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UNESCO Geopark Designation Lake Toba, North Sumatra, Indonesia: Econometric Descriptive Analysis Before and After

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study analyzes land-use changes in the lakeside area of Lake Toba in Toba Regency before and after its designation as a UNESCO Global Geopark in 2020. Using satellite imagery, drone-assisted surveys, and field observations, the study quantifies specific changes in land cover and evaluates the impact of Geopark designation on environmental, social, and economic sustainability. Between 2015 and 2023, natural vegetation increased by 8%, erosion-prone areas reduced by

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12%, and compliance with zoning regulations improved by 15%. Environmental indicators such as phosphate concentrations dropped from 0.5 mg/L to 0.2 mg/L, while dissolved oxygen levels rose from 4.5 mg/L to 6.0 mg/L, signaling better water quality. However, challenges remain, including uneven community participation and gaps in zoning enforcement. Socially, community income from ecotourism activities increased by 25%, based on surveys and interviews conducted with local residents and stakeholders. The study highlights the importance of collaborative management frameworks involving governments, communities, and private sectors to ensure sustainable development. The findings provide strategic policy recommendations for adaptive environmental management, offering a replicable model for other tourism regions in Indonesia and beyond.

Keywords: Lake Toba; UNESCO geopark; land use; environmental sustainability; community involvement.

1. INTRODUCTION

Land use reflects human activities that physically alter the Earth's surface, with significant implications for ecological, social, and economic systems (Turner, 2007 and Lambin, 2006). Urban areas often experience rapid land-use changes, yet rural regions, including lakeside zones, face mounting challenges from unsustainable land-use practices (Nyamweya, 2023 & Ali, 2024). These practices often disrupt ecological functions, particularly in critical areas like riparian zones, where unchecked exploitation leads to environmental degradation and socioeconomic risks (Habel, 2021 and Karangi, 2017).

Lake Toba, the world's largest volcanic lake and a UNESCO Global Geopark, holds immense ecological, cultural, and economic value. The Geopark designation in 2020 aimed to promote conservation, sustainable tourism, and local development. However, the lakeside areas have faced persistent challenges, including deforestation, unplanned settlements, and intensive fish farming, which have exacerbated erosion, reduced water quality, and strained local biodiversity. These issues underline the need for integrated spatial and environmental management (Narendra, 2021; Basuki, 2021; Cooper 2010).

This study investigates the impact of the Geopark designation on land-use changes in Lake Toba's lakeside areas between 2015 and 2023, focusing on ecological recovery, regulatory enforcement, and socioeconomic outcomes. Unlike prior research that emphasizes general land-use dynamics (Salazar, 2023 and Apriyanto 2023), this study incorporates spatial data analysis, stakeholder interviews, and field observations to provide a comprehensive evaluation of the Geopark's effectiveness.

Key objectives include:

1. Quantifying changes in land use and environmental quality before and after the Geopark designation.
2. Assessing the impact of zoning regulations and conservation programs on mitigating ecological damage.
3. Evaluating socioeconomic changes, particularly community involvement in sustainable tourism and natural resource management.

By addressing these aspects, this research contributes to the global understanding of how geoparks can integrate environmental preservation with sustainable development. The findings aim to support policy recommendations for adaptive management in Lake Toba and similar regions worldwide.

2. RESEARCH METHODOLOGY

2.1 Research Location and Time

This study was conducted in the lakeside areas of Lake Toba, specifically within the administrative region of Toba Regency. Geographically, Toba Regency lies between coordinates 2°03'–2°40' North Latitude and 98°56'–99°40' East Longitude, at an elevation of 900–2,200 meters above sea level. The regency is bordered by Simalungun Regency to the north, Labuhan Batu and Asahan Regencies to the east, North Tapanuli Regency to the south, and Humbang Hasundutan Regency to the west.

The research focused on nine sub-districts within the lakeside areas: Ajibata, Lumban Julu, Porsea, Uluan, Siantar Narumonda, Sigumpar, Laguboti, Balige, and Tampahan. Data collection was conducted from January to December 2024.

2.2 Data Sources

This study utilized two types of data:

1. Primary Data

- Collected through field observations, including identifying recent land-use changes, visual documentation, GPS-based location mapping, drone-assisted surveys, and satellite imagery analysis before and after the Geopark designation.

