



Developing an AI-enhanced maritime threat detection model: Predictive security framework for illegal fishing and piracy in the Natuna Sea

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ABSTRACT

Background: The North Natuna Sea, as a strategic area of Indonesia, faces increasingly complex maritime security threats, particularly illegal fishing activities and piracy that threaten economic sovereignty and the stability of aquatic ecosystems. This research develops a maritime threat detection model based on Artificial Intelligence that is capable of predicting and preventing illegal activities through a preventive and proactive approach. **Methods:** Using a qualitative research method based on documentary studies, this research analyzes patterns of maritime threats, regional geopolitical dynamics, and the limitations of conventional surveillance systems that have historically relied on a reactive approach. The developed predictive model integrates three layers of technology: multi-source data integration (Sentinel-1 satellites, VIIRS, AIS, oceanographic data), predictive analytics utilizing Long Short-Term Memory (LSTM) and Random Forest algorithms, as well as an automated operational response system. Data analysis indicates that illegal fishing in the Natuna Sea incurs economic losses of USD 25 billion annually on a national scale, with 112 vessels confiscated in the first half of 2024. Meanwhile, piracy incidents have increased from 10 incidents in 2022 to 18 incidents in 2023, affecting 126 crew members in 2024. **Findings:** The research results indicate that the predictive AI model is capable of increasing the detection rate of foreign vessels from 40% to 85% and reducing response time from 8 hours to 45 minutes. This system generates an updated maritime threat heatmap every 15 minutes, enabling the optimization of patrols and saving fuel consumption of up to 30%. **Conclusion:** This research contributes to the transformation of Indonesia's maritime security paradigm from a reactive approach to a predictive-preventive one, supporting the enforcement of economic sovereignty in Indonesia's Exclusive Economic Zone (EEZ), and providing high-tech solutions to address non-traditional security challenges in the contemporary era. This model can be adapted as a best practice for other island countries facing similar maritime threats, while also reinforcing collective maritime security mechanisms within the framework of regional and global cooperation. **Novelty/Originality of this article:** The preventive defense framework specifically developed for the conditions of the Natuna Sea adopts a proactive approach that takes into account the unique geographical characteristics, regional maritime traffic patterns, and the geopolitical dynamics of the area.

KEYWORDS: artificial intelligence; maritime security; Natuna sea.

1. Introduction

Indonesia, as the world's largest archipelagic nation with a maritime area reaching 5.8 million square kilometers (Fardah, 2015), faces highly complex maritime security challenges. This is particularly true in the strategic Natuna Sea, which holds immense geopolitical significance as a direct border area with the South China Sea. The Natuna Sea's

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position at the crossroads of regional geopolitical interests makes it an arena for territorial claim contests between Indonesia and several regional countries, while also serving as a buffer zone against China's increasingly aggressive expansion of its nine-dash line claim. As part of Indonesia's Exclusive Economic Zone (EEZ), the Natuna Sea not only boasts rich fishery resources and abundant energy reserves, with potential natural gas reserves reaching 222 trillion cubic feet, but also functions as a vital international trade route connecting East Asia with the Middle East and Europe. This strategic geographical position, while offering significant economic benefits, also renders the region highly vulnerable to various maritime security threats. These threats are exacerbated by regional geopolitical dynamics, particularly illegal fishing and piracy, which have become chronic problems with massive economic, ecological, and geopolitical impacts (Phayal et al., 2024)

The economic and ecological consequences of illegal fishing and maritime piracy in the North Natuna Sea present a multidimensional crisis that threatens the sustainability of Indonesia's maritime sector. From an economic perspective, illegal fishing activities result in estimated national losses of USD 25 billion annually, a staggering figure that underscores how weak surveillance in vast waters like the Natuna Sea directly contributes to these losses (KKP, 2025; Sari, 2023). The Natuna Sea, despite its rich fishery resources, remains vulnerable due to the lack of permanent monitoring, making it a prime target for foreign vessels engaged in illegal fishing. Although the government, through the Ministry of Marine Affairs and Fisheries/*Kementerian Kelautan dan Perikanan* (KKP), has implemented repressive measures—such as seizing 112 illegal vessels in the first half of 2024, six of which were captured in the North Natuna Sea—these actions have failed to address the ongoing and cumulative damage (Angela, 2024).

Beyond economic losses, the ecological impact of illegal fishing poses long-term threats to Indonesia's marine biodiversity. Destructive practices like trawling and blast fishing not only drastically reduce fish populations but also devastate coral reef ecosystems and seabed habitats, which regenerate slowly and are vulnerable to permanent damage (Dulvy et al., 2024). If this destruction continues, it will not only cripple the fisheries sector but also harm coastal communities that depend on marine resources, exacerbating socioeconomic instability and deepening structural poverty in these regions.

Meanwhile, piracy as a non-traditional threat further worsens Indonesia's maritime security situation. Regionally, piracy in Southeast Asia has seen a significant rise, with 18 incidents recorded in Indonesian waters in 2023, up from 10 the previous year (ICC Commercial Crime Services, 2024). Recent research suggests that reducing illegal fishing without economic empowerment for coastal communities may inadvertently shift criminal activity from illegal fishing to piracy, which is perceived as more lucrative in times of economic uncertainty (Phayal et al., 2024). This demonstrates that solutions to maritime crime cannot be sectoral but must instead be integrated into inclusive and sustainable coastal development strategies.

