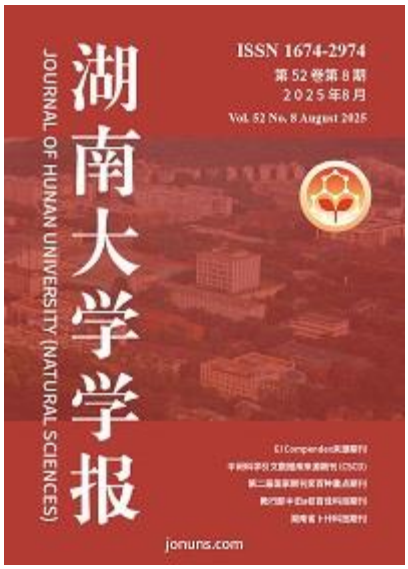

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Optimizing Spatial Planning in the Lake Toba Region for Sustainable Tourism and Community Empowerment

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Abstract: The development of national strategic tourism areas such as Lake Toba requires an integrated and sustainability-driven approach. However, the region faces significant challenges, including fragmented spatial planning, escalating ecological pressures, and limited involvement of local communities in tourism governance. This study proposes strategies for optimizing spatial planning through sustainability-oriented and holistic community empowerment frameworks. A mixed-methods approach was employed, integrating GIS-based spatial analysis, questionnaire surveys of residents and tourists, social-ecological system (SES) analysis, SWOT, the Analytical Hierarchy Process (AHP), Participatory Rural Appraisal (PRA), and Triple Bottom Line (TBL) evaluation. Results indicate severe land-use fragmentation and intense pressure on water quality and green spaces, particularly in key tourism nodes such as Parapat, Tuk-Tuk (Samosir), and Balige. AHP prioritization identifies ecological integrity as the

highest strategic priority (weight = 0.36), followed by socio-cultural considerations (0.26) and infrastructure development (0.18). Although community participation in spatial management is currently moderate, it requires systematic strengthening to ensure long-term socio-ecological resilience. GIS-based zoning delineates high-risk environmental zones and reveals opportunities for expanding community-based ecotourism. The study underscores the imperative of integrating environmental conservation, inclusive local engagement, and adaptive spatial planning to inform sustainable tourism policy and development in the Lake Toba region.

Keywords: Lake Toba, sustainable spatial planning, community empowerment, GIS analysis, sustainable tourism, environmental management.

优化多巴湖地区空间规划，促进可持续旅游业发展和社区赋权

摘要：多巴湖等国家战略旅游区的开发需要采取综合的、以可持续性为导向的方法。然而，该地区面临着重大挑战，包括空间规划碎片化、生态压力不断上升以及当地社区在旅游治理中的参与度有限。本研究提出了通过以可持续性为导向的整体社区赋权框架来优化空间规划的策略。研究采用了混合方法，整合了基于GIS的空间分析、居民和游客问卷调查、社会生态系统(SES)分析、SWOT分析、层次分析法(AHP)、参与式乡村评估法(PRA)和三重底线(TBL)评估。结果表明，该地区土地利用碎片化严重，水质和绿地面临巨大压力，尤其是在巴拉帕特、图克图克（萨摩西岛）和巴利格等关键旅游节点。层次分析法优先级排序将生态完整性确定为最高战略优先事项（权重=0.36），其次是社会文化因素（权重=0.26）和基础设施建设（权重=0.18）。尽管社区参与空间管理的程度目前尚不高，但需要系统性地加强，以确保长期的社会生态韧性。基于GIS的分区划分划定了高风险环境区域，并揭示了拓展社区生态旅游的机会。该研究强调了整合环境保护、包容性地方参与和适应性空间规划的必要性，以便为多巴湖地区的可持续旅游政策和发展提供参考。

关键词：多巴湖, 可持续空间规划, 社区赋权, GIS分析, 可持续旅游, 环境管理

1. Introduction

Sustainable tourism has become a central pillar in the development of global destinations, including Indonesia, due to its multifaceted impacts on the economy, society, and environment [1]-[4]. As one of Indonesia's National Super Priority Destinations, Lake Toba requires optimized spatial planning to balance economic development with environmental and cultural preservation [5], [6]. However, inconsistent spatial governance has exerted mounting pressure on local ecosystems and limited the meaningful participation of local communities in tourism decision-making [7], [8].

Sustainable tourism integrates environmental, socio-cultural, and economic dimensions to ensure that tourism meets present needs without compromising future opportunities [9]-[11]. Achieving this balance demands coordinated commitment from governments, local communities, and private sector stakeholders to safeguard natural resources, cultural heritage, and local livelihoods [12].

Key implementation strategies include community-based tourism (CBT) and strengthened cooperative management models [13]. Empowering local communities not only enhances economic benefits but also reinforces socio-cultural identity and resilience. Critically, their active involvement serves as a buffer against the adverse effects of mass tourism, helping to

protect both environmental integrity and cultural authenticity [14].