2. Secondary Data

- Obtained from official documents and relevant institutions, including:

- Base maps (Indonesian Topographic Map, scale 1:50,000).
- Thematic maps such as regional spatial plans (RTRW), indicative maps of spatial utilization violations, geological maps, and rainfall data.
- Demographic data and spatial policies from agencies such as BPS (Statistics Indonesia), the Public Works and Housing Office (PUPR), and the Regional Development Planning Agency (Bappeda) of Toba Regency.

This study utilized a combination of primary and secondary data:

2.2.1 Primary data

- **Field Observations**: Direct observations of lakeside conditions, with a focus on areas affected by land-use changes, were conducted to validate remote sensing results.
- **Drone-Assisted Surveys**: High-resolution imagery was captured using drones to complement satellite imagery and improve spatial accuracy.
- **Stakeholder Interviews**: Semi-structured interviews were conducted with local residents, community leaders, and experts to gather qualitative insights on socioeconomic impacts and community engagement.

2.2.2 Secondary data

- **Spatial Data**: Includes topographic maps (scale 1:50,000), thematic maps (e.g., land cover, spatial plans, geological features), and rainfall data sourced from government agencies.
- **Demographic and Policy Data**: Collected from the Toba Regency Development Planning Agency (Bappeda), Statistics Indonesia (BPS), and relevant ministries.
- **Environmental Data**: Water quality metrics, including phosphate levels and dissolved oxygen, were sourced from local environmental monitoring agencies.

2.3 Data Collection Methods

2.3.1 Ground truthing

Field visits were conducted to validate GIS and remote sensing data, particularly for high-impact areas identified through satellite and drone imagery.

2.3.2 Interviews and surveys

To assess the social and economic impacts of the Geopark designation, interviews were conducted with 50 local stakeholders, including residents, community leaders, and tourism operators.

2.3.3 Spatial data processing

The Simple Additive Weighting (SAW) method was used to analyze spatial suitability for land use, combining parameters such as elevation, distance from the shoreline, and compliance with zoning regulations. Overlay techniques were applied using GIS software to identify changes in land use and zoning compliance between 2015 and 2023.

2.4 Data Analysis

2.4.1 Quantitative analysis

- **Land Cover Changes**: Analyzed through time-series satellite imagery and drone-assisted surveys, focusing on vegetation cover, erosion-prone areas, and zoning compliance.
- **Environmental Indicators**: Water quality data (e.g., phosphate levels, dissolved oxygen) were statistically compared before and after the Geopark designation.
- **Socioeconomic Metrics**: Changes in community income, employment in tourism, and local participation rates were quantitatively assessed.

2.4.2 Qualitative analysis

Findings from interviews were coded and analyzed to identify recurring themes related to community involvement, conservation awareness, and stakeholder collaboration.

2.4.3 Zoning analysis

Overlay techniques were used to assess zoning regulation enforcement and identify areas of compliance and violation. A single map displaying before-and-after scenarios was produced for clarity, as suggested by reviewers.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Overview of toba regency

Toba Regency, part of North Sumatra Province, is located within the Lake Toba area and has been designated as a UNESCO Global Geopark. This research focuses on nine sub-districts within the lakeside area: Ajibata, Lumban Julu, Porsea, Uluan, Siantar Narumonda, Sigumpar, Laguboti, Balige, and Tampahan. Geographically, Toba Regency lies between 2°03'-2°40' North Latitude and 98°56'-99°40' East Longitude, with elevations ranging from 900–2,200 meters above sea level. The region features diverse topography, including flat, sloping, and steep areas.

3.1.2 Physical and demographic conditions

Toba Regency covers a total area of 2,021.80 km², divided into 16 sub-districts. Its varied topography influences land cover and usage patterns.

The population of Toba Regency in 2023 reached 213,850 people, with an average density of 109.86 people per km².

