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Development of Hydrographic Risk Assessment in Planning Hydrooceanographic Survey and Charting Areas

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Abstract. As an archipelagic country, Indonesia faces significant challenges in ensuring maritime safety and conducting effective hydrographic surveys. The Hydrographic Risk Assessment (HRA) approach is used to identify high-risk areas caused by outdated or inaccurate hydrographic data, dense vessel traffic, and the strategic or economic value of certain regions. This study aims to develop a multi-criteria decision-making model to determine national hydrographic survey priorities more efficiently and adaptively, in accordance with Indonesia's complex maritime geography. The analysis results indicate that Navigational Safety (0.47) and Data Quality (0.35) are the most dominant criteria influencing survey prioritization. Sub-criteria such as Traffic Volume (0.32), Bathymetric Conditions (0.17), and CATZOC (Category Zone of Confidence) (0.14) serve as key indicators in the decision-making process. Areas such as the Indonesian Archipelagic Sea Lanes (ALKI) (0.26), Strategic Straits (0.15), and Strategic Ports (0.12) are identified as top priorities for survey implementation. These findings suggest that a risk-based and geospatial data-integrated approach provides a strong foundation for designing more targeted and impactful hydrographic survey policies. The research recommends several strategies, including enhancing the resolution and coverage of nautical charts, developing a national geospatial hydrographic information system, and utilizing modern survey technologies such as autonomous survey vessels and satellite data integration. Accordingly, this assessment model is expected to strengthen institutional capacity in supporting maritime safety, optimizing marine spatial planning, and promoting sustainable management of Indonesia's vast and dynamic maritime domain.

Keywords: Hydrographic Risk Assessment, Navigational Safety, Maritime Strategy, ANP, Geospatial Information, CATZOC, Pushidrosal.

INTRODUCTION

Strengthening the sovereign management of maritime territory is a strategic factor in ensuring the protection of marine resources, reinforcing the nation's position in international trade, and addressing potential threats to national territorial integrity (Fita, 2025). Within this context, the Indonesian Navy (TNI AL) bears the responsibility of upholding law and maintaining security within the national maritime jurisdiction in accordance with national legislation and international law ratified by Indonesia (Zubaidi, Wiyana, & Ramadhani, 2024). In line with these duties, the Navy also carries out national defense functions through the continuous development and enhancement of naval power (Braithwaite, Berger, Gilday, & Schultz, 2020). These two roles are mutually reinforcing in strengthening Indonesia's position as a sovereign maritime nation capable of facing various security challenges within its territorial waters (Sugiharto, 2025).

The capability of the Indonesian Navy in maintaining the stability of national waters does not only rely on military strength, but also on non-military aspects such as ensuring maritime safety through accurate marine environmental data (Iswardhana, 2024). Such data are vital for supporting navigation safety, operations, and the sustainable management of marine resources (Glaviano et al., 2022). Therefore, the Hydro-Oceanographic Center of the Indonesian Navy (Pushidrosal) plays a central role in ensuring maritime safety and security through scientific and technical approaches in the fields of hydrography, oceanography, marine surveying and mapping, as well as the management of national marine geospatial data.

Hydrographic surveying serves as the backbone of marine information systems and nautical chart production in Indonesia (Suhartotok, 2020). The reliability of survey data is essential to guarantee the accuracy and validity of the information produced—an aspect that is also critical for military operations requiring detailed spatial data on maritime and coastal conditions to support national defense strategies (Potamos, Stavrou, & Stavrou, 2024). Hence, the availability of high-quality hydro-oceanographic survey data produced by hydrographic offices through systematic survey and mapping activities must ensure the delivery of highly accurate marine geospatial information (Pratellesi, 2017).

In 2022, the compilation of hydrographic survey data conducted by Pushidrosal since 2010 showed that national bathymetric data coverage had only reached 5.24% of Indonesia's total marine area. This figure reflects the relatively low level of data fulfillment when compared to Indonesia's vast marine area, which covers approximately 6.4 million square kilometers (Purba et al., 2025). Consequently, achieving the government's maritime development goals requires an accelerated and well-planned effort to meet the demand for comprehensive bathymetric data (Nasution, Zulkarnaini, & Simanjuntak, 2023). This should be achieved through an effective assessment of hydrographic environmental conditions that considers economic, defense, and security aspects across all Indonesian waters using a risk-based operational prioritization approach (Xiao et al., 2022).

