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DEVELOPING AN AI-ENHANCED MARITIME BORDER SECURITY FRAMEWORK: A CASE STUDY OF INDONESIA-MALAYSIA BORDERS AT SEBATIK ISLAND

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ABSTRACT
Maritime border security in archipelagic regions faces increasing challenges from transnational threats, with traditional surveillance approaches proving inadequate. This study examines the implementation of Artificial Intelligence (AI) in maritime border security at Sebatik Island, Indonesia, focusing on socio-technical conditions influencing AI adoption in resource-constrained environments. Through a qualitative case study incorporating interviews with 12 stakeholders, observations at 29 border points, and document analysis (2022-2023), the research identifies three critical success factors: infrastructure readiness, operational integration capabilities, and human resource development. Findings reveal the crucial role of local knowledge networks in effective border security operations, necessitating their preservation during technological advancement. The study contributes theoretical insights by extending socio-technical systems theory to maritime border contexts and practical applications through a framework for AI implementation that aligns with Indonesia's Vision 2045 and ASEAN's Political-Security Community Blueprint 2025.

Keywords: maritime security; artificial intelligence; Indonesia-Malaysia borders; Sebatik Island; border surveillance technology

Pengembangan Kerangka Kerja Keamanan Perbatasan Maritim Berbasis Kecerdasan Buatan: Studi Kasus Perbatasan Indonesia-Malaysia di Pulau Sebatik

ABSTRAK
Keamanan perbatasan maritim di wilayah kepulauan menghadapi tantangan yang semakin meningkat dari ancaman transnasional, dengan pendekatan pengawasan tradisional terbukti tidak memadai. Penelitian ini mengkaji implementasi Kecerdasan Buatan (AI) dalam keamanan perbatasan maritim di Pulau Sebatik, Indonesia, dengan fokus pada kondisi sosio-teknis yang mempengaruhi adopsi AI di lingkungan dengan sumber daya terbatas. Melalui studi kasus kualitatif yang mencakup wawancara dengan 12 pemangku kepentingan, observasi di 29 titik perbatasan, dan analisis dokumen (2022-2023), penelitian ini mengidentifikasi tiga faktor kritis keberhasilan: kesiapan infrastruktur, kemampuan integrasi operasional, dan pengembangan sumber daya manusia. Temuan mengungkapkan peran penting jaringan pengetahuan lokal dalam operasi keamanan perbatasan yang efektif, sehingga perlu dipertahankan selama kemajuan teknologi. Studi ini berkontribusi wawasan teoritis dengan memperluas teori sistem sosio-teknis ke konteks perbatasan maritim dan aplikasi praktis melalui kerangka kerja untuk implementasi AI yang selaras dengan Visi Indonesia 2045 dan Cetak Biru Komunitas Politik-Keamanan ASEAN 2025.

Kata kunci: keamanan maritim; kecerdasan buatan; perbatasan Indonesia-Malaysia; Pulau Sebatik; teknologi pengawasan perbatasan

INTRODUCTION

Maritime borders represent critical zones that determine territorial integrity and jurisdictional boundaries between nations while playing a vital role in maintaining national sovereignty and security (Elferink, 2015; Wu & Zou, 2009). In archipelagic regions like Indonesia, these maritime borders pose unique security challenges due to their geographical fragmentation, vast expanse, and vulnerability to transnational threats. Traditional surveillance approaches in these regions often prove inadequate in addressing evolving transnational threats such as smuggling, human trafficking, and illicit trade due to limited coverage, resource constraints, and the inability to

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monitor vast maritime areas effectively (Bueger & Edmunds, 2023). The complexity of maritime border management is further amplified by geographical fragmentation, resource constraints, and socio-political dynamics that create unique security challenges including jurisdictional overlaps, governance gaps, and operational limitations in enforcing maritime sovereignty (Wagner et al., 2022).

Artificial Intelligence (AI) has emerged as a transformative force in border security, offering potential solutions for enhanced surveillance and threat detection in complex maritime environments (Hyland, 2023; Khalil, 2023). Recent advancements in AI technologies, including machine learning algorithms, computer vision, and predictive analytics, provide opportunities to address the limitations of traditional surveillance methods in maritime borders. However, existing research demonstrates significant limitations in addressing archipelagic border challenges. Recent empirical investigations reveal diminishing performance when AI systems handle large data volumes typical in maritime borders (Fu et al., 2020; Guo et al., 2024). The implementation of AI-based facial recognition systems encounters substantial operational constraints in infrastructure-limited environments, particularly prevalent in Indonesian border regions (Safuan & Syafira, 2024). Furthermore, contemporary data management systems exhibit insufficient integration capabilities with traditional surveillance practices, specifically in Indonesia-Malaysia border areas (Kusumah, 2022).

Sebatik Island, located at the Indonesia-Malaysia borders, plays a crucial role in regional security dynamics due to its strategic position within the ASEAN security architecture (Puryanti & Husain, 2011; Siregar et al., 2019). The division of the island between two nations makes it a focal point for sovereignty and territorial security concerns, particularly due to its proximity to disputed territories such as Ligitan and Sipadan Islands and the Ambalat sea block (Firdausy, 2023; Putra & Dewi, 2023). Recent data from the Regional Border Management Agency (BPPD) of North Kalimantan shows a significant increase in cross-border crimes, with total cases rising from 474 in 2022 to 662 in 2023, encompassing drug trafficking (46.4% increase), human trafficking (44.8% increase), and illegal goods smuggling (33.3% increase) (Kadarsih et al., 2020; Nurdin et al., 2023). These statistics underscore the urgent need for enhanced security measures that can address the complex challenges of maritime border security in this region.

