frequent hydrographic data acquisition (76%), more accurate navigation technologies (67%), and better bathymetry data (64%).

Advanced disease management systems, smart ports, and precision aquaculture were also of interest, with each receiving 39% of the vote.

It is important to note that the percentages were calculated using a weighted average formula *((3*high+medium-low)/3)*.

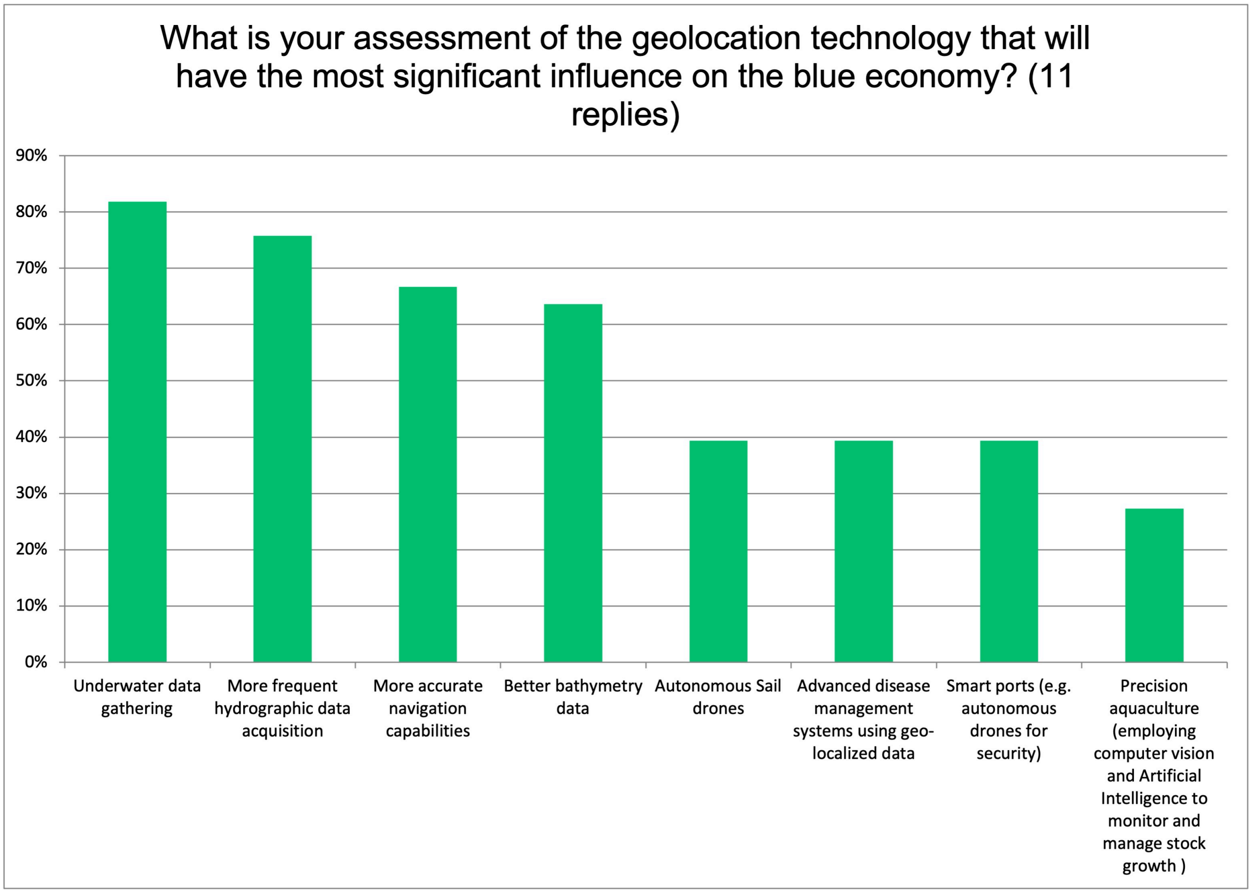


Figure 34 — Summary of influential geolocation technology on the blue economy

4.2. Contributions

The following table summarizes the contributions of each Participant. Details for each contribution are provided in subsequent sections.

Table 7 — Caribbean Theme Participant Contributions

ORGANIZATION	DELIVERABLE	SCENARIO
Hartis	D121	Application of OGC and IHO Standards for Sustainable Development of Offshore Wind Farms
OceanWise	D122	Assessment of Navigational Charts as a Component of Marine Spatial Planning
HSR	D123	Hurricane Health Risk Assessments as a Key Component of Disaster Management

ORGANIZATION	DELIVERABLE	SCENARIO
Compusult	D124	Ocean Plastic Concentrations post-Hurricane Irma
GGIS	D125	Leveraging intra-agency data products for storm surge modelling in the Caribbean

4.2.1. D121: Application of OGC and IHO Standards for Sustainable Development of Offshore Wind Farms

The Caribbean region has a vast potential for offshore wind energy, which, if harnessed effectively, could contribute substantially to renewable energy goals.

The International Renewable Energy Agency (IRENA) reported in 2019 that the Caribbean region has an offshore wind energy potential of approximately 750 GW. The problem at hand revolves around making informed decisions for the optimal placement of offshore wind farms (OWFs) in the Caribbean region. Stakeholders, including renewable energy developers, environmental agencies, local communities, and regulatory bodies, are grappling with the challenge of identifying suitable locations for OWFs that balance economic feasibility with environmental sustainability.

Background

Hartis is a dynamic marine ICT Company headquartered in Athens, Greece, specializing in geospatial technologies with a focus on nautical cartography and navigation within the maritime and sea tourism sectors. The core expertise lies in developing advanced navigation products and services, particularly sailing guides and nautical charts. With a commitment to enhancing safety in sailing practices, Hartis leverages a strong proficiency in geographic information systems and remote sensing technologies to deliver cutting-edge solutions.

Hartis provides a standards-based integrated system for creating web-based nautical charts. These charts adhere to the latest standards set by the International Hydrographic Organization (IHO), particularly the S-101 standard, harnessing open hydrospatial data from marine spatial data infrastructures (MSDI) and qualified volunteered geographic information (VGI) sources. A notable feature of the platform is the utilization of open-source geospatial libraries and web-map vector technologies, allowing the building of dynamic and interactive components. Through the deployment of software scripts, automated charts are produced with enhanced efficiency. A major focus of the product platform incorporates web services for seamless end-to-end automation and integration with satellite-derived bathymetry for precise seabed topography representation.

4.2.1.1. Approach

The focus of the FMSDI Caribbean project is the development of an Offshore Wind Farm Decision Support Service (OWF-DSS). The OWF-DSS integrates diverse data sources and geospatial technologies to guide the selection of offshore wind farm locations with key suitability indicators associated with marine ecosystems, local communities, and existing infrastructures.

The OWF-DSS enables stakeholders to make well-informed decisions regarding the placement of OWFs, ensuring a balance between sustainable energy generation and environmental preservation.

The OWF-DSS is designed to integrate various data sources and leverage geospatial technologies to ensure the optimal placement of wind farms that are both economically viable and environmentally sustainable. The decision-making process involves a multi-criteria analysis considering factors such as local and international regulations, environmental conditions, and available resources.

Key considerations of the OWF-DSS include:

- **Data Requirements**

Accurate and high-resolution data from both marine and land environments are essential. This includes data on wind speed, water depths, seabed characteristics, geology, existing infrastructure (cables, pipelines), military and aviation reserved areas, marine traffic, wave patterns, shipwrecks, biodiversity, protected areas, and land-related data such as cadastre, land use, and infrastructure.

- **Landing Position Selection**

To Identify the optimal landing positions for cables that transport electricity generated by the wind farm to the power grid on land, multiple potential positions need to be evaluated based on factors like distance to shore, existing infrastructure, and environmental impacts.

- **Cable Routing**

Careful planning of cable routes within the wind farm and to the shore is required to minimize disruptions to marine life and coastal ecosystems. Factors like water depth, seabed conditions, and distance between turbines are considered.

- **Environmental Protection**

Evaluation of potential impacts on marine life, migratory bird patterns, and other factors that could affect the long-term sustainability of the wind farm is required. Protection of marine ecosystems and biodiversity is a priority.

- **Optical Pollution Minimization**

Assessing options to minimize visual impact on coastal communities and ecosystems. The OWF-DSS considers potential effects on local communities, industries like tourism, fishing, and other environmental factors.

- **Economic Viability**

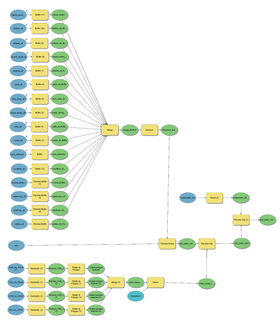
Balancing the economic feasibility of OWFs with potential infrastructure costs, cable routing complexities, and environmental mitigation measures impacts the region’s economic viability.

- **Regulatory Compliance**

Regulatory compliance includes navigating complex local and international regulations to select sites that adhere to legal requirements and standards.

4.2.1.2. Solution Architecture

The OWF-DSS incorporates a multi-criteria analysis methodology implemented as a complex workflow assessing potential wind farm locations and taking into account a wide range of factors.



The OWF-DSS consists of several key components as follows.

- **Data Sources**

Various data sources contribute critical information for wind farm site selection. These sources include marine spatial data infrastructures (MSDI), hydrospatial data, volunteered geographic information (VGI), satellite-derived bathymetry, and more. These data sources form the foundation of our decision support system.

- **Import Engine**

The Import Engine is responsible for collecting and transforming raw geospatial data from diverse sources into a standardized format suitable for analysis and visualization. This component ensures data consistency, accuracy, and compatibility, facilitating further processing.

- **Database and GeoServer**

The processed data is stored in a PostgreSQL database with PostGIS capabilities. This spatial database management system enables efficient storage, retrieval, and management of geospatial data. The GeoServer component implements the OGC API Features standard, allowing users to access and retrieve geospatial data using standardized APIs.

- **Process Automation**

Process automation is achieved by utilizing an ArcGIS workflow. This workflow guides the multi-criteria analysis for wind farm site selection and integrates ArcGIS tools and geoprocessing functions to evaluate potential locations based on various criteria, such as wind conditions, environmental impact, infrastructure availability, and regulatory compliance.

- **Users**

The end users, including stakeholders such as marine engineers, environmental scientists, and decision-makers, access the decision support system through user-friendly interfaces. QGIS is used for data visualization, allowing users to explore maps and gain insights into the geospatial context. The ArcGIS-based user interface provides interactive tools for scenario analysis and decision-making.

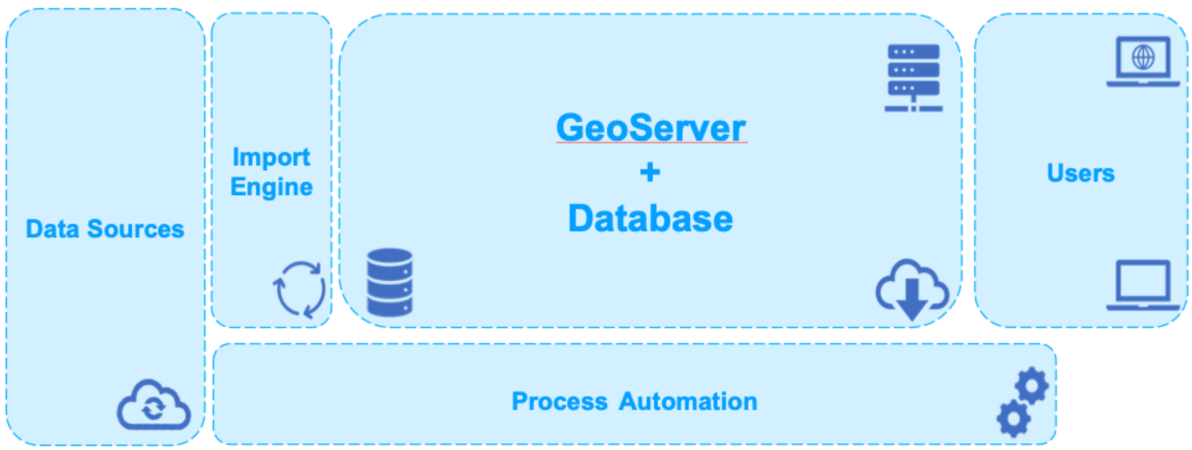


Figure 35 — OWF-DSS Solution Architecture

Spatial Coverage

The project's area of interest is the collection of Exclusive Economic Zones (EEZs) for the islands of Anguilla, the British Virgin Islands (BVI), the Cayman Islands, and the Turks and Caicos Islands.