On the other hand, sustainable tourism development demands careful planning, particularly through ecotourism initiatives in customary lands and dedicated nature conservation efforts [15]-[17]. A study in the Guguk Customary Forest demonstrated that engagement with environmentally conscious tourists reinforced sustainable tourism practices. Supporting infrastructure, such as eco-friendly accommodations and culturally grounded tourism activities, also plays a vital role in conserving natural resources while enhancing local livelihoods [18].

Ultimately, sustainable tourism must be embedded within the broader sustainable development framework, in alignment with the United Nations Sustainable Development Goals (SDGs) [19]-[20]. The necessity of cross-sectoral synergy is underscored, particularly with education and technology, to strengthen sustainable destination promotion and management [21]. Achieving this transformation is not the responsibility of a single actor; rather, it requires consistent, integrated collaboration among multiple stakeholders across government levels and local communities [22].

Although tourism growth significantly contributes to regional income, it simultaneously exerts substantial pressure on Lake Toba's environmental carrying capacity [23], [24]. Optimizing spatial planning is therefore critical to effectively balance land-use allocation, tourism infrastructure development, and natural resource conservation [25]-[27]. The geopark and ecotourism frameworks already established in the region offer strong potential for integration into sustainability-oriented spatial planning strategies [28], [29].

Beyond environmental considerations, holistic community empowerment is essential to ensure that tourism revenues benefit local populations, not only external or large-scale investors [30]-[32]. In this context, participatory planning approaches that incorporate local wisdom and prioritize community-driven infrastructure development are particularly relevant [33]-[35].

Achieving sustainable tourism in the Lake Toba region further requires cross-sectoral synergy: spanning spatial planning, environmental management, tourism, education, and information technology [36], [37]. Destination development grounded in local cultural identity and ecological sustainability can significantly enhance Lake Toba's competitiveness at both national and international levels [38].

The urgent need to integrate sustainability-oriented spatial planning with holistic local community empowerment in the development of the Lake Toba tourism area underscores the timeliness and relevance of this study [1], [8]. Without strategic planning interventions, unchecked tourism growth risks accelerating environmental degradation and exacerbating the socio-economic marginalization of local communities, thereby undermining progress toward the Sustainable Development Goals (SDGs) in the region [6], [39].

Previous research has addressed aspects of sustainable tourism in Lake Toba. For instance, its economic, environmental and cultural impacts were examined by [1], while the role of geoparks in destination development was explored by [28]. However, few studies have synthesized spatial planning optimization and community empowerment within a unified, integrative framework, particularly in the context of Indonesia's designated super-priority tourism destinations.

This study therefore aims to: (1) identify and evaluate spatial planning strategies that support sustainable tourism development in the Lake Toba region, and (2) propose a holistic community empowerment model designed to enhance the social, cultural, and economic sustainability of local livelihoods.

2. Methodology

This study employs a mixed-methods approach, integrating quantitative and qualitative techniques to holistically examine spatial planning optimization in the Lake Toba region across social, economic, cultural, and environmental dimensions [40]. A participatory methodology was also implemented, actively engaging local communities and key stakeholders in the research process.

Furthermore, the study adopts a social-ecological systems (SES) framework to analyze the dynamic interactions between human activities and environmental processes in the Lake Toba area.

2.1. Study Area and Timeframe

The study was conducted in the Lake Toba region, encompassing seven surrounding

regencies: Samosir, Toba, Humbang Hasundutan, North Tapanuli, Dairi, Pakpak Bharat, and Karo. Fieldwork and data collection were carried out between June and December 2024.

2.2. Data Types and Sources

This study utilized both primary and secondary data. Primary data were collected through:

- Structured questionnaire surveys administered to local residents and tourists,
- In-depth interviews with community leaders, tourism entrepreneurs, and local government officials, and
- Focus group discussions (FGDs) with diverse community groups.

Secondary data, including spatial maps from the Regional Spatial Plan (RTRW), tourism statistics, environmental quality indicators, and relevant regional development policy documents, were obtained through documentary analysis.