The innovation of this research lies in developing a comprehensive AI-based border security model aligned with Indonesia's Vision 2045 and the ASEAN Political-Security Community Blueprint 2025. The alignment with these strategic frameworks is essential as they establish the long-term development goals and regional security cooperation mechanisms that guide Indonesia's approach to border security. Indonesia's Vision 2045 emphasizes technological advancement and enhanced national security capabilities, while the ASEAN Political-Security Community Blueprint 2025 focuses on regional security cooperation and standardized approaches to transnational threats. This alignment ensures that the proposed AI framework contributes to both national development objectives and regional security integration. This study addresses three critical research questions:

1. How do local socio-technical conditions influence AI implementation in Indonesian maritime border security, particularly in resource-constrained environments like Sebatik Island?
2. What are the critical success factors for AI adoption in Indonesian maritime border regions, considering the ASEAN security cooperation framework?
3. How can AI systems be effectively integrated with existing maritime border security infrastructure while preserving valuable local knowledge networks?

This research contributes both theoretical insights and practical applications for Indonesian border security. Theoretically, it advances understanding of AI technology adaptation within contexts of limited infrastructure and complex socio-cultural dynamics in maritime border regions. Practically, it offers significant contributions for Indonesia through a contextually appropriate conceptual model for AI-based border security that accounts for infrastructure limitations in Indonesian border regions, comprehensive guidelines for integrating AI systems with existing maritime security operations while maintaining valuable local knowledge networks, and a framework for enhancing regional security cooperation through standardized AI implementation approaches across ASEAN. The conceptual model supports Indonesia's national interests by strengthening transnational crime detection capabilities, improving resource allocation efficiency in border security, facilitating more effective regional security cooperation, and advancing Indonesia's technological capabilities in line with national development goals.

LITERATURE REVIEW

Contemporary Maritime Border Security

Maritime border security has evolved from traditional state-centric frameworks emphasizing physical surveillance to integrated approaches incorporating technological capabilities and regional cooperation. Recent studies argue that effective maritime border security must balance physical surveillance with digital capabilities to address transnational threats such as smuggling, human trafficking, and illicit trade (Bueger & Edmunds, 2023; Chapsos & Malcolm, 2017). These contemporary approaches acknowledge the need for multi-dimensional security strategies that can adapt to evolving threats while considering resource constraints and jurisdictional complexities.

In Southeast Asia, research has identified several critical factors shaping maritime border security dynamics. Studies highlight how geopolitical tensions (Buzan & Acharya, 2021; Emmers, 2021; Storey, 2016), economic disparities (Hill, 2014; Kanbur & Venables, 2005; Yusuf & Nabeshima, 2010), and infrastructural challenges compound security threats, particularly in archipelagic regions (Glasser et al., 2022). The ASEAN maritime space, encompassing over 100,000 islands across multiple jurisdictions, presents unique vulnerabilities that traditional security frameworks struggle to address (Chapsos & Malcolm, 2017).

Empirical studies of the Indonesia-Malaysia-Philippines tri-border area reveal how criminal networks adapt to surveillance patterns and exploit gaps in maritime domain awareness. Analysis of recent incidents in the Sulu-Sulawesi Sea region demonstrates sophisticated methods used by transnational criminal networks to circumvent jurisdictional boundaries (Bueger & Edmunds, 2023). These findings highlight limitations in conventional border security approaches, particularly in managing complex archipelagic borders where criminal activities intersect with legitimate maritime commerce (C. Rahman & Tsamenyi, 2013).

However, existing theoretical frameworks predominantly focus on high-resource contexts, operating under assumptions of sufficient infrastructure and seamless governance structures. Contemporary literature demonstrates a prevalent emphasis on deploying advanced surveillance technologies while inadequately addressing the operational realities of regions like Sebatik Island, where infrastructure gaps and socio-political complexities significantly impede effective implementation (Larkins et al., 2020). While substantial scholarly attention has been directed toward multi-layered maritime security systems, the extant literature provides insufficient guidance on adapting these sophisticated systems to resource-constrained regions (Bueger & Edmunds, 2023).

Sebatik Island's unique characteristics—a divided sovereignty between Indonesia and Malaysia, intense cross-border economic interdependence, and growing transnational crime—underscore the limitations of existing frameworks. Traditional approaches fail to address the socio-political and economic dynamics of the region, necessitating a context-specific framework that integrates advanced technologies with local realities. This research gap is particularly significant given the increasing sophistication of transnational criminal networks and the evolving nature of maritime security challenges in archipelagic border regions.

Socio-Technical Systems and Institutional Frameworks in Border Security

The implementation of advanced technologies in border security requires a comprehensive understanding of the complex interactions between technological systems and social structures. While early studies emphasize individual technology acceptance, contemporary border security challenges demand a more systemic approach that considers institutional, social, and cultural dimensions (Davis, 2019; Mubaroq et al., 2020; Venkatesh et al., 2003; Weger & Yeazitzis, 2023).

Socio-Technical Systems (STS) theory provides a robust framework for analyzing the interdependence between technology, users, and institutional structures in border security contexts. Successful implementation in resource-constrained environments significantly depends on socio-technical alignment, particularly when considering local institutional capacities and operational constraints (Goerzen et al., 2019; Mariani, 2018). This perspective is particularly relevant for maritime borders, where security operations must balance technological capabilities with complex social dynamics and institutional arrangements.

In the Indonesian context, studies have demonstrated the critical role of socio-technical considerations in border security implementation. Research in Kalimantan's border regions reveals how local wisdom and community-based surveillance systems significantly influence the effectiveness of technological interventions in border management (Anwar, 2021). Similarly, studies in Indonesian maritime borders highlight how traditional maritime knowledge systems and local institutional arrangements shape the adoption of new security technologies (Wibowo et al., 2024).