3.1.3 Land use changes (2015–2023)

a. Overview of Changes

Between 2015 and 2023, significant transformations occurred in the land use of Lake Toba's lakeside areas, driven by both human activities and the Geopark designation. Using satellite imagery, drone-assisted surveys, and GIS analysis, this study quantified key changes:

- **Vegetation Cover**: Increased by 8%, from 47% (2015) to 55% (2023), due to reforestation and conservation initiatives.
- **Erosion-Prone Areas**: Reduced by 12%, largely attributable to the planting of local species like pine and erosion-resistant grasses.
- **Compliance with Zoning Regulations**: Improved by 15%, as stricter enforcement discouraged activities such as unregulated construction and intensive fish farming.
- A single, detailed map was developed to illustrate these changes clearly, showing before-and-after scenarios for both land use and zoning compliance.

b. Environmental Indicators

Water quality improvements were significant:

- **Phosphate Levels**: Decreased from 0.5 mg/L to 0.2 mg/L, aligning with government standards.
- **Dissolved Oxygen**: Increased from 4.5 mg/L to 6.0 mg/L, indicative of healthier aquatic ecosystems.
- These metrics underscore the positive impact of reduced floating net cage (FNC) farming and improved waste management in the region.

The morphology and geology of Lake Toba, as illustrated in Fig. 2, are key factors influencing the dynamics of shoreline changes. The availability of satellite imagery data used in this study enables accurate visual interpretation to identify areas prone to abrasion. This data serves as the foundation for designing more adaptive spatial planning policies.

The phenomena of abrasion and erosion along the shoreline of Lake Toba not only reflect geological issues but also highlight the need for a comprehensive approach to managing this area. Through a combination of conservation strategies and community participation, potential threats to Lake Toba’s ecosystem can be minimized, while maximizing its economic benefits as a world-class geopark.

3.1.4 Land cover analysis of lake toba's lakeside

Lake Toba is recognized as a UNESCO Global Geopark for its unique geological, ecological, and cultural values. The designation of Lake Toba as a UNESCO Global Geopark is the result of extensive efforts involving research, policy development, and collaboration among various stakeholders to enhance the protection and sustainable utilization of the region. These efforts began years before the official designation on July 2, 2020, when Lake Toba achieved its status as a UNESCO Global Geopark, an esteemed international recognition. This designation is not merely an acknowledgment but also a responsibility to sustainably manage and develop the area. It carries the hope that Lake Toba will serve as not only an international tourism destination but also a center for education and research on science, culture, and environmental sustainability.

Table 1. Area by sub-district in Toba regency

District	Area (Km²)
Balige	91,05
Tampahan	24,45
Laguboti	73,90
Habinsaran	408,70
Borbor	176,65
Nassau	335,50
Silaen	172,58
Sigumpar	25,20
Porsea	37,88
Pintu Pohan Meranti	277,27
Siantar Narumonda	22,20
Parmaksian	45,98
Lumban Julu	90,90
Uluan	109,00
Ajibata	72,80
Bonatua Lunasi	57,74
Total	2.021,80

Source: BPS Toba Regency, 2024

Below are the results of the 2023 land cover analysis of Lake Toba’s lakeside areas. This analysis reveals variations in land use within the lakeside region. Based on satellite imagery and field surveys, the land cover within 50 meters of Lake Toba's lakeside boundary in Toba Regency can be classified as follows:

3.1.5 Analysis of land conditions before and after geopark designation

The designation of Lake Toba as a UNESCO Global Geopark in 2020 marked a pivotal milestone in environmental conservation and sustainable management efforts in the area. However, prior to this designation, the land conditions in Lake Toba's lakeside zones faced numerous serious challenges caused by uncontrolled human activities. Extensive land exploitation, including large-scale deforestation and unplanned settlement development, posed significant threats to biodiversity and the stability of Lake Toba’s ecosystem. These activities not only disrupted environmental balance but also accelerated soil erosion along the lakeside boundary and increased the risk of abrasion.

As a strategic area with high economic and tourism potential, resource exploitation at Lake Toba often lacked a conservation-focused approach. The conversion of natural forests into agricultural or residential land, land clearing for tourism infrastructure development, and fish farming activities using floating net cages (FNC) without proper waste management increased the pressure on the ecosystem. Consequently, the lake's water quality deteriorated, natural vegetation in the lakeside zones drastically declined, and local biodiversity was disrupted.

Following the Geopark designation, significant changes were observed in the management of lakeside areas. The designation introduced a new framework emphasizing sustainability principles in natural resource utilization. Activities such as fish farming with FNCs are now regulated more strictly in terms of quantity and location to prevent negative impacts on water quality. Furthermore, tourism infrastructure development must comply with stringent environmental regulations, including waste management requirements and the prohibition of construction in critical zones.

