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Integrating Oceanographic Variability and Small-Scale Fishers' Local Ecological Knowledge for Sustainable Fishing Ground Management in Eastern Indonesian Waters

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Abstract

This study analyzes the integration of oceanographic variability and small-scale fishers' local ecological knowledge (LEK) for sustainable fishing ground management in Eastern Indonesian waters. The region is characterized by strong seasonal dynamics driven by monsoonal systems, sea surface temperature fluctuations, and productivity shifts that influence fish distribution patterns. These environmental conditions create highly dynamic fishing grounds that are difficult to predict using conventional scientific models alone. A systematic synthesis of interdisciplinary literature was conducted, focusing on fisheries oceanography, LEK, and adaptive management frameworks. The analysis shows that oceanographic variables such as chlorophyll-a concentration, sea surface temperature, and ocean currents strongly determine the spatial distribution of pelagic fish stocks. However, fishers' LEK provides complementary fine-scale information based on long-term ecological observation, including environmental cues such as water color, wind patterns, bird activity, and lunar cycles. Oceanographic data provides macro-scale predictive capacity, while LEK offers micro-scale contextual accuracy. Their integration improves fishing ground identification, enhances decision-making, and reduces uncertainty in data-limited fisheries. The study concludes that hybrid knowledge systems are essential for strengthening sustainable fisheries governance in Eastern Indonesia. Integrating scientific oceanographic analysis with LEK supports adaptive management, improves ecological resilience, and enhances livelihood sustainability in small-scale fisheries.

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Introduction

Eastern Indonesian waters represent one of the most complex marine socio-ecological systems in the world. The region is characterized by high oceanographic variability driven by monsoonal circulation, sea surface temperature fluctuations, and nutrient dynamics that influence fish distribution patterns (Apriansyah et al., 2024; Hendiarti, 2016). These conditions create highly dynamic fishing grounds that shift spatially and temporally, posing significant challenges for small-scale fisheries that depend on daily

environmental predictability. In such environments, fishers rely not only on formal scientific information but also on accumulated experiential knowledge developed through long-term interaction with marine ecosystems.

Local ecological knowledge (LEK) and traditional ecological knowledge (TEK) have been increasingly recognized as essential components in fisheries science and management. These knowledge systems provide detailed observations on species behavior, seasonal migration, and environmental indicators that are often absent from conventional scientific datasets (Collins, 2013; Lima et al., 2017). Studies have demonstrated that fishers can identify subtle ecological changes such as shifts in fish abundance, changes in water color, and variations in current patterns that correlate with oceanographic variability (Bevilacqua et al., 2016; Ramenzoni, 2015). However, despite its empirical value, LEK remains underutilized in formal fisheries governance structures.

The integration of scientific oceanographic data and LEK is increasingly viewed as a necessary approach for sustainable fisheries management. Johannes et al. (2000) emphasized that ignoring fishers' knowledge leads to significant gaps in understanding marine ecosystems. Similarly, Silvano et al. (2022) argued that multidimensional knowledge systems strengthen ecological assessments and improve management outcomes. In Eastern Indonesia, where data scarcity is a persistent issue, integrating both knowledge systems is particularly relevant for improving fishing ground prediction and resource sustainability (Alati et al., 2025).

Oceanographic variability plays a central role in shaping fish distribution. Parameters such as sea surface temperature, chlorophyll-a concentration, and thermocline depth influence primary productivity and fish aggregation behavior (Makhtar & Qatrunnada, 2025). Remote sensing studies further confirm that seasonal variability determines the availability of pelagic fish stocks in Indonesian waters (Hendiarti, 2016). However, scientific models often operate at coarse spatial and temporal scales, limiting their ability to capture localized ecological dynamics experienced by small-scale fishers.