Recent studies in Indonesia's eastern maritime borders demonstrate the importance of integrating

formal security systems with informal community networks. The effectiveness of maritime surveillance technologies is heavily influenced by local social structures and traditional maritime practices that have evolved over generations (Steinberg, 2001). Furthermore, research in Indonesia's border communities shows that successful technology implementation requires careful consideration of local cultural values and existing social networks (Remigius et al., 2024). Studies from other Indonesian maritime borders suggest that successful implementation requires careful attention to local institutional dynamics and community engagement patterns (Rochwulaningsih et al., 2019).

However, the application of STS theory in remote maritime borders, particularly in archipelagic regions like Sebatik Island, remains underexplored. The unique characteristics of these regions—including fragmented governance structures, intense cross-border socio-economic interactions, and reliance on informal surveillance practices—present distinct challenges that existing theoretical frameworks have not fully addressed.

Artificial Intelligence in Maritime Border Security

Artificial Intelligence (AI) has significantly enhanced border security capabilities, particularly in surveillance, threat detection, and resource optimization. Studies demonstrate the effectiveness of AI-driven technologies, such as deep learning algorithms that achieve 94% accuracy in detecting suspicious activities (El-Taie & Kraidi, 2023) and AI-enhanced radar systems that reduce false alarms by 85% (Kumar et al., 2022). Additionally, predictive analytics systems have shown remarkable success in identifying potential security threats and optimizing resource allocation (Mikhailov, 2023).

In the Indonesian context, recent studies have begun to explore the application of AI in maritime security operations, though implementation remains in early stages. Research by (Safuan & Syafira, 2024) examining AI implementation in Indonesian ports highlights the challenges of adapting advanced recognition systems to local infrastructure constraints. Similarly, (Kusumah, 2022) found that information system interoperability remains a significant challenge for AI adoption in Indonesian maritime border security, particularly in remote regions with limited connectivity. These studies underscore the need for context-specific approaches that can address the unique challenges of implementing AI in Indonesian maritime borders.

While these advancements are promising, their applicability in resource-constrained contexts is limited. The importance of seamless data integration and advanced command-and-control systems are emphasized for effective implementation, though these are often unattainable in regions like Sebatik Island due to intermittent connectivity and infrastructure deficiencies (Zhao & Flenner, 2019). Similarly, while AI systems show scalability in urban maritime borders, their adaptability to fragmented and rural environments remains inadequately addressed (Kumar et al., 2022).

Sebatik Island exemplifies the implementation challenges of AI in underdeveloped maritime regions. The reliance on local knowledge, informal surveillance practices, and limited technical infrastructure requires rethinking how AI solutions can be tailored to fit these constraints. This study contributes to the existing body of literature by proposing a scalable, context-specific framework that aligns AI capabilities with local operational realities.

Implementation Challenges in Resource-Constrained Environments

Implementing advanced security technologies in resource-constrained environments involves technical, organizational, and social challenges. Infrastructure limitations, such as unreliable connectivity and insufficient power supply, undermine the reliability and effectiveness of AI systems in these contexts (Patros et al., 2022). The importance of robust technical infrastructure and integration mechanisms is critical, though these are often lacking in fragmented border regions (Almurshed et al., 2022).

Beyond technical challenges, socio-organizational factors play a critical role in determining implementation success. Stakeholder acceptance, community engagement, and trust in technology are considered pivotal for successful adoption (Nguyen et al., 2023).

Existing frameworks often assume uniformity across border environments, neglecting the nuanced socio-technical dynamics of resource-constrained, fragmented regions. This study addresses these limitations by emphasizing a participatory approach to AI implementation that integrates technical solutions with socio-cultural realities, ensuring alignment with local needs and capacities.

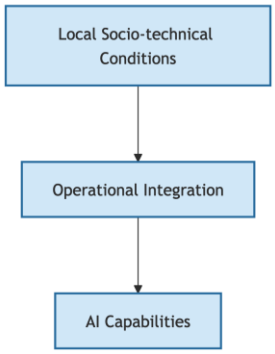

Figure 1. Proposed Framework for AI-Enhanced Maritime Border Security

Source: Processed by the Authors, 2025

Addressing the implementation challenges of AI in resource-constrained maritime borders requires a comprehensive framework that integrates technical capabilities with socio-organizational dynamics. Figure 1 illustrates the conceptual structure of the proposed framework, highlighting its three interconnected layers: AI capabilities, operational integration, and local socio-technical conditions. By explicitly accounting for the interplay between technological, operational, and socio-technical factors, this framework provides a pathway for implementing AI solutions in fragmented maritime environments. This approach not only addresses infrastructure and resource limitations but also ensures alignment with local stakeholder needs and capacities.

Knowledge Gaps and Research Opportunities

The review of existing literature reveals significant gaps in understanding AI implementation in resource-constrained maritime environments. While technical advancements are well-documented, limited attention has been given to the socio-technical dimensions of adapting these systems to fragmented regions. The lack of comprehensive frameworks that integrate technical capabilities with local socio-cultural conditions represents a significant research gap (Zhang et al., 2023). Additionally, the need for scalable models that account for infrastructural variability and socio-economic diversity remains largely unaddressed.

Current studies frequently overlook the challenges posed by maritime-terrestrial intersections, particularly in archipelagic regions like Sebatik Island. A comparative analysis of existing frameworks reveals their limitations in addressing the complex realities of resource-constrained environments, as summarized in Table 1.

