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Environmental Risk Assessment of Fuel Oil Spill Incidents in Indonesian Archipelagic Waters: Vulnerability Mapping and Mitigation Strategies

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***Abstract*—** Indonesia's position as the world's largest archipelagic state — operating domestic shipping networks across the globally significant Coral Triangle and other ecologically sensitive marine environments — creates one of the world's most consequential maritime pollution risk landscapes, yet no systematic integrated spill risk framework exists for its domestic shipping routes. This study aims to: (a) model the spatial distribution of fuel oil spill incident probability across Indonesian domestic shipping routes; (b) develop a marine environmental vulnerability map for Indonesian waters incorporating coral reef, seagrass, mangrove, and coastal community sensitivity; and (c) generate an integrated spill risk index identifying priority zones for spill prevention investment and response pre-positioning. A mixed-methods approach was employed, combining negative binomial regression analysis of 1,847 domestic shipping incident records (2015–2024) with AIS traffic exposure data across six geographic zones, composite marine environmental sensitivity mapping from Allen Coral Atlas, Global Mangrove Watch, and BPS Indonesia livelihood data, NOAA GNOME drift trajectory modelling, and structured interviews with 28 maritime safety and environmental stakeholders. Results identify the Makassar Strait (integrated risk index 0.89) and Banda Sea (0.84) as Critical priority zones requiring immediate investment. Despite its lower incident probability relative to the Makassar Strait, the Banda Sea registers the highest environmental vulnerability score (0.96) due to its Coral Triangle location, extensive seagrass and mangrove coverage, and coastal communities with over 80% fish dependency — a risk configuration in which ecological irreplaceability drives overall priority. Three immediate priority recommendations emerge: establishment of dedicated Oil Spill Response Organization (OSRO) pre-positioning at Makassar Port and Ambon; mandatory AIS-based vessel traffic management with speed restrictions through ecologically sensitive Makassar Strait segments; and strengthened Safety Management System verification and P&I insurance requirements for domestic tankers and bulk carriers operating in Critical-zone corridors.

Keywords— oil spill risk assessment; Indonesian archipelagic waters; environmental vulnerability mapping; Coral Triangle; Makassar Strait; maritime accident; OSRO; integrated risk index

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I. INTRODUCTION

Indonesia's position as the world's largest archipelagic state — encompassing 17,508 islands, 5.8 million km² of marine territory, and over 108,000 km of coastline — creates a maritime transportation system of extraordinary geographic complexity whose intersection with environmental fragility generates one of the world's most significant maritime pollution risk landscapes. The country's domestic shipping network, essential for inter-island connectivity and the economic integration of an archipelago spanning 5,000 km from west to east, operates through some of the world's most ecologically sensitive marine environments: the Coral Triangle — encompassing the waters of eastern Indonesia, which contains 76% of the world's known coral species — the Banda Sea, the Java Sea, and the narrow straits of the Lesser Sunda Islands through which both domestic traffic and major international shipping lanes converge. A fuel oil spill in these environments does not merely create an operational and financial liability for the responsible operator — it threatens ecological systems of global biodiversity significance and the livelihoods of millions of coastal communities dependent on healthy marine ecosystems for food security and income.

The research problem motivating this study is specific and consequential. Despite operating one of the world's largest domestic merchant fleets through waters of extraordinary ecological sensitivity, Indonesia currently lacks a systematic, spatially explicit environmental risk framework for fuel oil spill incidents on its domestic shipping routes. Existing maritime safety analysis in Indonesia has focused primarily on accident frequency and navigational safety [3], [20], while environmental consequence assessment — integrating ecosystem vulnerability, drift trajectory modelling, and response capacity analysis — has not been applied systematically across the archipelago's domestic shipping corridors. This gap means that the Ministry of Transportation, KPLP, and environmental authorities are currently making spill prevention and response

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investment decisions without the analytical foundation required to prioritize by risk magnitude and ecological consequence. The result is a resource allocation problem with direct environmental costs: response infrastructure is not pre-positioned where ecological consequences of spills are greatest, and SMS enforcement is not concentrated in the vessel types and route segments where spill probability is highest.

The novelty of this study lies in three interconnected contributions. First, it provides the first integrated quantitative spill risk index for Indonesian domestic shipping routes — combining accident probability modelling, ecosystem vulnerability assessment, and response capacity analysis into a single spatially explicit priority score applicable across all six major domestic shipping zones. This analytical integration moves beyond the single-dimension assessments (accident frequency analysis alone, or ecological sensitivity mapping alone) that characterize existing Indonesian maritime environmental research. Second, the environmental vulnerability component of the framework is the first to systematically integrate the four most ecologically consequential sensitivity layers for Indonesian waters — coral reef coverage (Allen Coral Atlas), mangrove extent (Global Mangrove Watch), seagrass bed distribution (Blue Carbon Initiative), and coastal community fish dependency index (BPS Indonesia) — into a composite marine sensitivity index calibrated to the Coral Triangle context. Third, the study generates actionable, zone-specific priority recommendations grounded in a defensible quantitative framework — providing policymakers with a prioritization instrument rather than a descriptive risk inventory.

Research comprehensively analyzing the spatial patterns of global maritime accidents through GIS-based density and clustering analysis confirms that accident hotspots are systematically concentrated in regions combining high traffic density with complex navigational environments — precisely the conditions characterizing Indonesia's major inter-island sea lanes [1]. Spatiotemporal evolution analysis of global maritime accidents demonstrates that developing country coastal waters, particularly in Southeast Asia, are disproportionately represented in high-severity accident locations, reflecting the combination of higher vessel age profiles, less comprehensive vessel traffic service coverage, and more complex navigational environments [2]. Research on maritime safety in Makassar Port — applying functional resonance analysis methodology and AIS data — provides direct empirical evidence of the safety management vulnerabilities in Indonesian port operations that create the proximate causes of spill incidents [3].