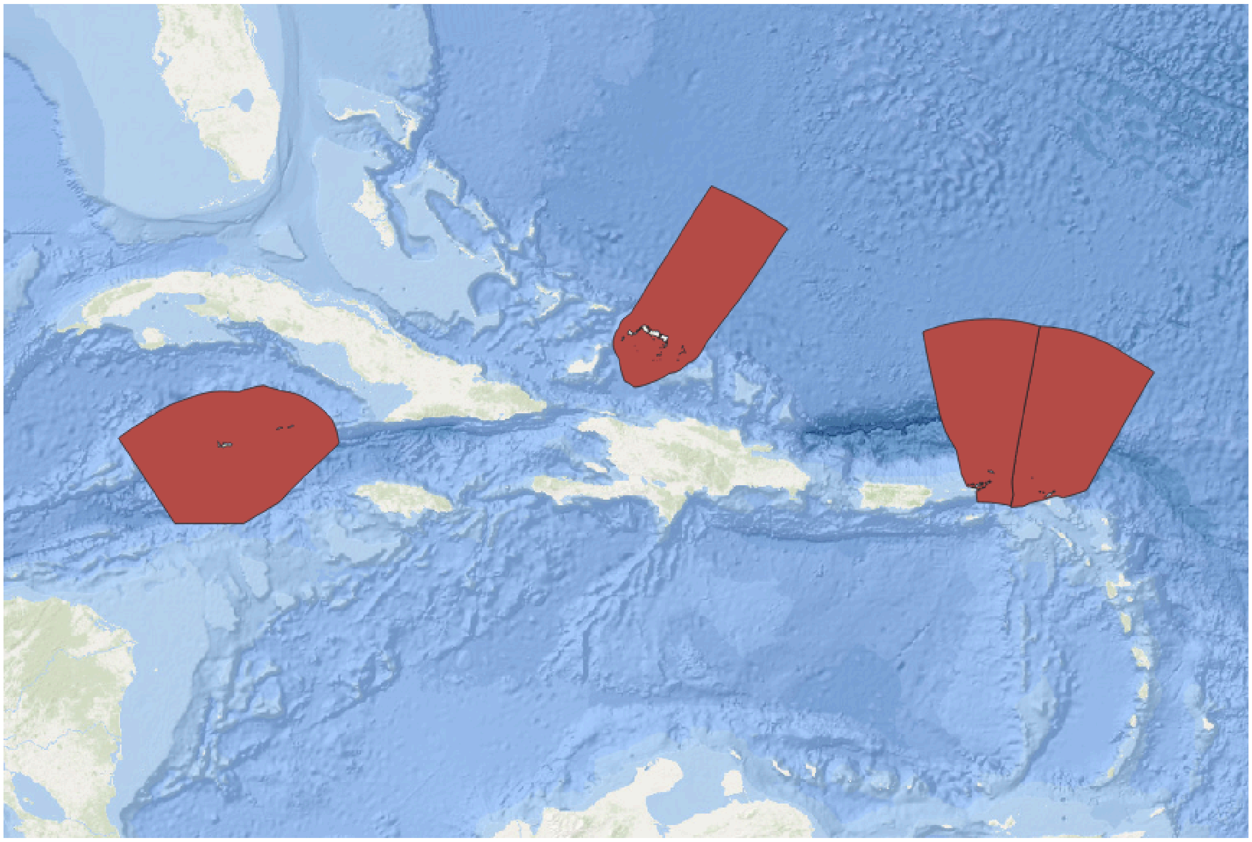


Figure 36 — Areas of Interest for Offshore Windfarm Analysis

Temporal Coverage

While there are datasets used that have a temporal dimension, such as the average wind speed in the region or marine traffic data, the service has been developed on the basis that the analysis takes into consideration the best currently available information.

Data and Platforms

- **Marine Regions**

Marine regions and boundaries were defined using data from the Marine Regions database. This information helps in the proper delineation of marine territories and compliance with regional regulations. Manual method to download data from url: https://www.marineregions.org/download_file.php?name=World_EEZ_v11_20191118_gpkg.zip OpenStreetMap (OSM): Geospatial information from OpenStreetMap (OSM) was utilized to access detailed maps and geographical features of the study area, including roads, buildings, and infrastructure. API is provided for automated data retrieval: https://overpass-turbo.eu/

- **GEBCO Bathymetric Data**

High-resolution bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO) were employed to analyze underwater topography and seafloor characteristics in the project area. Manual method to download data from url: https://download.gebco.net/

- **Wind Atlas**

Wind speed and wind direction data, essential for renewable energy assessments, were obtained from the Wind Atlas. These data support the evaluation of wind energy potential in the study region. API is provided for automated retrieval of data, e.g., for Anguilla: https://globalwindatlas.info/api/gis/country/AIA/wind-speed/10

- **World Database of Protected Areas**

Information on protected natural areas and conservation zones was sourced from the World Database of Protected Areas. This dataset aids in ensuring environmental compliance within the project's geographical boundaries. Manual method to download data from url: https://d1gam3xoknrgr2.cloudfront.net/current/WDPA_Oct2023_Public_shp.zip

- **NOAA S-111 Surface Water Currents**

This dataset, from the National Oceanic and Atmospheric Administration (NOAA), provides essential insights into surface water currents, aiding in the understanding of oceanographic patterns and dynamics. NOAA is providing online source for downloading S-111 data: https://noaa-s111-pds.s3.amazonaws.com/index.html#ed1.0.1/model_forecast_guidance/rtofs_east/. The data is updated every 12 hours and contains surface current forecasts for up to 72 hours

Standards & Interoperable Technologies

Addressing the challenges of locating offshore wind farms in the Caribbean requires a baseline of industry standards and best practices utilizing a combination of geospatial technologies.

- *OGC Features API*
  The OGC Features API provides a modern and efficient way to access and interact with geospatial data on the web. The standard is used for data discovery, access, and interoperability.

- *IHO S-100 Standards*

S-101 is the international standard for nautical charts and provides the core reference model for marine features and objects represented on nautical charts.
IHO S-111 models the critical information about surface water currents, which is invaluable for maritime and environmental applications.

- *GeoServer with OGC API Features*

GeoServer enables the publication and retrieval of geospatial data in a standardized and efficient manner following the latest OGC developments. GeoServer's capabilities enhance data sharing and support the integration of diverse datasets.

- *PostgreSQL Database with PostGIS*

The backend infrastructure leverages PostgreSQL with PostGIS capabilities. This spatial database management system is responsible for the storage of geospatial data. PostGIS extends PostgreSQL with geospatial functions, enabling advanced spatial queries and analyses. PostGIS data is integrated seamlessly with GeoServer which allows the end user to have a direct access to geospatial data.

- *Data Visualization with QGIS*

QGIS is employed for data visualization and analysis. Its user-friendly interface and extensive cartographic features are leveraged to create informative maps, analyze data relationships, and gain insights into the geospatial context.

- *Decision Support System using ArcGIS Workflow*

The OWS-DSS platform is implemented as an ArcGIS workflow. The platform offers powerful geospatial analysis tools and supports the creation of a comprehensive system that addresses multiple criteria for wind farm site selection.

- *User Interface and Visualization:*

The client solution integrates QGIS for generating compelling visualizations and ArcGIS for providing an intuitive user interface ensuring that stakeholders can interact with the decision support system, explore different scenarios, and understand the outcomes.

4.2.1.3. Challenges & Future Work

- **Data Volume and Processing**

Integrating and processing data from multiple sources can lead to challenges in data volume and processing time. Efficient data management and optimization are necessary to ensure timely analysis.

- **Workflow Complexity**

The complexity of the multi-criteria analysis workflow, especially within ArcGIS, can impact system performance. Proper workflow design, optimization, and efficient utilization of tools are essential to maintain responsiveness.

- **Integration Challenges**

Integrating different tools such as GeoServer, PostgreSQL, QGIS, and ArcGIS requires careful configuration and compatibility checks. Ensuring seamless communication and data flow among these components is critical.

- **Data Accuracy**

The accuracy and reliability of analysis outcomes depend on the accuracy of input data. Any inconsistencies or inaccuracies in data sources can affect the validity of the decisions made.

4.2.2. D122: Assessment of Navigational Charts as a Component of Marine Spatial Planning

There are many different users within the marine domain ranging from energy, shipping, resource extraction, and leisure. Hydrographic offices collect a wealth of information but only a small percentage is actually shown on a navigational chart. While navigation data are an important component of Marine Spatial Planning, the data requirements for various stakeholders dependent on the shared-use of the marine space extend beyond the traditional navigation products. Identifying what feature types may exist or may be limited on a navigational chart is the first step in understanding the role of navigation data within a healthy Marine Spatial Planning initiative.

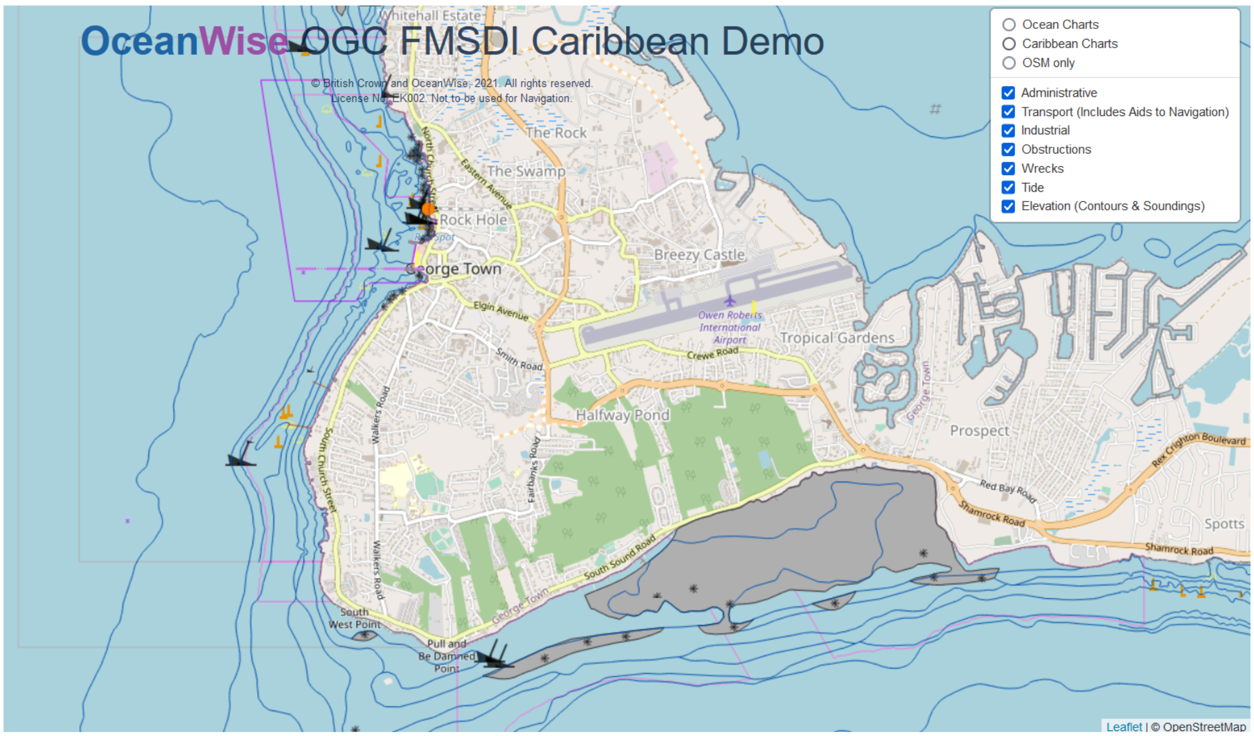


Figure 37 — OceanWise Demonstrator

Sources of data for marine applications can be much more complex and expensive to collect. Such datasets may be proprietary in nature with licensing restrictions limiting their availability which can also mean such data products may be hidden away in archives without a necessary discovery mechanism. Often the only source of marine geospatial data for an area is a nautical chart. Nautical charts have been designed to make it easy and clear to navigate ocean waters but when it is the only source of data available, it limits the activities dependent on the marine domain. Where countries are collecting more comprehensive data these can be used to either replace or supplement features from the nautical chart.

Background

OceanWise is a UK-based marine data company providing applications, services, and tools that enable safer and smarter management of marine operations. The OceanWise team has spent many years working with marine mapping data and the application of navigational data products for non-navigational use. The development of these extended navigational data products is designed to the specific requirements of those working in the coastal domain.

4.2.2.1. Approach

An essential component of the D103 Caribbean theme is identifying the availability and gaps in marine-related datasets required to further the development of marine capabilities within the Caribbean islands. Data products and associated standards purposed outside the traditional requirements associated with navigation are integral to the safe use of the shared marine environment. As such, it is important to identify the gaps in information against various stakeholder needs, potential integration issues with third party data products, and the suitability of navigation data for scenarios that go beyond navigation.