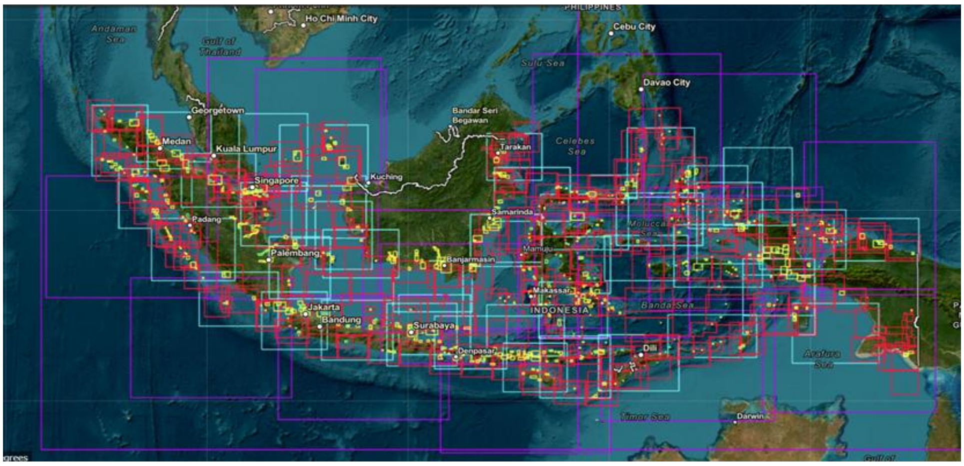

Figure 1. Pushidrosal Nautical Chart Catalogue

Source: www.ihdc.pushidrosal, accessed March 3, 2025

One of the strategies that can be implemented in planning survey and mapping operations is to apply risk-based assessment in maritime and coastal areas through Hydrographic Risk Assessment (HRA) (Hoem, Veitch, & Vasstein, 2022). This assessment aims to identify and mitigate threats that may hinder operational activities—whether natural or human-induced (Carbonelli et al., 2025). In practice, the method utilizes geospatial data analysis to interpret and understand potential risks (Albano & Sole, 2018). The application of spatial analysis helps evaluate maritime safety risks by considering ecological, hydrographic, and social factors that contribute to environmental degradation, both globally and locally (Pagano, Fernetti, Busetti, Ghribi, & Camerlenghi, 2023).

The HRA method is designed to identify high-risk areas in hydro-oceanographic surveys so that survey priorities can be determined more effectively and efficiently. This approach has been successfully applied in several studies, such as New Zealand's LINZ Hydrographic Risk Assessment and the United States' NOAA Hydrographic Survey Prioritization. These methods have proven effective in identifying high-risk zones using geospatial analysis integrated with multi-criteria decision-making processes (Vignesh, Anandakumar, Ranjan, & Borah, 2021). However, such approaches have not yet been specifically tested or implemented at the national scale in Indonesia (Kerstens, Spiller, Leusbrock, & Zeeman, 2016).

Despite the proven success of HRA methodologies internationally, these approaches have not yet been specifically adapted, tested, or systematically implemented at the national scale in Indonesia (Wisnubroto, Sunaryo, & Susilo, 2025). This represents a critical gap in Indonesia's maritime governance infrastructure (Hadiningrat, Wiradanti, & Umar, 2024). Challenges include insufficient data availability, uneven survey coverage, Indonesia's diverse geomorphology, and the absence of a clear strategy for accelerating hydrographic data acquisition through risk analysis (Lutfiananda et al., 2022). The uniqueness of Indonesia's maritime environment—characterized by complex archipelagic geography, diverse oceanic conditions ranging from shallow coral reefs to deep ocean trenches, active tectonic zones, and highly variable oceanographic parameters—necessitates the development of a context-specific HRA model that accounts for these distinctive national characteristics. Furthermore, existing international HRA frameworks were designed primarily for single-nation maritime zones with relatively homogeneous geographic conditions, whereas Indonesia's archipelagic nature requires an integrated approach that considers inter-island connectivity, multiple concurrent maritime jurisdictions, and the simultaneous management of internal waters, archipelagic waters, territorial seas, and exclusive economic zones.