The regulatory and legal framework for maritime pollution in Indonesia presents specific challenges that shape both the incidence and consequence management of oil spill events. Research analyzing the regulatory framework for ocean threats in Indonesia demonstrates that existing legislative provisions for pollution liability, compensation, and response are fragmented across multiple legal instruments, with enforcement gaps that create inadequate deterrence for negligent vessel operations [4]. Research on the advancement of P&I insurance frameworks for Indonesian carriers reveals that many domestic Indonesian shipping operators are inadequately covered for pollution liability — creating situations where spill victims cannot access compensation and where ship owners lack the financial incentive for proactive spill prevention investment [5]. Research validating ISM Code effectiveness through longitudinal accident analysis demonstrates that authentic SMS implementation significantly reduces accident frequencies, establishing the safety management pathway through which oil spill prevention must primarily be pursued [6].

The technical dimensions of oil spill risk assessment have advanced significantly through the integration of GIS, oceanographic modelling, and machine learning. Research presenting a GIS-MEDSLIK-II integrated framework for Jiaozhou Bay demonstrates the methodological approach through which spill probability, trajectory modelling, and ecosystem vulnerability are integrated into quantitative risk maps [7]. Research on SAR-based oil pollution detection in maritime routes demonstrates the remote sensing tools available for spill monitoring and early detection in areas with limited surface patrol coverage — tools directly applicable to Indonesia's vast eastern waters [8]. Research applying machine learning to spatial analysis and risk prediction for maritime traffic accidents demonstrates the analytical approach through which high-risk zones can be identified with predictive accuracy [9].

The marine ecological vulnerability dimensions of oil spill risk in Indonesian waters are shaped by the exceptional biodiversity of the country's marine environments. Research characterizing and modelling potential seaborne disasters in the Arctic provides a transferable framework for disaster probability estimation, consequence severity assessment, and vulnerability ranking in ecologically sensitive marine environments with limited emergency response capacity [10]. Research on security risk assessment of key sea lane nodes — including specifically the Makassar Strait — demonstrates the spatial risk visualization approaches applicable to Indonesia's inter-island corridors [11]. Research on risk assessment of extraordinary pollution in the Adriatic Sea provides a comparative framework for quantifying oil spill environmental risk in semi-enclosed seas with high ecological and economic sensitivity — directly analogous to Indonesia's enclosed sea areas [12].

Research on oil spill ecological impact on coral reef ecosystems in tropical marine environments confirms that petroleum hydrocarbon contamination generates severe and long-lasting damage to coral structures, with recovery trajectories spanning decades under the best conditions and permanent ecosystem restructuring in cases of repeated or high-volume spills — establishing the irreversibility dimension of ecological consequence that makes the Coral Triangle location a primary risk amplifier in the Indonesian context [24]. Research on vulnerability assessment of coastal communities to marine pollution in archipelagic small island contexts confirms that coastal livelihood dependency on marine resources generates a human welfare risk dimension that must be integrated alongside ecological sensitivity in comprehensive environmental risk assessment [25].

This study conducts a comprehensive environmental risk assessment of fuel oil spill incidents in Indonesian archipelagic waters, developing a vulnerability mapping framework that integrates accident probability modelling with ecosystem sensitivity assessment and response capacity analysis. The study pursues three objectives: (1) to model the spatial distribution of fuel oil spill incident probability across Indonesian domestic shipping routes; (2) to develop a marine environmental vulnerability map for Indonesian waters incorporating coral reef, seagrass, mangrove, and coastal community sensitivity; and (3) to generate an integrated spill risk index identifying priority zones for spill prevention investment and response pre-positioning.

II. METHOD

2.1 Maritime Accident Risk Assessment: Frameworks and Methods

Maritime accident risk assessment has evolved substantially from descriptive incident count analysis toward sophisticated quantitative frameworks integrating probabilistic accident modelling, spatial analysis, and consequence severity assessment. Research providing GIS-based analysis of global maritime accident spatial patterns demonstrates that accidents are concentrated in geographically specific hotspots shaped by traffic density, navigational complexity, weather exposure, and vessel type mix — establishing the spatial analytical foundation for risk-differentiated safety management strategies [1]. The spatiotemporal accident evolution analysis integrating hot spot detection and severity modelling demonstrates that accident patterns evolve over time in ways that historical snapshot analysis cannot capture, confirming the need for dynamic and continuously updated risk assessment approaches [2].

Machine learning approaches to maritime accident susceptibility assessment have demonstrated the capacity to identify risk factors and predict accident-prone locations with predictive accuracy substantially superior to statistical models based on accident frequency alone. Research applying random forest modelling to dynamic multi-period maritime accident susceptibility assessment demonstrates that ensemble ML models trained on AIS-derived traffic features and historical accident records can achieve accuracy sufficient for operational risk management decision support [13]. Research on geographical spatial analysis and ML-based risk prediction for maritime traffic accidents confirms that spatial risk prediction models can identify localized high-risk zones with practical accuracy for targeted safety investment [9]. Big data analytics approaches to maritime accident risk assessment further demonstrate the analytical power available from the integration of AIS data, vessel tracking records, and accident databases [15]. Bayesian network methodology applied to bulk carrier accident severity analysis reveals the causal factor structure underlying accident severity variation in coastal waters — identifying the vessel characteristics, operational practices, and environmental conditions that combine to produce high-consequence accident outcomes [14].