Electronic Navigational Charts (ENC) are vector data sets that support all types of marine navigation. Navigational data for Anguilla and the Cayman Islands are benchmarked against data availability for similar areas in the UK. This work effort creates a baseline of navigation data products available across regions while identifying gaps in information affecting the strategic development of marine planning initiatives for the Caribbean.

4.2.2.2. Solution Architecture

ENC data are processed through OceanWise's toolset that builds a 'Marine Themes Vector' product. Marine Themes Vector is a dataset extending the INSPIRE information model and supplemented with source datasets where available.

Chart boundaries are removed and attributes simplified for easy querying in a GIS environment and more suitable as a base dataset for marine spatial planning. Making these datasets available via OGC compliant web services enables the data to be managed and updated while still available for use by any client with a license to use the data. Web Feature Services are particularly useful as the data are delivered in a vector format which can be used for analysis, rather than as a static image.

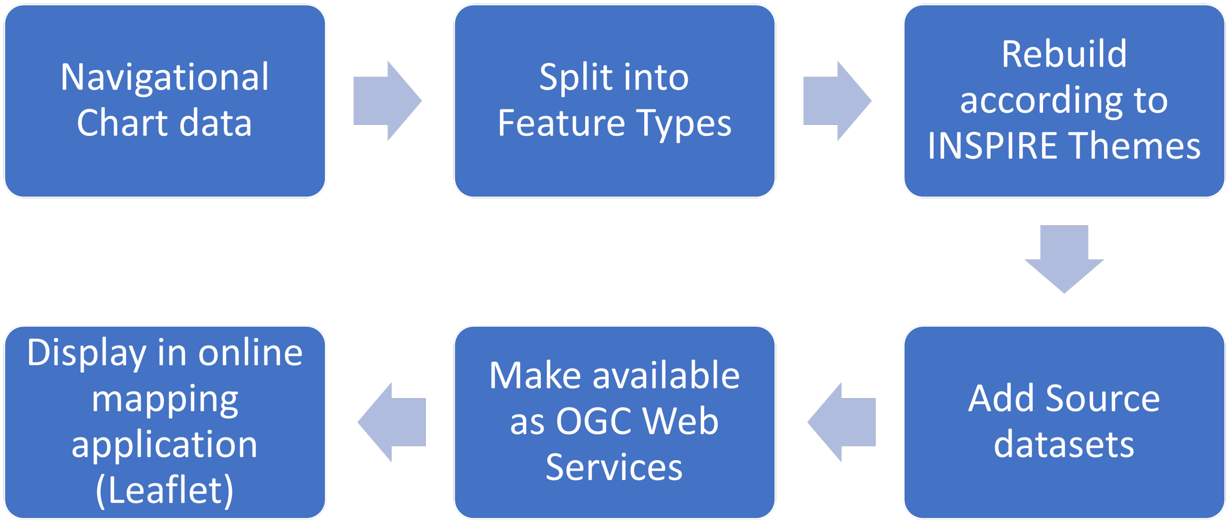


Figure 38 — OceanWise Wind Farm DSS Processing Workflow

Although there are standards for nautical chart data (S-57/S-100) which are well structured, they can be complex for any kind of analysis (attribution is particularly complex). Marine Themes Vector has been established to simplify the attribution to make it easier to use while still keeping all of the information.

Once processed the data are extracted so the same size areas are compared. Using standard querying functionality in a GIS, each feature type found in the datasets is listed and counted enabling an easy comparison between the UK and Caribbean areas.

Data and Platforms

Source navigation data are provided by the UKHO in S57 format. Datasets sourced from official Caribbean authorities include: * public Moorings Grand Cayman published; Department of Environment Cayman Islands Government [https://doe.ky/resources/public-moorings/]; * source data from authorized/approved third parties; * mandatory and recommended IMO shipping lanes published by Rule10 Digital [https://www.rule10digital.com/]; and * Complete Wrecks and Obstructions database from UKHO.

Standards & Interoperable Technologies

The source nautical chart data are currently in S57 format. Most other source datasets used are not available as any specific standard and the suppliers do not have plans to use these standards.

Data delivery/sharing is provided via OGC Web Feature Services and Web Map Services as these are most widely consumable by those undertaking Marine Spatial Planning and are not affected by the clients choice of GIS system.

4.2.2.3. Summary of Findings

In most cases there were considerably fewer feature types in each theme in the Caribbean area than in the UK. The themes which were generally consistent between the UK and Caribbean areas were the Elevation Layer Covering Depth Areas, Contours and Soundings, and Obstructions Layer. Administrative (or Functional Areas in IGIF-Hydro terms) and Industrial (human made features) had noticeably lower numbers of features with some feature types, for example, Harbour Areas, Caution Areas, and navigation aids (e.g., lateral buoys) not existing at all.

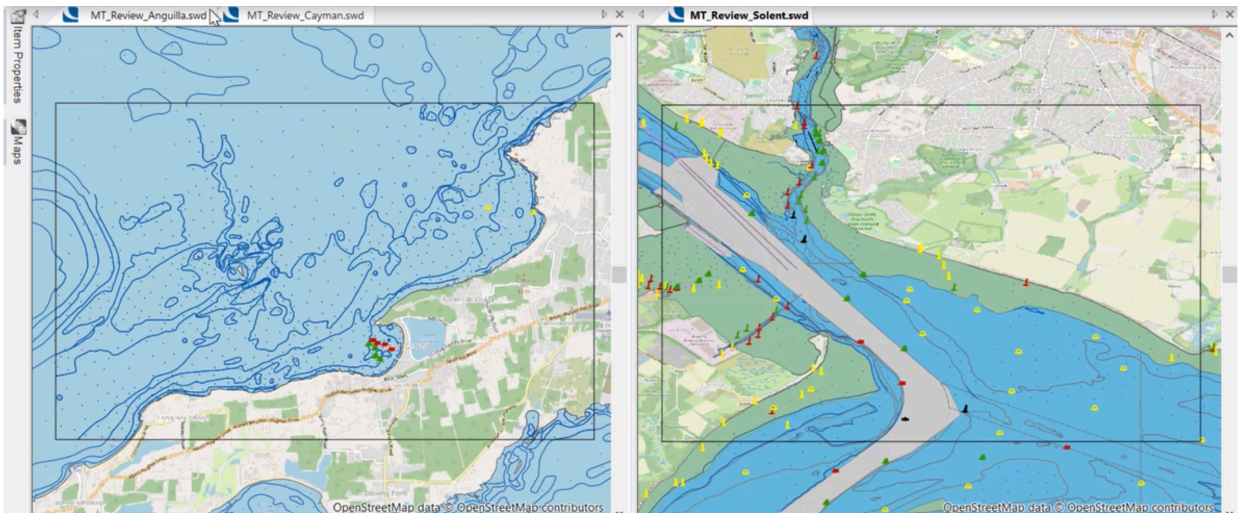


Figure 39 — Comparison of navigation aids between Caribbean (left) and UK (right)

Without access to the raw data used by the Hydrographic Offices for Charting or the actual country source data, it was not possible to say whether these feature types exist in the Caribbean areas or whether they have not been charted. OceanWise was able to find some publicly available data on moorings for the Cayman islands and demonstrate that these were not completely charted. However, it is unclear as to whether the Hydrographic Office did not have access to the source data or it may not have been included in order to reduce the complexity of the chart. As the purpose of an ENC is navigation, features may be ignored that make the chart overly complex or are not relevant at the ENC scale.

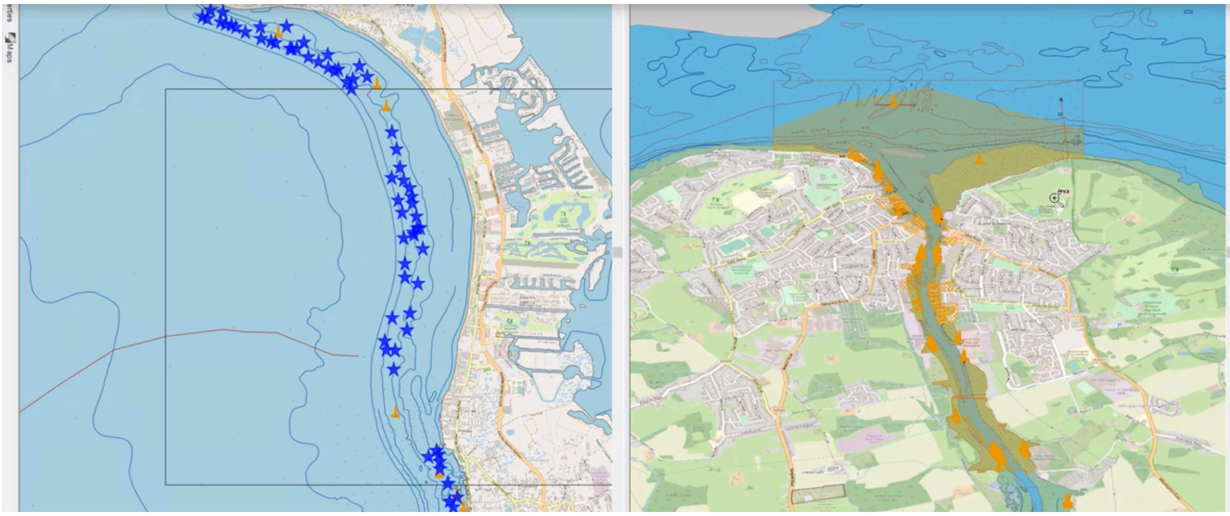


Figure 40 — Source moorings in Caribbean, not in Chart (left), moorings included in UK chart (right)

Across chart boundaries, there can be differences in features that are captured or displayed which is particularly noticeable between ENCs of different scales. The larger scale data may have more detail but can then impact the suitability of the data for non-navigational purposes. For example, where contours and associated depth areas are discontinuous, using these features for any kind of reliable density analysis becomes impossible. Also, understanding uses of an area can be impacted if features are shown on one chart but not shown on the adjacent chart; it may be assumed that the feature does not exist, whereas it may be the case that the feature simply has not been charted.

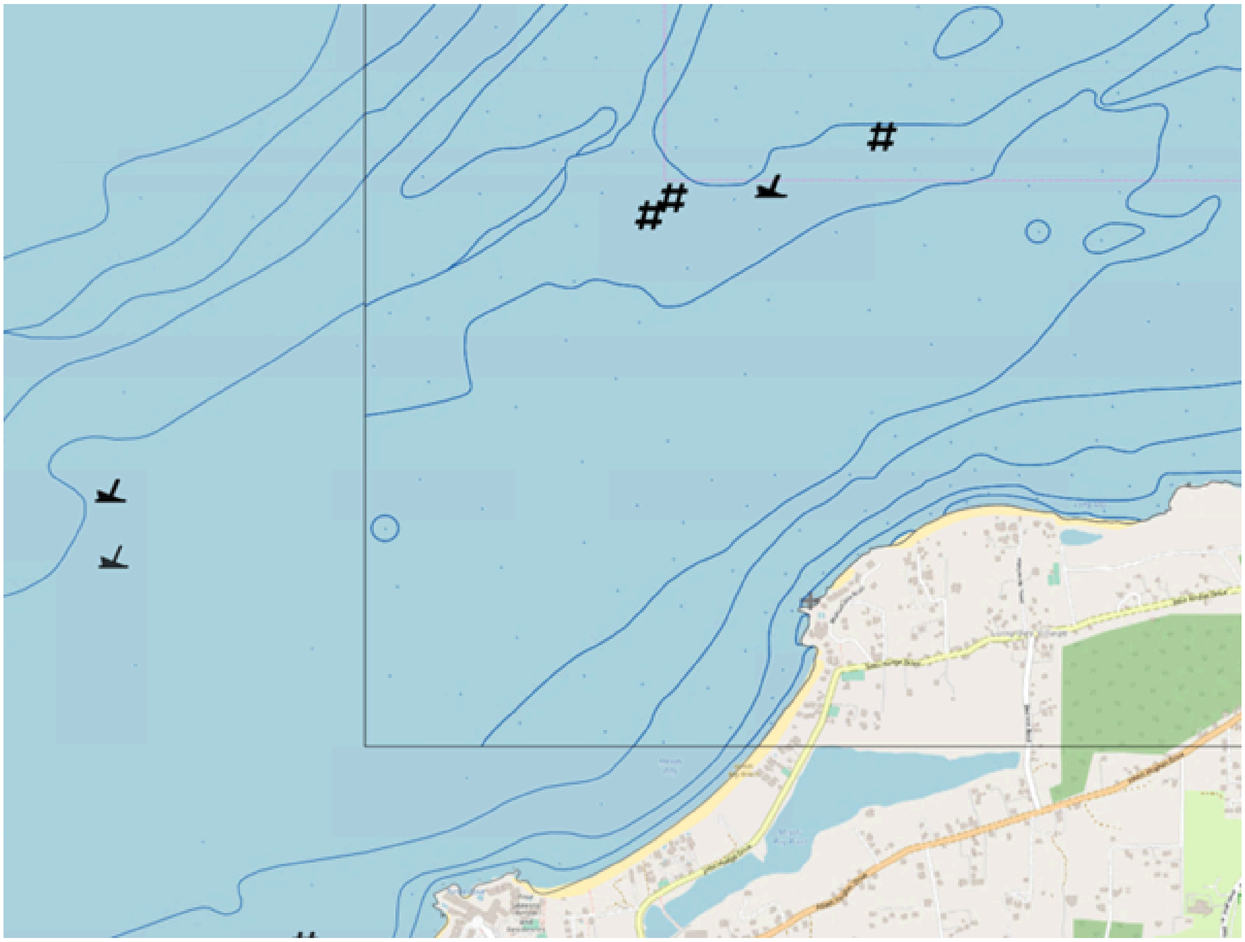


Figure 41 — Discontinuous features across chart boundaries

The coastline is one area which has historically caused issues when dealing with the land-sea interface. Different definitions, scale, coordinate reference systems, and date of capture can all affect where the coastline is drawn, making it difficult to match up between datasets. Some of these issues can be agreed upon for the purposes of a national geospatial data strategy but may not solve them all.

