Multi-Criteria Decision Analysis Framework for Bathymetric Data Accuracy Assessment in Marine Spatial Data Infrastructure

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Abstract: Marine Spatial Data Infrastructure (MSDI) simplifies the discovery, access, management and reuse of marine geospatial data with bathymetric data being one of the most basic components. But bathymetric data obtained over a long time period through a variety of technologies are highly heterogeneous in accuracy, uncertainty, completeness of documentation, and data formats, which pose serious obstacles to the systematic incorporation of MSDI. The proposed research is a Multi-Criteria Decision Analysis (MCDA) framework, which combines two complementary classification criteria, including technology-based accuracy levels based on sensor specifications, positioning systems, and the survey era with IHO S-67 Category Zone of Confidence (CATZOC) levels. The framework yields a two-dimensional decision matrix that gives nine secondary levels of accuracy and three levels of primary level of accuracy consolidated. The methodology is presented with the application of the case study on 9 bathymetric datasets (1991 - 2023) provided by the Hydrographic Office (NHO), National Aquatic Resources Research and Development Agency (NARA), Sri Lanka. A 2023 bathymetric survey of the Negombo Harbor with Kongsberg EA440 single-beam echo sounder and Stonex RTK positioning system was assessed in detail, which was classified as Technology Tier 4 and CATZOC Level B, and Level 5 - Standard Plus was classified as secondary and Level 2 - Moderate as primary. Completeness analysis of metadata showed that there were dramatic changes in trends over time with a documentation completeness of pre-2000 datasets (12.5% complete) and post-2015 surveys (75.0% complete). The proposed framework gives the hydrographic offices a clear, repeatable and resource efficient framework to evaluate heterogeneous holdings of bathymetric data and come up with evidence-based conclusions on whether the dataset is relevant to various marine tasks.

Keywords: *Marine Spatial Data Infrastructure (MSDI), Bathymetric Data Accuracy, Multi-Criteria Decision Analysis, CATZOC, Classification.*

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I. INTRODUCTION

Spatial Data Infrastructure (SDI) enables the discovery, access, management, distribution, reuse, and preservation of geospatial information using combined structures of technologies, policies, and institutional structures (Aalders & Moellering, 2001). Marine Spatial Data Infrastructure (MSDI) is the domain-specific extension of SDI to the marine realm, which allows managing marine spatial information such as bathymetry, oceanography, marine geology, marine infrastructure, administrative boundaries, and marine ecosystems comprehensively (IHO C-17, 2023; Foglini and Grande, 2023). Bathymetric data mapping the submerged surface of oceans and other water bodies is one of the most fundamental and the most widely used data themes in MSDI (Kearns and Breman, 2010). Bathymetric data continues to be used in a variety of marine activities as well as safe navigation charting, although at present, the majority of marine activities are supported through bathymetric data such as marine spatial planning, coastal zone management, environmental monitoring, underwater construction, offshore resource exploration, marine conservation, climate change research, and scientific oceanography (Hell et al., 2012; Li et al., 2023).

Bathymetric data is crucial to all marine applications because poor quality might result in losing considerable amounts of money, ecological harm, failure of infrastructure, and the loss of human lives (IHO S-44, 2022). As a result, hydrographic offices, data-gathering agencies have a mandate to disseminate correct, properly documented bathymetric

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information using MSDI platforms, and users need to be provided with easy, clear, and standardized information about the accuracy status of data sets to ascertain fitness-for-purpose (Contarinis et al., 2018; Hasara et al., 2025). Nonetheless, hydrographic offices have worldwide collections of archives of bathymetric data assembled over several decades, many of them dating between the middle of the 20th century and the current time span, and these collections are of a highly heterogeneous nature on several levels. The spectrum of technological diversity goes between lead lines and sounding poles with a vertical uncertainty of ±1.05.0 m to analog and computerized single-beam echo sounders to the current multibeam systems with vertical uncertainty of ±0.050.15 m (Li et al., 2023; Hughes Clarke, 2018). Depending on visual bearings or sextant fixes, Transit Doppler, autonomous GPS, differential GPS, and current RTK-GNSS have positioning accuracies ranging from ±50100m to ±0.020.05m respectively (IHO S-44, 2022). Prior to 2000 surveys often lack uncertainty documentation, and do not often have quantitative Total Propagated Uncertainty (TPU) or Total Vertical Uncertainty (TVU) or Total Horizontal Uncertainty (THU) values (Hare et al., 2011). Metadata completeness is also systematically improved over time, as structured metadata based on international standards did not appear before 2010, and the older datasets contained significant gaps in documentation (Hasara et al., 2025). Format heterogeneity encompasses many manufacturer-specific raw formats, many processed formats in ASCII and binary form, and not matching coordinate reference systems and vertical datums. Special Order and IHO S-44 specifications Survey uses and related IHO S-44 specifications range from Special Order to Orders 1a, 1b, and 2, with a lot of pre-formal survey order data usually existing before formal survey order specification at all.

