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A Systematic Analysis of GIS as a Decision Support Tool for the Sustainable Management of Floating Net Cages in Lake Batur, Bali, Indonesia

Analisis Sistematik SIG sebagai Alat Pendukung Keputusan untuk Pengelolaan Keramba Jaring Apung yang Berkelanjutan di Danau Batur, Bali, Indonesia

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ABSTRAK

Perluasan budidaya ikan menggunakan sistem keramba jaring apung (KJA) di Danau Batur, Bali telah menimbulkan berbagai tantangan lingkungan, antara lain eutrofikasi, sedimentasi, penurunan kualitas air, serta konflik dengan sektor pariwisata dan pemangku kepentingan budaya. Studi ini bertujuan untuk menganalisis secara sistematis potensi sistem informasi geografis (SIG) sebagai alat bantu pengambilan keputusan dalam pengelolaan KJA yang berkelanjutan di Danau Batur, Bali, Indonesia. Dengan menggunakan metode tinjauan pustaka yang terstruktur, studi ini mengevaluasi penerapan SIG dalam penataan ruang budidaya perairan pada berbagai sistem perairan tawar di Indonesia dan wilayah internasional yang sebanding. Analisis mengidentifikasi variabel biofisik dan sosio-spasial utama yang penting untuk penempatan KJA secara optimal, seperti kedalaman air, kadar oksigen terlarut, arus perairan, kedekatan dengan zona sensitif, serta akses terhadap infrastruktur. Studi kasus dari Danau Toba, Danau Maninjau, dan Waduk Cirata menunjukkan efektivitas SIG dalam menentukan zona budidaya yang sesuai, mengevaluasi daya dukung lingkungan, dan mengurangi konflik pemanfaatan ruang. Meskipun memiliki potensi tinggi, pemanfaatan SIG di Danau Batur masih terbatas akibat lemahnya koordinasi kelembagaan, kurangnya integrasi data spasial, dan rendahnya keterlibatan pemangku kepentingan. Studi ini menyimpulkan bahwa SIG, jika dipadukan dengan pemetaan partisipatif dan selaras dengan kerangka regulasi, dapat mendukung tata kelola budidaya yang transparan, ekologis, dan sensitif terhadap nilai budaya. Artikel ini juga memberikan rekomendasi untuk membangun sistem zonasi berbasis SIG, meningkatkan mekanisme perizinan dan pengawasan, serta mengintegrasikan data lingkungan dan sosial-budaya dalam pengambilan keputusan spasial. Temuan ini berkontribusi pada penguatan perencanaan budidaya berkelanjutan di Danau Batur dan danau-danau dataran tinggi lainnya di Indonesia.

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ABSTRACT

The rapid expansion of fish farming using the floating net cage (FNC) system in Lake Batur, Bali, has given rise to various environmental challenges, including eutrophication, sedimentation, declining water quality, and conflicts with the tourism sector and cultural stakeholders. This study aims to systematically analyze the potential of Geographic Information Systems (GIS) as a decision support tool for sustainable FNC management in Lake Batur. The study uses a systematic literature review to examine relevant GIS applications in aquaculture zoning across freshwater systems in Indonesia and comparable international contexts. The analysis identifies key biophysical and socio-spatial variables essential for optimal cage placement, such as water depth, dissolved oxygen, current flow, proximity to sensitive zones, and infrastructure access. Case studies from Lake Toba, Lake Maninjau, and the Cirata Reservoir demonstrate the effectiveness of GIS in delineating suitable aquaculture zones, evaluating environmental carrying capacity, and reducing spatial conflicts. Despite its high potential, the use of GIS in Lake Batur remains limited due to weak institutional coordination, a lack of integrated spatial datasets, and minimal stakeholder engagement. This study concludes that when coupled with participatory mapping and aligned with regulatory frameworks, GIS can support transparent, ecologically sound, and culturally sensitive aquaculture governance. The paper recommends establishing GIS-based zoning, improving licensing and monitoring systems, and integrating environmental and socio-cultural data into spatial decision-making. These findings contribute to advancing sustainable aquaculture planning in Lake Batur and other highland lake systems in Indonesia.