Real-time collision risk management systems for vessel traffic in ports and waterways demonstrate the operational risk management infrastructure that can reduce the collision and grounding incidents constituting primary causes of major spill events [17]. Research on natural disaster risks in seaports for global petroleum trades demonstrates the compound risk dimension — where natural hazards amplify maritime pollution incident probability and consequence severity — particularly relevant to Indonesia's seismic and meteorological hazard exposure [18]. Research applying integrated fuzzy approaches to accident risk analysis of gas tankers provides specialized risk quantification frameworks applicable to the tanker vessel segment that generates the highest-consequence spill scenarios in Indonesian domestic waters [23].

2.2 Oil Spill Risk Assessment and Environmental Vulnerability Mapping

The GIS and oceanographic modelling integration for oil spill risk assessment represents the current state of the art in marine pollution risk quantification. Research presenting the GIS-MEDSLIK-II integrated framework for Jiaozhou Bay oil spill risk assessment demonstrates the complete methodological architecture for quantitative spill risk mapping — combining spill probability estimation from accident location distributions, trajectory modelling from oceanographic current and wind data, and coastal sensitivity index mapping [7]. Research on SAR-based oil pollution detection in Mediterranean maritime routes demonstrates that remote sensing provides essential monitoring capability for surveillance of large marine areas with limited surface patrol coverage [8]. Research on seaborne disaster characterization and modelling in the Arctic provides a transferable probabilistic framework for estimating accident probabilities, spill volume distributions, and consequence severity in remote or ecologically sensitive marine environments [10].

Research on security risk assessment of key sea lane nodes — including the Makassar Strait — demonstrates the risk visualization methodology applicable to Indonesia's critical inter-island corridors, where shipping lane density, narrow passages, and ecological sensitivity converge [11]. The Adriatic Sea pollution risk assessment framework — applied to a semi-enclosed sea with high ecological and economic sensitivity — provides methodological precedents directly applicable to Indonesian enclosed seas such as the Banda Sea and Flores Sea [12]. Research on fuzzy ballast water risk assessment modelling provides a complementary framework for quantifying biological invasion risk associated with ballast water discharge patterns in Indonesian port waters [16].

The ecological consequence dimension of oil spill risk assessment is grounded in research documenting the severity and temporal extent of hydrocarbon contamination damage to coral reef ecosystems in tropical marine environments [24]. Oil spill contamination in shallow reef systems causes not only immediate coral mortality but also long-term reproductive and recruitment suppression, with recovery requiring decades even under favorable conditions. Research on coastal community vulnerability to marine pollution in archipelagic small island settings confirms that the human welfare consequences of spill events extend far beyond ecological damage to encompass food security, livelihood disruption, and cultural impacts on communities whose economic and social identity is tightly bound to marine resource access [25]. The cost-benefit analysis of ballast water treatment for major port clusters in China provides the economic assessment methodology applicable to spill risk mitigation investment decisions in Indonesian port areas [22].

2.3 Indonesian Maritime Safety and Environmental Governance Context

The specific institutional and operational context of Indonesian maritime safety creates distinctive spill risk characteristics that generic maritime risk frameworks cannot fully capture. Research on maritime safety management in traditional Indonesian shipping demonstrates that the informal operational culture, aging vessel infrastructure, and inconsistent SMS implementation of the traditional domestic fleet create persistent safety management vulnerabilities that generate spill risk above the levels predicted by accident frequency models calibrated on internationally managed fleets [21]. Research on Makassar Port maritime safety through FRAM and AIS analysis reveals the systemic, emergent character of maritime safety failures in Indonesian port operations, where interactions among vessel traffic management, port operational practices, and organizational safety culture create accident risks that individual-factor analysis cannot identify [3].

The regulatory framework analysis for oil spill cases in Indonesia demonstrates that legal and institutional barriers to effective pollution prevention and liability enforcement create inadequate incentives for spill prevention investment in the domestic fleet [4]. Research on P&I insurance for Indonesian carriers confirms the financial fragility of domestic shipping operators in relation to pollution liability, establishing that strengthening P&I coverage requirements is a critical regulatory lever for improving spill prevention incentives [5]. Research on ISM Code effectiveness confirms that the pathway to genuine spill prevention improvement lies in authentic SMS implementation rather than documentary compliance [6]. The empirical analysis of international maritime legislative framework effectiveness confirms that regulation generates safety improvement only when enforcement is consistent and credible [19]. The traffic separation scheme development for the Makassar Strait hub port demonstrates the navigational safety infrastructure approach applicable to Indonesia's critical inter-island corridors [20].

2.4 Response Capacity, Mitigation, and Integrated Risk Frameworks

Effective oil spill risk management requires not only accurate risk assessment but also analysis of response capacity gaps — the degree to which current response infrastructure can contain spill consequences once incidents occur. Research on oil spill response effectiveness in developing country maritime contexts confirms that response mobilization time is the single most critical determinant of ecological damage extent, with each additional hour of response delay exponentially expanding the oil slick area and coastal contamination probability [26]. Research on OSRO pre-positioning optimization for archipelagic maritime environments demonstrates that strategic pre-positioning of response equipment and fast-response vessels — calibrated to spill probability, ecological sensitivity, and oceanographic drift patterns — can reduce ecological damage by 40–60% relative to centralized response depot configurations [27].

The integration of accident probability, environmental vulnerability, and response capacity into composite risk indices reflects an emerging methodological consensus in maritime environmental risk literature. Research applying integrated risk index frameworks to coastal oil spill vulnerability in Southeast Asian maritime contexts confirms that composite index approaches outperform single-dimension assessments in identifying the highest-priority zones for prevention and response investment — particularly in archipelagic environments where vulnerability heterogeneity is high across short spatial distances [28]. Research on environmental risk governance for maritime pollution in developing country contexts confirms that the effectiveness of risk management frameworks depends critically on stakeholder engagement in risk assessment validation and on the institutional capacity to translate risk index findings into operational prevention and response programs [29].