Furthermore, the assessment of ecological elements such as environmental conditions, currents, waves, tides, and seafloor geomorphology has not yet received adequate attention. These factors are essential in survey planning and prioritization, as they relate not only to navigation risk but also to the complex biophysical and oceanic dynamics of Indonesia. The integration of these oceanographic and ecological parameters into a unified decision-support framework represents a novel contribution of this research, extending beyond conventional HRA approaches that typically focus predominantly on navigational and economic factors.

This study aims to develop a comprehensive Hydrographic Risk Assessment (HRA) model to support the planning of hydro-oceanographic survey areas in Indonesia. The objectives include identifying relevant factors in the application of HRA, analyzing strategies to accelerate the fulfillment of accurate and comprehensive hydro-oceanographic data, and formulating an ideal HRA model for planning national hydrographic survey and mapping operations, particularly within Pushidrosal. The novelty of this research lies in its development of Indonesia's first nationally integrated HRA framework that systematically combines multi-criteria decision analysis (specifically the Analytic Network Process method) with geospatial risk modeling, expert-validated prioritization criteria, and operational feasibility considerations tailored to Indonesia's institutional capacity and resource constraints. Unlike existing international models that were developed for maritime nations with different geographic, institutional, and operational contexts, this study creates an adaptive, scalable, and sustainable methodology specifically designed for archipelagic states facing similar challenges of vast maritime territories, limited survey resources, and complex stakeholder requirements. Through these steps, HRA is expected to become an effective tool for supporting sustainable hydro-oceanographic survey and mapping planning in Indonesia.

MATERIALS AND METHODS

This study employed a qualitative research method with a descriptive-analytical approach. In this study, qualitative methodology was applied to explore and comprehend the phenomena of hydrographic risk holistically.

This research adopted a qualitative-exploratory approach, focusing on strategic phenomena in the national hydro-oceanographic domain. Two primary data sources were used: primary data, obtained through in-depth interviews with hydrography experts and practitioners involved in the planning and implementation of hydro-oceanographic surveys in Indonesia, and secondary data, derived from official documents, survey reports, nautical charts, and scientific publications related to survey planning and hydrographic risk analysis at national and international levels. Primary data were gathered from experts selected based on their strategic roles and extensive experience—averaging over five years of active service in hydrography, cartography, or oceanography—ensuring the reliability and depth of their input from both technical and policy perspectives. Secondary data supported triangulation of primary data and provided a normative framework for interpreting the results.

The types of data collected were qualitative, comprising descriptive, narrative, and contextual information that captured the elements involved in hydro-oceanographic survey area planning and priority determination based on the HRA approach. Descriptive data included characteristics of geographical conditions, seabed texture, and surveyed areas. Narrative data consisted of expert experiences and explanations regarding survey policies and implementation processes. Observational data were based on direct observations of interactions, field dynamics, and operational challenges. Interview data provided insights obtained from structured and unstructured interviews with experts. Documentary data were written records such as official reports, technical notes, survey results, and policy regulations. As Creswell and Creswell (2018) emphasized, qualitative data—whether textual or visual—served to interpret meaning, context, and relationships among observed phenomena.

The primary research instruments were interview guides and questionnaires. The interview guide explored expert opinions and experiences related to the planning, implementation, and evaluation of hydrographic survey and mapping activities conducted by Pushidrosal. The questionnaire was structured to quantify expert judgments for subsequent analysis using the Analytic Network Process (ANP) method.

To ensure the validity and reliability of the findings, a multi-stage data collection and processing procedure was applied. Data were gathered through several techniques: in-depth interviews (IDI), conducted to explore experts' understanding, experiences, and perspectives on specific issues related to hydrographic risk and survey prioritization; observation, performed to directly observe communication patterns, decision-making processes, and operational challenges in field implementation; and documentation, which focused on analyzing written, visual, and digital materials relevant to the research topic, including technical guidelines, operational reports, survey data, nautical charts, and literature from organizations such as IHO, IMO, and BIG.