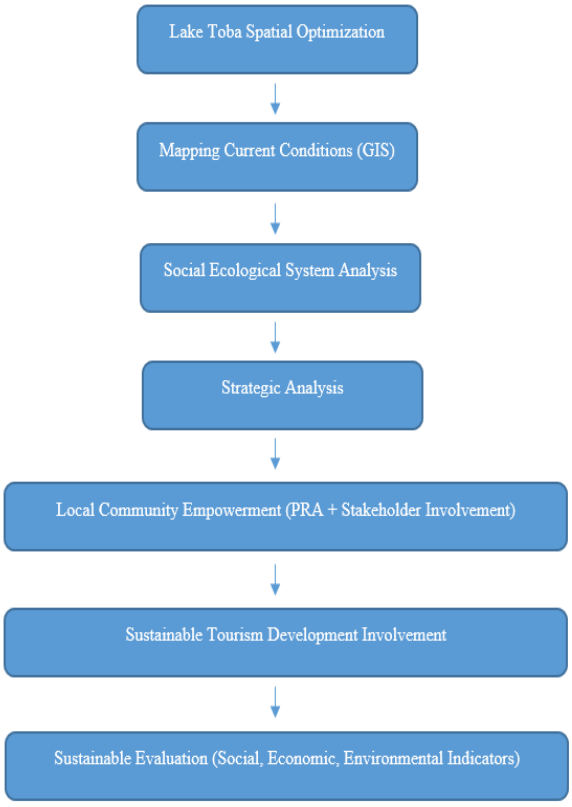

Figure 1. Conceptual framework of sustainable tourism development in Lake Toba (designed by the authors)

2.3.Data Collection Techniques

The following data collection methods were employed:

1. Surveys to gather quantitative data on local residents' and tourists' perceptions of spatial planning and tourism management.
2. In-depth interviews with community leaders, tourism managers, and local government officials to explore their perspectives in depth.
3. Focus Group Discussions (FGDs) to enhance participatory analysis and co-identify community-driven solutions.
4. Spatial data acquisition using satellite imagery and official land-use maps.

2.2. Data Analysis Techniques

Data analysis was conducted in five integrated stages:

1. GIS-based mapping to visualize current land-use patterns, tourism zones, and conservation areas across the Lake Toba region.
2. Social-Ecological System (SES) analysis to examine interactions between human activities and ecosystem dynamics, thereby assessing environmental pressures and impacts.
3. SWOT analysis to identify internal strengths and weaknesses, as well as external opportunities and threats to regional development; complemented by the Analytical Hierarchy Process (AHP) to prioritize strategic actions in spatial planning optimization and community empowerment.
4. Participatory analysis using Participatory Rural Appraisal (PRA) and Stakeholder Analysis to ensure inclusive engagement of local communities and relevant actors in the planning process.
5. Sustainability evaluation based on Triple Bottom Line (TBL) indicators—encompassing social, economic, and environmental dimensions—to assess outcomes of spatial optimization and empowerment interventions.

2.3. Population and Sampling

The study population comprised local residents living in the Lake Toba region, tourists visiting the area, and stakeholders engaged in tourism governance and development.

A mixed sampling strategy was applied:

- Purposive sampling was used for in-depth interviews, selecting key informants based on predefined criteria (e.g., active involvement in spatial or tourism management, or demonstrated influence within the community).

- Stratified random sampling was employed for surveys of residents and tourists to ensure proportional representation across key strata, including geographic location, age group, and tourist origin (domestic vs. international).

The final sample sizes were as follows:

1. Local community: From a total population of approximately 1,360,000, a representative sample of 400 respondents was selected.
2. Tourists: From an estimated annual visitation of ~450,000, a sample of 400 tourists was drawn.
3. Stakeholders: From an estimated pool of 50–100 active stakeholders, 15–25 key informants were selected through purposive sampling.

This approach is designed to yield a representative understanding of on-the-ground conditions, capturing perspectives from local communities, tourists, and stakeholders involved in the sustainable tourism–based optimization of spatial planning.

3. Results and Discussion

The satellite-derived map of the Lake Toba region reveals a diverse ecosystem dominated by natural vegetation encircling the expansive lake (Figure 2). Lake Toba itself constitutes the central geographic feature, surrounded by predominantly green landscapes that suggest relatively well-preserved natural conservation areas, particularly along the western and northern perimeters of the region.

Figure 2. Google satellite imagery of the study area

Several road networks (depicted as gray lines in Figure 2) traverse the landscape surrounding Lake Toba, linking key settlements such as Parapat, Balige, and Pangururan. These routes also delineate zones exhibiting signs of ecological degradation attributable to anthropogenic activities. Major tourist sites, indicated by red star symbols, are concentrated along strategic locations, particularly the Samosir coastline and the Parapat area, reflecting the spatial clustering of tourism development.

In contrast, transparent green overlays highlight areas of high ecological value that remain relatively intact and hold significant potential for conservation or community-based ecotourism. This spatial representation underscores the critical need for stringent land-use governance to balance ongoing tourism expansion with the preservation of natural ecosystems, especially as evidence of human-induced environmental pressure becomes increasingly apparent in vulnerable zones.