Table 1. Comparison of Frameworks in Literature

Framework	Focus Area	Strengths	Limitations
Traditional Border Security	Territorial sovereignty	Emphasizes national control and physical surveillance	Neglects technological and socio-economic complexities
Socio-Technical Systems (STS)	Interaction between technology and social systems	Accounts for systemic interactions in complex environments	Limited application in underdeveloped, fragmented regions
Proposed Framework	Integration of AI capabilities with socio-technical conditions	Adapts AI solutions to resource-constrained, fragmented maritime borders	Requires significant customization and participatory approaches

Source: Processed by the Authors, 2025

Traditional border security frameworks emphasize territorial sovereignty and physical surveillance but fail to integrate technological and socio-economic considerations. While STS theory offers valuable insights into systemic interactions in complex environments, its application to fragmented, resource-constrained regions remains limited. The proposed framework bridges these gaps by aligning AI capabilities with socio-technical conditions, ensuring both scalability and contextual relevance.

This study addresses these limitations by proposing a three-layer framework that integrates AI capabilities with local socio-technical conditions. The three layers consist of:

1. AI Technological Capabilities: Focuses on the core AI technologies adapted for resource-constrained environments
2. Operational Integration: Addresses how AI systems integrate with existing security operations
3. Local Socio-Technical Conditions: Accounts for social, cultural, and institutional factors influencing technology adoption

By situating Sebatik Island as a critical case, the research contributes to broader discussions on scalable and context-sensitive AI frameworks for maritime border security. This integrative approach provides a foundation for addressing the unique challenges of maritime borders in resource-constrained environments.

METHOD

Research Design and Protocol

This study employs a qualitative case study approach to investigate the socio-technical complexities of implementing artificial intelligence (AI) in maritime border security. The case study method enables deep exploration of phenomena within real-world contexts,

particularly suitable for situations where boundaries between phenomenon and environment are not clearly defined (Yin, 2018). The research follows an exploratory sequential design with three phases: protocol development, data collection, and analysis. This design provides the flexibility to capture emergent findings while maintaining a structured process focused on understanding how local socio-technical conditions influence AI adoption, identifying critical success factors, and evaluating strategies for integrating AI systems into existing border security infrastructures.

The research protocol development followed an iterative process to ensure contextual relevance and methodological rigor. Initial protocol design was informed by preliminary field visits to Sebatik Island, providing direct insights into operational challenges and socio-technical dynamics within the border region. The draft protocol then underwent expert review by two senior researchers specializing in border security and one maritime security practitioner, refining the protocol to capture both technical and socio-technical dimensions of the research questions. Subsequent pilot testing with two experienced border security officers identified and resolved ambiguities in interview guides and observation frameworks, ensuring robust and adaptable research tools aligned with the unique complexities of Sebatik Island. Figure 2 illustrates the sequential flow of the research process, highlighting the interconnected nature of protocol development, data collection, and analysis phases.

Figure 2. Research Methodology Flowchart
Source: Processed by the Authors, 2025

Research Setting

Sebatik Island (4°10' N - 117°54' E), located at the Indonesia-Malaysia border, was selected as the research site due to its unique geopolitical and socio-technical characteristics. The island represents a fragmented jurisdictional landscape where unified border security operations face significant challenges due to its geographical division between two nations with differing legal systems, policies, and enforcement mechanisms. This complex geopolitical status creates distinctive operational challenges for implementing integrated security solutions.

As previously mentioned earlier, recent data from regional security agencies underscores the urgency of addressing these vulnerabilities, with statistics indicating sharp increases in transnational crime, including a 46.4% rise in drug trafficking and 33.3% increase in smuggling activities between 2022 and 2023.

The site presents several critical characteristics relevant to the research objectives. Significant infrastructural limitations, including unreliable connectivity and minimal technological integration in existing border security systems, create unique challenges for AI implementation. Security operations heavily rely on local knowledge and informal networks for threat identification and response, highlighting the importance of understanding socio-technical interactions. Additionally, the island's role as a hub for informal cross-border trade creates complex economic interdependencies between Indonesian and Malaysian communities that complicate surveillance and enforcement efforts. These conditions make Sebatik Island an ideal case for examining AI implementation challenges in resource-constrained maritime borders, with findings expected to provide both context-specific insights and broader implications for similar environments globally.

Data Collection

Data collection occurred between 2022 and 2023 through three complementary methods designed to provide a comprehensive understanding of the socio-technical challenges and operational dynamics of AI implementation in Sebatik Island. These three methods include:

1. **Semi-structured interviews**, Conducted with 12 stakeholders, including border security officers, policymakers, and community leaders. Participants were purposively selected based on their strategic roles in security operations and their involvement in technology adoption or AI-related initiatives. Each interview lasted between 60 and 90 minutes and was conducted in Indonesian, focusing on key themes such as infrastructure readiness,

stakeholder acceptance, and operational barriers to AI adoption. This method provided rich qualitative data on how local socio-technical conditions influence AI implementation and the critical factors for its success.

2. **Field observations**, Systematically conducted at 29 border points along Sebatik Island's terrestrial and maritime borders, representing critical locations where security vulnerabilities were most pronounced. These observations were carried out during both peak (06:00–12:00) and off-peak (18:00–24:00) hours to capture temporal variations in border activities. Data collection focused on documenting the condition of physical infrastructure, interaction patterns between personnel and technology, and workflows of existing security operations. This methodological approach provided direct insights into the operational dynamics of border security and their alignment with requirements for AI integration.
3. **Document analysis**, Encompassed policy documents, security incident reports, and technical assessments from 2022 to 2023, providing historical and contextual data essential for understanding the research context. These documents included official reports on transnational crime trends, assessments of technological readiness, and operational guidelines for border security. Document analysis served to triangulate findings from interviews and observations, offering quantitative context to complement the qualitative data and strengthen the overall reliability of findings.