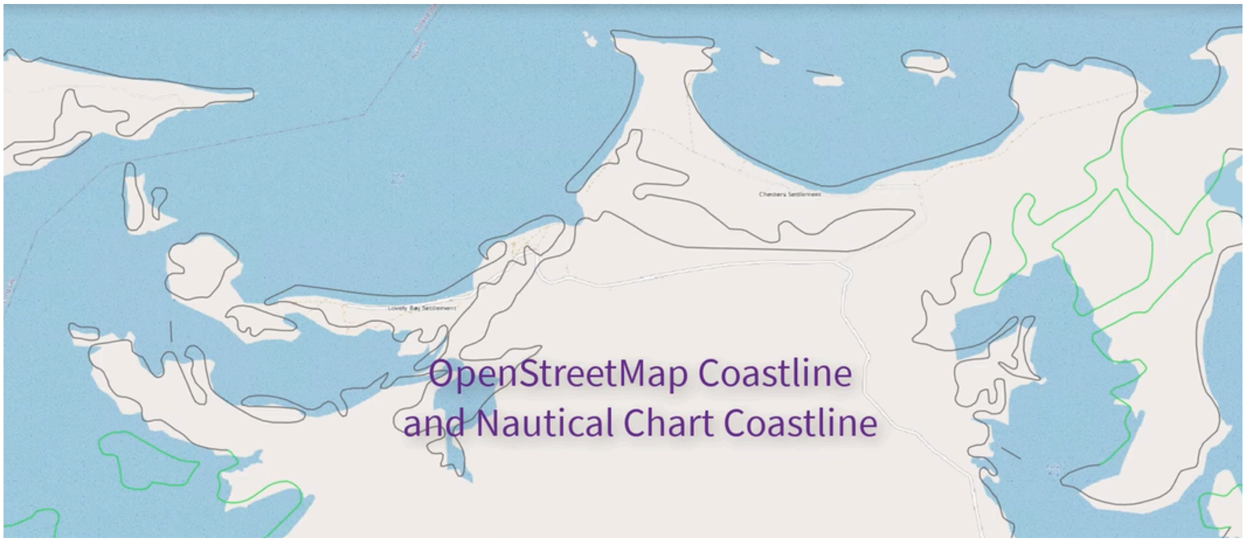


Figure 42 — Variations in coastline definition between different data sources

Overall navigation data have use where there is nothing else available and as a basis for data in a standard form, however it should always be used in conjunction with source data.

Detailed results of the project assessment may be found in Annex C.

4.2.2.4. Challenges & Future Work

- License Restrictions

The associative license of the source data restricted the publishing of the feature information as an OGC Feature service. As such, the demonstrator platform was configured as a view-only map service created and deployed using the open-source platform Leaflet.

- IHO S-100 standards

S-100 series data would have been useful to test however it was not available for the areas of interest. With the complexities of implementing the standard, it will be difficult for non-experts who create and manage the source datasets to align their data creation with S-100 standards. If data creations are not aligned, it will be difficult to combine these variety of datasets.

4.2.3. D123: Hurricane Health Risk Assessments as a Key Component of Disaster Management

Historically, the island nations of the Caribbean have experienced many destructive hurricanes that disrupt and take lives as well as put the governments of the islands under extreme pressure to mitigate damage and lead recovery efforts. Between 1960 and 2013, the Caribbean has experienced 264 hurricanes, accounting for 95% of total damages from all natural disasters in the area (Burgess et al., 2018). Furthermore, the vulnerability of the overall population is higher, with over half of the population living within a mile of the coast. With the effects of climate change on the rise, the region is even more vulnerable to hurricanes and is experiencing a continuous increase in disastrous weather events (Vosper et al., 2020). Between 2016 and 2020, a total of nine tropical cyclones struck 21 Caribbean countries and territories, affecting 13.5 million persons in total and causing almost $90 billion USD in economic damages (Dookie Spence-Hemmings, 2022). Climate change has also contributed to causing hurricanes to move slower and “stall,” subjecting coastal regions to much longer periods of heavy rain and winds resulting in more damage (Ornes, 2018). Yet, the region essentially has no comprehensive quantitative risk and anticipated loss assessment (Bertinelli et al., 2016).

Anguilla

Anguilla is a small, 35-square mile island nation which is home to nearly 16,200 people (UN in Action — Anguilla, n.d.). Compared to other Caribbean islands, Anguilla has a relatively large fiscal shortage due to hurricanes, standing at losing 2.4% of fiscal revenue in the next 10 years (Ouattara et al., 2018). Economic damage resulting from Hurricanes Maria and Irma was estimated at $290 million USD in the months after the hurricanes. Furthermore, 90% of Anguilla’s housing stock was severely damaged, 42% of structures were damaged, and over 1,500 electric poles fell that took 6 months to fully restore (Regional Overview: Impact of Hurricanes Irma and Maria — Dominica, 2017). After the hurricanes, the United Nations Development Program (UNDP) supported the government of Anguilla in conducting a Post-Disaster Needs Assessment as part of a program modeled to improve recovery and resilience in the Caribbean. Anguilla has reached some milestones in relation to hurricane preparedness and response, including increasing their capacity to assess hazard impacts and implement disaster risk reduction strategies.

The Bahamas

The Bahamas comprises more than 700 low-lying islands and cays with ridges that rarely exceed 15 to 20 meters. Its location (north of Cuba and Haiti and east of Florida) makes the islands more vulnerable to hurricanes than any other islands in the Caribbean and the low-lying nature makes the group of islands particularly vulnerable to the effects of these hurricanes. The island nation is also expected to lose up to 48% of fiscal revenue every 10 years (Ouattara et al., 2018). The Bahamas has been subject to several devastating hurricanes in the last decade, including hurricane Dorian in 2019, causing $2.5 billion USD in damage, ruining hospitals, schools, and fisheries and making almost 3000 homes uninhabitable (Vosper et al., 2020). The severity of Hurricane Dorain pushed the government of The Bahamas to create and release the Resilient Recovery Policy, focusing on providing context and guidelines to ensure a timely recovery and rebuilding process after a disaster. However, the government does recognize that it lacks the financial, technical, and human resources needed to address this problem (Thompson, 2021).

Commonwealth of Dominica

The Commonwealth of Dominica is a relatively small island nation slightly smaller than New York City at 750 square kilometers. The island has a unique landscape, covered by dense, unexplored rain forests and is known as a “beautiful, unspoiled tropical preserve” along with its volcanic nature creating an uneven, rugged terrain. In 2017, Hurricane Maria caused catastrophic damages that directly affected more than 80% of the population and more than 90% of roofs were damaged or destroyed. Overall, Dominica suffered nearly $931 million USD in losses, equivalent to 224% of Dominica’s 2016 GDP. Six years later, many residents are still left with damaged homes as the island has yet to fully recover. A total of 23,500 homes were destroyed during Hurricane Maria. In the recovery and reconstructive phase, nearly 7,000 new homes were built with material that can withstand another category 5 hurricane, however, not everyone on the island has access to these homes and another severe hurricane could be disastrous (Siegler, 2023).

Background

Based in Rockville, Maryland, HSR.health is a geospatial data analytics company that specializes in utilizing geospatial technologies, health, social, and environmental data, AI techniques, and public health models to predict the spread and severity of disease — whether infectious, chronic, or social — and assist public health and emergency response decision makers mitigate disease spread and/or allocate resources to treat the affected. The core GeoMD platform is designed as a scalable, multi-tier, cloud-native, and *health focused* spatial data infrastructure.

4.2.3.1. Approach

Every year tens of millions of people are impacted by hurricanes and islands such as those in the Caribbean are especially vulnerable. Identifying where resources and personnel need to be sent within affected areas to help the local population is a core part of a disaster response effort.

Previous contributions to the OGC Disaster Pilot(s) and the FMSDI Arctic pilot provide extensions to the GeoMD platform delivering a Wildland Fire Health Indicator, a Drought Health Indicator, and a Bioaccumulation Health Risk Index. Further extending this framework, the Caribbean pilot will provide a Hurricane Health Risk Index for determining the underlying health and social conditions of the population impacted by a hurricane. This information is used to inform policy for hurricane impacted areas and provide emergency response managers the necessary decision support guidance to aid response, resource allocation, and evacuation efforts.

4.2.3.2. Solution Architecture

The Hurricane Health Risk Index is calculated through a weighted combination of the health and social characteristics of the impacted population. These characteristics define the populations that, due a range of factors, partially including challenges with mobility, powered devices, medical conditions that require regularly scheduled care (e.g., dialysis) are at a higher risk of severe negative health outcomes during and after a hurricane has occurred.

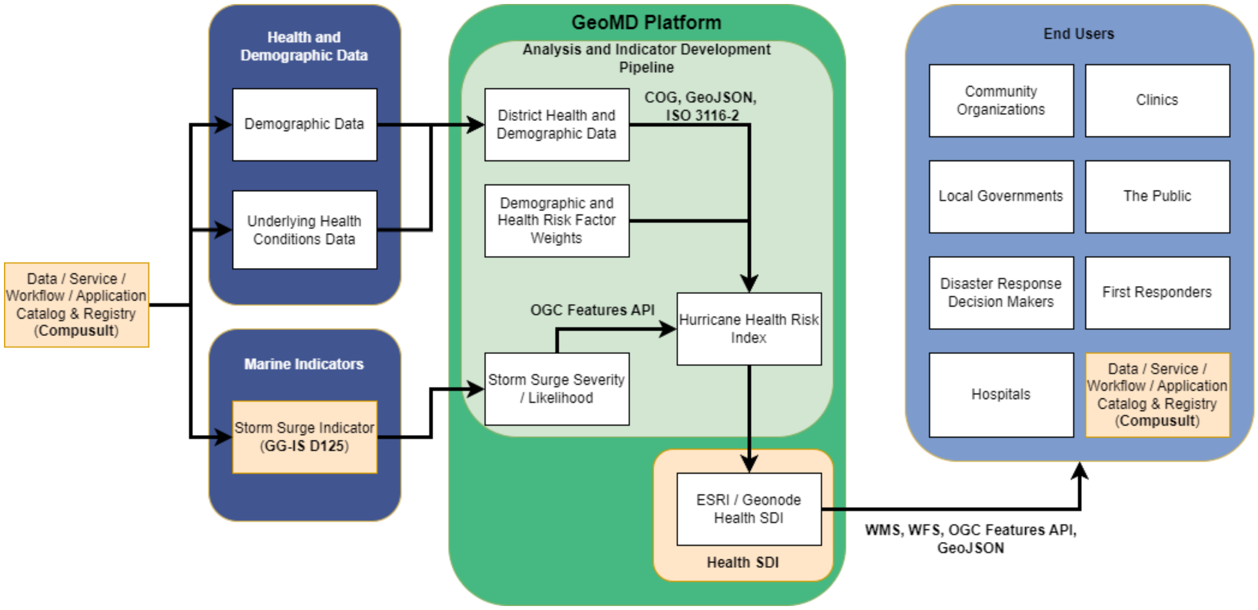


Figure 43 — HSR Health Index Processing Workflow

The demographic and health data came from a variety of sources for each country and are listed in the Datasets section of this report. Data of hurricane storm paths were retrieved from the U.S. National Oceanic and Atmospheric Administration (NOAA). As the storm surge indicator from GG-IS becomes available it will be incorporated to demonstrate the ability to expand the Risk Index with additional indicators.