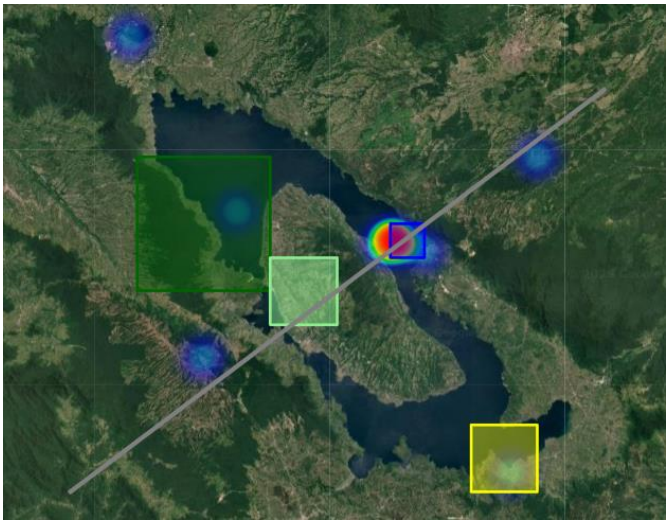

Figure 3. Tourist heatmap and zoning of the Lake Toba

An interactive map of the Lake Toba region, integrating tourist distribution heatmaps with land-use zoning (Figure 3), offers a comprehensive overview of the area's spatial dynamics. The heatmap reveals intense tourist activity concentrated in Parapat, Tuk-Tuk (Samosir), Tomok, and Balige, identifying these locations as primary tourism hubs and focal points of tourism-driven economic activity. The high visitor density in these zones underscores an urgent need for more effective sustainable

tourism management, particularly with regard to environmental carrying capacity.

The accompanying zoning map delineates functional land-use categories across the region. Conservation areas are depicted in dark green, signifying zones of high ecological value that must be safeguarded from conversion or degradation. Tourism and recreation zones appear in blue, designating areas either currently supporting or formally designated for tourism development. Settlement zones, shown in yellow, are distributed across strategic locations, typically adjacent to major transportation corridors. Additionally, light green patches highlight underutilized or secondary green spaces that present valuable opportunities for expanding ecological buffers amid rapid infrastructure expansion.

The integration of heatmap and zoning data reveals potential land-use conflicts in several parts of the Lake Toba region, as well as areas with high potential for community-based ecotourism development. This combined visualization serves not only as an analytical tool but also as a foundation for more adaptive, participatory, and sustainability-oriented spatial planning.

GeoJSON-based mapping of tourist distribution and land-use zoning elucidates the complex spatial interplay between human activity and the region's ecological structure. Tourist activity is highly concentrated in Parapat, Tuk-Tuk (Samosir), Tomok, Balige, Pangururan, and Merek, identifying these as primary economic hubs while simultaneously highlighting zones most vulnerable to environmental pressure.

Land-use zoning reflects a relatively clear functional differentiation: conservation areas predominantly coincide with regions of intact natural vegetation; tourism and recreation zones are concentrated along coastlines and established tourist destinations; and residential areas, interspersed with green spaces, form transitional buffers between conservation and tourism functions (Figure 4).

This imbalance in distribution shows the challenges in maintaining the sustainability of the Lake Toba ecosystem, especially in areas with limited conservation space but intensive tourism activities. Therefore, these data emphasize the need for more adaptive spatial planning based on a conservation approach and integrating tourist distribution as a main variable in planning the management of the Lake Toba area.

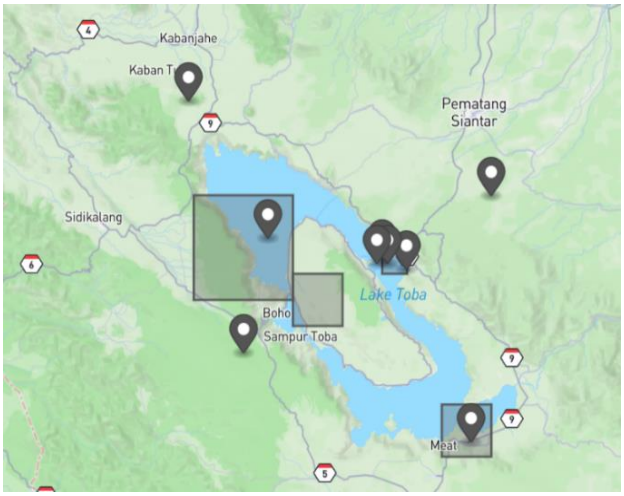

Figure 4. Zoning of the Lake Toba Area and Tourist Heatmap

To prioritize dimensions for sustainable spatial planning, pairwise comparisons were conducted among key stakeholders using the Analytical Hierarchy Process (AHP). The resulting weights and consistency ratio are presented in Table 1.

Table 1. Normalization results and weighting criteria (compiled by the authors)

Criteria	Priority Weight
Ecological Aspects	0.36
Socio-Cultural Aspects	0.26
Infrastructure Aspects	0.18
Economic Aspects	0.12
Aspects of Legal and Planning	0.08

Consistency ratio (CR) = 0.05 → < 0.1, means consistent.

Perceptions of local communities regarding tourism impacts and infrastructure quality were assessed through structured surveys. Key findings on service adequacy and cultural-economic outcomes are summarized in Table 2.