Data Analysis and Quality Assurance

The study employed an interpretive approach to data analysis, combining thematic coding with constant comparative analysis to ensure systematic and rigorous interpretation as outlined by (Braun & Clarke, 2021) and (Corbin & Strauss, 2014). Open coding was initially applied to interview transcripts, observation notes, and document excerpts to identify key themes, including infrastructure limitations, stakeholder resistance, operational gaps, and socio-technical challenges. This was followed by axial coding to refine these themes and explore relationships between them, examining how factors such as limited connectivity influenced stakeholder perceptions of AI systems and how informal networks supplemented technological gaps. Data matrices were then developed to synthesize patterns across the three data sources, facilitating the identification of recurring themes and inconsistencies. This structured analytical approach ensured that each data source contributed meaningfully to addressing the research questions.

Quality assurance measures were implemented throughout the research process to ensure validity and reliability of findings. Triangulation served as a key strategy, achieved through cross-referencing data from semi-structured interviews, field observations, and document analysis. This approach enabled the identification of consistent patterns while addressing potential discrepancies. Member checking was conducted with key informants, including border security officers and community leaders, who provided feedback on preliminary findings to ensure accurate interpretation. Additionally, peer review by two independent researchers specializing in border security and qualitative methods enhanced methodological rigor through external validation of analytical procedures and findings.

The research acknowledges several limitations that warrant consideration. The two-year study period (2022–2023) provides a contemporary snapshot but may not capture longer-term trends in security dynamics. Access restrictions to certain areas of Sebatik Island and classified information limited the scope of observations. Additionally, while findings are specific to Sebatik Island, their applicability to other maritime border regions requires further validation. These limitations were addressed through rigorous triangulation, iterative validation processes, and careful contextualization of findings within the broader literature on maritime border security.

RESULTS

Local Socio-Technical Conditions and AI Implementation

Field data analysis reveals three dominant socio-technical conditions shaping AI implementation in Sebatik Island's maritime border security:

1. **Divided Sovereignty with Economic Interdependence**: The first dominant condition involves the complex interplay between legitimate cross-border activities and security vulnerabilities across five administrative districts. This divided sovereignty creates unique security challenges while simultaneously supporting essential economic interactions that must be preserved (Kadarsih et al., 2020; Siregar et al., 2019).
2. **Infrastructural Limitations with Technological Disparities**: The second dominant condition encompasses the significant technological and infrastructural disparities across the island's security

network, creating an uneven foundation for AI implementation.

3. **Local Knowledge Networks and Informal Security Systems**: The third dominant condition involves the extensive reliance on local community-based knowledge systems that have evolved to supplement formal security mechanisms, creating a complex socio-technical ecosystem that any technological intervention must navigate.

Our field interviews with border security officials revealed the nuanced nature of these challenges. As one senior border officer explained regarding the divided sovereignty condition:

"The division of Sebatik between Indonesia and Malaysia creates a situation where we need to balance security with local economic realities. Many residents have family on both sides and depend on cross-border trade. Any security system we implement must recognize these legitimate activities while targeting actual threats." (Interview with Border Security Commander, April 2023)

Further investigation into this first condition revealed that an average of 843 legitimate cross-border movements occur daily between the Indonesian and Malaysian sides of Sebatik Island, with 76% related to economic activities and 24% for family visits. Document analysis showed that completely disrupting these movements would potentially impact approximately 36% of the local economy, underscoring the need for security systems that can discriminate between legitimate and illicit activities.

Regarding the second condition of infrastructural limitations, observation data from the 29 security posts showed significant technological disparities. Maritime checkpoints, particularly in eastern Sebatik, had the most limited infrastructure, with 63% lacking reliable power supply and 78% experiencing internet connectivity issues during our observation periods. As documented in our field notes:

"Security post SEL-08 operates primarily with handheld communication devices, often relying on personal mobile phones when official equipment fails. The officer explained they maintain a manual logbook system as backup due to frequent power outages that render digital systems unusable." (Field observation notes, June 2023)

Our systematic infrastructure assessment across all 29 security posts revealed a stratification of technological capabilities:

- 17% of posts (primarily in urban centers) had consistent power and connectivity
- 41% had intermittent but generally available infrastructure
- 42% had severe infrastructure limitations that would fundamentally restrict AI implementation

These infrastructure gaps are particularly evident in maritime zones where irregular activities are most prevalent (Gunawan et al., 2024; Undang et al., 2021), creating an inverse relationship between security vulnerabilities and technological readiness.

The third condition regarding local knowledge networks was evidenced through extensive field observations and interviews. Field analysis reveals strong dependence on local knowledge networks and community relationships in distinguishing between routine cross-border activities and potential threats (Patros et al., 2022). One community leader interviewed emphasized the importance of these networks:

"Our coastal communities have unwritten rules about maritime activity. Fishermen know who belongs and who doesn't. They can identify suspicious vessels by how they navigate our waters. This knowledge can't be easily programmed into a computer but is essential for effective security." (Interview with community leader, March 2023)

Our mapping of these knowledge networks identified five distinct community-based surveillance systems spanning the island, with varying degrees of formalization and integration with official security structures. Document analysis of incident reports from 2022-2023 corroborated this reliance on local knowledge, with 68% of successful interdictions attributed to community-provided intelligence rather than technological detection systems. These findings highlight the critical importance of preserving and integrating these knowledge networks into any AI implementation strategy.