In contrast, fishers' LEK provides high-resolution contextual information based on direct observation and repeated interaction with marine environments. Fishers recognize fishing ground shifts based on bird activity, water clarity, lunar cycles, and wind patterns (Ramenzoni, 2015). This knowledge is adaptive and evolves in response to environmental change, making it a valuable complement to scientific data. Studies by Pinheiro Lima et al. (2017) show that LEK can accurately describe spatial and temporal fish distribution patterns, particularly in regions with limited scientific monitoring.

The importance of integrating LEK into fisheries management has been widely documented. Stephenson et al. (2016) demonstrated that participatory approaches improve decision-making quality and enhance compliance with management regulations. Similarly, Garibay-Toussaint et al. (2024) highlighted that combining scientific and local knowledge increases ecosystem resilience under climate variability. In small-scale fisheries, this integration supports adaptive management by incorporating both empirical measurements and lived experiences (Indriana et al., 2023).

Despite its benefits, institutional barriers remain significant. Fisheries governance systems often prioritize quantitative scientific data while marginalizing qualitative local knowledge (Collins, 2013). This creates a disconnect between policy design and on-the-ground fishing practices. In Eastern Indonesian waters, this gap is further amplified by geographic dispersion, limited monitoring infrastructure, and socio-economic dependence on fisheries.

The novelty of this study lies in its integrative analytical framework that combines oceanographic variability with LEK to develop a more comprehensive understanding of fishing ground dynamics. Unlike previous studies that treat scientific and local knowledge separately, this research synthesizes both systems to identify convergence points that enhance predictive accuracy and management relevance. The approach aligns with adaptive fisheries management principles that emphasize flexibility, inclusivity, and ecological responsiveness (Kaya & Sajriawati, 2023; Narwadan et al., 2024).

This study aims to address three main issues: first, the extent to which oceanographic variability determines fishing ground dynamics in Eastern Indonesian waters; second, how LEK complements scientific data in identifying fishing zones; and third, how integrated knowledge systems can improve sustainable fisheries governance. By addressing these questions, the study contributes to the development of a hybrid knowledge framework that supports ecological sustainability and socio-economic resilience in small-scale fisheries systems.

Methodology

This study employed a qualitative-analytical approach based on a systematic literature synthesis integrated with a framework combining Local Ecological Knowledge (LEK) and oceanographic variability. This approach was selected because the research object is inherently multidimensional, involving the interaction between marine environmental dynamics and the experiential knowledge of small-scale fishers in the waters of Eastern Indonesia. The method enables a robust conceptual synthesis for developing an integrative model of sustainable fishing ground management.

The initial stage involved identifying and selecting relevant scientific literature from reputable international and national journals addressing oceanographic variability, Local Ecological Knowledge (LEK), Traditional Ecological Knowledge (TEK), and small-scale fisheries management. The literature was purposively selected based on thematic relevance, methodological compatibility, and empirical contributions to sustainable fisheries management. The selected studies included fisheries oceanography research (Apriansyah et al., 2024; Hendiarti, 2016), LEK and TEK studies (Lima et al., 2017; Damayanti et al., 2025), and knowledge integration models (Garibay-Toussaint et al., 2024; Silvano et al., 2022).

Data extraction was conducted systematically by classifying the collected information into three primary categories. The first category consisted of oceanographic variables, including sea surface temperature, chlorophyll-a concentration, ocean currents, and primary productivity indicators associated with fish distribution (Makhtar & Qatrunnada, 2025). The second category comprised LEK indicators, including fishers' knowledge of fishing seasons, fish migration patterns, natural environmental cues, and traditional fishing calendars (Ramenzoni, 2015). The third category focused on community-based fisheries management approaches and adaptive fisheries policies (Kaya & Sajriawati, 2023; Narwadan et al., 2024).

The extracted data were subsequently analyzed using content analysis and comparative thematic analysis. Content analysis was applied to identify patterns linking oceanographic variables with fishers' perceptions of fishing ground dynamics. Comparative thematic analysis was employed to identify similarities, differences, and potential integration points between scientific findings and LEK. During this stage, each study was coded according to major themes, including ecosystem dynamics, seasonal changes, fish distribution, and fishing strategies.