The economic repercussions of piracy extend far beyond direct losses from ship robberies or hijackings. They also include wide-ranging domino effects, such as, Increased maritime insurance costs, disruptions to logistics and energy supply chains, and declining investor confidence in Indonesia's maritime sector stability (Pratson, 2023). These challenges are compounded by legal ambiguities in the South China Sea, which create jurisdictional gray zones where maritime criminals exploit gaps in international law to evade enforcement (Rogiers, 2024). A clear example of this vulnerability is dark fishing, vessels operating without activating their Automatic Identification System (AIS)—identified by Global Fishing Watch in at least 15 foreign vessels near the Natuna Sea. The absence of a predictive system capable of mapping cross-border crime hotspots further weakens Indonesia's reactive and fragmented maritime security framework.

The conventional maritime surveillance system currently operated by various Indonesian security institutions, including the Maritime Security Agency (*Badan Keamanan Laut Republik Indonesia/Bakamla*), the Indonesian Navy (*Tentara Nasional Indonesia/TNI AL*), and the Ministry of Marine Affairs and Fisheries (KKP), still relies on traditional

approaches. These include physical patrols using ships and aircraft, and land-based radar systems with limited coverage (Afriansyah et al., 2024). The limitations of conventional radar systems lie in their limited detection range, typically only able to detect vessels within a 20-50 nautical mile radius from the coast. Meanwhile, illegal fishing and piracy activities often occur in deep waters beyond radar reach. Conventional ship patrols face significant operational constraints: limited operating time due to refueling and maintenance needs, restricted maneuverability in bad weather, and very high operational costs reaching USD 10,000-15,000 per day per patrol vessel. This conventional approach is also reactive, only able to respond to threats after they occur, and lacks predictive analytics capabilities to anticipate the patterns and locations of potential illegal activities. Consequently, the conventional system leaves many blind spots in maritime surveillance, exploited by illegal fishing and piracy operators. It suffers from low detection effectiveness and slow response times, often being too late to prevent damage that has already occurred.

The rapid development of Artificial Intelligence (AI) and machine learning technologies in the last decade has opened revolutionary opportunities to transform maritime security approaches through real-time large-scale data processing capabilities. AI technology can integrate and analyze multiple data sources simultaneously. These sources include optical and radar satellite data, Automatic Identification System (AIS) signals, coastal radar systems, Internet of Things (IoT) sensors installed on various maritime platforms, as well as weather and oceanographic data (Zhao et al., 2025). Deep learning-powered computer vision can analyze high-resolution satellite imagery to identify suspicious vessels that have switched off their AIS or are performing abnormal maneuvers (Li et al., 2024). Meanwhile, predictive analytics algorithms can process historical patterns to forecast areas and times with a high probability of illegal fishing or piracy occurring (Watson et al., 2023). This capability is becoming increasingly crucial, as data from the International Maritime Bureau reports a drastic rise in crew affected by piracy and armed robbery – from 41 people in 2022 to 73 in 2023, reaching 126 in 2024. This escalation of violence in maritime crime demands more sophisticated early detection systems (International Chamber of Commerce, 2024).

Although previous research has explored the application of AI technology in the maritime security domain, most has focused on limited applications like ship detection from satellite imagery or separate AIS pattern analysis. None have developed a comprehensive model specifically designed to simultaneously detect multiple threats within the unique geographical and operational context of Indonesian waters. Previous studies also generally used datasets from waters with different characteristics, such as the Mediterranean Sea or North Atlantic waters, which have vastly different weather patterns, maritime traffic density, and oceanographic characteristics compared to Indonesia's tropical waters. This research gap creates an urgent need to develop an AI model specifically tailored to the operational and environmental characteristics of the Natuna Sea. This urgency is heightened by recent estimates suggesting that up to 40% of all seafood products are caught illegally each year, directly contributing to food insecurity in communities across Indonesia due to rapidly declining fish populations.

The escalating complexity of maritime security threats in the contemporary era, driven by intensifying maritime economic activities, shifting global trade patterns, and increasingly volatile regional geopolitical dynamics, demands innovative solutions capable of anticipating and responding to threats proactively rather than reactively. Developing an AI-enhanced maritime threat detection model capable of providing a high-accuracy and high-precision early warning system is a strategic imperative for safeguarding Indonesia's maritime sovereignty and protecting national economic interests. The predictive model developed in this research is expected to be operationally implemented by Indonesian maritime security institutions to enhance situational awareness, accelerate the decision-making process, and optimize the allocation of limited surveillance resources.

The significance of this research extends beyond the context of Indonesian maritime security, holding broader implications for regional and global security cooperation frameworks. The successful development and implementation of this model could become

a best practice adaptable by other archipelagic nations facing similar challenges. It could also contribute to strengthening collective maritime security mechanisms within the ASEAN Maritime Security and Indo-Pacific Strategy cooperation frameworks. Furthermore, this model could support the implementation of various international initiatives combating transnational maritime crimes, including the UN Convention on the Law of the Sea (UNCLOS) and the Regional Cooperation Agreement on Combating Piracy and Armed Robbery against Ships in Asia (ReCAAP). This would provide a significant contribution to regional and global maritime security stability.

2. Methods

The research method employed in this study is a qualitative approach, with data collection conducted through documentation study. The qualitative approach was selected because of its capacity to reveal and deeply understand complex social, political, and security dynamics, particularly within the context of non-traditional maritime threats in the North Natuna Sea. This research does not aim to quantify phenomena, but rather to explore the patterns, meanings, and strategies used in efforts to develop an artificial intelligence-based early detection system for illegal fishing and sea piracy activities.