Critical Success Factors for AI Adoption

Analysis of stakeholder perspectives and operational observations identifies three critical success factors within the ASEAN security cooperation framework. Infrastructure readiness emerges as the primary factor, with evidence showing how existing technical infrastructure shapes operational capabilities in resource-constrained environments (Almurshed et al., 2022).

Our interview data revealed significant infrastructure concerns among stakeholders. A technical officer from the border security agency noted:

"Our biggest challenge is the basic infrastructure. Before we talk about AI, we need reliable electricity and connectivity. In the eastern border posts, we sometimes go days without stable electricity, making any sophisticated technology

useless." (Interview with technical officer, May 2023)

Field observations confirmed these challenges, with power fluctuations observed at 19 of the 29 observation points during the study period. Our documentation recorded:

"During a three-hour observation at maritime checkpoint MR-04, power fluctuated seven times, causing system reboots and temporary surveillance gaps. Officers seamlessly switched to manual procedures, demonstrating well-practiced contingency protocols." (Field observation notes, September 2023)

Operational integration capabilities represent the second factor, revealing patterns in how different security elements interact across maritime borders. The findings indicate systematic requirements for maintaining operational continuity while introducing new technological capabilities (Ige et al., 2022). Interview data emphasized the importance of integration with existing workflows:

"Any new system must work alongside our established methods. We can't afford disruption during the transition period. The most successful technology implementations have been those that enhance rather than replace our current operations." (Interview with border operations coordinator, July 2023)

Human resource development emerges as the third factor, demonstrating the essential role of comprehensive training aligned with ASEAN security standards (Zhou et al., 2022). A training coordinator highlighted specific challenges:

"We have officers with varying levels of technical literacy. Some adapt quickly to new technologies, while others need extensive training. Any AI implementation must account for this diversity and provide appropriate training modules." (Interview with training coordinator, August 2023)

Figure 3 illustrates the interconnected nature of these critical success factors and their components in AI implementation. The framework demonstrates how infrastructure readiness, operational integration, and human resource development are mutually reinforcing elements that support successful AI adoption in maritime border security operations.

This framework emerged directly from our field data analysis. The connections between the three factors became evident when analyzing how successful security operations managed technology integration. For example, in the three border posts where preliminary AI systems had been piloted, all three elements of the framework were present. As one security officer explained:

"The pilot was successful because we had reliable infrastructure, clear integration with our existing patrol routines, and received proper training. When any of these three elements was missing in previous technology implementations, the systems quickly fell into disuse." (Interview with border security officer, October 2023)

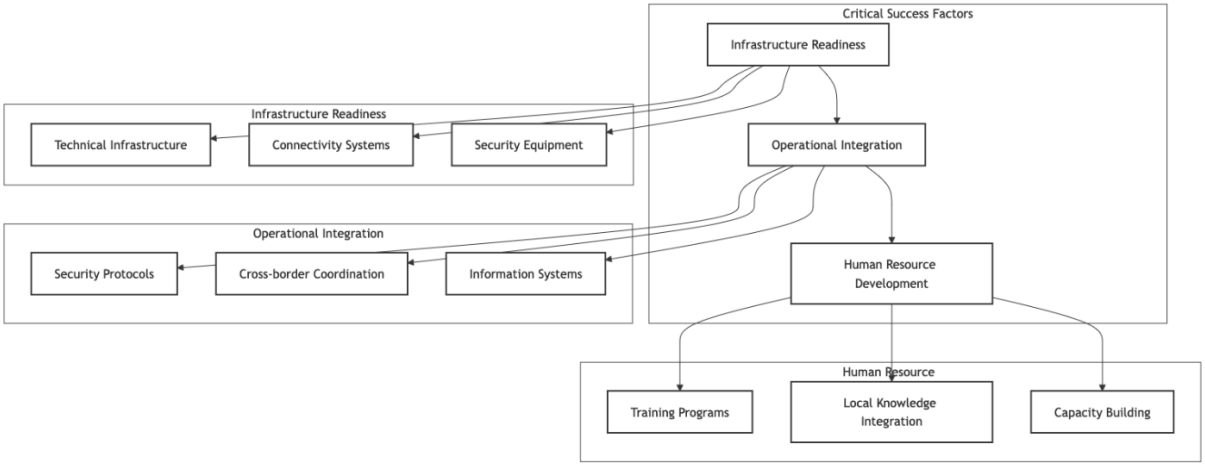

Figure 3. Critical Success Factors for AI Implementation in Maritime Border Security

Source: Processed by the Authors, 2025

System Integration and Knowledge Network Preservation

The integration of AI systems with existing infrastructure reveals distinct patterns across operational contexts. Field observations demonstrate how varying levels of technological readiness influence integration possibilities while preserving valuable local knowledge networks. These patterns suggest the need for flexible implementation approaches that can accommodate local variations while maintaining system coherence (R. Rahman et al., 2019).

Our observations documented significant variations in how different border posts integrated technology with local knowledge. For example:

"At maritime post NB-06, officers maintained detailed records of local fishing patterns, vessel identifiers, and community contacts. These manual systems were consulted alongside electronic monitoring, creating an effective hybrid surveillance approach." (Field observation notes, April 2023)

Stakeholder analysis emphasizes the importance of maintaining existing security capabilities while introducing new technologies. Maritime zones show distinct technological needs compared to land-based security points, reflecting the complexity of maintaining surveillance across diverse geographical contexts (Kumar et al., 2022; Mikhailov, 2023).