The qualitative data were processed systematically to maintain accuracy and analytical depth. This involved transcription—converting recorded interviews into written text to preserve meaning and completeness of expert responses; coding—identifying and labeling key information based on predefined indicators aligned with the research questions; classification—organizing coded data into themes such as survey acceleration strategies, geomorphological challenges, and risk factors in HRA; and data grouping for ANP input—classifying data into variable clusters for pairwise comparison analysis in the ANP model, processed using Super Decisions software to derive the relative weights of risk factors.

The unit of analysis referred to the element or entity that constituted the focal point of the research. In this study, the primary unit of analysis was Pushidrosal, as the institution with hydrographic expertise and authority in Indonesia. Expert informants—primarily naval officers specializing in hydrography and involved in survey policy formulation—were selected proportionally to represent critical aspects of hydrographic data collection acceleration, risk comprehension, and survey prioritization using the HRA approach.

Data analysis was conducted in several stages by combining qualitative interpretation with quantitative weighting to answer the research questions. Four main techniques were used: narrative analysis, to interpret expert experiences and opinions on survey strategies, technical challenges, and policy implementation; content analysis, to categorize patterns and themes emerging from interviews, observations, and documentation; literature review, to reinforce empirical findings with theoretical and policy references, ensuring contextual alignment with international hydrographic standards; and priority analysis using ANP, to determine the relative weights of risk factors and survey area priorities.

The Analytic Network Process (ANP) was employed to identify the relative weights of risk factors and establish a hierarchy of survey area priorities. The ANP analysis procedure included identification of relationships among criteria and sub-criteria—mapping interdependencies between elements at the main and sub-criteria levels, based on literature review and expert consultations; pairwise comparison matrix—experts evaluated pairs of criteria using Saaty's 1–9 scale to express the relative importance of one element over another; geometric mean calculation—aggregating expert judgments through the geometric mean method to produce consistent composite values representing group consensus; and supermatrix construction—producing an unweighted supermatrix, followed by a weighted supermatrix, a limit supermatrix, and normalization to ensure each cluster's total equals one for comparability across elements.

RESULTS AND DISCUSSION

This section presents the analytical findings from the Analytic Network Process (ANP) assessment and discusses their implications for hydrographic survey prioritization in Indonesia. The analysis is organized into five key subsections: criteria categorization and validation, identification of priority survey alternatives, quantitative weighting of criteria and sub-criteria, spatial prioritization of survey areas, and comparative validation against international frameworks.

The analytical process in this study began with the identification of key criteria influencing the determination of priority areas for hydro-oceanographic surveys. These criteria were established based on an extensive literature review and in-depth expert interviews. Subsequently, the prioritization of survey areas was conducted using the Analytic Network

Process (ANP) method, which enables interdependence and feedback relationships among elements such as vessel traffic density, bathymetric data age and resolution, CATZOC ratings, and oce anographic as well as ecological factors.

The combination of qualitative and quantitative analysis provided a comprehensive and objective weighting system for each criterion. This integrated spatial and statistical approach supports adaptive and efficient planning of hydrographic survey operations at the national level.

Categorization of HRA Criteria

At the initial stage of data processing, expert interviews were conducted to elicit insights regarding the study's objectives and operational context. The interviews produced argument-based responses reflecting the participants' perceptions and professional experiences. Based on these discussions, a set of criteria and sub-criteria were established, validated through both literature review and expert consensus.

Questionnaires were then developed using these criteria, comprising structured questions designed to systematically collect information. The resulting data were used to assign relative importance ratings to each criterion, forming the foundation for the ANP weighting process.

The main criteria identified in this study include: **Navigational Safety**, **Data Quality**, **Economic Value**, **Strategic Value**, and **Environmental Considerations**. Each criterion contains relevant sub-criteria used to assess the level of risk and priority for survey planning.

These criteria were analyzed through the **Analytic Network Process (ANP)** to account for interconnections between elements. The combined use of qualitative interviews and quantitative questionnaires produced a holistic understanding of how each criterion contributes to the prioritization model.