To enhance analytical validity, this study adopted a conceptual triangulation approach. Triangulation was performed by comparing findings from empirical studies employing diverse methodologies, including remote sensing, ecosystem modeling, and fisheries ethnography. This approach ensured that the synthesized findings were supported not only by theoretical perspectives but also by empirical evidence relevant to practical fisheries management (Bevilacqua et al., 2016; Stephenson et al., 2016).

The next stage involved developing an integrative conceptual model. This model was constructed by linking oceanographic variables with LEK indicators within a unified analytical framework representing fishing ground dynamics. Oceanographic variables functioned as biophysical indicators determining fish resource availability, whereas LEK served as an experience-based observational system that strengthened local interpretations of environmental changes. Integrating these two knowledge systems produced an adaptive framework capable of improving fishing ground prediction accuracy, particularly in regions with limited scientific data.

Within the conceptual spatial analysis, this study also adopted principles of fisheries potential zone mapping derived from previous literature. Earlier studies demonstrated that oceanographic variability is directly associated with the spatial distribution of pelagic fish species (Hendiarti, 2016; Safruddin et al., 2019). These scientific findings were integrated with LEK descriptions of traditional fishing locations to identify consistent spatial patterns between scientific observations and local ecological knowledge.

Furthermore, the study incorporated an adaptive fisheries management approach emphasizing flexibility in fisheries resource governance. This perspective is based on the principle that fisheries systems must simultaneously adapt to environmental and social changes (Ramm, 1995; St. Martin et al., 2007). Within this framework, LEK was positioned not merely as complementary knowledge but as a central component of the fisheries decision-making process.

To maintain the quality of the synthesis, each selected publication was evaluated using three principal criteria: source credibility, thematic relevance, and contribution to knowledge integration. Studies that failed to satisfy these criteria were excluded from the final analysis. This evaluation process ensured that the resulting synthesis was supported by a rigorous academic foundation and met the standards expected for publication in reputable scientific journals.

The final stage consisted of developing a comprehensive conceptual framework illustrating the relationships among oceanographic variability, LEK, and sustainable fishing ground management. This framework was presented through both narrative and visual synthesis based on the reviewed literature. It was used to explain how integrating scientific knowledge with local ecological knowledge can enhance both ecological resilience and the socio-economic sustainability of small-scale fisheries in Eastern Indonesia (Silvano et al., 2022; Garibay-Toussaint et al., 2024).

This research methodology emphasizes interdisciplinary integration across fisheries oceanography, human ecology, and fisheries policy studies. The proposed approach provides a comprehensive analytical foundation for understanding the complexity of fishing ground dynamics while highlighting the importance of synergizing scientific knowledge and local ecological knowledge to support the sustainable management of fisheries resources in highly dynamic marine environments.

Results and Discussion

The synthesis of interdisciplinary studies shows a consistent relationship between oceanographic variability and small-scale fisheries dynamics in Eastern Indonesian waters. Sea surface temperature, chlorophyll-a concentration, current systems, and seasonal monsoon patterns strongly influence fish distribution and fishing ground formation (Apriansyah et al., 2024; Hendiarti, 2016; Makhtar & Qatrunnada, 2025). At the same time, local ecological knowledge (LEK) provides complementary fine-scale observations that are not captured by satellite or model-based systems (Lima et al., 2017; Silvano et al., 2022).