Although this is a very rich heterogeneity, any given bathymetric dataset has the potential value to work in a particular application. The legacy surveys are invaluable in understanding seafloor for examining seafloor change, evaluating coastal erosion, morphological evolution, and setting environmental baselines of the past (Mayer, 2006). Modern high-precision surveys favor the safety of navigation, the design of the engineering, and the determination of the legal boundaries. The dilemma that faces MSDI data custodians is thus not on inclusion of heterogeneous datasets, but the issue of how to measure, record and communicate the accurate status of such datasets in a standardized, transparent and understandable format by the users.

The existing methods of measuring quality of bathymetric data have a number of limitations in implementations in the context of MSDI integration. IHO S-44 has accuracy requirements of the planned surveys, but it lacks any mechanism of measuring the current, completed surveys against the requirements (IHO S-44, 2022). The category quality labels in IHO S-67 CATZOC classification are tailored to Electronic Navigational Charts and need a significant degree of manual interpretation and are not made to be optimal in MSDI discovery and selection contexts where datasets are used in non-navigational ways (IHO S-67, 2020). The current method of manual expert evaluation, which is used in most hydrographic offices, takes 45 to 60 minutes per dataset, has inter-evaluator variability with Cohen k values of 0.67 to 0.78 and cannot be scaled across data holdings with thousands of datasets (Hasara et al., 2025). Metadata standards like ISO 19115 and IHO S-102 define what is supposed to be reported as metadata but have no information on how to compare the information that is reported to give overall accuracy measurements or quality ratings (IHO S-102, 2022; ISO 19115, 2014). The previous studies have dealt with bathymetric uncertainty modelling (Hare et al., 2011), data quality dimensions (Veregin, 1999), the development of the MSDI framework (Tavra et al., 2017; Racetin et al., 2022), and the conceptual accuracy classification (Hasara et al., 2025). Nevertheless, there is no developed, multi-criteria operational decision model to specifically and repeatability engage the quality of heterogeneous bathymetric data to be included in the MSDI incorporation that is empirically validated by referencing actual holdings of hydrographic data.

This paper eliminates this gap by developing and implementing the Multi-Criteria Decision Analysis framework that combines accuracy levels based on technology with the IHO S-67 CATZOC classification. The framework is demonstrated through a comprehensive case study utilizing nine bathymetric datasets spanning 1991 to 2023 from the Hydrographic Office, Sri Lanka, with detailed assessment of a 2023 Negombo Harbor survey providing complete classification exemplification. The research also examines the changes in documentation completeness in metadata over 40 years and makes evidence-based suggestions on how retrospective metadata documentation, metadata calibration documentation standardization and prioritization of the resurvey should proceed. It is intended that the methodology can be duplicated by hydrographic offices with similar problems of heterogeneous legacy and modern bathymetric data collections.

II. LITERATURE REVIEW

A. Marine Spatial Data Infrastructure and Bathymetric Data

Marine Spatial Data Infrastructure has developed as the leading framework related to managing marine geospatial data based on theories of terrestrial SDI first discussed in the 1990s (Aalders & Moellering, 2001). The International Hydrographic Organization has also played a significant role in building up MSDI with the publication C-17 "Spatial Data Infrastructures: The Marine Dimension" that also gives detailed guidance to hydrographic offices on MSDI implementation, data management schemes, the necessity of standardization, metadata protocols, and governance schemes (IHO C-17, 2023). The publication highlights the principles of FAIR data Findable, Accessible, Interoperable, and Reusable and outlines 4 basic pillars of MSDI, including data and metadata, technical standards, technology and infrastructure, and policy and governance.

Bathymetric data is a thematic layer of MSDI and its significance is identified in more than one international structure. Since 1903, IHO and Intergovernmental Oceanographic Commission (IOC) have organized the compilation of global bathymetric data, and resulting in worldwide gridded bathymetric products (IHO B-11, 2019). The IHO Data Center of Digital Bathymetry (DCDB) maintains and publicly accessible crowdsourced bathymetry,

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which appreciates the importance of opportunistic depth observations by vessels of opportunity (IHO B-12, 2022). Bathymetry based on satellites has become an added service to shallow waters mapping and IHO B-13 is a guide on the procedures, standards and characterisation of uncertainty (IHO B-13, 2024).

