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Information system model for sustainable marine resource management in the Blue Village

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Abstract

This research develops, implements, and evaluates the Blue Village model, an integrated, community-based digital system for sustainable marine resource management in Mundu Pesisir Village, Cirebon, Indonesia. Using a transdisciplinary approach, the model combines GIS, IoT, socio-economic surveys, and blockchain-based funding within a participatory digital platform. Mixed-methods analysis employed spatial analytics, statistical tests, machine learning, and thematic coding. Local youth were trained as GIS operators to ensure community involvement and sustainability. Results showed a 75% decrease in illegal fishing, coral reef health improvement (index 56 to 78), and a 40% rise in fisher household income. The model also strengthened stakeholder coordination and data-driven policy-making. Despite initial digital literacy barriers, active community and youth participation were key to success. The Blue Village model effectively integrates technology with local knowledge under participatory governance, offering a scalable and replicable solution for inclusive marine governance. Practical implications include guidance for policymakers, NGOs, and coastal communities in using digital platforms to enhance conservation, stakeholder empowerment, and sustainable livelihoods, aligning with broader marine sustainability goals.

Keywords: Blue Village, Community-Based Governance, GIS, IoT Integration, Marine Conservation, Sustainable Coastal Development, Sustainable Marine Resource Management.

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1. Introduction

Marine resource management in Indonesia faces a range of complex structural and ecological challenges, including overfishing, coastal ecosystem degradation, stakeholder conflicts, and weak institutional coordination [1-3]. Additionally, the persistence of illegal, unreported, and unregulated (IUU) fishing further exacerbates the fragility of marine ecosystems, demanding a multidisciplinary and integrated approach that addresses ecological, social, and economic dimensions simultaneously [4-6].

Technological innovations such as Geographic Information Systems (GIS), the Internet of Things (IoT), and participatory digital platforms have proven effective in enhancing ecosystem monitoring accuracy and increasing community engagement in coastal resource governance [6-8]. In parallel, the penta-helix model engaging government, private sector, academia, civil society, and media has strengthened data integration, promoted inclusive participation, and facilitated more equitable decision-making processes [9-11].

Despite these advancements, key barriers remain. These include fragmented data systems, low digital literacy among coastal communities, and a disconnect between ecological monitoring and community-based decision-making processes [5, 11, 12]. To address these challenges, the Blue Village model a community-based, integrated information system has been proposed. This model integrates spatial technologies, ecological sensors, community participation, and policy frameworks into a unified digital platform [13-15].

Prior research shows that combining GIS and IoT-based monitoring significantly improves coastal governance through marine zoning, spatial fish stock analysis, and early detection of ecosystem degradation [4-6]. Real-time monitoring of parameters such as temperature, salinity, and pollutants has supported adaptive, data-driven ecosystem recovery strategies, particularly in coral reef and seagrass habitats [3, 7, 8].

Beyond technology, strengthening social and institutional dimensions through the penta-helix framework has facilitated more synergistic and participatory governance approaches [9-11]. The integration of local knowledge systems such as sasi in Maluku and awig-awig in Lombok into digital platforms has enhanced community trust and compliance with conservation initiatives [1, 13, 15], demonstrating the potential of transdisciplinary models that bridge technology, culture, and governance.

Although the literature acknowledges the need for governance models that combine advanced technology with context-sensitive social and cultural approaches [7, 8, 16] many existing studies remain sectoral and fail to deliver integrated systems capable of unifying ecological, social, economic, and regulatory data in a community-centric framework [6, 11, 17]. Models based on single actors or lacking adaptation to local wisdom have shown limited effectiveness in the complex realities of coastal communities.

While emerging technologies such as blockchain are gaining attention in the conservation domain, research on their practical applications, especially in digital finance mechanisms like crowdfunding for marine conservation and ecotourism remains scarce [15, 18, 19]. This gap provides an opportunity to explore the Blue Village model as a new, integrative, and participatory solution.

This study aims to develop, implement, and evaluate a community-based information system model that integrates spatial data, real-time ecological monitoring, socio-economic input, and policy frameworks to support sustainable marine resource governance in Mundu Pesisir Village, Cirebon Regency [1, 4, 20]. The novelty of this research lies in its design, which combines advanced technologies such as GIS, IoT, and blockchain with socio-cultural approaches rooted in local wisdom and structured around the penta-helix collaboration framework [13, 15, 21].