Oceanographic Variability and Fishing Ground Formation

Table 1. Key Oceanographic Drivers of Fishing Grounds

Parameter	Function	Impact on Fisheries
Sea surface temperature	Regulates habitat suitability	Controls fish migration
Chlorophyll-a	Indicator of productivity	Determines feeding zones
Ocean currents	Transport mechanism	Affects larval dispersal
Monsoon winds	Seasonal forcing	Shifts fishing grounds

The synthesis of interdisciplinary literature reveals a strong and consistent relationship between oceanographic variability and the spatial-temporal dynamics of small-scale fisheries in Eastern Indonesian waters. Across the reviewed studies, oceanographic parameters such as sea surface temperature, chlorophyll-a concentration, thermocline depth, and seasonal current patterns function as primary drivers of fish aggregation and migration behavior (Apriansyah et al., 2024; Hendiarti, 2016; Makhtar & Qatrunnada, 2025). These environmental factors determine the formation of productive fishing grounds that shift dynamically across seasons, especially under the influence of monsoonal cycles.

The findings indicate that Eastern Indonesian waters represent a highly dynamic marine ecosystem where fishing ground predictability is low when relying solely on conventional scientific datasets. Satellite-

based oceanographic models show strong capability in mapping broad-scale fishing zones, yet they often fail to capture micro-scale variability that directly influences small-scale fishers' operational decisions (Safruddin et al., 2019; Indrayani et al., 2025). This gap creates a significant mismatch between modeled fishing zones and real fishing practices at the community level.

Oceanographic Variability and Fishing Ground Dynamics

Oceanographic variability plays a structural role in shaping fish distribution patterns. Seasonal upwelling events, shifts in sea surface temperature, and nutrient availability directly influence primary productivity and the abundance of pelagic fish species. Studies in Indonesian waters demonstrate that lower sea surface temperatures and higher chlorophyll-a concentrations are strongly associated with increased fish aggregation, particularly for small pelagic and tuna species (Apriansyah et al., 2024). Similarly, Hendiarti (2016) confirms that interannual climate variability modifies fish abundance patterns through changes in ocean circulation and productivity.

Local Ecological Knowledge as a Complementary System

Local ecological knowledge (LEK) emerges as a critical complementary system that fills the interpretative gap left by scientific data. LEK provides fine-scale, experience-based observations that capture ecological variability at the community level. Fishers consistently identify patterns related to fish behavior, seasonal migration, and environmental cues such as water color, wind direction, bird activity, and lunar cycles (Ramenzoni, 2015; Lima et al., 2017).

Johannes et al. (2000) emphasize that exclusion of fishers' knowledge from fisheries science leads to incomplete understanding of marine ecosystems. This is particularly evident in Eastern Indonesian waters, where ecological complexity and limited monitoring infrastructure restrict scientific observation capacity. LEK functions as a real-time monitoring system developed through long-term interaction with the marine environment.

Bevilacqua et al. (2016) demonstrate that fishers' ecological knowledge significantly improves ecosystem modeling accuracy. Their findings show that anecdotal observations, when systematically structured, can fill critical data gaps in fisheries science. Similarly, Silvano et al. (2022) argue that integrating indigenous and local knowledge enhances ecological interpretation and strengthens adaptive management systems.

In this study, LEK contributes particularly to the identification of micro-scale fishing ground shifts that are not captured by satellite-based models. Fishers' ability to interpret subtle environmental changes allows them to adjust fishing strategies rapidly in response to ecological variability.

Integration of Oceanographic Data and LEK

The integration between oceanographic variability and LEK produces a more comprehensive understanding of fishing ground dynamics. The synthesis shows that both systems converge in identifying key environmental indicators that influence fish distribution. For example, fishers' perception of "cold water patches" aligns with satellite-detected sea surface temperature anomalies, while observed increases in fish abundance correspond with chlorophyll-a peaks identified in remote sensing data.