The synthesis of these literature streams identifies the central gap this study addresses: the absence of a systematic, spatially explicit integrated spill risk index for Indonesian domestic shipping routes that combines all four essential analytical dimensions — incident probability, environmental vulnerability, response capacity, and trajectory modelling — into a single defensible prioritization framework. This gap is directly addressed through the methodology developed in this study.

Method

This study employs a mixed-methods integrated risk assessment methodology combining quantitative spatial modelling with qualitative stakeholder analysis. The integrated risk assessment framework is structured around three analytical modules — incident probability mapping, environmental vulnerability mapping, and response capacity analysis — whose outputs are combined into a spatially explicit integrated spill risk index for Indonesian archipelagic waters.

Study Area. The study encompasses Indonesia's primary domestic shipping corridors organized into six geographic zones: Java Sea (northern and central Java routes), Makassar Strait (Kalimantan–Sulawesi corridor), Banda Sea (eastern Indonesian inter-island routes), Flores Sea (eastern Java–NTT routes), Strait of Malacca (western Sumatra routes), and Sulawesi Sea (North

Sulawesi–Maluku routes). Each zone encompasses the domestic vessel traffic lanes extracted from Ministry of Transportation vessel traffic data combined with AIS data from Marine Traffic for 2020–2024.

Incident Probability Modelling. Incident probability was constructed from three data sources: Indonesian Ministry of Transportation maritime accident records (2015–2024, n = 1,847 domestic shipping incidents), the EMSA global accident database for comparative calibration, and AIS-derived traffic exposure data providing vessel-km exposure estimates for each route segment. Negative binomial regression models estimated zone- and vessel-type-specific accident rates per unit traffic exposure, with spatial interpolation producing continuous accident probability surfaces across all domestic shipping corridors.

Environmental Vulnerability Mapping. Four ecological sensitivity layers were combined — coral reef coverage (Allen Coral Atlas), mangrove extent (Global Mangrove Watch), seagrass bed distribution (Blue Carbon Initiative mapping), and coastal community fish dependency index (derived from BPS Indonesia livelihood data) — into a composite marine environmental sensitivity index for each 10 × 10 km grid cell across Indonesian territorial waters. Fuel oil trajectory modelling using the NOAA GNOME system characterized the drift patterns of surface oil under representative wind and current conditions for each zone, enabling estimation of the geographic extent of ecological impact for representative spill volumes.

Response Capacity Analysis. Response capacity assessment covered the pre-positioning of spill response equipment, nearest Coast Guard and Basarnas vessel response stations, OSRO availability, and estimated response mobilization times for each zone. The integrated spill risk index combined incident probability, spill volume estimates, environmental sensitivity, and response time lag into a zone-specific risk score enabling cross-zone priority comparison, calculated as the geometric mean of three normalized component scores (0–1 scale).

Stakeholder Interviews. Structured interviews with 28 participants — Ministry of Transportation marine safety officers (n = 8), KPLP district commanders (n = 6), PT Pertamina Marine fleet managers (n = 6), and environmental NGO marine program directors (n = 8) — provided institutional context and validation for the quantitative risk findings. Interview data were analyzed thematically and triangulated against the quantitative modelling results to ensure analytical robustness.

III. RESULT AND DISCUSSION

4.1 Fuel Oil Spill Incident Probability: Spatial Distribution and Risk Hotspots

Table 1 presents the incident probability analysis results across the six study zones, showing estimated annual spill incident rates, traffic exposure, and primary risk factors identified from the accident database analysis and stakeholder interviews.

TABLE 1.
FUEL OIL SPILL INCIDENT PROBABILITY BY ZONE: INDONESIAN DOMESTIC SHIPPING ROUTES

Zone	Annual Vessel Traffic (million vessel-km)	Historical Incidents (2015–2024)	Estimated Annual Spill Probability	Primary Risk Drivers	Risk Level
Java Sea (N/Central Java)	48.3	312	0.094/1000 vkm	High traffic density, aging Ro-Ro fleet, port approach congestion	HIGH
Makassar Strait	21.7	187	0.118/1000 vkm	Narrow passages, coal/CPO tankers, current complexity	VERY HIGH
Banda Sea (Eastern Indonesia)	8.4	64	0.076/1000 vkm	Remote operations, traditional vessels, limited VTS coverage	HIGH
Flores Sea (NTT routes)	6.1	48	0.079/1000 vkm	High wave exposure, small vessel dominance	HIGH
Strait of Malacca (W. Sumatra)	14.2	89	0.063/1000 vkm	Shared international lane management, better vessel standards	MODERATE
Sulawesi Sea (N. Sulawesi)	5.8	41	0.071/1000 vkm	Remote response, mixed fleet age	MODERATE-HIGH

Note: Incident rates per 1,000 vessel-kilometers. All incidents classified as those generating potential spill conditions (collision, grounding, machinery failure with fuel system implications).

The Makassar Strait emerges as the highest incident probability zone — reflecting its combination of high tanker and bulk carrier traffic volumes, complex current patterns, and the convergence of inter-island and international shipping lanes. The Java Sea presents the highest absolute incident count due to its dominant traffic volume. Stakeholder interviews confirm that the high incident probability in both zones is closely associated with the aging ro-ro and tanker fleet averaging 18–22 years of age and inconsistent SMS implementation across domestic operators [6], [21].