1. INTRODUCTION

1.1 Background

Aquaculture has become essential to global food production, contributing significantly to food security, economic development, and livelihoods, particularly in developing countries (Han & Bu, 2023). Facing net cage (FNC) has gained popularity among various aquaculture systems due to their low initial investment and scalability (Yunika & Karuniasa, 2020; Wiradana et al., 2022; Suryawan et al., 2019). However, without proper spatial planning and environmental oversight, the rapid and often unregulated expansion of FNC can lead to ecological degradation and social conflicts, especially in ecologically sensitive freshwater ecosystems such as volcanic lakes (Musdalifah et al., 2022; Quan & Wang, 2020; Ditya et al., 2022; Agbam et al., 2025; Budiasa et al., 2018).

Lake Batur, located in the highlands of Bali, Indonesia, is a freshwater volcanic lake of high ecological, cultural, and economic importance (Utama et al., 2024). The lake is a critical water source for agriculture, drinking water, and hydroelectricity, and supports a thriving local fish farming industry primarily using floating net cages. Over the past two decades, the growth of this aquaculture activity has significantly improved local incomes but also triggered serious environmental issues, such as eutrophication, sedimentation, and reduced water quality, along with increasing conflicts with tourism and conservation stakeholders (Shrestha et al., 2016; Kashindye et al., 2015). The proliferation of FNC in Lake Batur has outpaced spatial regulation and monitoring capacity (Garno et al., 2024; Kaban et al., 2023; Lusia et al., 2023). Reports from government agencies and independent studies have highlighted that many cages are placed without considering the lake's ecological carrying capacity or zoning guidelines, often overlapping with tourism zones, water intakes, or sacred sites. Such uncontrolled development undermines the lake's environmental sustainability and the aquaculture sector's long-term viability (Simangunsong & Hidayat, 2017; Putri, 2019; Suryawan et al., 2019).

Addressing these challenges requires a data-driven and integrated approach to spatial planning and environmental management. Geographic Information Systems (GIS) offer a powerful tool for collecting, analyzing, and visualizing spatial and ecological data to support sustainable aquaculture planning (Sabrina, 2020; Wanchana & Sayan, 2018; Wicaksono et al., 2020; Xia et al., 2014). In particular, GIS can help identify suitable locations for FNCs based on multiple criteria such as depth, water current, dissolved oxygen, temperature, proximity to human settlements, and potential for stakeholder conflict (Zaniboni et al., 2024; Wang et al., 2021; Sunardi et al., 2022).

Previous studies have demonstrated the effectiveness of GIS in aquaculture zoning across various freshwater and coastal systems in Indonesia and globally. Examples from Lake Toba (Siringoringo et al., 2023; Sunaryani et al., 2018), Lake Maninjau (Junaidi et al., 2022; Syandri et al., 2020), and the Cirata Reservoir (Sunardi et. al., 2022; Suryawan et al., 2019) have shown how GIS-based zoning has helped in delineating sustainable aquaculture areas, minimizing conflicts, and ensuring compliance with environmental regulations. These successful applications underline the potential of replicating similar approaches in Lake Batur to support evidence-based decision-making (Xia et al., 2014; Habibie et al., 2021; Haghshenas et al., 2021). Despite the recognized potential of GIS, its application in Lake Batur remains limited and fragmented. While local authorities or NGOs have conducted some mapping initiatives, there is a lack of integrated, participatory, and policy-aligned GIS applications tailored to the specific challenges of Lake Batur. Moreover, local capacity for data management, spatial analysis, and decision-making support remains underdeveloped, posing further barriers to effective implementation (Gimpel et al., 2018; Simangunsong & Hidayat, 2017; Budiasa et al., 2018; Garno et al., 2024).

This study provides a systematic review of relevant scientific literature and technical reports to evaluate the potential and readiness of using GIS as a decision-support tool for sustainable FNC management in Lake Batur. The study underscores the urgency of adopting a systems-thinking approach to spatial aquaculture management. It demonstrates how, when properly implemented, GIS can bridge the gap between science, policy, and practice in supporting sustainable freshwater fisheries.