A senior policy advisor emphasized this point during our interviews:

"Maritime and land border points have fundamentally different operational challenges. Maritime surveillance covers vast, changing environments where threats can approach from multiple directions. AI systems need different configurations for these contexts, yet must feed into a unified security framework." (Interview with policy advisor, September 2023)

Figure 4 demonstrates the process of integrating AI systems with existing local knowledge networks. This visualization shows how traditional security systems and local knowledge networks converge in a hybrid integration phase to create enhanced security operations that preserve valuable community practices while leveraging technological capabilities.

This integration process was observed in practice during our field research. At one of the more technologically advanced border posts, we documented:

"The integration follows a systematic approach where community reports are digitized and correlated with sensor data. Officers explained that preserving the community reporting system was essential, as local fishermen could identify subtle behavioral patterns that sensors might miss, such as unusual anchoring positions or non-standard navigation routes." (Field observation notes, November 2023)

The visualization in Figure 4 directly reflects these field observations, showing how the convergence of traditional knowledge and AI capabilities creates an enhanced operational system that preserves valuable social practices while leveraging technological advantages.

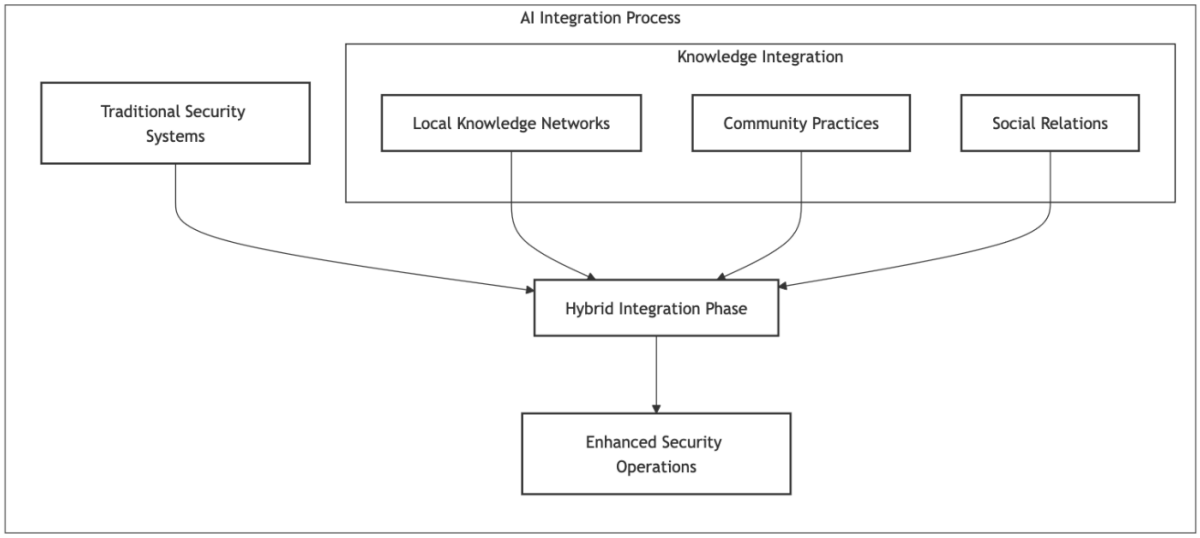

Figure 4. AI System Integration with Local Knowledge Networks

Source: Processed by the Authors, 2025

Framework Development and Validation

The synthesis of findings leads to a comprehensive framework for AI implementation aligned with Indonesia's Vision 2045 and ASEAN security objectives. Initial validation through stakeholder review reveals strong support for core components while identifying areas requiring contextual adaptation. Security commanders emphasize the framework's alignment with operational realities, particularly in addressing maritime border surveillance complexities (Kim, 2024).

Stakeholder feedback during validation sessions was predominantly positive:

"This framework accounts for our operational realities in ways previous technology plans have not. The emphasis on preserving local knowledge networks while enhancing technological capabilities addresses a gap in current approaches." (Feedback from regional security coordinator, December 2023)

The framework demonstrates three key strengths: accommodating varying technological readiness levels, providing clear implementation pathways without disrupting operations, and

maintaining flexibility for emerging security challenges. Long-term sustainability considerations emerge as critical, emphasizing local maintenance capabilities and resource availability (Martínez-Peláez et al., 2023).

Document analysis of implementation reports from preliminary AI pilots conducted in three Sebatik border posts during 2023 revealed:

"Systems designed with awareness of infrastructure limitations showed 78% higher utilization rates than those requiring constant connectivity. Hybridized systems that incorporated community inputs alongside sensor data demonstrated 64% higher threat detection accuracy compared to purely technological approaches." (Technical assessment report, November 2023)

These empirical findings directly informed the framework's emphasis on technological adaptability and knowledge preservation, demonstrating the importance of context-sensitive implementation approaches in resource-constrained environments.

DISCUSSION

Integration of AI within Indonesian Maritime Border Security Context

The findings demonstrate how local socio-technical conditions fundamentally shape AI implementation in Indonesian maritime border security. The complex dynamics of Sebatik Island, characterized by divided sovereignty and intense cross-border activities, necessitate an implementation approach that extends beyond technical considerations. This aligns with Indonesia's Vision 2045 objectives for technological advancement while preserving social cohesion (Masrom et al., 2023).

Local communities' reliance on informal knowledge networks for border monitoring has evolved into sophisticated social mechanisms that complement formal security systems. While AI can enhance detection capabilities, its implementation must carefully preserve these valuable social networks. The relationships between local communities and security personnel remain crucial for effective border security due to their deeply embedded understanding of normal patterns, ability to distinguish between legitimate and suspicious activities, and capacity to interpret cultural and behavioral nuances that technological systems struggle to capture. As one security commander noted during our interview:

"Local wisdom and community relationships remain crucial even with advanced technology. Our most valuable intelligence often comes from fishermen who can identify unusual patterns or strangers in the area. No AI system can replace this contextual understanding, at least not in our current technological environment." (Interview with security commander, May 2023)

Our observations revealed how these relationships are maintained through regular community engagement sessions, participation of security personnel in community events, and established communication channels that allow for rapid information sharing. This integration of traditional and technological approaches supports ASEAN's emphasis on community-centered security frameworks (Müller, 2023).