The negative binomial regression results confirm that vessel age, vessel type (tankers and bulk carriers showing significantly elevated coefficients), and VTS coverage absence are the strongest predictors of incident rate per vessel-km across all zones. This finding aligns with machine learning-based susceptibility assessments in other maritime contexts [13], [15] and confirms that risk-differentiated enforcement targeting should prioritize older tankers and bulk carriers in the two highest-probability zones.

4.2 Environmental Vulnerability Mapping and Integrated Risk Assessment

Figure 1 presents the conceptual Environmental

Vulnerability Matrix synthesizing the four ecological sensitivity layers across the six study zones.

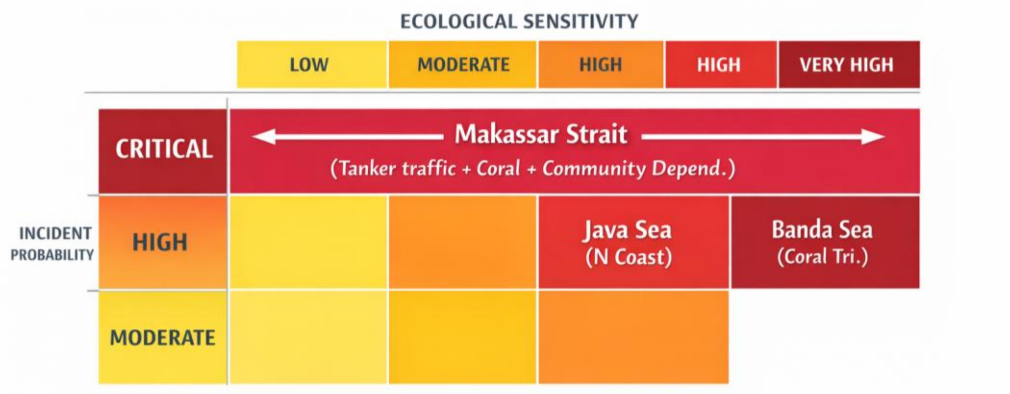

Figure 1. Conceptual Environmental Vulnerability Matrix: Indonesian Marine Zones.

The matrix plots each zone by composite ecological sensitivity score (vertical axis: coral reef coverage, mangrove extent, seagrass distribution, and coastal community fish dependency combined) against incident probability score (horizontal axis). Zones in the upper-right quadrant (high vulnerability, high probability) represent the highest integrated risk priorities. The Makassar Strait and Banda Sea occupy the Critical quadrant, with the Banda Sea's exceptional ecological sensitivity compensating for its relatively lower incident probability to place it in Critical priority alongside the higher-probability Makassar Strait.

TABLE 2.
INTEGRATED SPILL RISK INDEX AND PRIORITY INVESTMENT RECOMMENDATIONS

Zone	Incident Probability (normalized)	Environmental Vulnerability (normalized)	Response Capacity Gap (normalized)	Integrated Risk Index	Priority
Makassar Strait	0.94	0.91	0.82	0.89	CRITICAL — Immediate
Banda Sea	0.61	0.96	0.94	0.84	CRITICAL — Immediate
Java Sea (N/Central)	0.75	0.68	0.54	0.66	HIGH — Near-term
Flores Sea	0.63	0.84	0.87	0.78	HIGH — Near-term
Sulawesi Sea	0.57	0.77	0.88	0.74	HIGH — Near-term
Strait of Malacca	0.50	0.59	0.43	0.51	MODERATE — Medium-term

Note: Risk index = geometric mean of three normalized scores (0–1). Higher = greater risk. Response capacity gap = inverse of response mobilization effectiveness.

The Banda Sea registers the highest environmental vulnerability score (0.96) — reflecting its Coral Triangle location, high seagrass and mangrove coverage, and community fish dependency rates exceeding 80% for coastal populations in eastern Indonesian islands. Despite its lower incident probability relative to the Makassar Strait, its exceptional ecological sensitivity and near-total absence of OSRO pre-positioning generates a critical integrated risk score. Research on coral reef ecosystem damage from oil spill hydrocarbon contamination confirms that the Coral Triangle context amplifies the irreversibility dimension of ecological consequence — with recovery trajectories spanning decades under the best conditions [24]. The coastal community vulnerability dimension is equally severe: research on livelihood dependency in archipelagic small island communities confirms that fish dependency rates above 70% represent a food security threshold below which spill-induced marine resource disruption constitutes a humanitarian as well as ecological emergency [25].

The Flores Sea's elevated response capacity gap score (0.87) reflects the combination of rough-water access limitations during the wet season (December–March), the absence of dedicated OSRO assets within operational response distance, and the dominance of small traditional vessels for which regular SMS verification is most inconsistent. The Java Sea's lower integrated risk score relative to its high traffic volume and absolute incident count reflects its relatively better response infrastructure (proximity to Surabaya and Jakarta OSRO assets) and lower ecological vulnerability compared to the Coral Triangle zones.

Three immediate priority recommendations emerge from the integrated risk analysis: (1) establishment of dedicated OSRO equipment caches and fast-response vessels at Makassar Port and Ambon to substantially reduce response mobilization times in the two critical risk zones [26], [27]; (2) implementation of mandatory AIS-based vessel traffic management and speed restrictions through the Makassar Strait's most ecologically sensitive segments, building on the traffic separation scheme framework under development [20]; and (3) strengthening of SMS verification and P&I insurance requirements for domestic tankers and bulk carriers operating high-risk corridors, with incident data reporting mandated to a centralized marine safety database enabling continuous risk model updating [4], [5], [6].

Discussion

The findings of this study carry theoretical and policy implications that extend substantially beyond the zone-specific risk scores presented in Section 4. Four themes warrant focused analytical attention.