Table 1. Categorization of Criteria and Sub-Criteria

No	Criterion	Sub Criteria
1	Cruise Navigation Safety	Ship Traffic Volume
		Frequency of Marine Accidents
		Meteorological and Oceanographic Conditions
		Bathymetry Conditions
2	Strategic Value	SLOC/SLOT Location
		Border Region
		Military and Security
		Special Economic Zones
3	Data Quality	Age of Map Data
		CAT ZOC
		Availability of Oceanography and Meteorology data
		Geographical Conditions of the region
4	Economic Value	Port Area/Maritime Infrastructure
		Economic Activity
		Marine Conservation Areas and Ecosystems

Source: Processed by the Researcher

The criteria developed in this study were compared with those used in the **LINZ Hydrographic Risk Assessment** model to ensure conceptual alignment and international comparability.

Table 2. Comparison of Research Criteria and LINZ Hydrographic Assessment Categories

Criteria/Sub-criteria	SWPRHP Category
CATZOC	Likelihood (ZOC rating)
Marine Accident Frequency	Likelihood (Traffic/Risk Exposure)
Bathymetric Condition	Likelihood (Bathymetric Uncertainty)
Special Economic Zone	Consequence (Economic/Strategic)
Meteorological and Oceanographic Conditions	Likelihood (Environmental Condition)
SLOC/SLOT Location	Consequence (Proximity/Routing Importance)
Economic Activity	Consequence (Economic Activity)
Border Area	Consequence (Border Area Risk)
Maritime Infrastructure	Consequence (Access/Infrastructure)
Economic Region	Consequence (Economic Asset)
Conservation Area	Consequence (Environmental Sensitivity)

Source: Processed by the Researcher

HRA Alternatives

In the context of this study, **alternatives** refer to candidate regions for hydrographic survey prioritization based on risk levels, strategic significance, and existing data conditions. Through in-depth interviews with experts from **Pushidrosal** and operational naval units, several maritime zones were consistently mentioned as high-priority survey areas. These include:

- **Sunda Strait**,
- **Malacca Strait**,
- **Natuna Sea**,
- **Indonesian Archipelagic Sea Lanes (ALKI I, II, III)**,
- **Eastern Indonesian Waters (Papua and Maluku)**,
- **Strategic Ports**,
- **Maritime Industrial Zones/Special Economic Zones (SEZs)**, and
- **The New Capital Region (IKN)**.

The frequency of expert mentions was analyzed to establish preliminary priority rankings for further ANP processing.

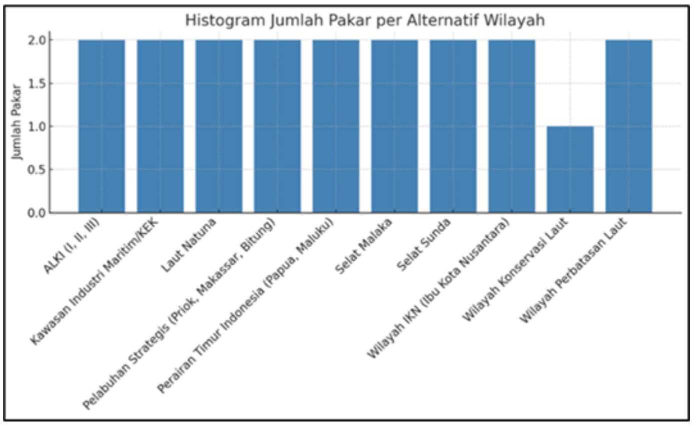

Figure 2. Histogram of Alternative Regions

Source: Processed by the Researcher

The histogram above illustrates the distribution of expert responses, showing the number of experts identifying each maritime region as a survey priority. The horizontal axis represents region names, while the vertical axis shows the frequency of mentions.

It can be observed that most experts consistently identified the same priority regions, particularly the **Sunda Strait, Malacca Strait, ALKI routes, Eastern Indonesia, and**

Strategic Ports. This consensus reflects a collective perception of the urgency for updated hydrographic data in these areas.

Although **Marine Conservation Areas** received fewer mentions due to their limited navigational activity, experts acknowledged their environmental importance. Conversely, **Border Waters**—while outside main shipping lanes—were recognized for their critical defense and sovereignty functions.

Thus, the overall expert consensus forms the basis for subsequent multi-criteria analysis using ANP to establish the final weighting structure.

Priority Analysis Results

The results of the ANP-based weighting process show that **Navigational Safety** holds the highest priority weight (**0.474851**). This finding highlights the fundamental importance of maritime safety in determining hydro-oceanographic survey priorities. High-risk zones for maritime accidents must therefore be targeted for immediate data updates to enhance both civilian and military navigation safety.