Using systematic analysis, this study seeks to contribute to the growing body of research on spatial decision support systems for aquaculture while offering practical recommendations for local governments, fish farmers, and environmental managers in Lake Batur. Emphasis is placed on the need for participatory mapping, integration of high-resolution ecological data, and institutional collaboration to ensure the long-term sustainability of aquaculture and the lake ecosystem. Synthesizing existing studies also highlights knowledge gaps and future research directions, particularly in integrating GIS with socio-economic data and real-time environmental monitoring systems. This is particularly important given the increasing impacts of climate variability, changing land use patterns, and tourism pressure in the Batur catchment area.

1.2 Research Objectives

The main objective of this study was to systematically analyze the role and effectiveness of Geographic Information Systems (GIS) as a decision support tool for guiding the sustainable spatial management of floating net cage (FNC) aquaculture in Lake Batur, Bali. The specific objectives were: (1) Examine the development of FNC aquaculture in Lake Batur and identify the challenges arising from suboptimal spatial management; (2) Analyze previous studies that have utilized Geographic Information Systems (GIS) in the management of aquaculture activities, particularly in the context of floating net cages; (3) Explore the potential and opportunities for applying GIS as a decision support tool in spatial planning and the sustainable optimization of floating net cage aquaculture in Lake Batur.

2. METHODS

This study employed a systematic literature review approach to evaluate the potential of Geographic Information Systems (GIS) as a decision support tool for sustainable floating net cage (FNC) aquaculture in Lake Batur, Bali. The methodology involved four key stages: (1) literature identification, (2) screening and selection, (3) data extraction, and (4) thematic analysis. A flowchart of the methodology and the number of selected publications studied is given in Figure 1.

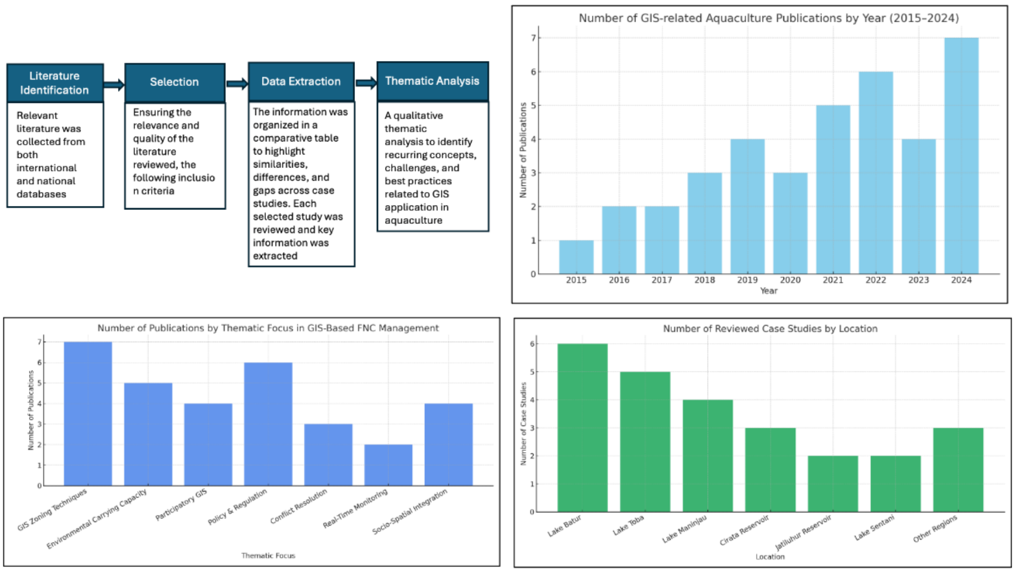

Figure 1. Flowchart of methodology and number of selected publications studied

2.1 Literature Identification

Relevant literature was collected from international and national databases, including Google Scholar, Scopus, ScienceDirect, and Garuda (Garba Rujukan Digital). In addition to peer-reviewed journals, grey literature such as technical reports, government publications, policy documents, and institutional proceedings was included to broaden the contextual understanding of aquaculture zoning and GIS applications in Indonesia and comparable regions.