Table 2. Local community perception (compiled by the authors)

Question	Answer	% of the respondents
Quality of road access	Good	52%
Green open space	Enough	48%
Community involvement	Enough	55%
Cultural preservation	Less Attention	42%
Economic benefits	Enough	50%
Waste management	Less	57%

Complementary insights were gathered from tourists to evaluate external perceptions of destination management. Results on infrastructure, cultural visibility, and environmental conditions are detailed in Table 3.

Table 3. Tourist Perceptions (compiled by the authors)

Question	Answer	% of the respondents
Quality of road access	Good	60%
Green open space	Adequate	55%
Community involvement	Large	45%
Cultural preservation	Notice	50%
Visible economic benefits	Large	40%
Waste management	Adequate	48%

While both groups report moderate satisfaction with road access and green space, significant concerns emerge regarding waste management (57% of locals rate it as "insufficient") and limited visibility of community benefits, particularly among tourists (60% perceive economic spillovers as low). These perceptual gaps are further corroborated by the Social-Ecological System (SES) analysis in Table 4, which directly links anthropogenic pressures, such as unregulated tourism infrastructure and inadequate waste systems, to tangible ecological outcomes, including habitat fragmentation, lake eutrophication, and green space loss. Together, these findings reveal a systemic misalignment between stated planning priorities and actual development practices, underscoring the urgency of adaptive governance that bridges policy intent with ecological and social realities.

Table 4. Social-Ecological System Analysis (compiled by the authors

Human Activities	Ecosystem Impact	Information
Massive tourism development (hotels and resorts)	Fragmentation of the natural habitat	Especially in Samosir and Parapat
Lack of waste management	Degradation of the Lake Water Quality	Especially in tourist centers
Urbanization of the villages	Pressure on the green space	Villages around Balige and Tomok
Traditional agricultural activities	Limited deforestation	On the slopes of the lake area

Human activities in the Lake Toba region have exerted significant ecological pressures, manifesting in multiple interconnected impacts. Large-scale tourism development, particularly in Samosir and Parapat, has driven the fragmentation of natural habitats. Inadequate waste management systems in high-traffic tourist centers have contributed to the degradation of lake water quality. Concurrently, the urbanization of villages around Balige and Tomok has intensified pressure on green spaces, reducing ecological buffers. While traditional agricultural practices on lakeside slopes have led to only limited deforestation, they nonetheless reflect

ongoing land-use transformation. Critically, these environmental stresses are exacerbated by a pronounced imbalance between economic exploitation and conservation efforts that is a gap further widened by the low level of local community participation in environmental stewardship.

The strategic direction for Lake Toba's sustainable development was further refined through a combined SWOT–AHP analysis. As shown in Table 5, the region's strengths (natural and cultural assets) are offset by systemic weaknesses in governance and infrastructure, while external pressures threaten its ecological integrity.

Table 5. SWOT + AHP analysis (compiled by the authors)

Strength	Weakness	Opportunity	Threat
Natural beauty of the iconic Lake Toba	Inadequate road infrastructure and waste management	Potential for Sustainable Ecotourism Development	Environmental degradation and lake pollution
Strong and unique Batak culture	Community participation in management remains low	Support from the central and regional governments	Land conversion without proper planning

Table 6 quantifies these insights, confirming ecological conservation (0.36) and socio-cultural empowerment (0.26) as the highest strategic priorities, providing a clear mandate for conservation-led spatial planning.

Table 6. AHP Strategic Priorities (compiled by the authors based on AHP data)

Priority	Weight	Information
Ecological Aspect	0.36	The main focus of environmental conservation
Socio-Cultural Aspect	0.26	Community empowerment and cultural preservation
Infrastructure Aspect	0.18	Improvement of accessibility and basic facilities
Economic Aspect	0.12	Strengthening the sustainable local economy
Legal and Planning Aspects	0.08	Preparation of spatial planning regulations for tourism

The AHP results (Table 6) indicate that the ecological dimension holds the highest strategic priority in the development of the Lake Toba region, with a weight of 0.36, confirming environmental preservation as the foundational pillar of sustainable development. The socio-cultural dimension ranks second (0.26), underscoring that community empowerment and cultural heritage conservation must be integrated coequally with ecological goals. Infrastructure development follows with a weight of 0.18, reflecting the need to improve accessibility and basic facilities to support, but not dominate, socioeconomic functions. Notably, economic (0.12) and legal/planning (0.08) dimensions are assigned lower priorities, signaling that economic growth and regulatory frameworks should serve as enabling instruments rather than primary drivers of regional development. This hierarchy affirms a conservation-led, community-centered approach to spatial planning in Lake Toba.