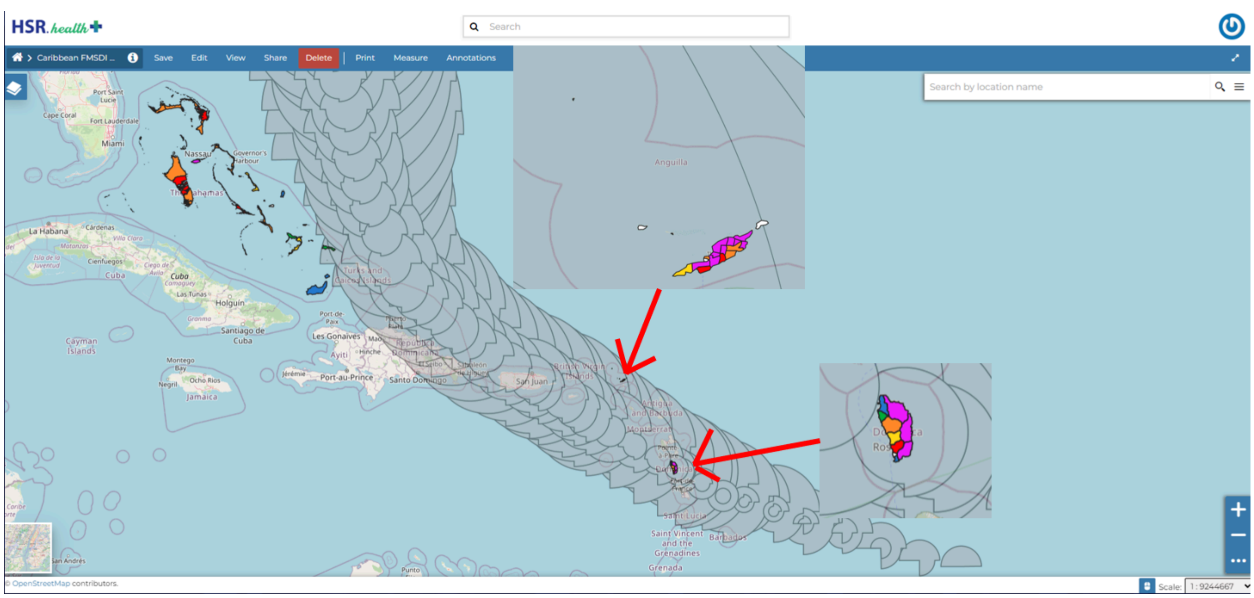


Figure 44 — HSR Health Index Processing Workflow

The Hurricane Health Risk Index for the Caribbean is published to HSR.health's Health Spatial Data Infrastructure on the Open GeoMD Platform which is built on the open source GeoNode and GeoServer stack. The Open GeoMD Platform and the indicators that it hosts serve as the persistent demonstrator for the FMSDI pilot along with publishing of the indicators to the OGC Records catalog.

The platform provides access to the indicators and persistent demonstrator through OGC open standards including Web Mapping Service (WMS), the Web Feature Service (WFS), and the OGC Features API.

Spatial & Temporal Coverage

The Hurricane Health Risk Index has been produced for Anguilla, the Commonwealth of Dominica, and the Bahamas based on information from the year 2020.

Data and Platforms

- **Anguilla**
  - Population Characteristics — Anguilla Statistics Department
  - Underlying Health Conditions — WHO / PAHO / diabetesatlas.org
  - Storm Paths — U.S. NOAA
  - Administrative Boundaries — GADM
  - Storm Surge Risk Indicator — GGIS
- **Bahamas**
  - Population Characteristics — Bahamas Department of Statistics
  - Underlying Health Conditions — WHO / PAHO
  - Storm Paths — U.S. NOAA
  - Administrative Boundaries — GADM
- **Commonwealth of Dominica**
  - Population Characteristics — Dominica Central Statistics Office
  - Underlying Health Conditions — Dominica Central Statistics Office
  - Storm Paths — U.S. NOAA
  - Administrative Boundaries — GADM

Standards & Interoperable Technologies

The primary standards utilized for the Hurricane Health Risk Index indicator include: WMS, WFS, OGC Features API, and ISO 3116-2. Efforts towards achieving alignment and broad agreement on formatting and standardization of social determinants of health data as well as public health data would be of value to the industry.

4.2.3.3. Challenges & Future Work

- **Data Granularity and Useability**

Within the Caribbean thread, the primary limitation identified in this pilot is the relative lack of available population and health data for each of the islands. The population and health data were limited both in the format and granularity. The data were often available through pdf reports which were time consuming to convert to csv tables. The granularity of the data was often national with only some of the data inputs being available at sub-national levels. Efforts to improve data collection and publishing throughout the Caribbean will lead to a better understanding of the population dynamics and allow for better indicator creation.

+ In future pilot efforts, the Hurricane Health Risk Index may be replicated throughout the Caribbean and expanded upon to support the integration of the indicator with available marine data and with additional health indicators. Additionally, HSR.health would like to work with local governments to express the value of improving the availability and granularity of health and social data.

- **Geospatial extensions to Health Standards**

Social and health data utilized for the health risk index are affected by a lack of accepted standards that align with the geospatial and temporal standards of the OGC. Research continues to identify opportunities to extend such relevant standards as ISO 3166-2, ISO/TC 215 Health Informatics, and HL7 with the OGC Feature and Coverage model.

4.2.4. D124: Ocean Plastic Concentrations post-Hurricane Irma

Plastics represent a widespread concern for coastal communities with growing evidence of microplastics entering the local food chain. Macroplastics, and plastic litter in general, also bring an economic cost to the Caribbean tourism industries as it transforms pristine beaches into collective areas of plastic waste. This effect is especially visible after major weather events in which larger plastics tend to concentrate around shallow shorelines.

Background

Compusult is a diversified information technology (ICT) company based in Mount Pearl, Newfoundland, Canada with offices in Den Hague, Netherlands and Virginia, USA. Compusult provides platforms and services focusing on Geospatial Data Discovery and Management Systems; Mobile Applications & Services; Asset Tracking & Inventory Control; Custom and Commercial Software and Electronics; and Assistive Technology for Persons with Disabilities.

The FMSDI Caribbean theme leverages the Compusult Web Enterprise Suite (WES). WES components are based on OGC and ISO standards and are compliant with many commercial/open-source tools and products. Compusult is a long-standing member of the OGC and active supporter of the Web Map Service (WMS), Catalog Service for the Web (CSW), and OGC GeoPackage specifications.

4.2.4.1. Approach

In WES, scenarios are managed by creating an associated Portfolio. A Portfolio provides the ability to manage, organize and track information associated with incidents and events. The Portfolio component has been optimized to support display and management of Common Operating Pictures (COPs) and the creation of situational views that organize and visualize content from disparate data sources and applications for a particular area of interest or topic.

Satellites collecting optical data provide an alternative approach to regional observations of plastic litter in the marine environment. To measure the distribution of plastics prior to and after Hurricane Irma, a WES portfolio is used to process and identify the concentrations of plastics in the Anguilla region using Sentinel-2 Level-1C imagery.

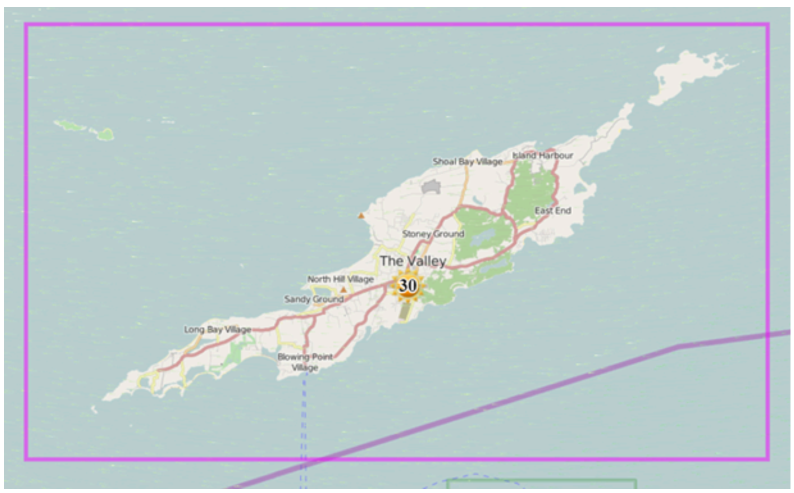


Figure 45 — Region of Interest: Anguilla

4.2.4.2. Solution Architecture

The WES portfolio is designed to process Sentinel-2 Level-1C imagery using a custom script to identify regions with plastic concentrations. The processing service is registered with the WES Catalog providing relevant OGC API client interfaces for Processes, Coverages, and Features.

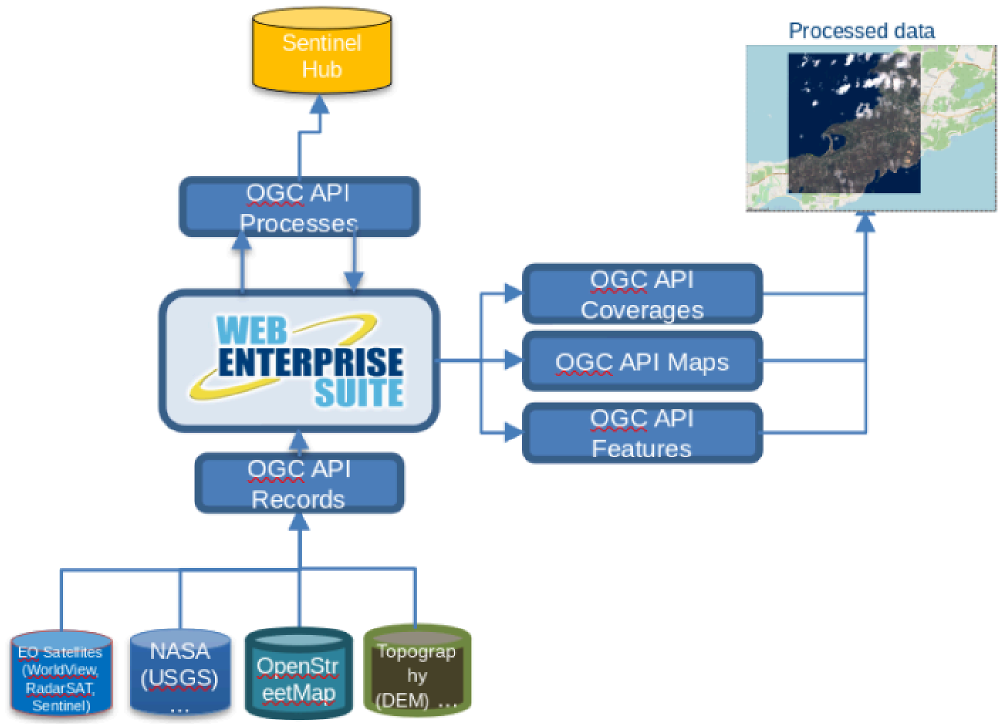
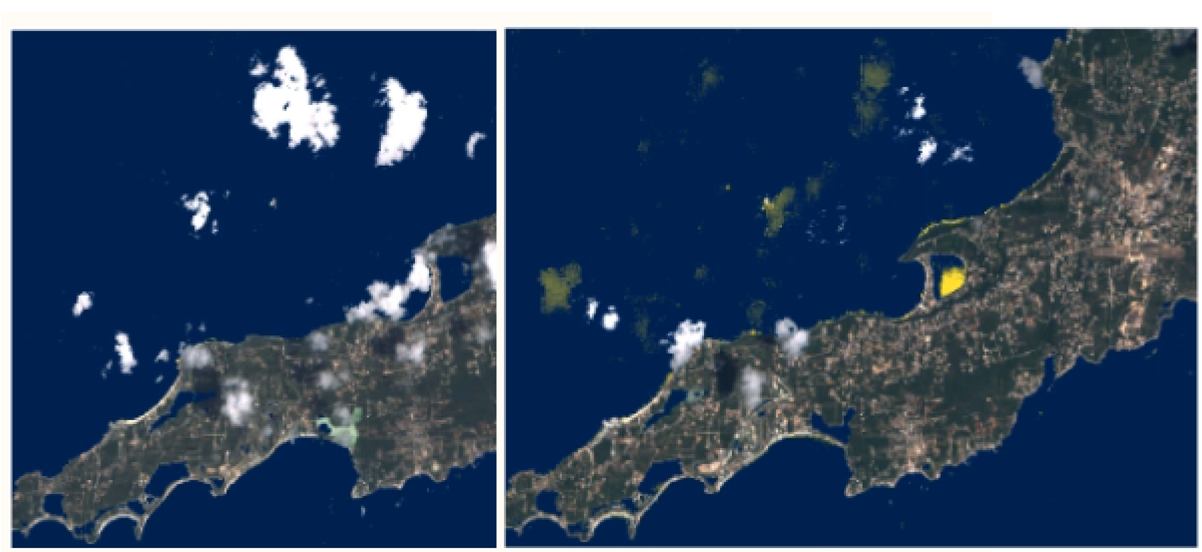


Figure 46 — WES Solution Architecture

A temporal period of interest is registered with the WES Catalog service based on the hurricane information provided through the NOAA National Hurricane Center. This service provides the trajectory of Hurricane Irma during the timeframe in which it traveled through the Anguilla region. Using this temporal period, the SentinelHub processing service is executed to identify plastic concentrations prior to Hurricane Irma and post-hurricane.