2.2 Screening and Inclusion Criteria

To ensure the relevance and quality of the literature reviewed, the following inclusion criteria were applied:

(a) Publications issued between 2014 and 2024;
(b) Articles written in English or Bahasa Indonesia;
(c) Studies focusing on the application of GIS in aquaculture management, particularly zoning, site suitability, or spatial planning;
(d) Studies with a methodological basis or applied case studies involving floating net cages (FNC) or similar aquaculture systems;
(e) Documents that address environmental, spatial, or socio-political factors in freshwater aquaculture governance.

2.3 Data Extraction

The information was organized in a comparative table to highlight similarities, differences, and gaps across case studies. Each selected study was reviewed, and key information was extracted, including:

(a) Study location and scale (e.g., lake, reservoir, marine);
(b) GIS methods or tools used (e.g., spatial overlay, multi-criteria analysis, participatory GIS);
(c) Decision-making variables (e.g., water depth, quality, currents, zoning regulations);
(d) Outcomes and effectiveness (e.g., improved zoning, reduced conflict, environmental impact mitigation);
(e) Relevance to the Lake Batur context.

2.4 Thematic Analysis

A qualitative thematic analysis was then conducted to identify recurring concepts, challenges, and best practices related to GIS application in aquaculture. Case studies from Lake Toba, Lake Maninjau, Cirata Reservoir, and other Indonesian water bodies were specifically compared to derive lessons applicable to Lake Batur. The analysis was structured around key thematic areas:

(a) Environmental suitability and carrying capacity;
(b) Spatial conflict and multi-use zoning;
(c) Integration of GIS into governance frameworks;
(d) Community participation and stakeholder engagement;
(e) Technological capacity and data availability.

3. RESULTS AND DISCUSSION

3.1 The Urgency of Optimizing Floating Net Cage (FNC) Aquaculture in Lake Batur

Floating net cage (FNC) aquaculture has experienced significant expansion in Lake Batur over the past two decades, driven by its economic potential to improve the livelihoods of local communities in the Kintamani region. The system's relatively low capital requirements, scalability, and adaptability to inland waters have made it a preferred method for freshwater fish farming in the region (Wibowo et al., 2025; Siringoringo et al., 2023). According to Garno et al. (2024), Gandhi et al. (2022), and Kaban et al. (2023), the number of cages in Lake Batur has grown beyond the recommended threshold, with cage units densely clustered in particular lake zones, especially near the main fish landing and feeding areas.

This unregulated and excessive growth has led to severe environmental degradation. Among the most pressing concerns is eutrophication, caused by accumulated uneaten feed, fish excreta, and organic matter beneath cages. Garno et al. (2024) found that nitrogen and phosphorus concentrations in Lake Batur have surpassed ecological thresholds, increasing the risk of harmful algal blooms and oxygen depletion. In parallel, sedimentation beneath cages has intensified, altering benthic ecosystems and reducing natural self-purification capacities (Budiasa et al., 2018; Kaban et al., 2023; Nopem et al., 2020; Putri et al., 2023; Sukmawati et al., 2019).

The spatial distribution of cages also raises multi-sectoral conflicts. In addition to being a productive aquaculture site, Lake Batur is a sacred lake for Balinese Hindus and a key tourism destination. Many cages have been installed near culturally sensitive areas such as Pura Ulun Danu Batur, causing tension between fishers and religious communities (Tanjung & Hutagaol, 2019; Lusia et al., 2023). Similarly, tourism operators have expressed concern over the visual pollution and water quality degradation affecting ecotourism potential. Such conflicts highlight the need for spatially informed zoning and transparent governance mechanisms (Gandhi et al., 2022). Another critical factor is the ecological fragility of volcanic lake systems. As a caldera lake with limited inflow and outflow, Lake Batur is more vulnerable to pollution accumulation and ecological imbalance than river-fed lakes or reservoirs (Kaban et al., 2023). These hydrological constraints limit the lake's natural resilience and underscore the need to control nutrient inputs and regulate cage density.