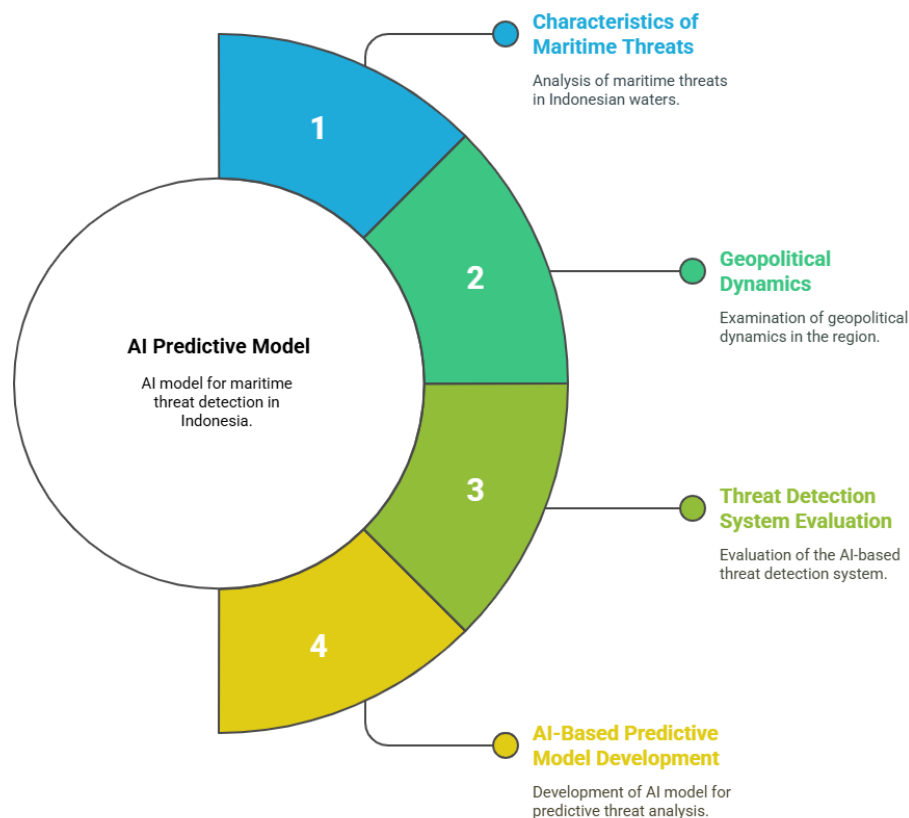


Fig. 1. Brainstorming

3. Results and Discussion

3.1 Characteristics of maritime threats in the Natuna Sea

The North Natuna Sea is one of Indonesia's strategic waters facing high-intensity, persistent, and multidimensional maritime threat complexities. This area is located in the northern part of the Natuna Islands and directly borders China's unilateral claim via the

"ten-dash line," which encompasses nearly the entire South China Sea. Consequently, it creates a zone of overlapping regional geopolitical interests involving Indonesia, Malaysia, Vietnam, and China (Liu & Scott, 2024). Paradoxically, the North Natuna Sea's geographical characteristics – rich in marine resources including abundant fishery potential and hydrocarbon reserves – create an attraction that triggers various threats to Indonesia's sovereignty and maritime security. The most evident manifestation is illegal fishing activities that have persisted for decades (Putra, 2024).

3.1.1 Patterns of IUU fishing activities

One of the most significant challenges to maritime security and fisheries resource sustainability in the North Natuna Sea is Illegal, Unreported, and Unregulated Fishing (IUUF), with a primary focus on illegal fishing activities that consistently dominate the problem (Khan et al., 2024). According to Automatic Identification System (AIS) data analyzed by the Indonesia Ocean Justice Initiative (IOJI) in February 2022, at least 12 Vietnamese-flagged fishing vessels and 8 Chinese-flagged fishing vessels were suspected of conducting illegal fishing activities in Fisheries Management Area/*Wilayah Pengelolaan Perikanan* (WPP) 711, which includes the North Natuna Sea region. These activities continued and peaked in May 2022, when satellite detection showed the presence of 60 Vietnamese fishing vessels within Indonesia's undisputed Exclusive Economic Zone (EEZ) (Putra, 2024).

Spatially, these Vietnamese vessels most frequently operated between coordinates 106.2° E to 109.1° E and 5.3° N to 6.2° N, all within Indonesia's Exclusive Economic Zone (EEZ) that is legally undisputed. IOJI observed a distinctive operational pattern: the vessels moved parallel in formations of two ships, spaced 300 to 400 meters apart. This indicates the use of pair trawls, a destructive fishing method banned in Indonesia (IOJI, 2025; Putra, 2024). These findings are not only based on technological observation but are also corroborated by testimonies from local fishermen in Natuna and Anambas who have long suspected the regular presence of Vietnamese vessels in these waters.

More alarmingly, this illegal fishing activity appears to be supported by escort actions by the official authorities of the perpetrators' home country. IOJI revealed that at least four Vietnam Fisheries Resources Surveillance (VFRS) vessels were suspected of providing direct escorts for these illegal activities. These vessels included Kiem Ngu 216 (KN216), KN220, KN268, and KN204, which were recorded actively operating near the Indonesia-Vietnam continental shelf boundary line, periodically entering the non-disputed zone up to 7 to 10 nautical miles beyond this boundary. This activity occurred from 2021 to mid-2022 and is strongly suspected to be part of a systematic strategy to protect Vietnamese fishing vessels violating Indonesia's EEZ boundaries.