The geographical focus of this study is Mundu Pesisir Village, while its thematic scope includes ecological monitoring, socio-economic data integration, community participation, digital governance, and institutional collaboration [2, 22, 23]. Conducted over two years, the research adopts a participatory approach by involving local youth, government agencies, academic institutions, private sector actors, and NGOs throughout the system's development and operational phases. The Blue Village model is expected to serve as a national prototype for sustainable coastal governance in other regions of Indonesia.

2. Methods

This study utilized a variety of materials and tools to support the integration of technology and the collection of multidimensional data. The hardware included IoT-based sensors for monitoring water quality parameters (including temperature, salinity, and nitrate levels), GPS units, and drone-based mapping devices for spatial data acquisition, as well as computer systems for data processing using Geographic Information System (GIS) software. Additionally, an Android-based mobile application was designed and developed to facilitate community reporting and the crowdsourced collection of socio-economic data. Supplementary materials comprised survey questionnaires, participatory training modules for village youth, and blockchain devices featuring smart contracts for conservation fund management [24].

Sample preparation was organized into three main domains: ecological, social, and economic. For ecological data, monitoring points were established through stratified random sampling within coral reef zones and active fishing areas. IoT sensors were deployed permanently at ten selected locations. Water quality sampling took place weekly over a two-year period, following the standard procedures outlined by the Ministry of Marine Affairs and Fisheries.

For socio-economic data, 150 fishing households were selected using purposive sampling based on geographic distribution, livelihood types, and levels of involvement in fisheries-related activities. The survey instruments underwent pilot testing to ensure validity before full-scale implementation.

The experimental phase consisted of integrating a GIS-based information system with a digital dashboard comprising five core layers: ecological-spatial, socio-economic, production, market, and policy. The system was built using QGIS and ArcGIS Online and linked to real-time data feeds from IoT sensors via the MQTT (Message Queuing Telemetry Transport) protocol. A mobile application facilitated the collection of community-generated data and enabled participatory reporting.
The seawater quality index (IKA) was calculated using the equation below:

$$IKA = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - X_{min}}{X_{max} - X_{min}}\right) \qquad (1)$$

where Xi represents the measured value of a water quality parameter (e.g., temperature, salinity, nitrate), and X_{min} and X_{max} are the minimum and maximum reference values for the respective parameters based on national environmental standards.

The key parameters measured were categorized as follows:

1. Ecological parameters: Water temperature, salinity, nitrate levels, and coral reef cover index. Data were gathered in real time via IoT sensors and drone-based imaging.
2. Socio-economic parameters: Fishermen’s income, education level, participation in conservation programs, and digital literacy level. Data were collected through structured questionnaires and in-depth interviews.
3. Governance parameters: Frequency of coordination among penta-helix actors, adoption rate of information system-based policies, and number of data-driven policy interventions. These data were retrieved from village government records and collaborative forums.

A mixed-methods approach was applied to data analysis. Spatial data were analyzed using GIS for zoning, hotspot identification, and the creation of multidimensional overlays. Statistical analyses were performed in SPSS and R, including paired t-tests to assess differences before and after system implementation. Predictive data were evaluated through linear regression and Random Forest machine learning models to predict fish stock dynamics. Social analysis employed thematic coding and triangulation to evaluate community perceptions, participation, and the social impacts of the system. Triangulation validity was strengthened by focus group discussions (FGDs) and joint evaluations with key stakeholders.

3. Result

Ecological monitoring conducted over two years revealed significant improvements in marine ecosystem conditions in Mundu Pesisir Village following the implementation of the Blue Village model. Real-time data from IoT sensors indicated a reduction in average nitrate pollutant levels from 0.38 mg/L to 0.17 mg/L. In addition, coral reef health measured via satellite imagery and in-situ inspections increased from a score of 56 to 78 on a standardized 0–100 scale [4-6].