Monitoring and enforcement limitations have compounded the problem. The local fisheries agency lacks adequate tools and trained personnel to systematically map, evaluate, and enforce FNC distribution based on ecological carrying capacity (Simangunsong & Hidayat, 2017; Garno et al., 2024). This institutional gap creates a regulatory vacuum that permits unsustainable practices to persist. Beyond the ecological and regulatory dimensions, climate change and land use changes in the Batur watershed have introduced new stressors. Variations in rainfall patterns and increased runoff have altered lake water levels and quality, further complicating aquaculture dynamics (Dauda et al., 2019; Falconer et al., 2020). These external pressures require adaptive management supported by timely spatial data and environmental monitoring.

Several studies have emphasized that sustainable aquaculture in volcanic lakes like Batur cannot be achieved without optimized spatial planning based on environmental capacity, social considerations, and regulatory alignment (Utama et al., 2024; Sabrina, 2020). As demonstrated in similar contexts like Lake Toba and Cirata Reservoir, spatial zoning based on Geographic Information Systems (GIS) can offer a science-based solution to balance production with protection (Wanchana & Sayan, 2018; Wicaksono et al., 2020; Sunardi et al., 2022). Table 1 compares floating net cage zoning studies in several lakes in Indonesia using the GIS approach. Studies of floating net cage zoning in Lake Batur, Bali, Indonesia are shown in Table 2.

Table 1. A comparison of floating net cage zoning studies in several lakes in Indonesia using the GIS approach

Study Location	**GIS Method / Zoning Approach**	**Zoning Criteria Variables**	**Key Findings**	**Ref.**
Lake Toba, North Sumatra	Spatial overlay	Depth, current, DO, water temperature	Optimal aquaculture zones identified at depths	Sunaryani et al., 2018
Lake Maninjau, West Sumatra	GIS, bathymetric mapping	Depth, dissolved oxygen, eutrophication	High-density FNCs are found in hypoxia-prone zones	Junaidi et al., 2022 Syandri et al., 2020
Cirata Reservoir, West Java	GIS and carrying capacity analysis	Effective area, rainfall, water quality	Carrying capacity exceeded; GIS is functional in evaluating FNC limitations.	Suryawan et al., 2019 Sunardi et al., 2022
Lake Sentani, Papua	Policy Model	Community input, depth, and accessibility	Collaborative zoning reduced spatial-use conflicts	Walukow et al., 2023
Jatiluhur Reservoir, West Java	GIS-based spatial modeling	Depth, distance to shore, and other lake activities	GIS supports aquaculture-tourism integration	Yunika & Karuniasa, 2020 Putri, 2019, Simangunsong & Hidayat, 2017
Lampung Bay	GIS	Mapping	Water quality and FNC	Wicaksono et al., 2020
Ambon Bay	GIS	Land	FNC	Murtiono et al., 2016

Table 2. Studies of floating net cage zoning in Lake Batur, Bali, Indonesia

Zoning Criteria Variables	**Key Findings**	**Ref.**
Cage density, aquaculture expansion, livelihood	Rapid FNC growth driven by economic livelihood needs; clustering in key areas	Budiasa et al., 2018, Wiradana et al., 2022, Sabrina, 2020
Nutrient load (N, P), eutrophication	Nutrient concentrations exceeded ecological thresholds, increasing the risk of an algal bloom.	Garno et al., 2024, Sukmawati et al., 2019

Zoning Criteria Variables	Key Findings	Ref.
Sediment accumulation, benthic change	Sediment build-up under cages reduces water quality and ecosystem function.	Utama et al., 2024, Kaban et al., 2023
Cultural zones, tourism overlap	FNCs near sacred and tourism zones cause spatial conflicts	Lusia et al., 2023
Lake morphology, caldera system	Limited inflow/outflow makes Batur highly vulnerable to pollution accumulation.	Garno et al., 2024

Optimizing FNCs in Lake Batur is not merely a technical issue but a multidimensional challenge involving environmental protection, spatial equity, cultural sensitivity, and institutional reform. Without immediate spatial planning intervention, the economic gains from aquaculture risk being offset by irreversible ecological damage and prolonged social conflict.

3.2 Study of GIS Utilization for FNC Location Determination in Other Regions

The application of Geographic Information Systems (GIS) in aquaculture spatial planning has evolved rapidly over the last decade. It has become a standard tool for supporting zoning decisions, particularly for floating net cage (FNC) aquaculture in freshwater and coastal ecosystems. Numerous lakes and reservoirs in Indonesia have been the subject of GIS-based studies to identify suitable aquaculture zones based on multi-criteria analysis (MCA), carrying capacity estimation, and stakeholder engagement models.