A notable incident occurred on June 19, 2022, when Kiem Ngu 268 (KN268) was detected 500 meters from the foreign fishing vessel BV5119TS, which was operating illegally within Indonesia's EEZ. When the Indonesian Navy (*TNI AL*) attempted an interdiction using the warship KRI STS-376, KN268 allegedly shadowed the operation, indicating an intent to obstruct Indonesia's law enforcement process. This pattern was also reflected in various previous incidents, including during the 2019–2020 period, strengthening the suspicion that the presence of VFRS vessels is not merely passive but actively supports violations of Indonesia's economic sovereignty. This phenomenon not only threatens national marine resources but also indicates serious challenges in implementing maritime diplomacy and law enforcement at Indonesia's maritime borders.

In their study titled *Illegal fishing and fisheries crime as a transnational organized crime in Indonesia*, Chapsos & Hamilton identified several key factors driving the prevalence of illegal fishing practices in the North Natuna Sea waters. These factors stem not only from external dynamics, particularly related to fishery conditions in neighboring countries bordering Indonesia directly, but also reflect several internal issues in the governance of the national maritime territory. First, the main pressure comes from the

phenomenon of overfishing in neighboring countries like Vietnam and China, which has depleted fish stocks in their own waters (Giang & Khanal, 2024; Zhang et al., 2021). To maintain the productivity of their fishing industries and ensure the continuity of supply for domestic and export markets, vessels from these countries are driven to seek new fishing grounds still rich in resources. The North Natuna Sea, ecologically endowed with large reserves of pelagic and demersal fish, becomes a prime target due to its strategic position and high biological wealth.

Second, geographical aspects and the law of the sea also facilitate the entry of foreign vessels into this region. The vastness of Indonesia's Exclusive Economic Zone (EEZ) in the North Natuna Sea waters, combined with its location directly bordering the high seas, creates significant surveillance gaps (Afriansyah et al., 2024). This area, although legally under Indonesia's exclusive jurisdiction, remains vulnerable due to its openness to infiltration by foreign vessels, particularly at border points far from the reach of authorities. The third, structural factor is the overlapping EEZ claims between Indonesia and Vietnam. This unresolved maritime boundary dispute creates a grey area in international law exploited by Vietnamese vessels to claim legitimacy for their operations in the region (Raharja & Karim, 2024). This was affirmed by the Southeast Asia Director of the Ministry of Foreign Affairs, Denny Abdi, during the task force (*Satuan Tugas/Satgas*)115 Coordination Meeting on October 13, 2020, who stated that the conflict of claims is the main reason for the high frequency of violations by Vietnamese vessels in the North Natuna Sea.

Fourth, there are limitations in the national maritime surveillance infrastructure, both in terms of technology, the number of patrol fleets, and human resources. The extremely vast surveillance area is disproportionate to the capacity of available officers and patrol vessels. This directly impacts the effectiveness of control and response to threats of maritime law violations in Indonesia's outermost waters (Wuwung et al., 2024). Finally, an equally important factor is the minimal presence of national fishing vessels in parts of the Natuna Sea, creating a void in domestic fishing activity. The underutilization of marine space by Indonesian fishing vessels indirectly opens opportunities for foreign vessels to enter and conduct illegal fishing activities unhindered, as the area appears unguarded (Yang & Zou, 2024).

3.1.2 Trends and patterns of sea piracy

In recent years, Southeast Asian waters have experienced a resurgence of armed sea piracy and robbery incidents, marking the return of non-traditional security threats to strategic sea lanes (Galgano, 2024). Data compiled during the first half of 2022 recorded 36 sea piracy incidents in Southeast Asia, showing an increase compared to the same period in 2021 with 35 incidents. Although this increase appears quantitatively slight, the trend demonstrates a persistent threat that cannot be ignored, particularly within the context of rising geopolitical tensions and extremely dense maritime trade volumes in this region (Fan et al., 2023). The Singapore Strait region is identified as the primary hotspot with the highest concentration of attacks, largely encompassing Indonesian waters. This strait is a golden global trade route traversed by over 100,000 cargo ships annually, carrying commodities worth billions of US dollars. The traffic density and high economic value of this route make it highly vulnerable to maritime crime. However, the increase in incidents has also spread northwards, including to the North Natuna Sea region, which is part of Indonesia's Exclusive Economic Zone (EEZ) and a strategic border area directly adjacent to the South China Sea (Jin & Feng, 2024).

The situation in the North Natuna Sea is further complicated by jurisdictional conflicts involving China's unilateral claim through the nine-dash line, which overlaps with Indonesia's EEZ around the Natuna Islands. This claim, unrecognized under international law, creates a legal grey area resulting in a surveillance vacuum exploited by maritime criminals, including pirates and organized criminal groups. Diplomatic tensions between Indonesia and China have also reduced the effectiveness of naval patrols and regional security cooperation, further heightening security risks in this area. Piracy patterns in the

Natuna region exhibit distinct characteristics. Attacks are typically carried out by small, loosely organized groups using speedboats to approach target merchant vessels transiting at low speeds or at anchor (Fan et al., 2023). Modus operandi include theft of valuable goods, temporary ship hijackings, and intimidation of crew members. In some cases, perpetrators have been found to utilize basic maritime intelligence, such as AIS tracking and visual observation, to select targets, indicating an adaptation of technology in their operations. Attacks tend to occur at night or under low visibility conditions, where opportunities for surveillance and intervention by authorities are reduced.