B. Bathymetric Data Accuracy Standards and Specifications

The IHO S-44 "Standards for Hydrographic Surveys" outlining the international accuracy standards for hydrographic surveys (IHO S-44, 2022) can be regarded as the world standard for hydrographic surveying accuracy. Introduced in 1968 and subsequently updated, the current edition, i.e., the sixth edition, comprises five individual orders, i.e., "Special Order," "Order 1a," "Order 1b," "Order 2," and "Exclusive Order." Each of the orders outlined in IHO S-44 has specifications that correspond to the standards required to fulfill the "Total Vertical Uncertainty" and "Total Horizontal Uncertainty" and "Detection of feature" and "Full search of seafloor" criteria. The "TVU" or "Total Vertical Uncertainty" is given as "TVU = SQRT (a^2 + b*d) ²" where "a" represents the uncertainty independent of the water depth, "b" represents the coefficient, and "d" denotes the water depth. The parameters "a" and "b" may vary as per the hydrographic survey orders. For example, while the "Special Order" follows 'a' as 0.15m and "b" as 0.0075, "Order 2" may follow 'a' as 1.0m and "b" as 0.023. The "TPU" or "Total Prop

The Category Zone of Confidence (CATZOC) classification system, which is described in "Mariners' Guide to Accuracy of Depth Information in Electronic Navigational Charts" (IHO S-67, 2020), gives a common basis for the communication of bathymetric data accuracy within ENC data. CATZOC ranks four variables: position, depth, seafloor coverage, and feature detection accuracy. CATZOC classes cover a range from the best (A1) through A2, B, C, D, and finally, unassessed data (U). IHO S-67 gives general guidelines for the application of CATZOC labels in the case where no detailed survey documentation is provided, including that systematic hydrographic surveys with contemporary multibeam systems and DGPS/RTK systems typically have an associated CATZOC of A1 or A2, information from Port Authorities is likely to have a CATZOC B, airborne LiDAR bathymetry will probably fall within CATZOC B or, in some instances, A2, satellite data will have a CATZOC C, information provided by private ship owners through crowdsourcing will have a CATZOC D, and if the data is older than 1980, it will likely fall within CATZOC B, C, or D, with older data likely classified at a poorer level.

C. Technological Evolution of Bathymetric Surveying

The literature has a wealth of information about the development of bathymetric surveying technology. A thorough analysis of the frontiers of seafloor mapping and visualisation was given by Mayer (2006), who traced the evolution of these technologies from lead lines and sounding poles to single-beam echo sounders and multibeam systems. Lurton (2002) laid the theoretical groundwork for comprehending the origins of ambiguity in acoustic depth measuring by establishing the fundamentals of underwater acoustics and sonar system design. In his synthesis of multibeam echosounder technology, Hughes Clarke (2018) discussed motion sensing integration, beamforming concepts, and sound speed correction techniques that are crucial for contemporary high-accuracy surveying.

Li et al. (2023) compiled quantitative analysis of accuracy improvement across technological generations, documenting vertical uncertainty progression from early mechanical SBES at ±5.0 m (1920s) through analog SBES at ±2.0 m (1950s), digital SBES at ±1.0 m (1970s), GPS-integrated SBES at ±0.5 m (1990s), high-frequency SBES at ±0.2 m (2000s), and to modern AI-enhanced systems achieving ±0.05 m (2020s). A similar progression is evident in multibeam systems, starting with early prototypes (1990) exhibiting ±1.0 m vertical accuracy, followed by SeaBeam 2112 (1995), reaching ±0.8 m, Simrad EM3000 (2000) ±0.5 m, Reson SeaBat 7125 (2005) ±0.3 m, Kongsberg EM2040 (2010) ±0.2 m, Teledyne T50-R (2015) ±0.15 m, and Fugro Equator system (2021) with ±0.05 m. This documented technological progression provides an empirical foundation for technology-based accuracy tier classification.

Hare, Eakins, and Amante (2011) proposed essential contributions in the subject of bathymetric uncertainty modelling, defining various types of underlying uncertainty factors, which comprised platform factors, sensor measurements, environmental factors, integration times, and calibration. The authors distinguished between various types of underlying uncertainty factors, i.e., those ascertaining vertical uncertainty factors only, horizontal uncertainty factors only, and both. Those encompassing both consisted of various factors including those ascertaining range, beam angle, and refraction.

D. Data Quality Dimensions and Metadata Standards

The ISO 19157 standard "Geographic information — Data quality" defines six principal data quality dimensions: completeness, logical consistency, positional accuracy, temporal accuracy, thematic accuracy, and usability (ISO 19157, 2013). Veregin (1999) provided theoretical foundation for spatial data quality parameters, distinguishing between accuracy (closeness to true values), precision (measurement refinement), resolution (smallest detectable detail), and consistency (absence of contradiction). These dimensions have been specifically adapted for bathymetric data quality assessment by numerous researchers.