Globally, GIS tools have been applied with increasing sophistication. Ecosystem-based GIS models for marine aquaculture siting, integrating physical, ecological, and socio-economic layers (Shrestha et al., 2016; Maciel & Peschel, 2018; Gimpel et al., 2018; Haghshenas et al., 2021; Puniwai et al., 2014; Quan & Wang, 2020; Xia et al., 2014; Zaniboni et al., 2024).

Recent advancements now involve dynamic GIS models and real-time integration of environmental sensors. For example, Xia et al. (2014) and Quan & Wang (2020) demonstrated how real-time water quality data integrated with GIS can provide adaptive zoning models for inland lakes in China. Moreover, spatial tools like multi-criteria decision analysis (MCDA) and analytical hierarchy process (AHP) are increasingly embedded within GIS platforms to enhance decision-making (Haghshenas et al., 2021; Habibie et al., 2021; Xia et al., 2014). These methods allow for the systematic ranking of site suitability based on expert-defined weights for each criterion (depth, DO, proximity to settlements, etc.).

In Indonesia, national-level initiatives are now supporting GIS use in aquaculture zoning. The Ministry of Marine Affairs and Fisheries (KKP) has published technical guidelines. GIS recommendation as a core planning tool by the sustainable aquaculture framework and ecological carrying capacity. The reviewed studies collectively demonstrate that GIS is not merely a mapping tool but a decision support system (DSS) that integrates spatial, ecological, and socio-economic dimensions. When properly implemented, GIS-based zoning contributes to (1) reducing environmental degradation, (2) minimizing multi-user conflict, (3) supporting equitable resource allocation, and (4) improving policy enforcement and transparency.

3.3 Determinants of Optimal Floating Net Cage (FNC) Location in Lake Batur

Determining suitable sites for floating net cage (FNC) aquaculture in Lake Batur requires integrating various biophysical, hydrological, and socio-spatial variables (Garno et al., 2024; Sukmawati et al., 2019; Lusia et al., 2023; Utama et al., 2024; Kaban et al., 2023). The complex ecological dynamics of volcanic lakes like Batur and high user pressure from multiple sectors (aquaculture, tourism, religion, and domestic water use) make site selection highly sensitive and multidimensional.

Lake Batur holds high spiritual value for Balinese Hindus and is a key tourism destination. GIS zoning must incorporate land use maps and visual buffer zones to avoid these sensitive areas. Before placing cages, the ecological limit of fish biomass that a water body can support without degrading water quality must be assessed.

The availability of support infrastructure, such as feeding docks, road access, electricity, and maintenance stations, affects operational efficiency. GIS can be used to optimize cage placement relative to infrastructure nodes. The success of zoning is not purely technical; it must align with community preferences, traditional knowledge, and local governance structures.

3.4 GIS Potential in Zoning and Planning Floating Net Cages (FNC) in Lake Batur

The use of Geographic Information Systems (GIS) in the spatial planning of aquaculture has evolved into a critical tool to support sustainable development, especially in areas with complex socio-ecological interactions, such as Lake Batur, Bali. GIS offers significant potential in zoning and planning floating net cage (FNC) aquaculture by integrating multidimensional datasets, enabling decision support, and facilitating spatial conflict resolution. In the context of Lake Batur—where aquaculture expansion has led to overlapping uses, environmental degradation, and regulatory gaps—GIS provides a robust, data-driven foundation for redesigning spatial allocations. Table 3 presents the GIS potential in FNC Management in Lake Batur.