Visualization in 3-dimensions is also provided through the WES client albeit with pixellated results.

Figure 47 — D124 - 3D Visualization of Plastic Concentration of Anguilla

Table 8 — D124 Coverage Dimensions

Spatial Coverage	The scenario focuses on the Caribbean Island of Anguilla, using the following bounding box: 18.30654, -063.20254 18.13715, -063.20254 18.13715, -062.91389 18.30654, -062.91389
Temporal Coverage	September 2017

Data and Platforms

- Sentinel Hub
  Ocean Plastic Detector Prototype Script: [https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ocean_plastic_detector/]
  Adapted to Sentinel-2 Level-1C images, the script separates land from water using the Normalised Difference Water Index (NDWI). Land is displayed as natural color. The presence of plastic materials in the water are displayed along a gradient from dark blue (no contamination) to yellow (heavy concentration of plastics).

- NOAA National Hurricane Center
  Trajectory information related to Hurricane Irma was sourced and persisted as a Feature Service within the WES Portfolio.

Standards & Interoperable Technologies

The WES portfolio for the Caribbean theme provides application service endpoints based on the OGC Coverages, Maps, and Features API.

An OGC Processes service endpoint allows clients to remotely initiate the plastic detection algorithm.

4.2.4.3. Challenges & Future Work

- Temporal Periods
  A challenge for the analysis was finding climate and storm data to visualize and to get accurate dates to utilize in the Ocean Plastic Detector process

- Visualization
  OGC Processes can be visualized in many different formats. As a result, there is a need to ensure the correct service is produced that accurately and effectively displays the results of the process in a meaningful way.

4.2.5. D125: Leveraging intra-agency data products for storm surge modeling in the Caribbean

The islands in the Caribbean are frequently impacted by tropical storms and hurricanes. These events, with their high winds and heavy rainfall, can cause serious damage to natural and built environments. In addition, tropical storms and hurricanes can induce storm surges where the sea inundates the land causing significant risk to life.

National governments, local authorities, and local disaster agencies need to make plans and preparations before and during a tropical storm or hurricane. Prior knowledge of areas vulnerable to storm surge events allow for the planning and distribution of resources as well as the strengthening of physical infrastructure such as sea walls and also provides a basis to support housing planning permission decisions for where to locate new towns or local housing developments.

The countries of focus for this project are The Bahamas, Anguilla, and the Commonwealth of Dominica. The Bahamas, with its numerous extremely low-lying islands, is significantly vulnerable to storm surges. When hurricane Dorian hit the Bahamas in 2019 passing through the islands of Great Abaco and Grand Bahama, the hurricane caused a storm surge on parts of these islands causing additional damage and loss of life, as well as trauma for those who survived. Dominica, on the other hand, is a mountainous, volcanic island. However, parts of its coastal areas may still be vulnerable to storm surges. Anguilla also has low elevation areas around its coastline which may also be vulnerable.

Background

Global Geo-Intelligence Solutions (GGIS) is a geospatial data analytics company delivering solutions in support of sustainable and resilient communities. GGIS turns geospatial data sourced from a wide range of pipelines into decision support information for disaster response and mitigation. One such project, an impact assessment to agriculture as a result of the 2017 hurricane system, combined multi-spectral satellite data with post disaster crowd-sourced data to quantify the regional impacts to the Commonwealth of Dominica, Antigua & Barbuda, and St Kitts & Nevis.

4.2.5.1. Approach

Modeling of storm surges is a very complex task. Some researchers have used the finite element modeling approach utilizing the coupled ADCIRC-SWAN model to investigate the surge and wave dynamics along the coastline of islands. The *ADvanced CIRCulation* (ADCIRC) model is based on the finite-element difference method and an unstructured computational grid. ADCIRC is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids.

The spectral wave model, *Simulating Waves Nearshore* (SWAN) is used to simulate wind induced waves on shallow water coastal zones. Researchers have used these models individually or in a coupled way to model storm surges. Other approaches included the computation of a general coastal vulnerability index based on factors such as coastal slope, geomorphology, etc. A storm surge–induced flood simulation methodology, called the *GIS-based subdivision-redistribution* (GISSR) methodology, is proposed for coastal urban environments. The methodology combines GIS with Manning's equation to calculate the volume of water flowing into the geographical area under consideration and then redistributes it appropriately over that area. It uses as input the time histories of the storm surge height and of tides along the coastline.

GGIS will be simulating two scenarios: (a) the impact of a hurricane hitting the selected islands causing a storm surge event, and (b) flooding from the heavy volume of rain fall. The simulation workflow will enable decision makers and planners to identify vulnerable areas and thus make appropriate decisions before, during, and after such major weather events. This information will be of use across various sectors such as disaster management, emergency responders, housing & infrastructure, agriculture, and health.

Navigational data as provided for the Caribbean theme were investigated for the data's application to those characteristics affecting the extent of coastal inundation. The modeling of storm surges is an area that benefits from the combining of the land and sea datasets as multiple factors on both land and sea influence its occurrence.

Static Risk Assessments:

A static risk assessment refers to areas that are vulnerable to storm surge events based on variables that do not change quickly over time. These variables represent elevation, bathymetry, and projected local sea level rise.

Dynamic Risk Assessments:

A dynamic risk assessment models elements that are fast changing, are characteristic of a major weather event, or are directly impacted by the storm. These elements represent tide, wind speed, air pressure, distance to the hurricane, etc.

The static and dynamic risk assessment models are based on set thresholds around the variables of interest. Outputs from the model produce a final integrated storm surge risk map. This approach is much more computationally light-weight than initial approaches such as the ADCIRC finite element modeling allowing for accurate and timely decision support information at critical time points. Post-event models such as the ADCIRC model, which are computationally expensive models, may be applied to improve the core static and dynamic risk assessment models.

4.2.5.2. Solution Architecture

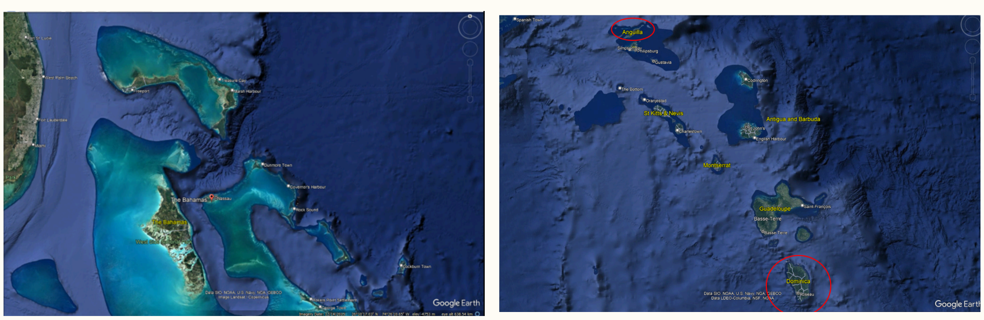
The GGIS platform simulates the conditions of storm surge and flooding associated with major weather events such as hurricanes and tropical storms. Simulations are designed to identify vulnerable areas and provide decision makers with timely information to mitigate risk through a responsive disaster management program.
The static risk assessment model is extended to ingest navigational data to complement the core feature model representing the coastal zone.

The storm surge risk assessment models the forcing of winds, change in air pressure, the profile of the coastline, and the shape and depth of the continental shelf. High tides are projected along a timeline coincident with the weather event as a 'worse case' scenario.

Spatial Coverage

The countries of interest are The Bahamas, Anguilla, and the Commonwealth of Dominica with focus on five coastal communities representing the largest populations. These are New Providence, Grand Bahama, Andros, Great Abaco ,and Eleuthera.

Table 9 — D125 Spatial Coverage



Sampling Coverage:

```
Sampling points were at 2 km spacing for Anguilla and 5 km for
Bahamas and Dominica
```

Figure 48

Temporal Coverage

The simulations extend through a 10-year time period based on current island conditions and forecasts. Adjustments to the static risk assessment model are based on projected local sea level rise estimates of 0.80 — 0.84 m by the year 2100. Kopp-2014

Data and Platforms

Key indicator variables were derived from various sources and transformed into the regional coordinate system for the Caribbean.

Table 10 — D125 Key Indicator Variables for Caribbean Features of Interest

KEY VARIABLE	SOURCE
Elevation data	ALOS PALSAR 30m DEM model
Bathymetry	GEBCO database
Hurricane Wind Speed, Pressure, Historic Trajectory	NOAA
Distance to hurricane	Derived from Trajectory data per use case
Tide, Sea Surface velocity and Breakpoints data	NOAA
Historical storm surge heights, locations, dates, etc.	SurgeDat database
Earth Observation Data	Sentinel 1 — Copernicus Data Store

Standards & Interoperable Technologies

- **OGC API Features:**

Simulation models are published to a service endpoint supporting the OGC API Features API.

4.2.5.3. Challenges & Future Work

- **Data Discovery and Data Extraction**

The initial data discovery phase extended beyond the original schedule as a result of delays in getting access to the requested UKHO datasets. Certain issues related to the interpretation of navigation datasets and terminology caused further delays to the project schedule; e.g., understanding ENC Cell references when requesting data. The data extraction for the 5km spaced (2km for Anguilla) sampling points also took some time; to compensate for the initial delays, the process was eventually automated.

- **Data Alignment**

A mismatch was observed between the Digital Surface Model and the Bathymetry data. The DSM data were used for the terrain model while the bathymetry data were used for the sea.

+ Output Validation: The risk map results were compared with local survey data of where a storm surge occurred in the Bahamas as a result of Hurricane Dorian in 2019. The Sentinel 1 analysis was also used to support the data validation. The storm surge model was implemented as a 'proof of concept' with opportunities identified to improve on the surge model in future work.

- **Scenario Planning**

The aim is to develop a fully automated process where the user inputs the area of interest and the trajectory and storm characteristics. The system would be able to extract and process the relevant data to provide the output maps within a short period (e.g., 30 minutes). This improvement positions the Storm Surge Modeling workflow as a core component of the Foresight DRM platform which can be used to assess the potential impact of approaching storms based on predicted paths. Alternatively, this improvement assists in planning into the future based on hypothetical paths 10 years in the future and assessing the storm surge risks.

4.3. Thread Summary & Future Work

The United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) are charged with the development of the Integrated Geospatial Information Management Framework (IGIF). The UN-GGIM aims to address global challenges regarding the use of geospatial information and to serve as a body for global policymaking in the field of geospatial information management.

The UN-IGIF-Hydro (IGIF-H) is an action of the United Nations Decade of Ocean Science for Sustainable Development and is intended for use by both developing and established geospatial programs that wish to implement the UN-IGIF Strategic Pathways in the marine domain. The IGIF-H also aims to ensure the inclusion of the marine domain in the larger geospatial information ecosystem.

An effective use of nautical charts for navigation complements the goals of the UN-GGIM as a reliable source of marine geospatial information. For the islands of the Caribbean, the opportunity exists to integrate navigation data as a foundational component of an integrated marine geospatial framework enabling efforts in support of the IGIF's nine strategic pathways.

4.3.1. Summary of Results

This pilot tasked participants to investigate the use of navigational data and standards across various application scenarios with focus on coastal resilience. The contributions were developed independently, each with a central focus on the effects of climate change to the economic growth of the Caribbean region. This initiative highlighted many common issues reinforcing the discussion around the suitability of navigation data for non-navigation purposes.

Overall, the participant contributions were able to demonstrate the usefulness of provided navigational, bathymetric, and meteorological data products as an integrated framework across the coastal marine domain with the following constraints.

4.3.2. Future Work

License Restrictions

Access to data proved to be a challenge for the project as delays in license availability through the UKHO impacted the initial deliverables. Participants such as OceanWise, as an existing licensee of UKHO data, were able to re-use licenses of UKHO data until a Data Exploration License was agreed between UKHO and OGC.