ISO 19115-1 (ISO 19115-1, 2014) codifies metadata standards for geographic information and specifies schema for describing digital geographic data, including information about identification, constraints, data quality, maintenance, spatial representation, reference systems, content, portrayal catalogues, distribution, metadata extension, and application schema. By defining the requirements for discovery, structure, quality, acquisition, and exchange set metadata for gridded bathymetric surfaces, the IHO S-102 "Bathymetric Surface Product Specification" (IHO S-102, 2022) expands on ISO 19115 for bathymetric applications. Even with these thorough specifications, there are always differences in implementation, especially when it comes to historical datasets.

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E. MSDI Implementation Studies

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Notably, Hasara et al. (2025) outlined the concept of accuracy classification systems for bathymetric data under MSDI by using technology-based tiers and CATZO levels to generate primary (High, Moderate, Low) and secondary (nine levels) classification systems. Evidently, their research proved that all bathymetric data sets, irrespective of accuracy levels, can effectively qualify to form MSDI if and only if their accuracy classification status is effectively communicated to different stakeholders by using comprehensive metadata documentation. However, their research mainly concentrated on providing a conceptual classification framework for bathymetric data sets rather than operationalizing it into an evaluation methodology to validate its effectiveness using extensive documentation completeness time series analysis. The current research builds on earlier research by operationalizing the accuracy classification framework into a comprehensive assessment methodology to validate its effectiveness using case studies.

III. METHODOLOGY

A. Study Area

The study area covers the coastal waters of Western Sri Lanka, stretching from the southern part of the Colombo district area, ranging from 6°35'13.04"N, 79°57'21.09"E to the northern part of the Gampaha district area, ranging from 7°16'19.85"N, 79°50'31.00"E. This area covers the coastal area along the border of the Colombo district and Gampaha district, stretching from the baseline to the limits of Sri Lanka's Territorial Waters. This geographical area has been shortlisted for study for three major reasons: Its marine importance, as it covers Sri Lanka's major commercial hub (Colombo Port) and many major fishery hubs that need to be surveyed regularly to ensure safety and efficiency in operations; Its data richness, as it is surveyed extensively, thus providing enough data to validate the methodologies used; and Its accessibility, as reliable data, historical as well as contemporary, are found in the Hydrographic Office, as they systematically archive such data from these waters.

B. Data

The Hydrographic Office of the National Aquatic Resources Research and Development Agency in Sri Lanka provided nine bathymetric surveys that were carried out between 1991 and 2023. Purposive sampling was used in the dataset selection process to guarantee representation across acquisition technologies (single-beam echo sounder n=7, multibeam echo sounder n=2), time periods (1990s n=2, 2000s n=3, 2010s n=2, 2020s n=2), survey purposes (land reclamation, sand boring, port maintenance, harbour development, site inspection), and data formats (raw survey files, processed XYZ, survey reports). The full list of datasets used in this investigation is shown in Table 1.

Table 1: Bathymetric Datasets Obtained from the Hydrographic Office, Sri Lanka

Dataset ID	Year	Survey Purpose	Technology	Positioning
67	1991	Proposed reclaiming of land from sea at Mutwal	SBES	Not documented
158	1999	Bathymetric survey of sand boring site at North Colombo	SBES	Not documented
198	2004	Sounding at Colombo Port (near JCT)	SBES	Not documented
204	2005	Bathymetric survey at Palliyawatte	SBES	DGPS (inferred)
238	2008	Bathymetric survey at Colombo Port	SBES	GPS
325	2015	Bathymetric survey at Mount Lavinia	MBES	RTK
342	2017	Bathymetric survey at Mutwal Harbour - Colombo Ship Yard	MBES	RTK
363	2021	Bathymetric survey at Sandborrow Site, Dehiwala	MBES	RTK
CONCMBH001_2023	2023	Bathymetric survey at Negombo for site inspection	SBES (EA440)	Stonex RTK (Corsnet)