Limitations within Indonesia's maritime surveillance system, particularly concerning real-time monitoring technology and a patrol fleet size disproportionate to the vast waters, are significant factors increasing vulnerability to piracy. Although the Indonesian Navy (*TNI AL*), Maritime Security Agency (*Bakamla*), and Ministry of Marine Affairs and Fisheries (*KKP*) have increased patrol frequency in vulnerable areas like the Natuna Sea, the scale and complexity of the region make conventional security strategies ineffective in countering threats (Afriansyah et al., 2024). Consequently, a new approach through the implementation of an Artificial Intelligence (AI)-based threat detection model has become an urgent necessity. This model is expected to recognize suspicious vessel movement patterns, detect dark shipping activities (vessels turning off AIS), and predict the likelihood of incidents based on variables such as vessel speed, trajectory patterns, and maritime traffic density.

3.2 Geopolitical dynamics and the grey zone area

The North Natuna Sea has become a focal point in the geopolitical dynamics of Southeast Asia, driven by China's maritime expansion claims in the South China Sea. China's unilateral assertion over maritime areas under its "ten-dash line" has sparked tensions with multiple nations, including Indonesia. Although Indonesia is not a claimant in the South China Sea dispute, much of its Exclusive Economic Zone (EEZ) in the North Natuna Sea falls within an area China unilaterally claims as part of its "traditional fishing ground" (Garcia & Bianco, 2025). This has placed Indonesia in a vulnerable position amid complex maritime conflicts, where state presence and the supremacy of international maritime law are tested by the aggressive tactics of a superpower (Larsson, 2024).

In recent years, China has intensified its vessel presence in the North Natuna Sea. This presence extends beyond fishing boats to include coast guard vessels (China Coast Guard/CCG), research ships, and even warships. Incidents such as CCG vessels cutting across the bows of Indonesian fishing boats within Indonesia's EEZ—as occurred in September 2022—reveal a systematic pattern of coercive and disruptive actions. Furthermore, coast guard escorts for Chinese fishing fleets, widely documented in sources, signal gray-zone operations (Putra, 2023). Gray-zone operations refer to non-military, coercive strategies deployed during peacetime to achieve political objectives without triggering open confrontation or direct military intervention (Larsson, 2024).

China's gray-zone operations in the North Natuna Sea are characterized by deploying civilian vessels (fishing boats) escorted by coast guard ships, with warships serving only as strategic reserves. This strategy creates legal ambiguity and complicates decisive law enforcement, as involved actors are not always military personnel (Erickson, 2024). Behind this approach lies institutional backing from Chinese domestic policies, such as the Coast Guard Law enacted in February 2021. This law grants the CCG full authority to take coercive actions—including the use of force—against foreign vessels deemed to violate China's sovereignty.

China's increased activity is also evident from the deployment of research vessels such as the Haiyang Dizhi 10, which operated for months in the North Natuna Sea, and the presence of the destroyer Kunming-172, demonstrating the military dimension of these claims (Natalia, 2021). Furthermore, China is actively reclaiming maritime features in the South China Sea, such as Fiery Cross Reef and Gaven Reefs, which are now equipped with comprehensive military facilities (Putra, 2023). These steps demonstrate the consistency of

China's strategy in consolidating de facto control over disputed areas, despite being in contravention of international law of the sea, including the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which both China and Indonesia have ratified.

For Indonesia, responding to these dynamics requires a dual approach: diplomacy and active presence. The Indonesian government has firmly stated that the ten-dash line has no basis in international law and cannot serve as the basis for claims over Indonesia's EEZ (Soeparna & Taofiqurohman, 2024; Yang & Zou, 2024). However, this legal position must be balanced with concrete actions on the ground. The routine presence of state vessels such as those of the Indonesian Navy (*TNI-AL*), the Maritime Security Agency (*Bakamla*), and the Ministry of Marine Affairs and Fisheries (*KKP*) in the North Natuna Sea region serves as a vital instrument for asserting Indonesia's sovereignty and sovereign rights (Afriansyah et al., 2024). Additionally, strengthening the presence of local fishermen in these waters is also an important strategy, symbolizing citizen involvement in defending national sovereign economic rights.

Thus, the geopolitical dynamics and gray-zone operations in the North Natuna Sea impact not only defense and diplomatic aspects but also necessitate an update to Indonesia's maritime security strategy. Developing an artificial intelligence-based early detection system capable of identifying patterns of gray-zone activities – such as the escort of fishing vessels by the China Coast Guard (CCG) or the movement of non-commercial research vessels – would be important for enhancing situational awareness and enabling responsive strategic decision-making.

3.3 Threat detection system evaluation

The Indonesian government has implemented various maritime threat detection instruments in the North Natuna Sea by combining sensor-based surveillance technology, interagency joint patrol operations, and defense infrastructure development (Sudirman & Rachmat Nugraha, 2024). However, the existing system still faces fundamental operational effectiveness challenges, particularly in addressing increasingly complex threat dynamics such as illegal, unreported, and unregulated fishing (IUUF) and gray-zone operation infiltrations by foreign states.

A core component of the current detection system is the use of Automatic Identification System (AIS) technology and high-resolution satellite imagery, operated by agencies like the Indonesian Maritime Security Agency (*Bakamla*) and the Indonesia Ocean Justice Initiative (IOJI). AIS enables real-time vessel tracking, while satellite imagery (e.g., from Sentinel-1 and VIIRS) detects "dark vessels" that deliberately disable AIS signals (Jung et al., 2024). IOJI's 2024 analysis revealed Vietnamese vessels deactivating AIS within Indonesia's Exclusive Economic Zone (EEZ), with satellite-detected ships frequently exceeding AIS data—indicating active monitoring evasion tactics.