+ Participants that did not have a pre-existing license were restricted in scope for each demonstrator which impacted the work effort investigating the application of UKHO navigation data as a base for marine spatial planning.

+ Consistent with the IGIF-Hydro Guidelines, licensing is a major issue for many marine datasets and will need resolution to further advance the IGIF initiative for any Caribbean nation. These nations would benefit from the experience of nations who already successfully license data (UK, Germany, and Denmark, for example) for non-navigational purposes.

External Data Products

It was also difficult to find other datasets that the Caribbean nations made publicly available which could supplement the navigation data; however as the point of the exercise was to investigate the suitability of navigation data for other purposes, this was considered less relevant. Comparing features with a Cell from the UK gave an interesting indication of how little data is included in navigational charts of the Caribbean region, although it was not possible to determine whether this was a result of non-existent features or not being charted.

+ This would be a useful exercise for the Caribbean data owners as part of a data audit to compare source datasets held with that in the navigational charts and identify features that would be useful for marine spatial planning but are not currently collected.

5

CONCLUSIONS

5 CONCLUSIONS

The FMSDI 2023 project focused primarily on the effects of climate change on coastal environments. Generally, the solutions successfully addressed the project requirements across the traditional lat,lon, and temporal dimensions with extended results addressing the vertical dimension for coastal terrains and climate indicators representing sea level rise and changing sea ice.

The client environments each provide time-instant 2-dimensional and 3-dimensional views of the impact on coastal environments from climate change using information derived from external data sources. Visualization of coastal inundation as a result of storm surge and sea rise simulations produced an effective workflow to communicate the vulnerabilities of coastal areas. Factors such as the bathymetric profile and other forcings on water bodies were not taken into account which would provide a truer representation of the vulnerability of coastal realms to severe weather events.

Testbed-19 GeoDataCube / Analysis Ready Data

In parallel to the FMSDI 2023 pilot, the OGC Testbed-19 initiative is evaluating certain concepts that may benefit future work related to this project. In particular, discussions on the role of the OGC GeoDataCube and OGC Analysis Ready Data (ARD) work products are relevant to addressing concerns of scale and multi-dimensional analytics. The FMSDI pilot demonstrates the use of the GeoDataCube architecture as a core component of the solution framework. The GeoDataCube platforms implement a reference system for each theme with an extended coverage model in compliance of the OGC Coverages and OGC Coverage Processing Service. The OGC ARD initiative is designed to identify and promote further capabilities of multi-dimensional analysis by abstracting the complexities of earth observation monitoring systems and producing satellite derived data products aligned with regional concerns.

OGC Building Blocks

The OGC Building Blocks initiative is developing a set of best practices for developing standards-based APIs for location-aware application frameworks. A building block is a reusable component that may implement a complete OGC API standard, one part of a multi-part standard, or more granular functionality within a standard. A conceptual model of the marine domain inclusive of the coastal realm and marine cadastres demonstrates an opportunity to formalize a feature model to assure alignment with external standards bodies such as IHO, IUCN, and GeoBON.

Demonstrator Program

The FMSDI 2023 project is the first pilot in OGC to require persistent demonstrators from each participant. These demonstrators are workflows and applications that stakeholders can access for outreach, testing, and experimentation purposes.The demonstrators will be available for a limited time period, until December 2024. Each persistent demonstrator from this pilot has unique characteristics. Some demonstrate how geospatial data and information can be used in an operational context, while others showcase current possibilities and identify gaps in the resources that can be discovered on the internet. These demonstrators include various data sources, metadata, access processes to online data, and various standards used for data discovery, access, and processing interfaces. Considering the varying solution platforms of each participant, different approaches were made available for review by stakeholders. Issues such as security (authentication and authorization) are bespoke for each participant with details provided through outreach to the stakeholders and participant contacts.

A

ANNEX A (INFORMATIVE) SINGAPORE DATUM RELATIONSHIPS & GEOREFERENCING SYSTEM

A ANNEX A (INFORMATIVE) SINGAPORE DATUM RELATIONSHIPS & GEOREFERENCING SYSTEM

SLA provided a *Digital Twin* representation of Singapore's cityscape as a 3-dimensional cadastre encoded as CityGML 2.0 TINrelief with a vertical datum based on the Singapore Height Datum (SHD) and horizontal projection based on SYV21 (EPSG:3414). The corresponding EPSG codes for application to the source data are: EPSG:3414 (SVY21 — horizontal); EPSG:6916 (SHD vertical); and EPSG: 6927 (SVY21 + SHD).

Land & Sea Datum Relationships

Singapore's land registry is based off the Singapore Height Datum (SHD) while the bathymetric profile for Singapore is based on the Admiralty Chart Datum. To reconcile vertical control points against the bathymetric heights, a simple arithmetic adjustment of -1.555m is applied to the seabed survey to indicate depth "below" SHD. In this way, the terrain and bathymetric vertical data are properly referenced consistently against the Singapore Height Adjustment.

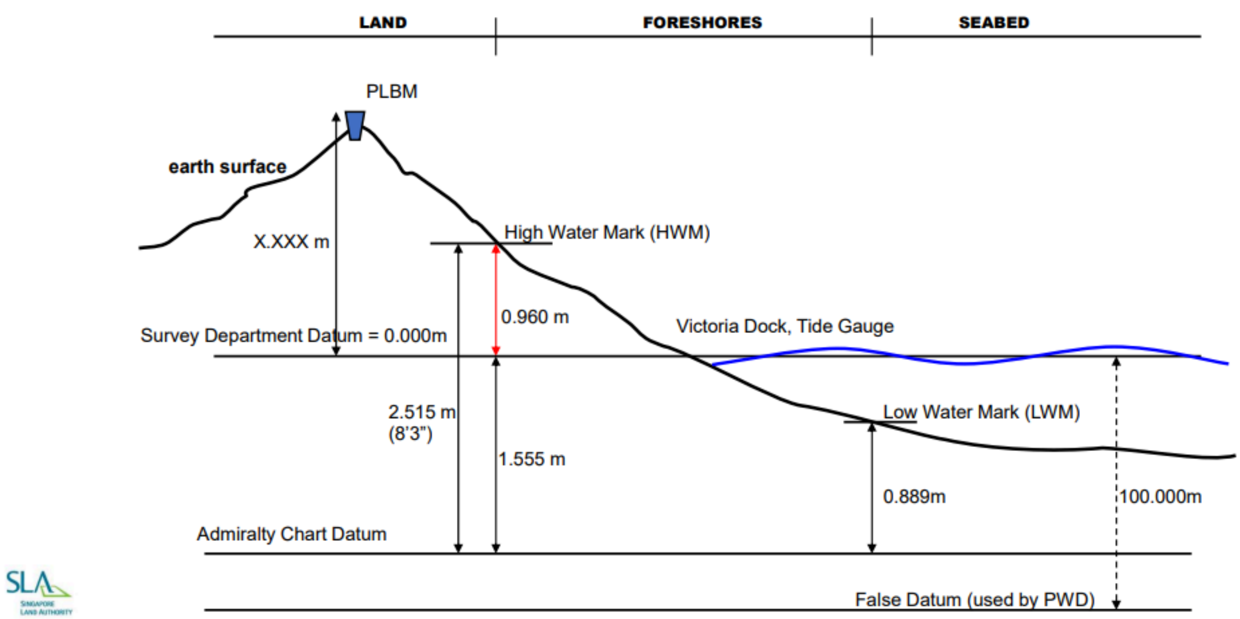


Figure A.1 — SLA-MPA Datum Relationships

SLA maintains the land-use cadastre up to the High Water Mark (HWM) demarcation while defining the extent of its coastal zone to a depth of 5m SHD.

Adjusting for GNSS vertical measurements

Singapore maintains an extensive network of vertical control points (a Datum-Precise Levelling Network) consisting of precise levelling benchmarks with vertical accuracy within 5mm SHD. To make use of satellite observations as an efficient means for geo-positioning, it was necessary for SLA to implement a regional geoid (SGeoid09) to convert recorded GPS heights to the Singapore Height Datum.

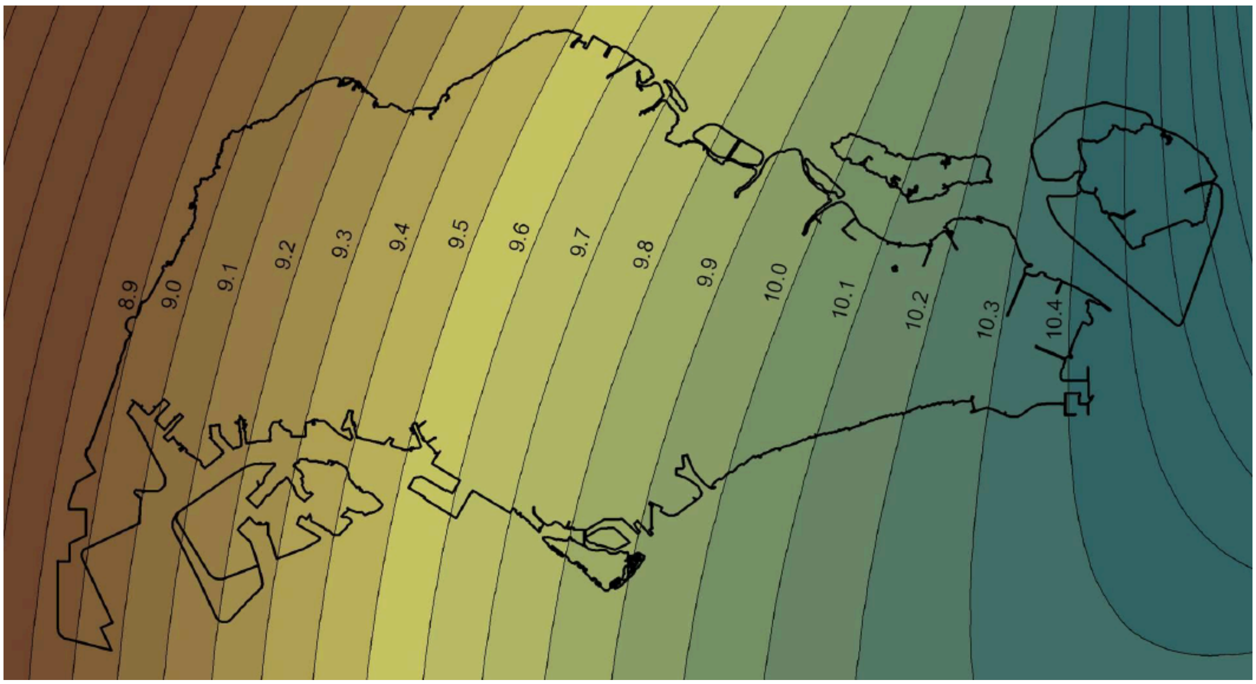


Figure A.2 — Singapore Geoid Model Adjustment

This reduced level or "orthometric height" accounts for the GPS recorded ellipsoidal height and applies a specific adjustment as a function of the geo-position (N,E) to produce the vertical height relative to SHD.
This is a very important factor when applying any geo-analysis concepts to the Singapore coastline so as to properly adjust the height datum for events such as coastal inundation using satellite-derived variables.

Reprojection & Transformation

A number of issues related to the use of CityGML in its native format were addressed through a transformation to a GeoTIFF encoding using Safe Software's FME platform.

Support from Safe Software Inc. was enlisted to review the state of the source SLA dataset and provide a transformation workflow to convert the TINRelief CityGML source data to GeoTIFF. The FME reprojection utility, CsmapReprojector, defaults to using the CS-Map coordinate system library; however, issues supporting the EPSG:3414 projection resulted in the use of the PROJReprojector extension to reproject the feature coordinates to the EPSG:4326 and

EPSG:3414 coordinate reference systems. The EPSG:4326 output was used to verify the georeferencing.

The FME extension, RasterDEMGenerator, was used to produce the raster digital elevation model with a horizontal resolution of 2 meters and a vertical resolution of 1 decimeter. The GeometryValidator extension to FME was used to repair issues with certain feature sets and the FME AttributeCreator was then used to preserve the record level metadata within the output GeoTIFF encoding.

NOTE: The OGC FMSDI project team would like to thank Dean Hintz, Strategic Solutions Manager at Safe Software, for his insight and support during this project.

B

ANNEX B (INFORMATIVE) D103 CARIBBEAN SURVEY

B ANNEX B (INFORMATIVE)

D103 CARIBBEAN SURVEY

OGC Federated Marine Spatial Data Infrastructure - Caribbean

Organization background Information

The Open Geospatial Consortium (OGC) has issued this Request for Information (RFI) on behalf of the UK Hydrographic Office (UKHO). The purpose of the RFI is to evaluate the availability of basic data, interfaces, and data formats in the Caribbean region.