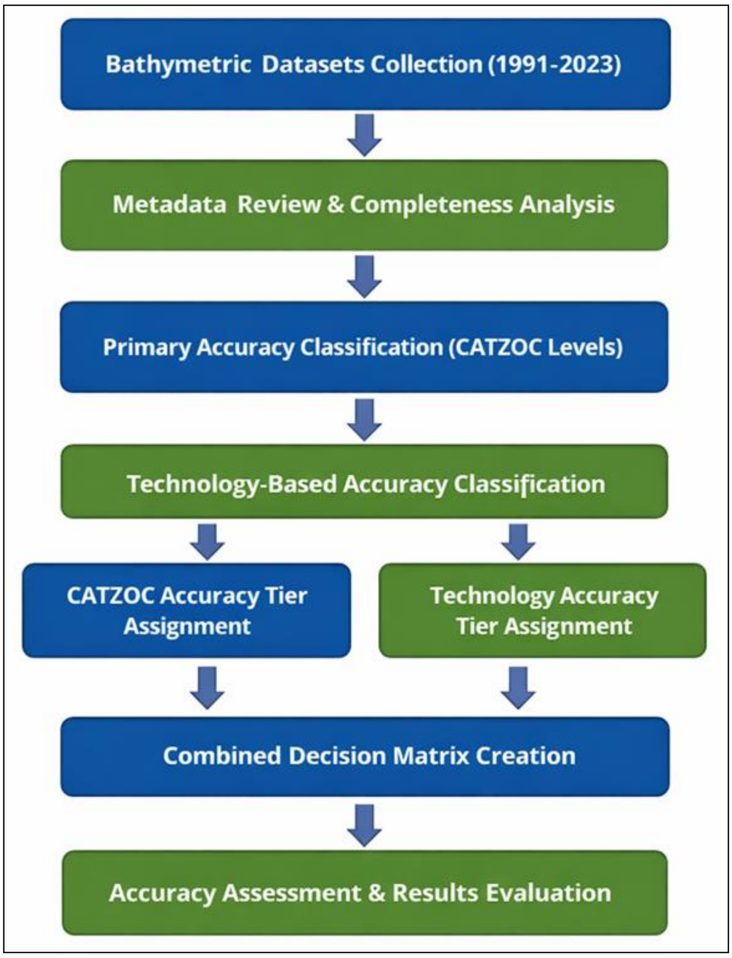

Fig 1: Methodology Flow Chart

C. Technology-Based Accuracy Tier Classification

A thorough examination of manufacturer specifications, peer-reviewed literature, and IHO publications led to the definition of seven technology-based accuracy categories (Hasara et al., 2025). A hierarchical decision-making process is used to assign tiers: the primary sounding equipment and, if documented, the specific manufacturer model is identified; the positioning system and its reported or inferred horizontal accuracy are identified; supplementary instrumentation, such as motion compensation, tidal correction methodology, and sound velocity profile measurement, are evaluated; and the overall tier is determined based on the lowest-performing critical component. The entire technology tier classification scheme is shown in Table 2.

Table 2: Technology-Based Accuracy Tier Definitions

Tier	Technology Categories	Representative Systems	Vertical Uncertainty	Positioning Typical	Era
Tier 1	Advanced Multibeam Echosounders High-Precision LiDAR AUVs/ROVs with MBES	Kongsberg EM304, EM2040 Teledyne T50-R Sonardyne Solstice	±0.05–0.15 m	RTK/PPK GNSS ±0.02–0.05 m	2020+
Tier 2	Standard Multibeam Echosounders High-grade Single-Beam	Kongsberg EM3000, EM302 Reson SeaBat 7125 Kongsberg EA640	±0.15–0.30 m	DGPS/SBAS ±1–5 m	2010–2020
Tier 3	Standard Single-Beam Side-Scan Sonar (bathymetry)	Kongsberg EA440 EdgeTech 4125	±0.30–0.50 m	GPS (autonomous) ±5–15 m	2005–2015
Tier 4	Early-generation Multibeam Digital Single-Beam	SeaBeam 2112, 3012 Simrad EM3000	±0.50–1.00 m	GPS/DGPS ±5–15 m	2000–2010
Tier 5	Satellite-Derived Bathymetry Basic Single-Beam	WorldView-2/3, Sentinel-2 Early digital SBES	±1.00–2.00 m	Various ±10–50 m	1990–2000
Tier 6	Basic Sonar Technologies Early-stage Crowdsourced	Analog SBES Opportunistic vessels	±2.00–5.00 m	Visual/Sextant Transit	1970–1990
Tier 7	Very Low Accuracy / Legacy	Lead lines Sounding poles	> ±5.00 m	Visual bearings	Pre-1970

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D. CATZOC Classification

CATZOC classification was assigned following IHO S-67 criteria and decision guidance. Accuracy of position was performed by using known values of THU or by inferring from the type of positioning used and period of use. Accuracy of depth was performed by using known values of TVU or by inferring from the type of equipment used and period of use. Assessment of seafloor coverage was based on known line spacing, swath width, and gaps present. Feature detection was assessed by inferring from beam width, line spacing, and specifications of sonar types (IHO S-67, 2020). The final value of CATZOC classification was determined by using the lowest value of all criteria assessed. Those datasets with insufficient documentation for criteria were given a classification of CATZOC U (Unassessed).