Furthermore, coordinated maritime patrols are routinely conducted by the Indonesian Navy (*TNI-AL*), *Bakamla*, the Ministry of Marine Affairs and Fisheries (*KKP*), and the Indonesian National Police (*Polri*). These operations include surveillance ships, maritime reconnaissance aircraft, and combat deployments like Navy Vessels/*Kapal Republik Indonesia (KRI)*. In 2024, for example, *Bakamla* deployed KN Tanjung Datu-301 and KN Pulau Dana-323 to repel China Coast Guard (CCG) vessels disrupting Pertamina's seismic survey operations. Nevertheless, these patrols remain reactive rather than predictive, lacking spatiotemporal analysis of historical threat trends, thus limiting early prevention efficacy (Do Nascimento et al., 2024).

Defense systems have also been enhanced through military infrastructure development in Natuna, including coastal radar operations (Satrad 212), strengthening of the Integrated *TNI* Unit, and optimization of Raden Sadjad Air Base and Selat Lampa Port. The Kogabwilhan I Joint Defense Command has developed an Integrated Fleet Weapon System (SSAT), integrating radar, satellite, and aerial patrol data into a unified monitoring platform (Mawangi, 2025). However, this system lacks full AI-driven data fusion capabilities to filter redundant data and generate precise early warnings (Rim, 2024; Zhao et al., 2025).

Key challenges in the current threat detection system include logistical constraints and budget limitations. The vast North Natuna Sea (≈ 1.3 million km^2) disproportionately exceeds active patrol fleet capacity, leaving high-risk zones unmonitored. Foreign vessels (e.g., from Vietnam and China) also deploy modern fishing technology and advanced sensing capabilities—including mothership-supported IUUF operations accelerating illegal catch evacuation. Interagency coordination (*TNI-AL*, *Bakamla*, *KKP*) is further hampered by the absence of a unified legal framework, causing jurisdictional overlaps and operational interoperability weaknesses.

The government has initiated policy measures to address these gaps. Through Presidential Regulation No. 34/2022 on Ocean Policy Action Plans, it promotes detection system modernization and drafts a Maritime Security Bill to unify maritime command. Indonesia also collaborates with the US and Australia to enhance Maritime Domain Awareness (MDA) via technology transfer, data fusion training, and cross-border monitoring integration. A critical assessment of Indonesia's current maritime threat detection system is its reactive nature and absence of predictive analytics to anticipate threats using historical trend and spatial pattern analysis. For instance, in an October 2024 incident, CCG vessels entered Indonesia's EEZ despite prior satellite detection—exposing a detection-to-response gap. Thus, transforming surveillance into a proactive model is imperative, integrating AI to accelerate detection, prioritize high-risk patrol zones, and strengthen data-driven security operations (Li et al., 2025). Without substantial investment in predictive technology and institutional reform, safeguarding sovereignty and security in the North Natuna Sea will remain fragile and vulnerable to exploitation by state and non-state actors.

3.4 Development of AI-based predictive model

To address escalating non-traditional threats in the North Natuna Sea, conventional approaches to safeguarding Indonesia's maritime security face increasingly evident limitations. The reactive surveillance systems currently employed—such as AIS monitoring and physical patrols by the Indonesian Maritime Security Agency (*Bakamla*) and Indonesian Navy (*TNI AL*)—demonstrate restricted effectiveness against rapidly evolving complex threat dynamics (Sunko et al., 2024). As Illegal, Unreported, and Unregulated (IUU) fishing and potential piracy intensify, the urgency for adopting predictive and preventive maritime security approaches becomes unavoidable (Do Nascimento et al., 2024).

The development of an artificial intelligence (AI)-based predictive model emerges as a transformative solution addressing current maritime threat detection deficiencies (Feng et al., 2024). Utilizing predictive analytics, this model not only processes existing data but also analyzes historical patterns and real-time indicators to anticipate potential threats before they materialize. For the North Natuna Sea—a strategic border zone between Indonesia and the South China Sea—this predictive capability is crucial for preventing sovereignty violations that could trigger diplomatic escalation or open confrontation.

Technically, this predictive system is designed with three main layers: data integration, predictive analytics, and operational response. In the first layer, data is collected from multiple sources including Sentinel-1 and VIIRS satellites, AIS signals, patrol logs from the Indonesian Maritime Security Agency (*Bakamla*) and Indonesian Navy (*TNI AL*), ocean current data from the Copernicus Marine Environment Monitoring Service (CMEMS), weather data from the Indonesian Meteorology, Climatology and Geophysics Agency (*Badan Meteorologi, Klimatologi, dan Geofisika/BMKG*), and reports from fishing communities via mobile-based maritime reporting applications. This data collection and processing is enhanced by edge computing technology, enabling rapid analysis aboard patrol vessels, and blockchain systems to verify the authenticity of civilian-reported data (Han et al., 2025).

The second layer, the analytical layer, constitutes the core of the predictive AI system. Here, the Long Short-Term Memory (LSTM) algorithm identifies temporal patterns in vessel movements, such as increased concentrations of Vietnamese vessels during the west monsoon or high-wave conditions that impede Indonesian patrols (Dong et al., 2024).

Simultaneously, the Random Forest algorithm classifies threats based on complex parameters including vessel speed, sudden course changes, sea surface temperature, and proximity to Exclusive Economic Zone (EEZ) boundaries (Fang et al., 2024). The integration of these algorithms enables the system to generate automated alerts—for example, when anomalies like AIS deactivation in high-risk zones or civilian reports of foreign vessel activity occur. The system then issues notifications with accurate threat probability assessments, such as illegal fishing probability 92%.