Table 3. GIS potential as a decision tool for the FNC Management in Lake Batur

Potential	Key findings	References
Multi-Criteria Spatial Suitability Mapping	GIS allows planners to combine spatial datasets—such as bathymetry, water quality, current flow, depth, dissolved oxygen, and land use—to generate suitability maps for aquaculture. Methods like Multi-Criteria Decision Analysis (MCDA) and Analytical Hierarchy Process (AHP) rank suitability to identify optimal zones. In Lake Batur, such integration could avoid eutrophication-prone areas while protecting tourism and spiritual zones.	Habibie et al., 2021 Estigade et al., 2019 Wicaksono et al., 2020
Environmental Carrying Capacity Visualization	Environmental capacity models—like the Dillon-Rigler phosphorus model—can be incorporated into GIS to visualize areas where cage density exceeds nutrient assimilation limits. Demonstrated this in the Cirata Reservoir, revealing the power of GIS in correlating nutrient load data with biomass thresholds, which is highly relevant for Lake Batur's eutrophication issues.	Maciel & Peschel, 2018, Shrestha et al., 2016
Decision Support for Policy Enforcement	GIS outputs can directly support regulatory frameworks by delineating legally recognized aquaculture zones and enabling real-time monitoring through geo-referenced cage inventories. In Bali, where spatial regulations exist but are weakly enforced, GIS could bridge policy with practice by providing digital zoning maps for licensing and inspection.	Habibie et al., 2021, Haghshenas et al., 2021, Xia et al., 2014
Early Detection of Spatial Conflict	Zoning maps generated via GIS can overlay various layers (tourism paths, spiritual zones, conservation areas) to identify overlapping or contested areas. This pre-emptive detection enables conflict-sensitive planning that reduces disputes between fish farmers, tour operators, and cultural authorities.	Gimpel et al., 2018, Quan & Wang, 2020

3.5 Integration of GIS with Environmental and Social Data

Integrating Geographic Information Systems (GIS) with environmental and social datasets enhances the effectiveness, inclusiveness, and sustainability of spatial planning in aquaculture. In Lake Batur's case, where ecological sensitivity and cultural complexity are prominent, such integration is vital for developing decision support systems that reflect real-world dynamics, accommodate multiple interests, and enable adaptive management. This section explores how GIS can serve as a unifying platform that blends ecological parameters with social, economic, and institutional dimensions to achieve spatial justice and ecological resilience. Integrated GIS systems improve ecological validity, social acceptance, and policy relevance. For Lake Batur, successful integration must involve local customary leaders, tourism authorities, and religious institutions in co-creating the zoning framework. The result is not just a technical map, but a spatial governance tool rooted in socio-ecological realities. Table 4 shows the integration of GIS with environmental and social data.

Table 4. Integration of GIS with environmental and social data

Issues	GIS Integration Potential
Environmental Data Layers in GIS	GIS excels in visualizing and analyzing environmental variables relevant to aquaculture, including: Water temperature, depth, current velocity, turbidity, chlorophyll concentration, and Nutrient loads (e.g., total phosphorus and nitrogen). Sediment thickness and oxygen depletion zones, Shoreline vegetation, and erosion potential. These datasets can be sourced from in-situ water sampling, remote sensing (e.g., Landsat, Sentinel-2), and real-time IoT sensors. For example, real-time water quality sensors integrated into GIS platforms could provide early warnings of water degradation, which is highly applicable for shallow, semi-enclosed systems like Lake Batur.
Socio-Spatial Data Integration	Beyond environmental factors, social datasets such as population density, community livelihood zones, cultural heritage sites, customary marine tenure areas, and tourism zones are essential in spatial planning. For Lake Batur, social data include Tourism routes and viewpoints, fishermen's household clusters and dependency levels, Traditional conflict zones, or local taboos. Integrating these into GIS allows decision-makers to account for local knowledge, land rights, and user conflicts in zoning design.
Multi-Stakeholder Mapping	GIS can serve as a boundary object for facilitating dialogue among stakeholders—fishers, government, religious leaders, tourism operators—by offering a visual platform that synthesizes their spatial interests. This fosters collaborative zoning and reduces policy fragmentation.
Tools for Integration: PGIS, MCDA, SDSS	Several tools enable integrating social-environmental data into GIS-based planning: Participatory GIS (PGIS) empowers communities to input their spatial knowledge. Multi-Criteria Decision Analysis (MCDA) balances ecological and social weights in site selection. Spatial Decision Support Systems (SDSS) are dynamic GIS platforms that combine simulation, scenario building, and stakeholder input for real-time planning.