E. Integrated Decision Matrix

The integrated decision matrix (Table 3) converts the two-dimensional evaluation of the Technology Tier and CATZOC Level into a one-dimensional ordinal accuracy classification. The underlying five principles of matrix design are overly conservative classification, where the final classification corresponds to the most restrictive dimension; monotonic ordering, where the classification increases monotonically with improving tiers and CATZOC; non-negotiable thresholds, where data failing the minimum requirement receives the next lower accuracy; unclassified avoidance, where classifications are used sparingly and only when necessary; and IHO alignment, where the output maps to established concepts of quality when applicable. Secondary accuracy levels include a detailed accuracy discrimination from Ultra-High (Level 1) through Provisional (Level 9), aggregating these into three primary accuracy levels delivering High accuracy into Levels 1-3, Moderate accuracy into Levels 4-6, and Low accuracy into Levels 7-9 for effective communication with the user.

Table 3: Integrated Accuracy Classification Matrix

CATZOC ↓ / Tier →	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	Tier 6	Tier 7
A1	Level 1	Level 2	Level 3	Level 4	—	—	—
A2	Level 2	Level 3	Level 3	Level 4	Level 6	Level 7	—
B	Level 3	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8
C	Level 4	Level 4	Level 5	Level 5	Level 6	Level 7	Level 8
D	Level 5	Level 5	Level 6	Level 6	Level 6	Level 7	Level 8
Below D	Level 6	Level 6	Level 7	Level 7	Level 8	Level 8	Level 9

Source: Proposed Accuracy Classification Matrix, (Hasara et al., 2025)

F. Metadata Completeness Assessment

A thorough 72-parameter metadata framework designed for bathymetric data documentation was used to evaluate the completeness of the metadata. This framework included seven categories: general information, identifying information, description, extent, accuracy parameters, point of contact, and meta-metadata. The acquisition equipment model, positioning system, TVU/THU/TPU values, calibration paperwork, processing software and lineage, sound velocity profile information, and tidal correction data were among the crucial accuracy-related criteria that were noted for each dataset. The percentage of documented parameters compared to all applicable parameters was used to compute completeness percentages.

IV. RESULTS

A. Technology Tier Assessment

The nine bathymetric datasets were evaluated, and the results showed a systematic evolution of technology tiers according to equipment specifications and survey era. Single-beam echo sounders of an unknown model with unrecorded location systems were used in the 1991 and 1999 surveys. Tier 6–7 (Low to Very Low accuracy) was awarded to these datasets based on equipment characteristics common of the era. There was insufficient documentation in either dataset to identify certain equipment models, calibration status, or uncertainty levels. The single-beam echo sounders used in the 2004, 2005, and 2008 surveys had increasingly better positioning (undocumented in 2004, inferred DGPS in 2005, and documented GPS in 2008), leading to Tier 4–5 (Moderate accuracy) classifications. Although there was no estimate of uncertainty, survey reports showed systematic data collecting with line spacing of 100–200 m. The 2015 and 2017 survey used multibeam echo sounder with RTK position, with classification Tier 2-3 (High Accuracy). The datasets provided TVU/THU data with references to processing software used, with more complete metadata. The 2021 survey was conducted with MBES with RTK position, Tier 2-3. The survey conducted in 2023 at Negombo, Sri Lanka, conducting survey CONCMBH001_2023, used Kongsberg EA440/SBG single beam echo sounder with Stonex RTK (Corsnet) position classification Tier 4 (Moderate accuracy) with SVP.

Table 4: Technology Tier Assessment for Nine NHO Bathymetric Datasets

Dataset ID	Year	Sounding Equipment	Positioning System	Technology Tier	Accuracy Level
67	1991	SBES (undetermined)	Not documented	Tier 6–7	Low–Very Low
158	1999	SBES (undetermined)	Not documented	Tier 6–7	Low–Very Low
198	2004	SBES (undetermined)	Not documented	Tier 5–6	Moderate–Low
204	2005	SBES (undetermined)	DGPS (inferred)	Tier 4–5	Moderate
238	2008	SBES (undetermined)	GPS	Tier 4	Moderate
325	2015	MBES	RTK	Tier 2–3	High

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342	2017	MBES	RTK	Tier 2–3	High
363	2021	MBES	RTK	Tier 2–3	High
CONCMBH001_2023	2023	Kongsberg EA440 SBES	Stonex RTK (Corsnet)	Tier 4	Moderate

B. *CATZOC Assessment*

The CATZOC classification was allocated according to available documentation with regard to position accuracy, depth uncertainty, seafloor coverage, and feature detection capability. All surveys carried out before 2010 were not documented quantitatively for the data uncertainty and variability; therefore, these were not considered for CATZOC classification. According to the IHO S-67 guideline, data age and technology limitations, these datasets were allocated CATZOC U (unassessed) and CATZOC C-D. The MBES carried out in 2015 and 2017 were carried out with data documented quantitatively at a position accuracy of ±2 to 5 meters and a depth uncertainty of ±0.2 to 0.5 meters, with full seafloor coverage and features, meeting the CATZOC classification criteria of B. Similarly, the 2021 MBES data met the CATZOC classification of B. The 2023 Negombo SBES data carried out showed a position accuracy of ±5 meters, a depth uncertainty of ±2 meters, a moderate bottom 75% data coverage with 200-meter line spacing, and features, meeting the CATZOC classification criteria of B.