The second most influential criterion is **Data Quality (0.359146)**, reflecting the critical role of accurate and reliable geospatial data in decision-making. The combination of safety and data quality underscores the need to prioritize areas with both operational hazards and outdated hydrographic information.

Meanwhile, **Economic Value (0.069690)** and **Strategic Value (0.069132)** received relatively lower weights but remain relevant, particularly in areas of high trade and defense significance. **Environmental Considerations (0.027182)** had the lowest weight, indicating that ecological factors, while important, are secondary in this context.

These results suggest a pragmatic, risk-driven approach emphasizing operational safety and data reliability as the foundation for hydrographic survey planning.

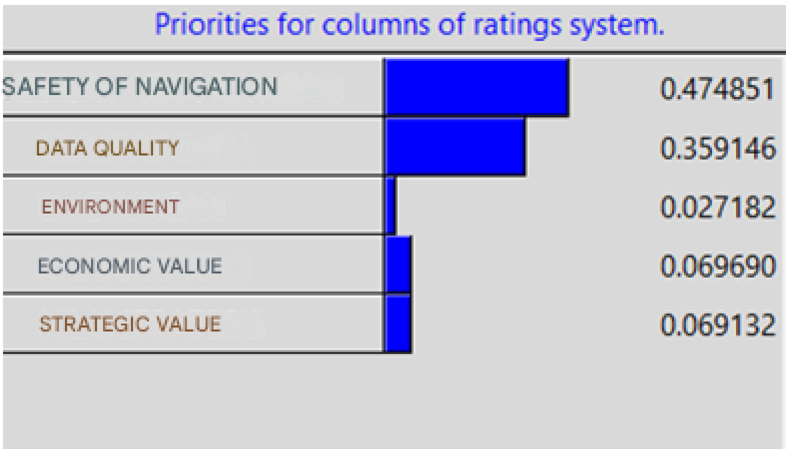

Figure 4. Criteria Weight Results

Source: Processed by the Researcher

Sub-Criteria Prioritization

Among sub-criteria, **Traffic Volume** obtained the highest priority weight (**0.318246**), confirming that maritime traffic intensity is the most significant determinant in prioritizing survey areas. The second-highest sub-criterion is **Bathymetric Condition (0.170340)**, emphasizing the need for updated depth data in complex seafloor environments. **CATZOC rating (0.141091)** follows as a key indicator of chart data reliability.

Other relevant sub-criteria include **Marine Accident Frequency (0.118012)**, **SLOC/SLOT Location (0.079729)**, **Border Area (0.050205)**, **Maritime Infrastructure (0.027711)**, and **Meteorological & Oceanographic Conditions (0.027730)**.

The lowest-ranked sub-criteria—**Conservation Areas (0.024723)**, **Special Economic Zones (0.015846)**, and **Economic Activity (0.026365)**—reflect lower relative influence, although they remain contextually relevant in national maritime planning.

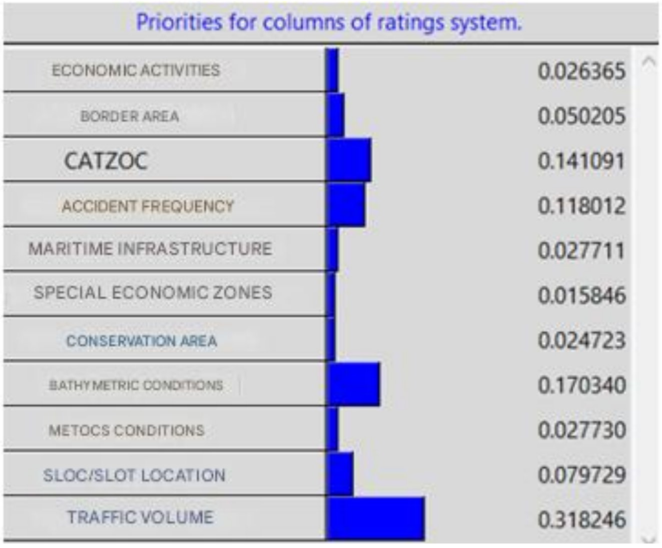

Figure 5. Sub-Criteria Weight Results

Source: Processed by the Researcher

Alternative Area Prioritization

The ANP results indicate that the **Indonesian Archipelagic Sea Lanes (ALKI)** hold the highest priority (**0.263125**), underscoring their critical role as major international shipping corridors with significant navigational risks. Next are **Strategic Straits (0.156798)**, **Strategic Ports (0.127290)**, and **Eastern Indonesian Waters (0.115182)**—all vital for national connectivity and maritime security.