The OGC is a collective, problem-solving community of more than 550 experts representing industry, government, research, and academia, collaborating to make geospatial (location) information and services FAIR - Findable, Accessible, Interoperable, and Reusable. The global OGC Community engages in a mix of activities related to location-based technologies: developing consensus-based open standards and best practices; collaborating on problem-solving in agile innovation initiatives; participating in member meetings, events, and workshops; and more. OGC's unique standards development process moves at the pace of innovation, with constant input from technology forecasting, practical prototyping, real-world testing, and community engagement. OGC is committed to creating an inclusive and sustainable future. Visit ogc.org for more info on our work.

Notes:

- Completing this form will require around 5 min of your time to answer 7 multiple choice questions.
- In multiple choice questions, please check all options that apply to your organization.
- All RFI Responses are due by:
  Sunday, 10 September 2023
  12:00 PM Eastern Time Zone
- Feedback captured in the survey will be included in the OGC FMSDI engineering report. For more information, please visit the OGC FMSDI Pilot Link: https://www.ogc.org/initiatives/fmsdi4/

The purpose of gathering your answers to background information is solely to understand the level of familiarity respondents have with the answers. Please note that all information gathered in this survey will be published anonymously.

* 1. Organization name:

____

* 2. Contact Name:

____

3. Position:

____

4. Email:

____

Data Availability

5. Is your organization a data user, data broker, data producer/owner, or do you work with geospatial data related to Marine or Coastal areas in the Caribbean region?

◯ Yes

◯ No

Data Type

The purpose of this page is to determine your organization's role in the marine ecosystem and the type of data you handle.

6. What type of data do you have or work with?

	User	Producer/owner	Broker/enabler	Data openly available (open source or free)?
Depth data models	☐	☐	☐	☐
Electronic Navigational Charts (ENC) products	☐	☐	☐	☐
Raster Navigational Chart (RNC) products	☐	☐	☐	☐
Maritime Limits	☐	☐	☐	☐
Seafloor Backscatter	☐	☐	☐	☐
Marine Protected Area data	☐	☐	☐	☐
Continental Shelf	☐	☐	☐	☐
Weather and Wave	☐	☐	☐	☐
Surface Currents	☐	☐	☐	☐
Marine Harbour Infrastructure	☐	☐	☐	☐
Bathymetric Surface	☐	☐	☐	☐
Catalogues of Nautical Products	☐	☐	☐	☐

Other (please specify)

7. Please indicate the format(s) of the data. You may select multiple options if applicable.

- ☐ OGC WMS/WFS, WCS,
- ☐ IHO S-57,
- ☐ IHO S-100
- ☐ GeoTIFF
- ☐ GeoPDF
- ☐ ShapeFile
- ☐ ESRI geodatabase
- ☐ GeoPackages
- ☐ GML
- ☐ KML/XML
- ☐ Other (please specify)

Interfaces

The purpose of this page is to determine the standards that your organization currently utilizes or those that you are considering implementing.

8. Do you currently use geospatial standards to access data and services? If so, what are the key geospatial standards you use?

- ☐ OGC WMS/WFS/WCS/WPS
- ☐ OGC API (e.g. features, records, etc.)
- ☐ IHO S-100 series
- ☐ GML
- ☐ RDL
- ☐ GDAL
- ☐ IHO S-57/S-52/S-63
- ☐ ECDIS
- ☐ AML
- ☐ I don't use any standards.
- ☐ Other (please specify)

Sustainable Blue Economy

The blue economy includes all industries and sectors related to oceans, seas, and coasts, whether they operate in the marine environment (such as shipping, fisheries, and energy generation) or on land (such as ports, shipyards, land-based aquaculture and algae production, and coastal tourism).

9. Are you involved in any sustainable activities related to the blue economy?

- ☐ Reconcile economic development,
- ☐ Improved livelihoods and social inclusion by protecting biodiversity and ecosystems
- ☐ Improved livelihoods and social inclusion by fighting the climate crisis
- ☐ Improved livelihoods and social inclusion by using resources responsibly
- ☐ Achieving the zero-pollution ambition.
- ☐ I am not involved
- ☐ Other (please specify)

10. Please rank the industries you believe contribute to the future of the blue economy.

	High contribution	Medium contribution	Low contribution
Traditional sectors (e.g., fishing, Oil and Gas, tourism, transport, recreation etc.)	○	○	○
Ocean renewable energy (e.g., Tidal Current, wave, etc.)	○	○	○
Blue bio-economy (e.g., parts of the economy that use renewable biological resources from sea – such as fish, animals and micro-organisms – to produce food, health, materials, products, textiles and energy)	○	○	○
Desalination	○	○	○
Industries connected to the on-land economy such as supply chains.	○	○	○

Other (please specify)

C

ANNEX C (INFORMATIVE) D122 OCEANWISE DETAILED ASSESSMENT

C ANNEX C (INFORMATIVE) D122 OCEANWISE DETAILED ASSESSMENT

For reference, the following tables identify the detailed results of the OceanWise project assessment based on Theme and Feature Type.

MTF ADMINISTRATIVE

Table C.1 — MTF Administrative Project Assessment

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Continental Shelf area (51020)	1	0	0
EEZ (51030)	1	0	0
REZ (51031)	1	0	0
Territorial Sea Areas (51040)	2	0	0
Civil and Criminal Jurisdiction Limit (51050)	2	0	0
Harbour Areas (51082)	1	0	0
Harbour area (administrative) (52010)	3	0	1
Anchorage Areas (52030)	12	5	1
Restricted Areas (54050)	11	2	3
Precautionary Areas (54051)	1	0	0
Caution Areas (54070)	4	0	0
Environmental Area (54081)	1	0	0
Total Features	40	7	5

MTF INDUSTRIAL

Table C.2 — MTF Industrial Project Assessment

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Pile, Undefined (40010)	1	0	0
Pile Post (40013)	1	0	0
Harbour facility undefined (41000)	1	0	0
Harbour facility dry dock (41010)	1	0	0
Harbour facility pontoon (41020)	1	0	0
Harbour facility mooring/warping facility Dolphin (41031)	1	0	0
Harbour facility mooring/warping facility post or pile (41035)	1	0	0
Mooring/Warping facility, Mooring buoy (41037)	1	0	0
Marine farm/culture oysters/ mussels (42012)	1	0	0
Floating oil barrier (43012)	1	0	0
Cable submarine undefined (44010)	1	0	0
Cable submarine power line (44011)	1	0	0
Pipeline (44020)	1	0	0
Diffuser (44040)	1	0	0
Shoreline construction undefined (45100)	1	0	0
Shoreline construction, breakwater (45101)	1	0	0
Shoreline construction, groyne (45102)	1	0	0
Shoreline construction pier (jetty) (45104)	1	0	0

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Shoreline construction wharf (quay) (45106)	1	0	0
Sea wall (45110)	1	0	0
Shoreline construction slipway (45113)	1	0	0
Shoreline construction sluice (45136)	1	0	0
Shoreline construction causeway (45140)	1	0	0
Total	**318**	**18**	**47**

MTF OBSTRUCTIONS

Table C.3 — MTF Obstructions Project Assessment

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Obstruction undefined (20010)	7	13	1
Obstruction foul area (20016)	0	10	3
Obstruction foul ground (20017)	0	1	0
Wreck non-dangerous wreck (20021)	0	2	0
Wreck dangerous wreck (20022)	1	16	3
Wreck showing any portion of hull or superstructure (20025)	6	9	3
Obstruction underwater rock (20040)	0	131	24
Total	**14**	**182**	**34**

MTF TRANSPORT

Table C.4 — MTF Transport Project Assessment

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Beacon, Cardinal, East (31012)	1	0	0
Beacon lateral port (31041)	16	0	0
Beacon lateral starboard (31042)	13	0	0
Beacon, Lateral, Preferred channel, Starboard (31043)	1	0	0
Beacon Special purpose/general (31060)	27	0	0
Buoy cardinal north (32011)	1	0	0
Buoy cardinal south (32013)	1	0	0
Buoy cardinal west (32014)	0	0	0
Buoy lateral port (32041)	3	4	0
Buoy lateral starboard (32042)	11	4	0
Buoy special purpose/general (32060)	17	2	2
Light float (33010)	1	0	0
Route, Fairway (34023)	2	0	0
Route recommended track (34026)	12	0	0
Route, Ferry, Cable (34032)	2	0	0
Navigation line, Transit line (35012)	1	0	0
Navigation line, leading line (35013)	4	0	0
Total	**112**	**10**	**2**

MTL ELEVATION

Table C.5 — MTL Elevation Project Assessment

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Bathymetry Contour (10021)	55	112	19
Bathymetry Sounding (10022)	785	874	98
Coastline undefined (13100)	32	34	4
Coastline steep coast (13101)	0	18	0
Coastline sandy shore (13103)	0	18	0
Coastline marshy shore (13108)	17	0	0
Coastline man made (13200)	75	0	0
Total	**1076**	**1056**	**121**

MTM ELEVATION

Table C.6 — MTM Elevation Project Assessment

DESCRIPTION (FEATURE_CODE)	SOLENT	ANGUILLA	CAYMAN
Bathymetry contour (10021)	65	121	19
Bathymetry Sounding (10022)	282	885	78
Coastline undefined (13100)	36	35	21
Coastline steep coast (13101)	0	17	0
Coastline sandy shore (13103)	0	18	0
Coastline, mangrove (13107)	0	0	9
Coastline marshy store (13108)	17	0	0
Coastline man made (13200)	79	0	30
Total	**1092**	**1076**	**157**

D

ANNEX D (INFORMATIVE) D134 CAFF SUMMARY OF BIODIVERSITY INDICES AND INDICATORS

D

ANNEX D (INFORMATIVE) D134 CAFF SUMMARY OF BIODIVERSITY INDICES AND INDICATORS

The following table summarizes the set of CAFF Biodiversity Indices and Indicators and the relationship to the Convention on Biological Diversity (CBD).

Table D.1 — CAFF Summary of Indices and Indicators

CBMP BIODIVERSITY INDEX	CBD LINKAGE
Species Composition	
Arctic Species Trend Index	✓
Trends in Abundance of Key Species	✓
Arctic Red List Index	✓
Change in Status of Threatened Species	✓
Trends in Total Species Listed at Risk	
Ecosystem Structure	
Arctic Trophic Level Index	✓
Water Quality Index	✓
Habitat Extent and Change in Quality	
Arctic Land Cover Change Index	
Trends in Extent of Biomes, Habitats and Ecosystems	✓
Arctic Habitat Fragmentation Index	

CBMP BIODIVERSITY INDEX	CBD LINKAGE
Trends in Patch Size Distribution of Habitats	
Fragmentation of River Systems	✓
Extent of Seafloor Disturbance	
Ecosystem Functions & Services	
Trends in Extent, Frequency , Intensity and Distribution of Natural Disturbances	
Trends in Phenology	
Trends in Decomposition Rates	
Human Health & Well-Being	
Arctic Human Well-being Index	
Trends in Availability of Biodiversity for Traditional Food and Medicine	✓
Trends in Use of Traditional Knowledge in Research, Monitoring and Management	
Trends in Incidence of Pathogens and Parasites in Wildlife	
Policy Responses	
Coverage of Protected Areas	✓

E

ANNEX E (INFORMATIVE) REVISION HISTORY

E ANNEX E (INFORMATIVE) REVISION HISTORY

DATE	RELEASE	AUTHOR	PRIMARY CLAUSES MODIFIED	DESCRIPTION
2023-05-08	0.0.1	Glenn Laughlin	all	initial version
2023-05-15	0.0.2	Glenn Laughlin	all	Refactored for OGC structure revisions March 20, 2023
2023-10-02	0.0.3	Glenn Laughlin	D101	Integration of ER Content based on demonstrators
2023-10-27	0.0.4	Glenn Laughlin	all	updates to each section based on current status and reviews
2023-11-06	0.1	Glenn Laughlin	all	candidate report for internal review
2023-11-15	0.2	Glenn Laughlin	D113-Ecere	updated ER content based on participant feedback
2023-11-15	0.3	Glenn Laughlin	D133-HSR; D123-HSR	updated citation references to bibliography
2023-11-22	0.4	Glenn Laughlin	all	Updates based on first review
2023-11-27	0.5	Glenn Laughlin	bibliography	Additional citations and format fixes
2023-11-30	0.6	Glenn Laughlin	all	Format changes and minor updates for project review
2023-12-05	0.7	Glenn Laughlin	Introduction and Summary	finalize role of pilot and project summary

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