Table 5: CATZOC assessment for CONCMBH001_2023 (Negombo Survey)

Criterion	**Assessment Basis**	**Value**	**CATZOC B Requirement**	**Result**
Position Accuracy	Documented	±5 m	±50 m	Exceeds
Depth Uncertainty	Documented TVU	±2 m	1.00 m + 2% depth (~1.2–1.5 m)	Meets
Seafloor Coverage	Documented	75%, 200 m lines	Full area search not achieved	Consistent
Feature Detection	Inferred	Moderate	Moderate	Consistent
Overall CATZOC				B

C. *Integrated Accuracy Classification*

Application of the integrated classification matrix produced secondary and primary accuracy classifications for all nine datasets. The 1991 and 1999 datasets classified as Tier 6–7, CATZOC U/D to Level 8 - Basic Primary Level 3 - Low. The 2004 dataset classified as Tier 5–6, CATZOC U/C to Level 6–7 - Standard/Low Primary Level 2–3 - Moderate to Low. The 2005 and 2008 datasets classified as Tier 4–5 and Tier 4, CATZOC U/C to Level 6 - Standard Primary Level 2 - Moderate. The 2015, 2017, and 2021 MBES datasets classified as Tier 2–3, CATZOC B to Level 4 - Enhanced Primary Level 2 - Moderate. The 2023 Negombo survey classified as Tier 4, CATZOC B to Level 5 - Standard Plus Primary Level 2 - Moderate.

Table 6: Integrated Accuracy Classification for Nine NHO Bathymetric Datasets

Dataset ID	**Year**	**Technology Tier**	**CATZOC**	**Secondary Level**	**Primary Level**
67	1991	Tier 6–7	U / D	Level 8 - Basic	Low
158	1999	Tier 6–7	U / D	Level 8 - Basic	Low
198	2004	Tier 5–6	U / C	Level 6–7 - Standard/Low	Moderate–Low
204	2005	Tier 4–5	U / C	Level 6 - Standard	Moderate
238	2008	Tier 4	U / C	Level 6 - Standard	Moderate
325	2015	Tier 2–3	B	Level 4 - Enhanced	Moderate
342	2017	Tier 2–3	B	Level 4 - Enhanced	Moderate
363	2021	Tier 2–3	B	Level 4 - Enhanced	Moderate
CONCMBH001_2023	2023	Tier 4	B	Level 5 - Standard Plus	Moderate

D. *Detailed Case Study: CONCMBH001_2023*

The Negombo Harbor bathymetric survey for Sri Lanka Reclamation and Development Corporation (SLLRDC) conducted from 29 November to 17 December 2023 gives extensive exemplification of the classification methodology. The purpose of this survey was the site inspection for bottom sand dredging, and the measurement area has the coordinates of 381817.05–389202.90 E, 502856.24–513150.89 N (Kandawala datum) with the depth range of 23.10–35.32 m (MSL vertical datum). Equipment: Kongsberg EA440 single-beam echo sounder, Stonex RTK (Corsnet)-real-time kinematic GNSS positioning, Valeport Sound Velocity Profile sensor, and autonomous pressure gauge for tidal correction. Acquisition software: HYPACK 2018; Platform: RV Samudrika; Average survey speed: 5 knots. Survey design: 200 m line spacing, 75% coverage, and no documented data gaps.

The accuracy characteristics were recorded as follows: 0.01 m raw, 1.5 m across-track, 0.09 m along-track processed, Total Vertical Uncertainty of 0.2 m, Total Horizontal Uncertainty of 2 m, and Total Propagated Uncertainty of 2.01 m. The survey was carried out in accordance with IHO S-44 Order 1B guidelines. The Kongsberg EA440 early-generation digital SBES technology was used to determine the Tier 4 designation that came from the technology tier evaluation. Based on moderate coverage, moderate feature detection capabilities, ±5 m location accuracy, and ±2 m depth uncertainty, CATZOC assessment validated Level B categorisation. The secondary level of Level 5-Standard Plus and the primary level of Level 2-Moderate were generated via integrated matrix classification.

The completeness of metadata documentation provided for the survey conducted in Negombo surpassed that provided for the pre-2010 surveys in the complete description of the devices used, positioning systems, additional tools used, TVU/THU/TPU systems employed, software used in processing the data, SVP casts provided, and tidal corrections used. The only significant shortfall in the metadata provided concerned the lack of any reference to calibration. The completeness of the metadata provided was found.