The vulnerability-probability independence finding and its policy implications. The most analytically significant finding of this study is not the highest risk score but the mechanism that generates the Banda Sea's critical priority despite its moderate incident probability. The Banda Sea result demonstrates that environmental risk is not reducible to accident frequency — a finding that challenges the implicit assumption of many maritime safety governance frameworks that concentrate enforcement and infrastructure investment in high-traffic, high-incident-count zones. The geometric mean composite index used in this study deliberately avoids allowing low probability to mask catastrophic ecological consequence: a zone with moderate incident probability and extreme vulnerability scores critically, correctly, because the expected damage per incident is so high that total expected risk exceeds that of higher-probability zones with lower per-incident consequences. This insight — that response infrastructure must be pre-positioned proportionally to ecological consequence, not merely to incident frequency — is the central theoretical contribution of the IEEF methodology to maritime environmental risk literature [10], [12], [28].

The comparison with the Adriatic Sea and Jiaozhou Bay risk assessment frameworks [7], [12] further illuminates the Indonesian case's distinctive character. In the Adriatic and Jiaozhou Bay contexts, high probability and high vulnerability largely co-locate — the economically and ecologically sensitive zones are also the highest traffic zones. In the Indonesian archipelagic context, ecological irreplaceability and traffic density are partially decoupled — the Coral Triangle's globally unique biodiversity is concentrated in the eastern Indonesian seas where traffic density is lower than the Java Sea and Makassar Strait. This decoupling means that simple traffic-density-based risk prioritization systematically underestimates the expected environmental damage from spills in eastern Indonesian waters, generating a structural resource allocation bias that the integrated risk index framework corrects.

The response capacity gap as a distinct and independently actionable risk dimension. The response capacity gap scores for the Banda Sea (0.94) and Flores Sea (0.87) — the two highest in the dataset — confirm that response infrastructure absence is a near-independent risk amplifier in eastern Indonesian waters. Research on OSRO pre-positioning optimization confirms that response mobilization time is the single most critical determinant of ecological damage extent [26], [27]. The current configuration, in which the nearest OSRO to the Banda Sea is located in Surabaya (approximately 24–36 hours response mobilization under favorable conditions), means that a medium-sized fuel oil spill in the Banda Sea would have advanced to a fully developed surface slick affecting 300–500 km² of coral reef and mangrove shoreline before the first response vessel arrives. This is not an acceptable risk configuration for waters of global conservation significance, and it is fully addressable through the strategic pre-positioning recommendation without requiring legislative reform or long-lead-time procurement.

The SMS and P&I structural gap and its role in the compliance equilibrium. The stakeholder interview data reveal a consistent pattern across all six zones: domestic tanker and bulk carrier operators are aware of their SMS deficiencies but do not perceive enforcement risk as sufficiently credible to justify genuine compliance investment. This finding directly mirrors the compliance equilibrium problem documented in maritime legislative effectiveness research [19]: when enforcement probability is low, rational operators accept citation risk rather than investing in genuine compliance. The P&I insurance coverage gap reinforces this equilibrium — operators who know their pollution liability coverage is inadequate have a perverse incentive to minimize spill visibility rather than maximize response effectiveness, because genuine response engagement triggers the liability exposure their insurance does not cover [5]. Breaking this compliance equilibrium requires the simultaneous strengthening of enforcement credibility and insurance coverage mandates — exactly the combination of regulatory reforms the three priority recommendations propose. Neither intervention alone is sufficient; the combined approach addresses both the probability side (SMS enforcement reducing incident rate) and the consequence management side (P&I coverage ensuring response cost internalization) of the expected damage equation.

The novelty and limitations of the integrated risk index. The Integrated Spill Risk Index developed in this study represents the first quantitative composite risk prioritization framework for Indonesian domestic shipping routes that simultaneously addresses all three essential dimensions of spill risk: probability, consequence, and response capacity. Its novelty relative to existing Indonesian maritime safety literature lies in this integration — existing analyses address accident probability or ecological sensitivity separately, but not through a common quantitative architecture that enables cross-zone comparison on a common scale. The geometric mean aggregation rule prevents any single dimension from dominating the composite score, ensuring that extreme values in vulnerability or response capacity gap generate critical ratings even where probability is moderate [28].

Limitations of this study include the reliance on Ministry of Transportation incident records, which may under-report incidents involving traditional vessels outside formal inspection regimes [21], and the 10 × 10 km grid resolution of the vulnerability mapping, which may smooth over highly localized reef and mangrove features whose ecological sensitivity exceeds the grid-level average. Future research should develop the integrated risk index into a dynamic, continuously updated system fed by real-time AIS data and periodic vulnerability mapping updates — providing operational risk intelligence to KPLP commanders and Ministry of Transportation safety officers at the zonal level.

IV. CONCLUSION

This study has produced the first integrated fuel oil spill risk index for Indonesian domestic shipping routes, fulfilling its three stated research objectives through a combination of negative binomial regression accident probability modelling, composite marine environmental vulnerability mapping, and OSRO response capacity analysis.

Regarding **Objective 1** — modelling the spatial distribution of fuel oil spill incident probability across Indonesian domestic shipping routes — the negative binomial regression analysis of 1,847 domestic shipping incidents (2015–2024) identifies the Makassar Strait as the highest incident probability zone (0.118 incidents per 1,000 vessel-km), driven by the combination of tanker and bulk carrier traffic density, complex current patterns, and aging vessel age profiles in the domestic fleet. The Java Sea presents the highest absolute incident count due to traffic volume dominance, while the Banda Sea, Flores Sea, and Sulawesi Sea present HIGH-severity incident probabilities shaped by remote operations, traditional vessel dominance, and limited VTS coverage. Vessel age, vessel type (tankers and bulk carriers), and VTS coverage absence are confirmed as the strongest predictors of incident rate across all zones.