The hierarchical structure of strategic priorities derived from the Analytical Hierarchy Process is visually summarized in Figure 5, which presents the relative weights of the five key dimensions for sustainable spatial planning in Lake Toba. This graphical representation aligns with the quantitative results in Table 6, reinforcing the primacy of ecological and socio-cultural considerations in policy design.

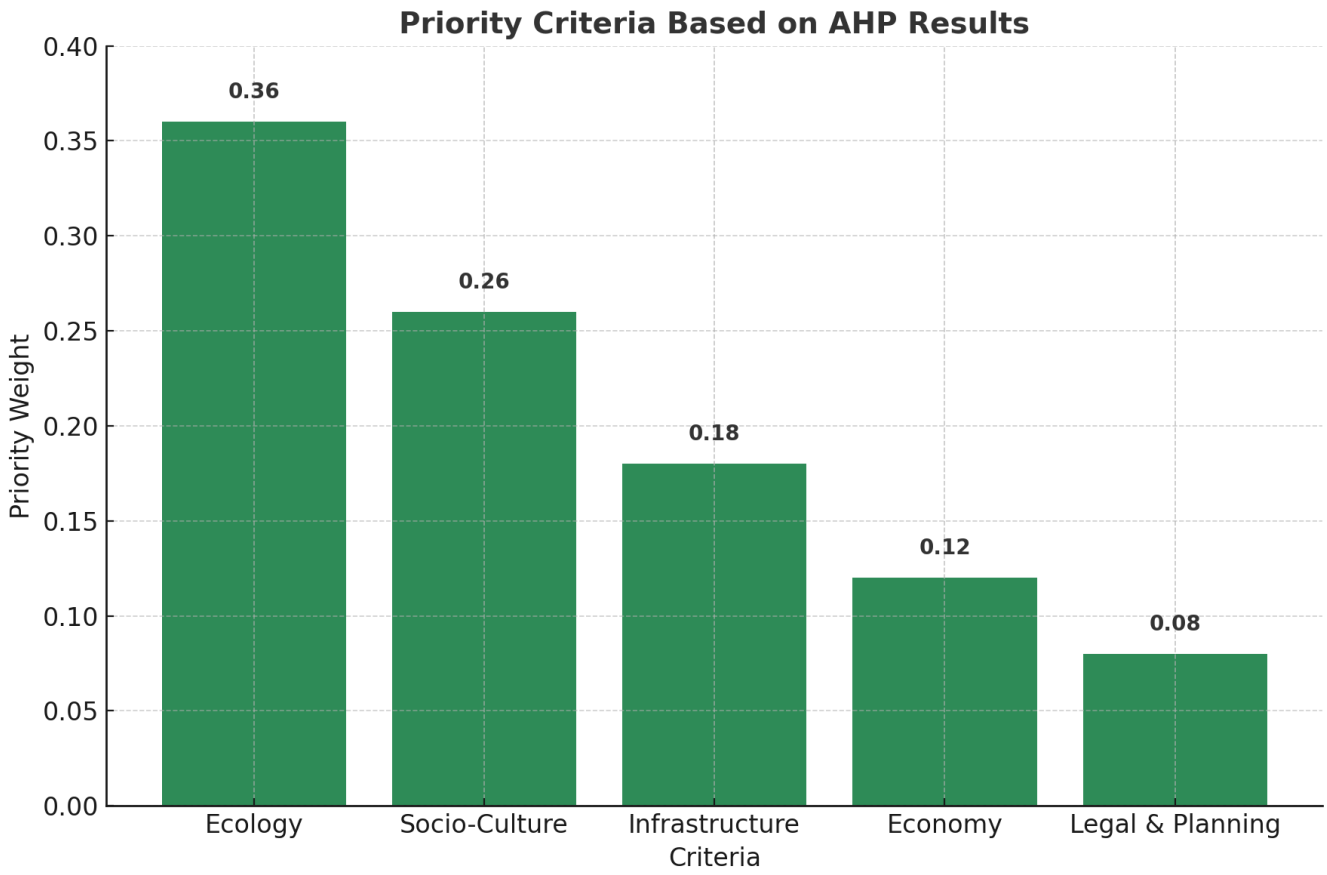

Figure 5. Priority criteria for sustainable spatial planning in the Lake Toba region based on AHP-derived weights

Effective spatial governance in complex socio-ecological landscapes requires inclusive decision-making that accounts for the diverse roles, interests, and capacities of all stakeholders. To this end, a participatory approach combining Participatory Rural Appraisal (PRA) and Stakeholder Analysis was employed to map actor dynamics in the Lake Toba region. As summarized in Table 7, local communities, despite holding medium influence, demonstrate high interest as cultural stewards and customary landowners, yet remain underrepresented in formal planning processes.