The third layer is the response layer, which translates analytical outputs into concrete actions. The system generates dynamically updated maritime threat heatmaps at 15-minute intervals, highlighting priority areas for patrols or drone surveillance. These maps are automatically transmitted via satellite networks to the nearest patrol units, complete with coordinates and action recommendations. In critical situations, the system can directly activate command protocols—deploying intelligence drones for visual confirmation, redirecting Fast Missile Boats (*KCR/Kapal Cepat Rudal*) to target areas, and issuing warnings to fishermen to avoid high-risk zones.

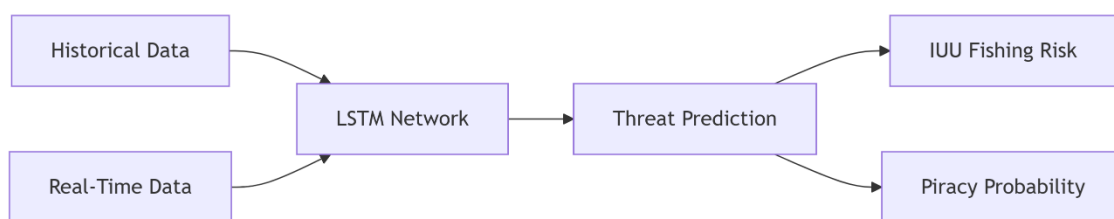


Fig. 2. Development of AI-based predictive workflow

In terms of effectiveness, the benefits of this system are highly tangible. According to simulations conducted by the Indonesian Maritime Security Agency (*Bakamla*), the detection rate of foreign vessels significantly increased from 40% to 85% following the integration of the predictive system (Zhao et al., 2025). Response time was also reduced from 8 hours to just 45 minutes, enabling swift intervention before violations occur. Operationally, efficiency improved substantially with patrol vessel fuel consumption decreasing by an estimated 30%, as patrols are now focused exclusively on high-risk zones rather than conducting random sweeps (Aguilar et al., 2025). Strategically, this predictive model strengthens Indonesia's national interests by enhancing its regional diplomatic position. AI-generated evidence serves as a foundation for formal diplomatic notes to other nations—such as China or Vietnam—when violations by their vessels occur (Nielsen et al., 2024). This approach reinforces Indonesia's position in defending its sovereign rights under UNCLOS 1982, providing irrefutable data-driven proof of infringements.

Based on Figure 3, it is concluded that data integration serves as the foundational bedrock for developing an effective predictive model. Data integration constitutes a crucial process that consolidates information from diverse sources to create a comprehensive database. Automatic Identification System (AIS) data provides real-time insights into vessel movements, identities, and navigation routes, enabling analysis to identify normal operational patterns and anomalies. Meanwhile, satellite imagery offers broad-area coverage and continuous monitoring of maritime activities in the Natuna Sea, including detection of vessels with deactivated AIS systems or those conducting suspicious operations within Indonesia's Exclusive Economic Zone.

Predictive algorithms form the core of the AI-based maritime security system, designed to analyze integrated data and generate accurate threat predictions. Anomaly detection algorithms identify deviations from standard operational norms, such as vessels operating in restricted zones, abrupt course changes, or illegal fishing activities. Pattern identification systems examine historical trends and recurring maritime activity patterns to characterize potential threats. Predictive algorithms subsequently process this information to forecast security incidents at specific locations and times, enabling maritime authorities to implement precisely targeted preventive measures.

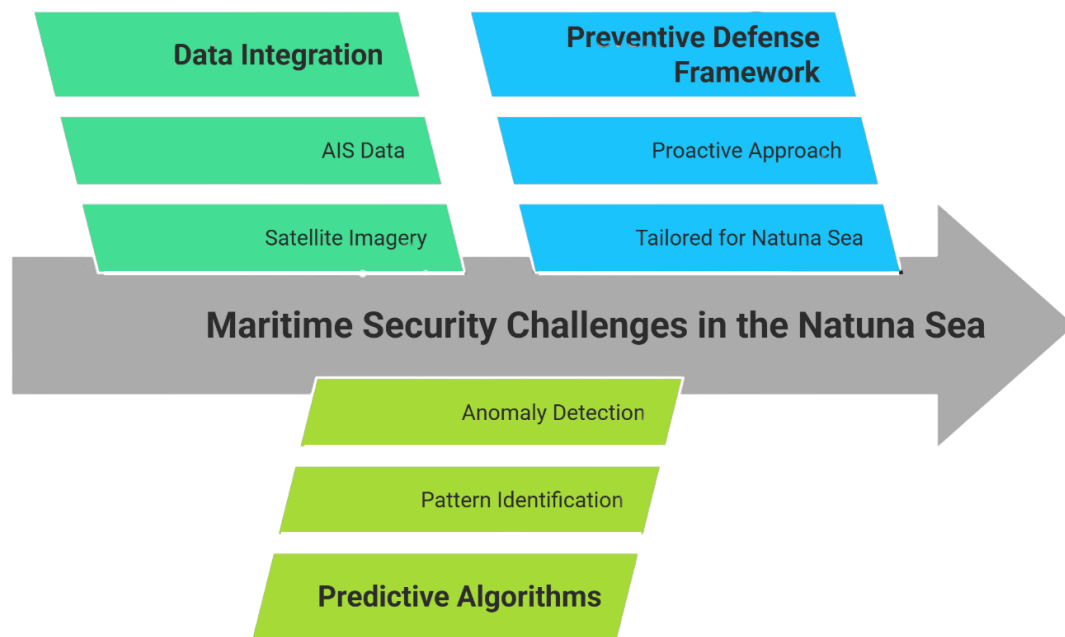


Fig. 3. Integrated framework for predictive maritime security in the Natuna Sea

The preventive defense framework formulated specifically for the North Natuna Sea represents a paradigm shift in Indonesia's maritime security strategy by emphasizing preemptive threat mitigation over reactive responses. Unlike conventional models that respond only after a violation or incident occurs, this framework is rooted in predictive analytics and AI-assisted decision-making to anticipate potential threats before they escalate into tangible breaches of sovereignty. By leveraging data-driven algorithms, the system allows for the strategic deployment of surveillance assets, ensuring that patrols and maritime enforcement efforts are concentrated in high-risk zones identified through real-time and historical pattern analysis.