Table 2. LEK Indicators Used by Small-Scale Fishers

LEK Indicator	Interpretation	Ecological Meaning
Water color change	Fish presence	High productivity zones
Bird aggregation	Predator activity	Fish schooling below surface
Wind direction	Fishing condition	Surface water movement

Lunar cycle	Catch timing	Behavioral fish rhythm

Integration of Scientific and Local Knowledge Systems

The integration of oceanographic data and LEK produces a more reliable fisheries management framework. Scientific data provides macro-scale environmental structure, while LEK refines local-scale decision-making. Garibay-Toussaint et al. (2024) show that combined knowledge systems improve resilience under climate variability. Stephenson et al. (2016) confirm that participatory integration enhances governance effectiveness. The convergence between both systems is evident in spatial fishing ground identification. Satellite-based SST anomalies correspond with fishers' identification of cold-water productive zones. Garibay-Toussaint et al. (2024) highlight that combining scientific and local knowledge improves climate resilience in small-scale fisheries. Their findings align with this study, which shows that integrated knowledge systems enhance predictive capacity and reduce uncertainty in fishing operations. Similarly, Stephenson et al. (2016) demonstrate that participatory knowledge integration improves fisheries governance outcomes by increasing data reliability and stakeholder engagement.

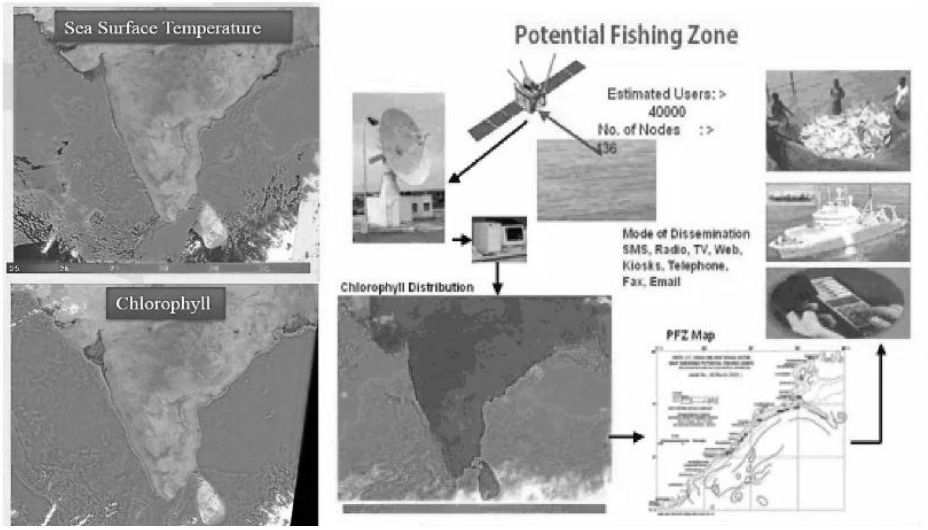

Figure 1. Conceptual Integration Model of Oceanography and LEK

The integration process also reveals that LEK provides temporal depth that scientific datasets often lack. Fishers' knowledge spans decades of environmental observation, enabling them to detect long-term ecological changes such as shifts in seasonal timing, changes in species composition, and altered migration routes. This temporal dimension is essential for understanding climate-driven variability in fisheries systems.

Adaptive Fisheries Management and Governance Implications

Adaptive fisheries management emerges as a central framework for operationalizing the integration of oceanographic variability and LEK. Ramm (1995) emphasizes that collaborative management systems improve sustainability outcomes by incorporating multiple knowledge sources. In Eastern Indonesia, where fisheries are highly decentralized, adaptive governance is particularly relevant.

St. Martin et al. (2007) argue that community-based fisheries management enhances ecological sustainability by strengthening local participation in decision-making processes. This study supports that argument by demonstrating that LEK provides actionable insights that can be directly incorporated into management strategies, particularly in identifying seasonal fishing zones and regulating effort distribution.

Kaya and Sajriawati (2023) further emphasize that adaptive management planning must consider socio-cultural dimensions of fisheries. This includes recognizing traditional knowledge systems as legitimate components of fisheries governance. The findings of this study reinforce the importance of institutional frameworks that formally integrate LEK into fisheries policy.

Narwadan et al. (2024) highlight that modern fisheries management must balance technological innovation with local knowledge systems. The results of this synthesis show that such balance is necessary to address both ecological uncertainty and socio-economic vulnerability in small-scale fisheries.