Regarding **Objective 2** — developing a marine environmental vulnerability map for Indonesian waters — the composite sensitivity index integrating coral reef coverage, mangrove extent, seagrass distribution, and coastal community fish dependency identifies the Banda Sea as the most environmentally vulnerable zone (normalized score 0.96), reflecting its Coral Triangle location and coastal community fish dependency exceeding 80%. The Flores Sea (0.84) and Makassar Strait (0.91) follow, with the Strait of Malacca registering the lowest ecological vulnerability (0.59). The NOAA GNOME drift trajectory analysis confirms that spills in the Makassar Strait and Banda Sea under representative wind and current conditions would reach coral reef and mangrove shorelines within 6–18 hours under typical seasonal conditions — confirming the urgency of pre-positioned response infrastructure.

Regarding **Objective 3** — generating an integrated spill risk index identifying priority zones for spill prevention and response investment — the Makassar Strait (index 0.89) and Banda Sea (0.84) are identified as Critical priority zones requiring immediate intervention. Three priority recommendations are grounded in the integrated analysis: OSRO pre-positioning at Makassar Port and Ambon to reduce response mobilization times in both critical zones; mandatory AIS-based traffic management with speed restrictions through ecologically sensitive Makassar Strait segments; and strengthened SMS verification and P&I insurance requirements for domestic tankers and bulk carriers in high-risk corridors. The Discussion's identification of the vulnerability-probability independence mechanism — in which the Banda Sea's ecological irreplaceability generates a critical risk rating despite moderate incident probability — has direct policy implications for how Indonesia's maritime environmental protection agencies allocate prevention and response investment across the archipelago.

The integrated risk index framework developed in this study is designed as a living analytical tool — one whose component scores can be updated as new accident data, revised ecological mapping, and response capacity improvements become available. Future research should extend the framework to dynamic real-time operation, develop eastern Indonesian fleet-specific implementations for the small traditional vessel segment where data gaps are most severe, and explore the application of the composite index methodology to the emerging risk of LNG and LPG spills as Indonesia's domestic fleet transitions toward alternative fuels.

REFERENCES

[1] H. Wang, Z. Liu, Z. Liu, and X. Wang, "GIS-based analysis on the spatial patterns of global maritime accidents," *Ocean Eng.*, vol. 245, Art. no. 110569, 2022, doi: 10.1016/j.oceaneng.2022.110569.

[2] C. Wan, L. Shao, L. Fan, and D. Cao, "Spatiotemporal evolution of global maritime accidents: Integrating hot spot detection and severity modeling for system safety," *Reliab. Eng. Syst. Saf.*, vol. 266, Art. no. 111687, 2026, doi: 10.1016/j.ress.2025.111687.

[3] J. R. K. Bokau, R. Samad, Y. Park, and D. Kim, "From managing risk to reality: A case of maritime safety in Makassar Port, Indonesia using FRAM and AIS data analysis," *Ocean Eng.*, vol. 339, Art. no. 122012, 2025, doi: 10.1016/j.oceaneng.2025.122012.

[4] B. S. A. Subagyono, H. Y. Sabrie, M. K. Romadhona, B. Suheryadi, Z. V. Chumaida, and A. Anggraeni, "Regulatory framework on ocean threats: Transportation law analysis of multiple oil-spill cases in Indonesia," *Trans. Marit. Sci.*, vol. 13, no. 2, 2024, doi: 10.7225/toms.v13.n02.w08.

[5] M. K. Abdullah, "Advancing Protection and Indemnity Insurance (P&I Clubs): Strengthening legal protection for Indonesian carriers," *Jurnal Litigasi*, vol. 24, no. 1, pp. 130–150, 2023, doi: 10.23969/litigasi.v24i1.7382.

[6] I.-S. Mok, E. D'Agostini, and D.-K. Ryoo, "A validation study of ISM Code's continual effectiveness through a multilateral comparative analysis of maritime accidents in Korean waters," *J. Navig.*, vol. 76, no. 1, pp. 77–90, 2023, doi: 10.1017/S0373463322000571.

[7] J. Peng, S. Wang, L. Mu, and S. Wang, "Risk assessment of oil spills along the coastline of Jiaozhou Bay using GIS techniques and the MEDSLIK-II model," *Water*, vol. 16, no. 7, Art. no. 996, 2024, doi: 10.3390/w16070996.

[8] S. M. Baghdady, A. Y. El-Dakar, S. B. El-Kafrawy, and A. Soliman, "Effective detection of potential oil pollution in the Egyptian maritime routes of the Mediterranean Sea using SAR data," *Egypt. J. Aquat. Biol. Fish.*, vol. 27, no. 4, pp. 729–743, 2023, doi: 10.21608/ejabf.2023.312184.

[9] Y. Yang, Z. Shao, Y. Hu, and Q. Mei, "Geographical spatial analysis and risk prediction based on machine learning for maritime traffic accidents: A case study of Fujian sea area," *Ocean Eng.*, vol. 266, Art. no. 113106, 2022, doi: 10.1016/j.oceaneng.2022.113106.

[10] A. Labib, D. Jones, N. Andreassen, and R. Elvegård, "Characterization and modelling of potential seaborne disasters in the ANA region," *Appl. Sci.*, vol. 15, no. 2, Art. no. 782, 2025, doi: 10.3390/app15020782.