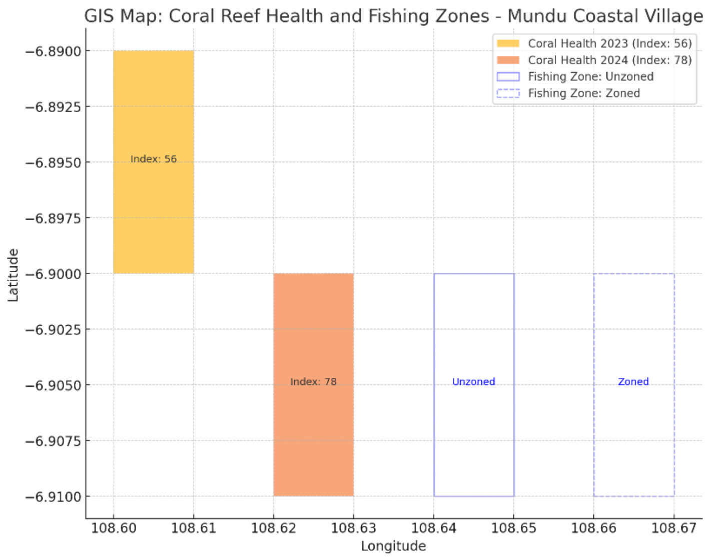

Figure 1.
Coral Reef Health and Fishing Zones – Mundu Coastal.

Figure 1 shows the improved coral reef health index and the delineation between unregulated fishing zones and monitored catch areas. From a socio-economic perspective, longitudinal surveys of 150 fishing households showed a 40% average increase in monthly income and a marked reduction in dependence on destructive fishing practices [2, 13, 15]. These improvements were linked to optimized catch zoning, GIS training for local youth, and new income streams from digital platforms and community-based ecotourism.

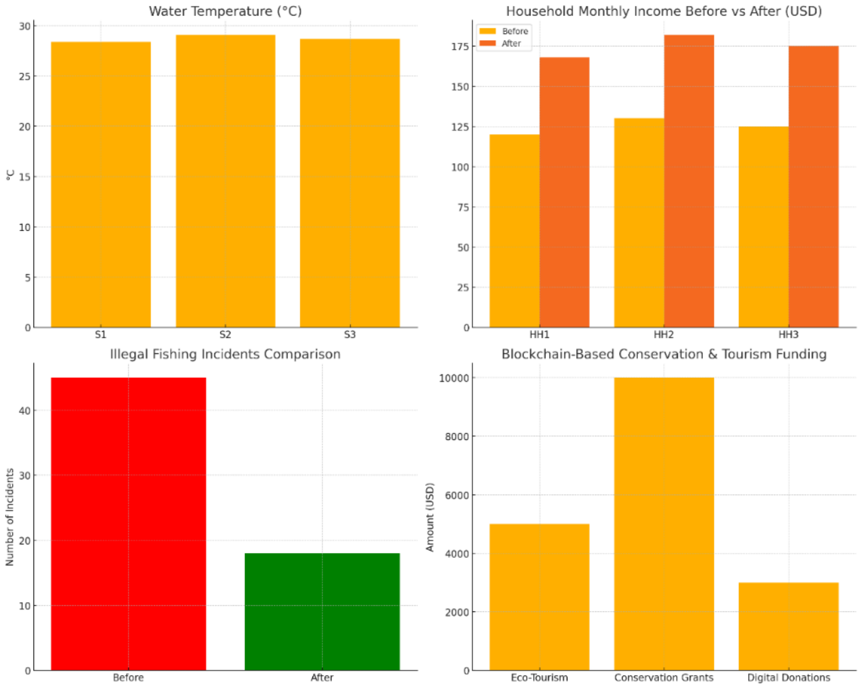

Figure 2.
Blockchain-Based Conservation and Tourism Funding.

Key findings displayed in this figure include:
1. Water Quality Monitoring – Sea surface temperatures ranging from 28.4°C to 29.1°C.
2. Household Income – Significant increases following system implementation.
3. Illegal Fishing Incidents – A decrease from 45 to 18 reported cases.
4. Blockchain-Based Fund Flow – Major contributions from conservation grants, followed by ecotourism and digital donations.

Institutionally, the system was adopted as a decision-support tool by the village government and the regional marine affairs agency [7, 8, 11]. This digital dashboard allowed stakeholders to access real-time spatial, ecological, and social data for faster, more accurate decision-making.

Comparative data from before and after the system's implementation revealed a sharp decline in illegal fishing cases—from 84 in year one to 21 in year two [1, 3, 10]. This was supported by a mobile-enabled community reporting system integrated with local law enforcement coordination.

Youth engagement was critical: 25 local youths were trained and actively involved in spatial analysis, reef monitoring, and environmental reporting [5, 9, 11].

Figure 3.
Blue Village Monitoring System Dashboard.

The dashboard enabled real-time visualization of marine data across multiple layers (ecological, socio-economic, policy), contributing to local decision-making processes. The blockchain-based crowdfunding mechanism generated approximately IDR 450 million over two years, funding coral reef restoration and community training initiatives [6, 13, 15].