Spatial and Temporal Fishing Ground Patterns

The spatial analysis derived from literature synthesis indicates that fishing grounds in Eastern Indonesian waters are highly dynamic and strongly influenced by seasonal monsoon systems. During the southeast monsoon, upwelling increases nutrient availability, leading to higher fish abundance in specific coastal zones. Conversely, during the northwest monsoon, fish distribution shifts offshore due to changes in current direction and water temperature.

Safruddin et al. (2019) demonstrate that potential fishing zones for pelagic fish in Teluk Bone are closely linked to oceanographic conditions. These findings align with LEK observations, where fishers adjust their fishing locations based on seasonal environmental cues. Ramenzoni (2015) further shows that traditional lunar calendars influence fishing effort allocation, demonstrating the integration of environmental cycles into decision-making systems.

The convergence of scientific and local spatial knowledge indicates that both systems independently identify similar productive zones, although through different epistemological pathways. This convergence strengthens the validity of integrated management approaches.

Discussion of Knowledge System Complementarity

The results confirm that oceanographic variability and LEK are not competing systems but complementary components of fisheries knowledge. Scientific data provides quantitative, large-scale environmental patterns, while LEK offers qualitative, localized, and time-sensitive observations. Together, they form a hybrid knowledge system capable of addressing the complexity of fisheries dynamics in Eastern Indonesia.

Collins (2013) emphasizes the need for conceptual clarity in integrating LEK into fisheries planning. This study contributes to that need by demonstrating a structured framework for synthesis. Lima et al. (2017) support this approach by showing that LEK can be systematically categorized and integrated into spatial fisheries analysis.

The integration also addresses critical limitations in current fisheries management, particularly in data-poor regions. By combining remote sensing data with experiential knowledge, uncertainty in fishing ground prediction can be significantly reduced.

Makhtar and Qatrunnada (2025) further highlight that predictive fishing zone models based on oceanographic parameters can significantly improve fishing efficiency. However, these models remain dependent on spatial resolution and data availability. In many coastal regions of Eastern Indonesia, limited in-situ oceanographic monitoring reduces the accuracy of predictive models, leading to uncertainties in fishing ground identification.

This limitation is particularly relevant for small-scale fisheries, which operate with minimal technological support and rely heavily on experiential knowledge. As a result, scientific models alone are insufficient to fully explain fishing behavior and spatial decision-making in these communities.

Conclusion

This study demonstrates that sustainable fishing ground management in Eastern Indonesian waters depends on the integration of oceanographic variability and small-scale fishers' local ecological knowledge. Oceanographic parameters such as sea surface temperature, chlorophyll-a concentration, ocean currents, and monsoonal systems form the primary biophysical structure that determines fish distribution patterns. These variables shape the formation, shift, and productivity of fishing grounds across seasonal cycles.

Local ecological knowledge provides a complementary dimension that strengthens the interpretation of environmental dynamics at a fine spatial and temporal scale. Fishers continuously observe environmental signals such as water color, wind direction, bird aggregation, and lunar cycles to locate productive fishing areas. These observations represent adaptive knowledge systems developed through long-term interaction with marine ecosystems.

The synthesis shows that both knowledge systems independently identify similar productive fishing zones, although through different mechanisms. Oceanographic models offer predictive capacity at a regional scale, while local ecological knowledge provides contextual precision at the community level. When combined, both systems reduce uncertainty in fishing ground identification and improve decision-making accuracy.

The integration of these knowledge systems also supports adaptive fisheries management. It enhances the ability of fishers and policymakers to respond to environmental variability and climate-driven changes. This approach improves resource efficiency, strengthens ecological resilience, and supports livelihood stability in small-scale fisheries.

However, the study also highlights structural limitations in fisheries governance. Scientific data is often prioritized over local knowledge, leading to weak integration at the policy level. Bridging this gap requires institutional recognition of local ecological knowledge as a valid and essential component of fisheries management.

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