Issues	GIS Integration Potential
Risk and Conflict Mapping	GIS can identify risk-prone zones—e.g., flood-prone shoreline settlements, fish kills, algal bloom hotspots—and overlay them with vulnerable communities to guide emergency management or relocation programs. In Lake Batur, this can help prevent aquaculture infrastructure in areas subject to rising nutrient loads or shoreline tourism intensification.
Case Studies Supporting Integration	Lake Maninjau: GIS and socio-economic indicators helped redefine aquaculture zones to reduce eutrophication and local conflict. Cirata Reservoir: Integrating household-level economic dependence on aquaculture improved spatial equity in FNC regulation. Jatiluhur Reservoir: GIS planning included recreation zones, showing how environmental and tourism interests can be reconciled.
Challenges in Data Integration	Inconsistent spatial resolution between environmental and social data. Limited GIS literacy among local stakeholders Poor institutional coordination for data sharing and the absence of standardized spatial datasets for culture-sensitive zones. Efforts aim to bridge these gaps through national guidelines, capacity building, and open-access geospatial data platforms.

3.6 Regulation and Policy of FNC Management in Lake Batur

Managing floating net cage (FNC) aquaculture in Lake Batur is governed by a complex intersection of national, regional, and local policies. However, a significant gap exists between regulation and enforcement despite existing legal frameworks. The proliferation of FNCs beyond the lake's ecological carrying capacity indicates a regulatory disconnect, weak spatial control, and limited institutional capacity. Addressing these challenges requires a deeper understanding of the regulatory landscape, institutional coordination, and integration of GIS-based spatial planning into governance frameworks.

At the national level, the Ministry of Marine Affairs and Fisheries (KKP) has issued several key policies supporting sustainable aquaculture management. These include Peraturan Menteri KKP No. 75/2016 on the General Guidelines for Aquaculture Spatial Planning, KKP Technical Guidelines (2017 & 2021) promoting the use of GIS and environmental carrying capacity for freshwater aquaculture zoning, Sustainable Aquaculture Roadmap (2020–2024) focusing on ecological limits, economic viability, and digital tools for spatial control (KKP, 2021). These documents advocate for aquaculture zoning based on scientific data, participatory processes, and inter-sectoral alignment—principles that remain underutilized in Lake Batur's current management practice.

Multiple agencies share jurisdiction over Lake Batur, including DKP Bali, Balai Wilayah Sungai Bali-Penida (BWS), Dinas Pariwisata, and local customary (adat) leaders, resulting in regulatory overlap and unclear authority in enforcement. Field investigations by Akira et al. (2023) with local fishers revealed inconsistencies in the licensing process for FNCs in Lake Batur. Several farmers operate with expired or informal permits, while monitoring and inspection activities are sporadic due to resource constraints.

4. CONCLUSION

Based on a systematic review of national and global case studies, this study confirms that Geographic Information Systems (GIS) offer a valuable decision support tool for the sustainable management of FNCs. GIS enables the integration of environmental, spatial, and social datasets to identify suitable aquaculture zones, monitor ecological capacity, reduce user conflicts, and support evidence-based policy enforcement. The findings underscore the need to operationalize GIS-based aquaculture zoning in Lake Batur through a participatory, data-driven, and policy-aligned framework. Therefore, the following key recommendations are proposed:

(a) Establishing a GIS-based spatial zoning system that delineates zones based on depth, DO levels, nutrient load, cultural and tourism areas, and infrastructure proximity.
(b) Strengthen institutional coordination to manage GIS-based zoning and monitoring activities.
(c) Integrating the environmental and socio-cultural data to expand GIS datasets to include real-time environmental monitoring (IoT sensors, remote sensing), sacred zones, and tourism development corridors to prevent conflict and enhance legitimacy.
(d) Implementing participatory mapping and community involvement that engage local fishers, religious leaders, and tourism stakeholders in zoning discussions using participatory GIS (PGIS) tools to ensure inclusivity and compliance.
(e) Aligning with National and Regional Policy Instruments to ensure Lake Batur's aquaculture zoning follows national and local regulations.
(f) Training local authorities, technicians, and community members in GIS operation, spatial data interpretation, and decision-support systems.

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