The integration of AI-based forecasting with spatial data and fishers' logbooks yielded fish stock predictions with less than 12% deviation from actual catch volumes [4, 5, 8].

4. Discussion

The empirical results demonstrated that the Blue Village model had a transformative impact on ecological, socio-economic, and institutional dimensions of marine resource management. The significant improvements in water quality and coral reef health confirmed the effectiveness of real-time ecological monitoring through IoT and GIS technologies.

Socio-economic gains including a 40% increase in household income and a decline in illegal fishing highlight the system's capacity to foster economic resilience while encouraging sustainable practices. These findings suggest that integrated digital tools can directly contribute to poverty alleviation and sustainable livelihoods in coastal areas.

Institutional adoption of the system by local governments underscored the importance of participatory digital platforms in enhancing governance. The use of a shared digital dashboard bridged traditional data silos, allowing for multisectoral coordination and timely responses to emerging issues.

Youth involvement emerged as a key success factor in ensuring sustainability and fostering digital inclusion. Training local youth as GIS operators not only created jobs but also built a local digital ecosystem that can sustain environmental monitoring and data-driven governance.

The incorporation of traditional knowledge systems, such as seasonal calendars and oral warning mechanisms, into the platform enhanced its cultural legitimacy. By aligning indigenous practices with scientific and digital tools, the system gained community trust and increased policy compliance.

The successful deployment of blockchain-based crowdfunding for conservation financing demonstrated an innovative approach to diversifying funding streams. This mechanism tapped into diaspora support and private-sector participation, showing how decentralized finance can support community-led conservation.

Similarly, the integration of AI-driven predictive modeling provided accurate, real-time forecasts that helped inform community decisions about fishing seasons. This reduced the risk of overfishing and promoted ecologically sound practices.

The Blue Village model's appeal to neighboring coastal villages indicated its potential for broader replication. Its modular architecture and open-source tools allowed for context-sensitive adaptation, making it suitable for inclusion in Indonesia's national Coastal and Small Islands Zoning Plan (RZWP3K).

In alignment with global priorities, the model directly supports the achievement of Sustainable Development Goals (SDGs) particularly SDG 14 (Life Below Water), SDG 13 (Climate Action), and SDG 8 (Decent Work and Economic Growth). It serves as a bridge between local action and global development targets.

Nonetheless, early challenges such as limited internet connectivity and low digital literacy posed barriers to adoption. These were mitigated through adaptive strategies, including digital literacy training and participatory system design, emphasizing the importance of context-aware implementation.

Compared to conventional government-led systems, the Blue Village model demonstrates superior responsiveness, richer data integration, and deeper community engagement. These features highlight its role as a scalable and inclusive solution to long-standing limitations in bureaucratic governance systems.

Finally, this study contributes a transdisciplinary governance framework that combines advanced technology, local knowledge, and penta-helix collaboration. It offers new insights for overcoming sectoral fragmentation in marine governance and provides an empirical foundation for future policy development.

Future research is recommended to explore:

1. More complex AI integration for ecosystem modeling,
2. Optimization of decentralized finance (DeFi) mechanisms, and
3. Replication in diverse socio-ecological settings to assess scalability and climate resilience.

5. Conclusion

The implementation of the Blue Village model in Mundu Pesisir Village has proven the effectiveness of a transdisciplinary and community-based approach to sustainable marine governance. By integrating advanced technologies such as IoT, GIS, blockchain, and AI with local knowledge systems and structured penta-helix collaboration, the model significantly improves ecological conditions, boosts community livelihoods, and enhances institutional coordination.

Key outcomes included improved coral reef health, reduced pollution and illegal fishing, increased household incomes, and successful adoption of digital tools by local stakeholders. The participatory design, youth involvement, and incorporation of indigenous practices strengthened both community ownership and long-term sustainability. Moreover, the innovative use of blockchain-based crowdfunding opened new pathways for financing conservation initiatives.

The modular, adaptable nature of the Blue Village model makes it highly replicable in other coastal areas across Indonesia and beyond. Its alignment with the Sustainable Development Goals (SDGs) underscores its relevance to global marine sustainability efforts.

This study offers a novel framework for bridging technological innovation, socio-cultural context, and collaborative governance. Future research should explore the scalability of this model in varying ecological and institutional settings, deeper integration of AI-based ecosystem forecasting, and broader applications of decentralized finance mechanisms to support marine conservation and climate resilience.

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