E. Metadata Completeness Temporal Analysis

Systematic assessment of the metadata completeness of the nine datasets indicated significant temporal trends. The pre-2000 datasets (1991, 1999) showed a near complete lack of structured metadata, with a mean metadata completeness of 12.5%. The basic necessary parameters, i.e., device type, positioning systems, calibration information, and uncertainty values, etc., were poorly documented. The data sets collected between 2000 and 2010 (2004, 2005, 2008) show a slight improvement, with a mean metadata completeness of 16.7%. Though the purposes of surveys, clients, and areas in general are documented, quantitative information regarding uncertainty, calibration, and processing are not provided. The documentation of "positioning" varied from no documentation (2004), to inference of DGPS (2005), and finally documentation of GPS (2008). With a mean completeness of 75.0%, the 2010–2020 datasets (2015, 2017) showed significant progress in tandem with the deployment of MBES and changing documentation standards. Systematic documentation was done for processing software, TVU/THU data, supplemental instrumentation, positioning systems (RTK), and device models. At 75.0%, the 2020–2023 datasets (2021, 2023) maintained their high level of documentation completeness. The total lack of calibration metadata documentation was a recurring major issue in all datasets, independent of time period.

Table 7: Metadata Completeness by Decade for nine NHO Bathymetric Datasets

Decade	n	Mean Completeness	Range	Critical Documentation Gaps
1990s	2	12.5%	12–13%	Device model, positioning, uncertainty, calibration, processing
2000s	3	16.7%	14–21%	Uncertainty values, calibration, processing lineage
2010s	2	75.0%	72–78%	Calibration metadata
2020s	2	75.0%	72–78%	Calibration metadata

V. DISCUSSION

The usefulness of the proposed framework as an operational MSDI assessment tool was demonstrated by its ability to distinguish between datasets from different eras and technological backgrounds. Technology tier serves as the main classification basis for pre-2010 datasets without uncertainty documentation, allowing historical surveys to be provisionally classified rather than excluded. CATZOC offers more accurate differentiation for datasets published after 2015 that include documented uncertainties. For MSDI applications, the framework's conservative approach assigning a lower categorization, when dimensions conflict is suitably cautious.

The documentation gap between pre-2010 and post-2015 datasets (12.5–16.7% vs 75.0% completeness) identifies clear priorities for retrospective metadata creation. Critically, calibration documentation is completely absent across ALL datasets, representing the most persistent deficiency requiring immediate remediation. These trends align with international findings (Tavra et al., 2017; Racetin et al., 2022). The framework addresses the IHO C-17 identified gap in operational methodologies for heterogeneous dataset assessment.

VI. CONCLUSIONS AND RECOMMENDATIONS

The research study developed and showed the feasibility of a Multi-Criteria Decision Analysis framework combining technology-based accuracy tiers with IHO S-67 CATZOC classification for bathymetric accuracy assessment in MSDI, using a case study with nine datasets from 1991 to 2023 obtained from the Hydrographic Office, Sri Lanka. The framework successfully distinguished datasets collected at different times and with different qualities, with pre-2000 SBES datasets classified at Tier 6 and 7, 2000s SBES datasets with GPS at Tier 4 and 5, 2010s MBES datasets with RTK at Tier 2 and 3, and modern SBES datasets with RTK at Tier 4. The CATZOC classification system showed sharp differentiation for datasets collected after 2015, with all MBES datasets and the 2023 Negombo SBES survey classified at CATZOC B.

The integrated matrix ensured the development of secondary classifications from levels 8-BASIC for the 1990s datasets to levels 4-ENHANCED for the MBES surveys. The Negombo survey is classified as level 5-Standard Plus and Primary Level 2-Moderate. Looking at the completeness of the metadata, it is clear that the completeness increased drastically from 12.5% in the 1990s to 75.0% in the 2020s. Notably absent in all datasets is the completely absent calibration documentation. This is the most critical metadata problem to be remedied. The NO needs to put in place a retrospective metadata creation approach for datasets collected before the year 2010, set up mandatory calibration documentation for all surveys in the future, develop standardized metadata templates using geo-database storage solutions, and develop MSDI discovery tools with accuracy filters.

IHO should make calibration metadata necessary in further S-102 upgrades, and regional hydrographic commissions should develop guidelines for legacy dataset documentation. The framework offers a replicable template for hydrographic offices worldwide facing the universal challenge of heterogeneous bathymetric data integration, and with methodical attention to metadata documentation, Sri Lanka's significant bathymetric data assets can be fully integrated into MSDI to support marine spatial planning, coastal management, engineering design, and navigation safety.

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➢ *Specific Recommendations:*

- Implement retrospective metadata creation for pre-2010 datasets
- Establish mandatory calibration documentation for all future surveys
- Adopt standardized metadata templates and geodatabase storage
- Develop MSDI discovery interface with accuracy filtering
- Elevate calibration metadata to mandatory status in S-102 revisions

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