This proactive approach not only enhances operational efficiency but also significantly improves response times, enabling maritime forces such as *Bakamla* and the Indonesian Navy to intercept and deter suspicious activities before they materialize into illegal fishing, piracy, or unauthorized incursions. Crucially, the framework is calibrated to account for the North Natuna Sea's distinctive features—its vast expanse, proximity to contested areas in the South China Sea, seasonal monsoon-driven current shifts, and the increasingly assertive presence of foreign actors operating under legal grey zones.

Nevertheless, system development faces significant challenges. Limited real-time data availability, bureaucratic resistance to technological adoption, and isolated legacy systems across institutions constitute primary obstacles. Addressing these requires data collaboration between the Indonesian Maritime Security Agency (*Bakamla*), Navy (*TNI AL*), National Institute of Aeronautics and Space (*LAPAN*), Geospatial Information Agency (*BIG*), Meteorological Agency (*BMKG*), and other entities through a national data fusion framework. Field operator AI literacy training is equally essential for optimal system utilization (Evans et al., 2024). Additionally, implementing standardized API gateways is prerequisite for ensuring cross-system interoperability.

Nigeria's experience in the Gulf of Guinea offers a relevant case study. Over the past two years, the country achieved a 60% reduction in piracy by adopting an AI platform integrating satellite data, local intelligence reports, and maritime surveillance (Balogun, 2024). Indonesia can adapt lessons from this approach, while accounting for tropical maritime characteristics, distinct geopolitical configurations, and local socioeconomic dynamics of Indonesian fishers.

With a development budget of IDR 1.2 trillion—representing merely 15% of annual conventional patrol expenditures—the Indonesian government possesses a substantial

opportunity to establish a high-tech, long-term maritime defense system. This AI system will not only enhance situational awareness but also comprehensively strengthen national resilience through preventive, measurable, and adaptive approaches responsive to evolving challenges.

4. Conclusions

This study confirms the urgency of transforming Indonesia's maritime security paradigm from a conventional, reactive approach to a predictive-preventive system based on artificial intelligence, in response to the escalation of non-traditional threats in the North Natuna Sea. A comprehensive analysis of the characteristics of maritime threats reveals that illegal fishing and maritime piracy have evolved into transnational, structured, and systematic phenomena, with economic losses reaching USD 25 billion annually on a national scale. Additionally, piracy incidents have increased from 10 cases in 2022 to 18 in 2023. The complexity of these threats is further exacerbated by regional geopolitical dynamics that create legal grey zones through non-military coercive operations—particularly the escorting of Vietnamese vessels by the Vietnam Fisheries Resources Surveillance (VFRS) and the unilateral expansion of China's maritime claims via the ten-dash line, which undermines Indonesia's economic sovereignty in the Natuna Sea's Exclusive Economic Zone (EEZ).

An evaluation of the conventional threat detection systems currently operated by Bakamla, the Indonesian Navy (*TNI AL*), and the Ministry of Marine Affairs and Fisheries (*KKP*) reveals fundamental limitations in surveillance coverage, response time, and predictive capability. The physical patrol and AIS-based monitoring systems exhibit low detection effectiveness (40%) and slow response times (8 hours). Moreover, the vast expanse of the North Natuna Sea (1.3 million km²) is disproportionate to the number of available patrol assets. These limitations create blind spots exploited by maritime criminals to conduct illegal activities, particularly through tactics such as dark fishing—disabling AIS signals and operating under the protection of foreign coast guard vessels. This condition underscores the inadequacy of traditional approaches in addressing the increasingly sophisticated and coordinated nature of contemporary maritime threats.

The development of an AI-based predictive model proposed in this study offers a transformational solution through the integration of three technological layers: A data integration layer combining Sentinel-1 and VIIRS satellite data, AIS signals, and oceanographic data; a predictive analytics layer utilizing Long Short-Term Memory (LSTM) and Random Forest algorithms; and an operational response layer producing real-time threat heatmaps. System simulations demonstrate significant improvements in operational effectiveness, with detection rates increasing from 40% to 85%, response times reduced from 8 hours to 45 minutes, and fuel consumption savings of up to 30% through risk-based patrol optimization. The system's ability to generate automatic alerts with high threat probability accuracy (up to 92%) enables Indonesian maritime authorities to implement precisely targeted preventive measures before violations occur.

The implementation of a preventive defense framework tailored to the unique characteristics of the North Natuna Sea marks a new paradigm in Indonesia's maritime security strategy—one that is not only reactive to actual threats but also proactive in anticipating potential sovereignty violations. This system makes a strategic contribution to strengthening Indonesia's diplomatic position by providing data-based evidence that can be utilized in delivering diplomatic notes to countries whose vessels commit violations. Thus, this AI-based predictive model serves not only as a technical instrument but also as a diplomatic tool that reinforces Indonesia's legitimacy in defending its sovereign rights under the 1982 UNCLOS and the principles of international maritime law.

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Author Contribution

The author conducted the conceptualization, methodology, data collection, analysis, interpretation, visualization, and manuscript preparation for this study.

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During the preparation of this work, the authors used Grammarly to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication

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