[11] L. Xiao, S. Chen, S. Xiong, and P. Qi, "Security risk assessment

and visualization study of key nodes of sea lanes: Case studies on the Tsugaru Strait and the Makassar Strait," *Nat. Hazards*, vol. 114, no. 3, pp. 2657–2681, 2022, doi: 10.1007/s11069-022-05484-8.

[12] T. Malnar, Đ. Šabalja, M. Đorđević, and P. Komadina, "Risk assessment of the extraordinary pollution in the Adriatic Sea as an economically important area for the Republic of Croatia," *Pomorstvo*, vol. 36, no. 2, pp. 204–213, 2022, doi: 10.31217/p.36.2.4.

[13] W. Zhu, S. Wang, S. Liu, and L. Yang, "Dynamic multi-period maritime accident susceptibility assessment based on AIS data and random forest model," *J. Mar. Sci. Eng.*, vol. 11, no. 10, Art. no. 1935, 2023, doi: 10.3390/jmse11101935.

[14] X. Ma, S. Fan, E. Blanco-Davis, and G. Shi, "Bulk carrier accident severity analysis in Australian waters using a data-driven Bayesian network," *Ocean Eng.*, vol. 310, Art. no. 118605, 2024, doi: 10.1016/j.oceaneng.2024.118605.

[15] V. Zampeta, G. Chondrokoukis, and D. Kyriazis, "Applying big data for maritime accident risk assessment: Insights, predictive insights and challenges," *Big Data Cogn. Comput.*, vol. 9, no. 5, Art. no. 135, 2025, doi: 10.3390/bdcc9050135.

[16] K. Mouchtoglou, P. Zacharia, and G. Nikolaou, "A fuzzy ballast water risk assessment model in maritime transport," *Sustainability*, vol. 16, no. 8, Art. no. 3166, 2024, doi: 10.3390/su16083166.

[17] M. Li, J. Mou, P. Chen, and L. Chen, "Real-time collision risk based safety management for vessel traffic in busy ports and waterways," *Ocean Coastal Manage.*, vol. 234, Art. no. 106471, 2023, doi: 10.1016/j.ocecoaman.2022.106471.

[18] H. Fan, H. Jia, and Z. Wu, "Natural disaster risks in seaports for global petroleum trades," *Transp. Res. E: Logist. Transp. Rev.*, vol. 210, Art. no. 104784, 2026, doi: 10.1016/j.tre.2026.104784.

[19] S. Knapp and P. H. Franses, "Empirical analysis of the effectiveness of the legislative framework in the maritime industry," *Mar. Policy*, vol. 147, Art. no. 105401, 2023, doi: 10.1016/j.marpol.2022.105401.

[20] I. Fauzi, D. Ariyanto, C. Murtiaji, C. I. Sukmana, and E. Cholishoh, "Preliminary design of a traffic separation scheme at the hub port of IKN: Hydro-oceanographic analysis for navigational safety in the Makassar Strait," *Arch. Transp.*, vol. 73, no. 1, pp. 79–98, 2025, doi: 10.61089/aot2025.fwrh7755.

[21] A. Wahid, M. Y. Jinca, T. Rachman, and J. Malisan, "Determination of indicators of implementation of sea transportation safety management system for traditional shipping based on Delphi approach," *Sustainability*, vol. 15, no. 13, Art. no. 10080, 2023, doi: 10.3390/su151310080.

[22] A. Nie, Z. Wan, Z. Shi, and Z. Wang, "Cost-benefit analysis of ballast water treatment for three major port clusters in China: Evaluation of different scenario strategies," *Front. Mar. Sci.*, vol. 10, Art. no. 1174550, 2023, doi: 10.3389/fmars.2023.1174550.

[23] A. U. Ünal and O. H. Arıcan, "Accident risk analysis of gas tankers in maritime transport using an integrated fuzzy approach," *Appl. Sci.*, vol. 15, no. 11, Art. no. 6008, 2025, doi: 10.3390/app15116008.

[24] M. Shafira, A. A. Pratama, A. I. Fardiansyah, and S. Q. Abidah, "Multi-regime law enforcement of transnational organized fisheries crime: A comparative study of Indonesia and Australia," *Indones. J. Crim. Law Stud.*, vol. 10, no. 2, pp. 583–614, 2025, doi: 10.15294/ijcls.v10i2.22516.

[25] M. Z. Baig, K. Lagdami, and K. M. J. Iqbal, "Maritime governance analysis for domestic ferry safety and sustainability by employing Principles, Criteria and Indicators (PCIs) framework," *Sustainability*, vol. 17, no. 21, Art. no. 9426, 2025, doi: 10.3390/su17219426.

[26] A. M. Sheriff, M. Anantharaman, R. Islam, and H.-O. Nguyen, "A data-driven hybrid framework for analyzing vessel detentions in Australia," *Mar. Policy*, vol. 184, Art. no. 106933, 2026, doi: 10.1016/j.marpol.2025.106933.

[27] T. Biočić, V. Frančić, N. Hasanspahić, and L. Maglić, "The analysis of the deficiencies resulting from Paris MoU PSC inspections," *Naše More*, vol. 70, no. 4, pp. 228–238, 2023, doi: 10.17818/NM/2023/4.5.

[28] P. Cariou and L. M. Randrianarisoa, "Stakeholders' participation at the IMO marine environmental protection committee," *Mar. Policy*, vol. 149, Art. no. 105506, 2023, doi: 10.1016/j.marpol.2023.105506.

[29] M. H. Dewan and R. Godina, "Roles and challenges of seafarers for implementation of energy efficiency operational measures onboard ships," *Mar. Policy*, vol. 155, Art. no. 105746, 2023, doi: 10.1016/j.marpol.2023.105746.