Table 7. Participatory analysis (PRA + stakeholder analysis)

Stakeholder Analysis

Stakeholder	Role	Interest	Strength
Local Community	Cultural and landowners	High	Medium
Local Government	Regulation and policy	High	High
Tourists	Consumers of the tourism service	Medium	Low
Environmental NGOs	Conservation and education	High	Medium
Private (Hotel/Travel)	Investment and development	High	High

The Participatory Rural Appraisal (PRA) results reveal that local communities express a strong willingness to play a more active role in tourism governance and environmental

conservation in the Lake Toba region, with a clear demand for capacity-building support, particularly in areas such as eco-guiding and hospitality training. This aspiration, however, is not fully matched by influence. Stakeholder analysis indicates that, despite their high interest as custodians of cultural heritage and customary land, local communities possess only moderate decision-making power. In contrast, local government agencies and private sector actors (e.g., tourism investors and operators) exhibit both high interest and high influence, positioning them as dominant drivers of regional development trajectories. This asymmetry underscores the need for institutional mechanisms that amplify community agency and ensure their meaningful participation in shaping sustainable tourism futures.

Table 8. Sustainability Evaluation (Triple Bottom Line)

Dimensions	Indicator	Evaluation
Social	Level of community participation and cultural preservation	Enough, the need to increase community involvement
Economic	Local economic benefits and SME growth	There is growth, but it is not evenly distributed
Environment	Water quality, green space, and waste management	Many ecological pressures that require intervention

The sustainability assessment of the Lake Toba region, conducted through the Triple Bottom Line (TBL) framework (Table 8), reveals a mixed performance across social, economic, and environmental dimensions. Socially, community participation in tourism governance and cultural preservation is perceived as adequate, yet deeper and more active engagement remains necessary to ensure inclusive decision-making. Economically, local benefits, particularly through the growth of micro, small, and medium enterprises (MSMEs), are evident, though their distribution is markedly uneven, favoring established tourism hubs over peripheral communities. Environmentally, however, the situation is concerning: persistent ecological pressure is reflected in declining lake water quality, shrinking green spaces, and inadequate waste management systems, indicating that current development patterns exceed local carrying capacity.

These pressures are spatially manifest in the region's fragmented land-use pattern, as revealed by GIS-based mapping. Tourism infrastructure and settlements are expanding rapidly in key nodes – Parapat, Balige, and Tuk-Tuk (Samosir) – while relatively intact natural vegetation persists in the western and northern peripheries, particularly in Pakpak Bharat and Humbang Hasundutan Regencies. This spatial dichotomy underscores a core tension in the region's development trajectory.

Further corroborated by socio-ecological system (SES) analysis, human activities, including unregulated tourism construction, village urbanization, and slope agriculture, have directly contributed to environmental degradation, most acutely in water quality. Both community and tourist surveys highlight widespread dissatisfaction with waste management and insufficient attention to cultural heritage, reinforcing a critical imbalance: economic exploitation continues to outpace investments in ecological resilience and socio-cultural integrity.

Collectively, these findings signal an urgent need for integrated, place-based interventions that recalibrate spatial planning toward conservation-led, community-anchored tourism development.

The SWOT analysis identifies the Lake Toba region's core strengths (its iconic natural landscape and the richness of Batak cultural heritage) amplified by strategic opportunities such as national-level support for tourism development. However, these assets are counterbalanced by critical weaknesses, particularly the limited involvement of local communities in governance, and significant threats, including environmental degradation driven by unregulated tourism infrastructure expansion.

This tension is further clarified by the Analytical Hierarchy Process (AHP), which assigns the highest strategic weight to ecological considerations (0.36), followed by socio-cultural

(0.26) and infrastructure dimensions (0.18). This prioritization signals that sustainable development in Lake Toba must be anchored in ecological conservation and community empowerment, rather than prioritizing physical or economic expansion alone.

Participatory Rural Appraisal (PRA) and Stakeholder Analysis corroborate this insight: local communities express a strong desire to engage more meaningfully in tourism management and environmental stewardship, yet institutional and private-sector actors have not established effective mechanisms to facilitate their participation. Consequently, decision-making remains concentrated among high-influence stakeholders, marginalizing grassroots voices.

This governance gap is reflected in the Triple Bottom Line (TBL) sustainability assessment, which confirms that while localized economic benefits are emerging, primarily through MSME development, environmental impacts, particularly water quality decline and inadequate waste management, remain inadequately addressed. Together, these findings underscore a systemic misalignment between policy priorities and on-the-ground realities, calling for a recalibration of spatial planning toward inclusive, conservation-led tourism governance.

This study builds upon and extends key insights from prior research on the Lake Toba region. Notably, the aquaculture carrying capacity of the lake was modeled, demonstrating that unregulated expansion of aquaculture and tourism has significantly degraded water quality [41]. Similarly, it was emphasized by [42] how tourism intensifies pressure on ecosystem services and advocated for GIS-based conservation zoning to support more resilient socio-ecological systems.