Border Waters (0.105097) rank moderately high due to sovereignty concerns, while **Natuna Sea (0.078201)** and **Conservation Areas (0.068145)** hold moderate priority related to environmental and resource management aspects. **The New Capital Region (IKN) (0.046420)** and **Maritime Industrial Zones (0.039742)** were ranked lowest, likely because of sufficient existing data and lower navigational risk.

The overall **inconsistency index of 0.05987** remains within the acceptable threshold (<0.1), confirming that expert judgments were consistent and statistically reliable.

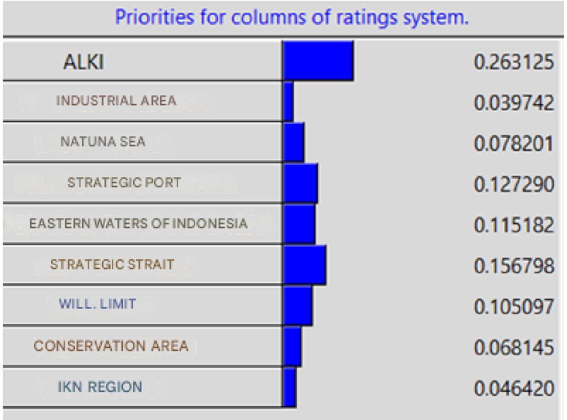

Figure 6. Alternative Area Weights
Source: Processed by the Researcher

Comparison with SWPRHP Criteria

The resulting ANP weights were then compared with the **SWPRHP** risk framework to evaluate conceptual alignment. Both approaches emphasize CATZOC and marine accident frequency as primary determinants, confirming the validity of using risk-based decision-making for hydrographic survey prioritization.

Table 11. Comparison between ANP Results and LINZ Hydrographic Assessment Categories

Criteria/Sub-criteria	SWPRHP Category	ANP Weight
CATZOC	Likelihood (ZOC rating)	0.29712
Marine Accident Frequency	Likelihood (Traffic/Risk Exposure)	0.20461
Bathymetric Condition	Likelihood (Bathymetric Uncertainty)	0.14641
Special Economic Zone	Consequence (Economic/Strategic)	0.09336
Meteorological & Oceanographic Conditions	Likelihood (Environmental Condition)	0.0485
SLOC/SLOT Location	Consequence (Proximity/Routing Importance)	0.04574
Economic Activity	Consequence (Economic Activity)	0.04345
Border Area	Consequence (Border Area Risk)	0.0443
Maritime Infrastructure	Consequence (Access/Infrastructure)	0.04209
Economic Region	Consequence (Economic Asset)	0.03442
Conservation Area	Consequence (Environmental Sensitivity)	0.05111

Source: Processed by the Researcher

The structural consistency between the ANP results and SWPRHP framework confirms the logical soundness of the developed model. Prioritizing **CATZOC** and **accident frequency** validates that risk-based decision-making in hydrographic survey planning must emphasize **navigational safety and data accuracy** as its core foundation.

CONCLUSIONS

This study developed a Hydrographic Risk Assessment (HRA) model to prioritize hydro-oceanographic survey areas in Indonesia, identifying Navigational Safety (0.474851) and Data Quality (0.359146) as the dominant criteria. High-priority areas include the Indonesian Archipelagic Sea Lanes (ALKI), Strategic Straits, and Strategic Ports. The model integrates economic, strategic, and environmental dimensions, essential for a holistic approach, and aligns with the international SWPRHP framework, confirming its validity. The implementation of this model, supported by accelerated data acquisition, institutional strengthening, and advanced survey technologies, is expected to enhance maritime safety, support national security, and promote sustainable marine management. For future research, it is recommended to further refine the model by incorporating dynamic, real-time data analysis and expanding its application to other archipelagic countries facing similar maritime governance challenges.

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