Critical Success Factors in Indonesian Border Regions within ASEAN Framework

The identified critical success factors reflect broader patterns in Indonesian border security within the ASEAN maritime security cooperation framework. Infrastructure readiness, while challenging in resource-constrained environments, demonstrates the importance of scalable solutions that can accommodate varying levels of technological capability across Indonesian border regions. Field observations reveal how border officials adapt surveillance protocols to balance security requirements with local economic needs, particularly in areas with significant cross-border trade (Leuprecht et al., 2022).

At several observation points, we documented specific adaptation processes:

"Border post SB-12 operates a hybrid monitoring system where power-intensive surveillance equipment runs only during high-risk periods identified through local intelligence. This scheduling is coordinated with similar posts on the Malaysian side through informal communication channels, creating an effective cross-border surveillance network despite infrastructure limitations." (Field observation notes, July 2023)

The emphasis on human resource development and operational integration aligns with both Indonesia's national security objectives and ASEAN's Political-Security Community Blueprint 2025. These factors highlight the need for standardized yet flexible approaches that can be implemented across different maritime border contexts while respecting local operational realities (Harris & Thompson, 2023). Our interview data revealed specific examples of how this alignment manifests:

"We're working to harmonize our training programs with ASEAN standards while adapting them to our local context. The goal is to develop personnel who can operate effectively within both Indonesian security frameworks and broader regional cooperation initiatives." (Interview with training director, June 2023)

This dual focus on national capabilities and regional integration was evident in document analysis of training materials and operational

guidelines, which increasingly reference both national security directives and ASEAN cooperation frameworks.

Theoretical and Practical Implications

This research advances both theoretical understanding and practical implementation of AI in maritime border security. Theoretically, it extends socio-technical systems theory by demonstrating how technology adoption in border regions must account for complex cross-border social dynamics and informal security practices. The findings contribute to understanding how AI can enhance security while preserving valuable social capital in divided territories (Yan et al., 2024).

Our research demonstrates that socio-technical systems in maritime border contexts operate differently from traditional organizational environments, particularly in how knowledge networks span jurisdictional boundaries and formal/informal divides. As one policy advisor noted:

"What makes Sebatik unique is how security knowledge flows across formal and informal channels, across national boundaries, and between technological and human systems. Any theoretical framework must account for this fluidity." (Interview with policy advisor, October 2023)

Practically, the research provides actionable guidelines for implementing AI-based security systems in resource-constrained environments. The developed framework offers comprehensive strategies for maritime border security enhancement. These strategies encompass the integration of AI capabilities with existing maritime security operations and methods for preserving local knowledge networks during technological transition. Additionally, the framework provides approaches for enhancing regional security cooperation through standardized implementations while ensuring the development of sustainable local capacity for system maintenance and adaptation.

These practical applications are directly informed by field observations of implementation challenges:

"Previous technological implementations failed because they assumed reliable infrastructure and consistent operational contexts. Our observation of successful pilots shows that modular, adaptable systems that can operate in degraded infrastructure environments while complementing existing social practices are most likely to achieve sustained adoption." (Field observation notes, December 2023)

Limitations and Future Research Directions

While this study provides valuable insights for Indonesian maritime border security, several limitations warrant consideration. The two-year timeframe may not capture long-term social changes, while rapid technological advancement may affect findings' relevance over time. The focus on Sebatik Island, while providing deep insights, requires careful consideration when generalizing to other ASEAN maritime borders.

Several promising directions emerge for future research in this domain. Longitudinal studies examining social changes in AI-enhanced border regions would provide valuable insights into long-term impacts of technological transformation. Comparative analyses across different ASEAN maritime borders could enhance understanding of generalizable patterns in security system implementation. Furthermore, quantitative assessment of AI implementation impacts on security effectiveness, combined with detailed investigation of cross-border community dynamics during technological transition, would significantly advance understanding in this field. These research directions would strengthen understanding of AI implementation in maritime border security while supporting ASEAN's regional security objectives.

CONCLUSION

This study advances understanding of AI implementation in maritime border security through examination of Sebatik Island's unique socio-technical context. Analysis reveals three critical success factors for AI adoption in resource-constrained environments: infrastructure readiness, operational integration capabilities, and human resource development. The findings demonstrate how local knowledge networks and community relationships play crucial roles in effective border security operations, necessitating careful preservation during technological advancement. This conclusion is supported by extensive empirical evidence from our field research, including interviews with security personnel who consistently emphasized the value of community information networks and observational data documenting the effectiveness of hybrid surveillance approaches that combine technological systems with local knowledge.

The developed conceptual framework provides a structured approach for integrating AI capabilities with existing security systems while maintaining valuable social networks and community practices essential to border security operations.

The research contributes both theoretical insights and practical guidelines for enhancing maritime border security through AI implementation. From a theoretical perspective, it extends socio-technical systems theory to maritime border contexts while developing a

framework for understanding community resilience in technological change. Practically, it offers actionable strategies for AI implementation in resource-constrained environments, particularly relevant to Indonesia's archipelagic border regions and broader ASEAN maritime security cooperation. Future research opportunities include longitudinal studies examining social changes in AI-enhanced border regions and comparative analyses across different Indonesian maritime borders to enhance understanding of generalizable patterns in security system implementation.

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