The research findings corroborate and deepen these earlier conclusions. Spatial analysis confirms pronounced land-use fragmentation around Lake Toba, driven by synergistic pressures from tourism infrastructure development, settlement expansion, and associated urbanization, all of which accelerate ecological degradation across multiple sub-watersheds. Crucially, the Analytical Hierarchy Process (AHP) results reinforce that ecological integrity (weight = 0.36) and socio-cultural resilience (0.26) must serve as the twin pillars of regional development strategy, thereby affirming that long-term sustainability hinges on both environmental protection and meaningful community empowerment.

Where this study advances the existing literature is in its integrative methodological framework. By incorporating participatory tools, specifically Focus Group Discussions (FGDs) and Participatory Rural Appraisal (PRA), alongside a comprehensive Triple Bottom Line (TBL) sustainability assessment, we capture not only biophysical trends but also the social and institutional dimensions of sustainability. Furthermore, the application of AHP to prioritize development strategies based on multi-stakeholder perceptions introduces a deliberative, consensus-driven dimension that has been underexplored in prior work on Lake Toba.

Collectively, these contributions strengthen the empirical and normative foundation for sustainable tourism governance in the region, offering a more holistic, community-anchored, and spatially explicit approach to optimizing the management of one of Indonesia's most iconic and vulnerable landscape-scale destinations.

Figure 6. Risk and Opportunity Map for Lake Toba

The spatial analysis reveals that areas categorized as high risk (red) are locations experiencing significant ecological pressure due to intensive development activities, particularly around major tourist centers (Figure 6). Moderate-risk (orange) zones are identified as transitional areas where signs of environmental stress are beginning to emerge but remain manageable with appropriate planning interventions. In contrast, areas with high opportunity (green) are regions with strong potential for ecotourism development and the preservation of green open spaces, given their relatively undisturbed natural conditions. Moderate-opportunity (blue) areas represent zones that could be sustainably developed under controlled, conservation-based planning, ensuring a balance between growth and ecological protection.

Spatial mapping of the Lake Toba region reveals an uneven distribution of risk and opportunity zones in the context of sustainable development. Areas at high risk of environmental degradation are concentrated around major tourist centers such as Parapat and Tuk-Tuk (Samosir), where tourism infrastructure expansion and new settlements have exerted pressure on local ecosystems—particularly water quality and green spaces. Moderate-risk zones are distributed across transitional areas between settlements and conservation zones. Conversely, opportunities for conservation-oriented development have been identified in locations still connected to intact natural green spaces, especially in the southwestern and northeastern parts of Lake Toba. These areas hold significant potential for ecotourism, green open space preservation, and community-based initiatives that can enhance socio-ecological sustainability.

Overall, the findings confirm that development in the Lake Toba region must be grounded in environmental conservation and community empowerment, with spatial planning informed by empirical spatial data and a comprehensive participatory approach.

4. Conclusion

This study demonstrates that sustainable management of the Lake Toba region must be grounded in environmental conservation and the holistic empowerment of local communities. Spatial analysis indicates that unregulated tourism development has contributed to green space fragmentation and intensified ecological pressures. Although local community involvement is emerging, its current scope remains insufficient to ensure long-term sustainability. Therefore, optimizing adaptive spatial planning, supported by empirical data, is essential to balance economic growth with cultural preservation and environmental protection.

The findings underscore the need for stricter spatial planning regulations to limit development in conservation zones and green areas, alongside community empowerment initiatives such as eco-guiding capacity building and the promotion of a culture-based creative economy. Tourism infrastructure development must adhere to green growth principles, with waste management and water quality control prioritized at every stage of destination planning.

This research is constrained by spatial and temporal limitations, as data collection occurred within a restricted timeframe and did not cover the entire Lake Toba region. Moreover, the complexity of local political dynamics is only partially reflected in the stakeholder analysis.

Future studies should integrate longitudinal assessments with multi-temporal satellite imagery to capture dynamic land-use patterns. Expanding stakeholder participation to include village-level and Indigenous communities is also critical. Furthermore, incorporating machine learning–based spatial prediction models holds promise for projecting future land-use change scenarios, particularly under accelerating climate change.

Declarations

Authors' Contribution

Conceptualization, M.A.K.H. and U.H.; methodology, M.A.K.H. and A.P.; software, A.A.N.; validation, M.A.K.H.; formal analysis, M.A.K.H. and U.H..; research, M.A.K.H., and L.J.; resources, L.J.; data curation, M.A.K.H., and U.H.; original drafting-drafting, all authors contributed equally; drafting-revising and editing, M.A.K.H.; visualization, A.P. and A.A.N.; supervision, M.A.K.H.; project administration, M.A.K.H. All authors have read and accepted the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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The research was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Boards of

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Informed Consent Statement

The study was developed with the prior signed consent of the participants.

Conflict of Interest

The authors declare that they had no conflicts of interest during the development of the research.

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