The Geopark designation also promoted rehabilitation efforts in degraded areas. Reforestation programs using local plants, such as pine trees and other endemic species, were implemented in lakeside areas to reduce erosion and restore the region's ecological functions. Additionally, the management of domestic and industrial waste around Lake Toba was improved to mitigate pollution, one of the primary threats to the lake's ecosystem.

As a Geopark, Lake Toba is viewed not only as a tourism asset but also as a center for education and conservation. This shift in paradigm—from uncontrolled exploitation to integrated utilization combined with ecosystem preservation—offers dual benefits: safeguarding ecological sustainability while enhancing Lake Toba’s appeal as a world-class global tourism destination.

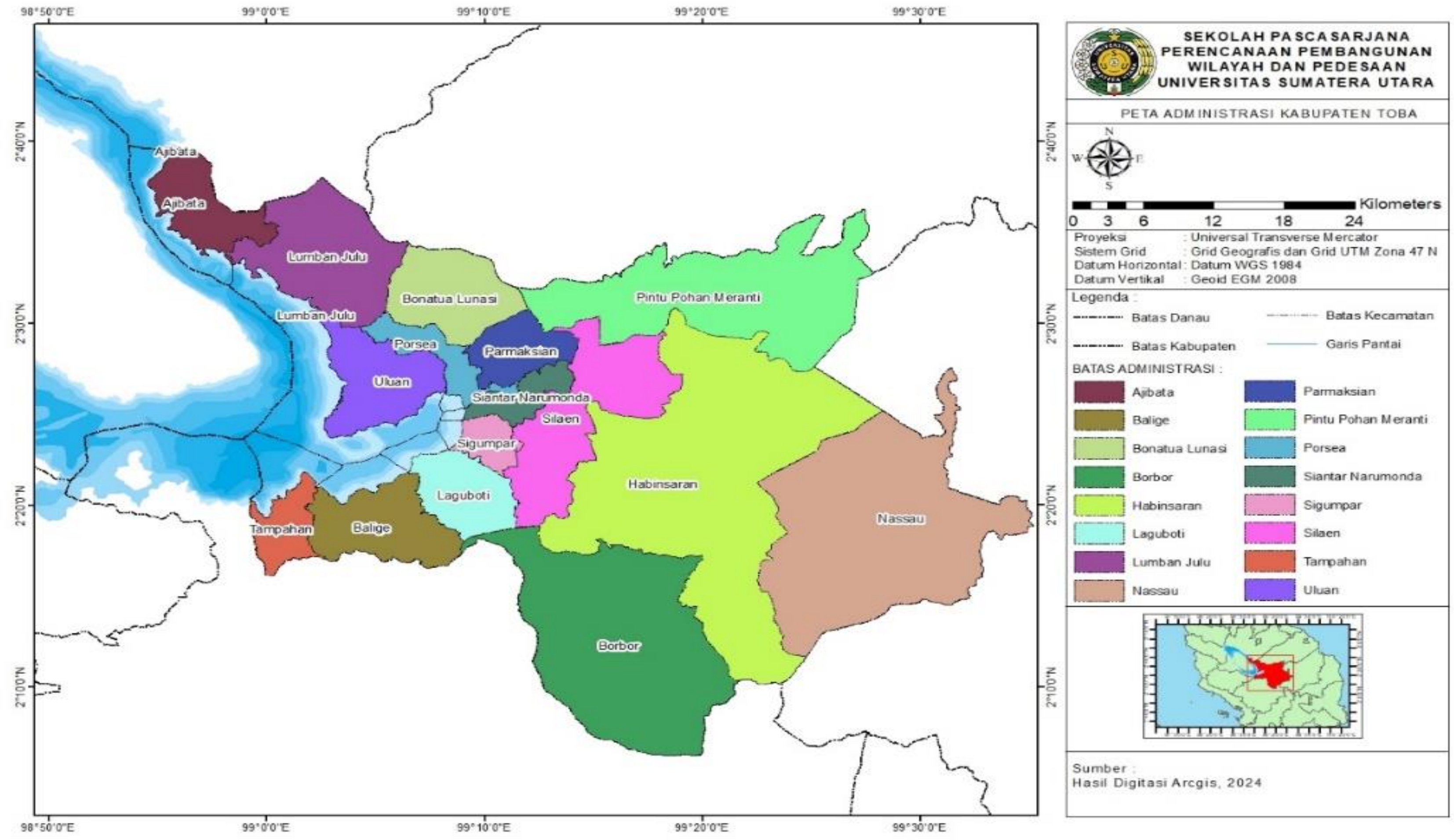

Fig. 1. Administrative map of toba regency
Source: ArcGIS Digitization, 2024

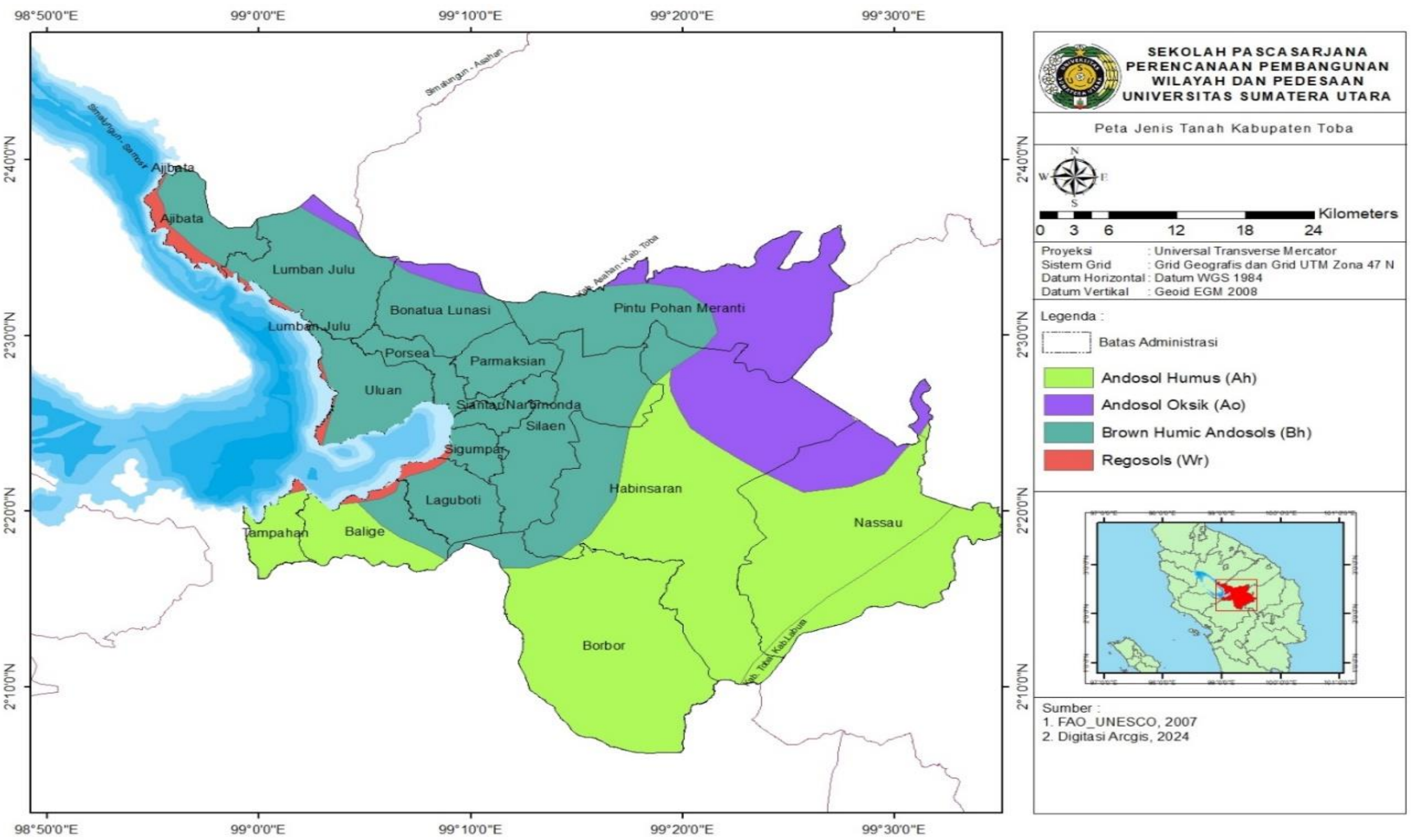

Fig. 2. Soil type map of toba regency

Source: ArcGIS Digitization, 2024

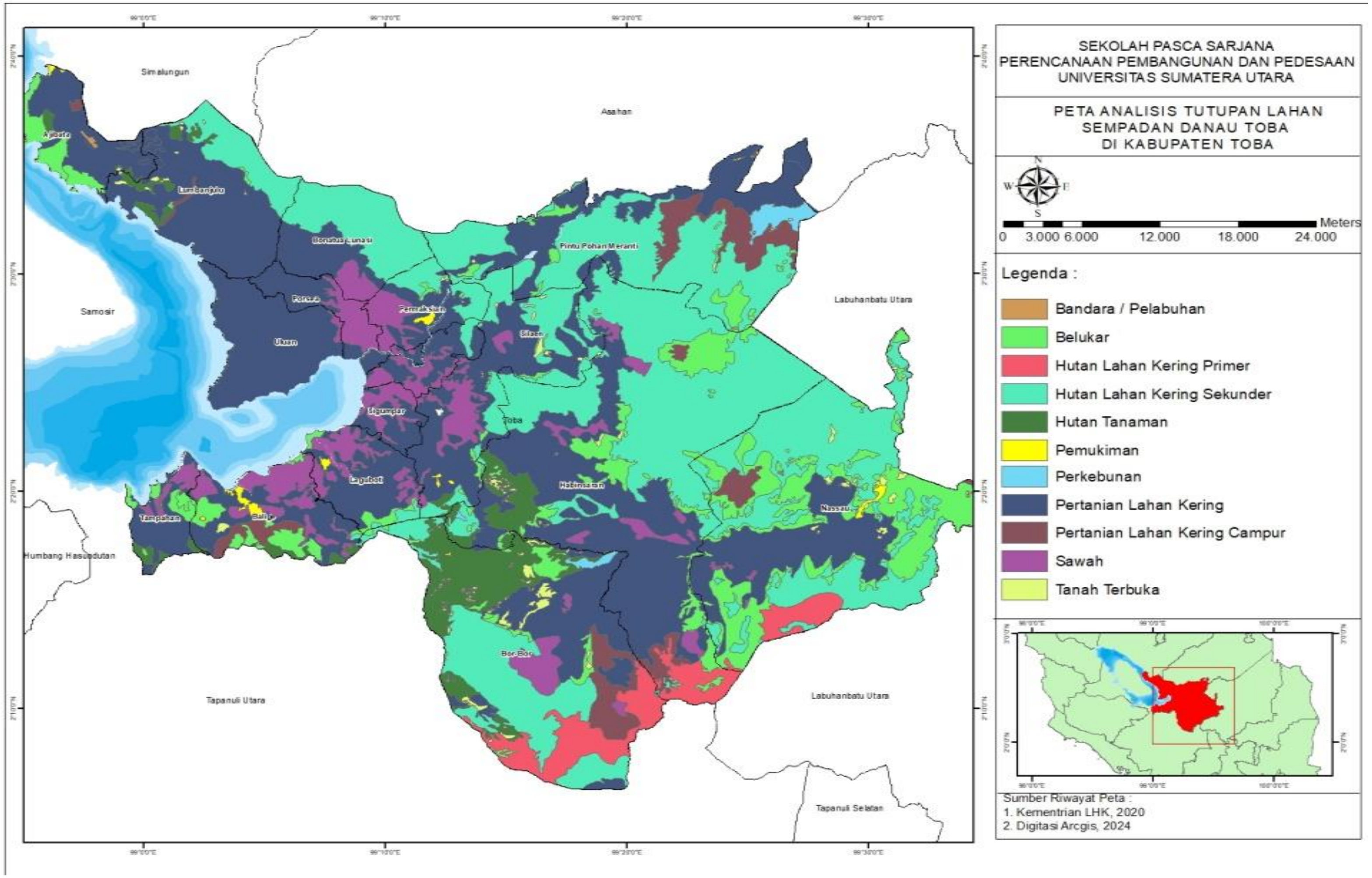

Fig. 3. Land cover map of lake toba in 2020
Source: Research Analysis, 2024

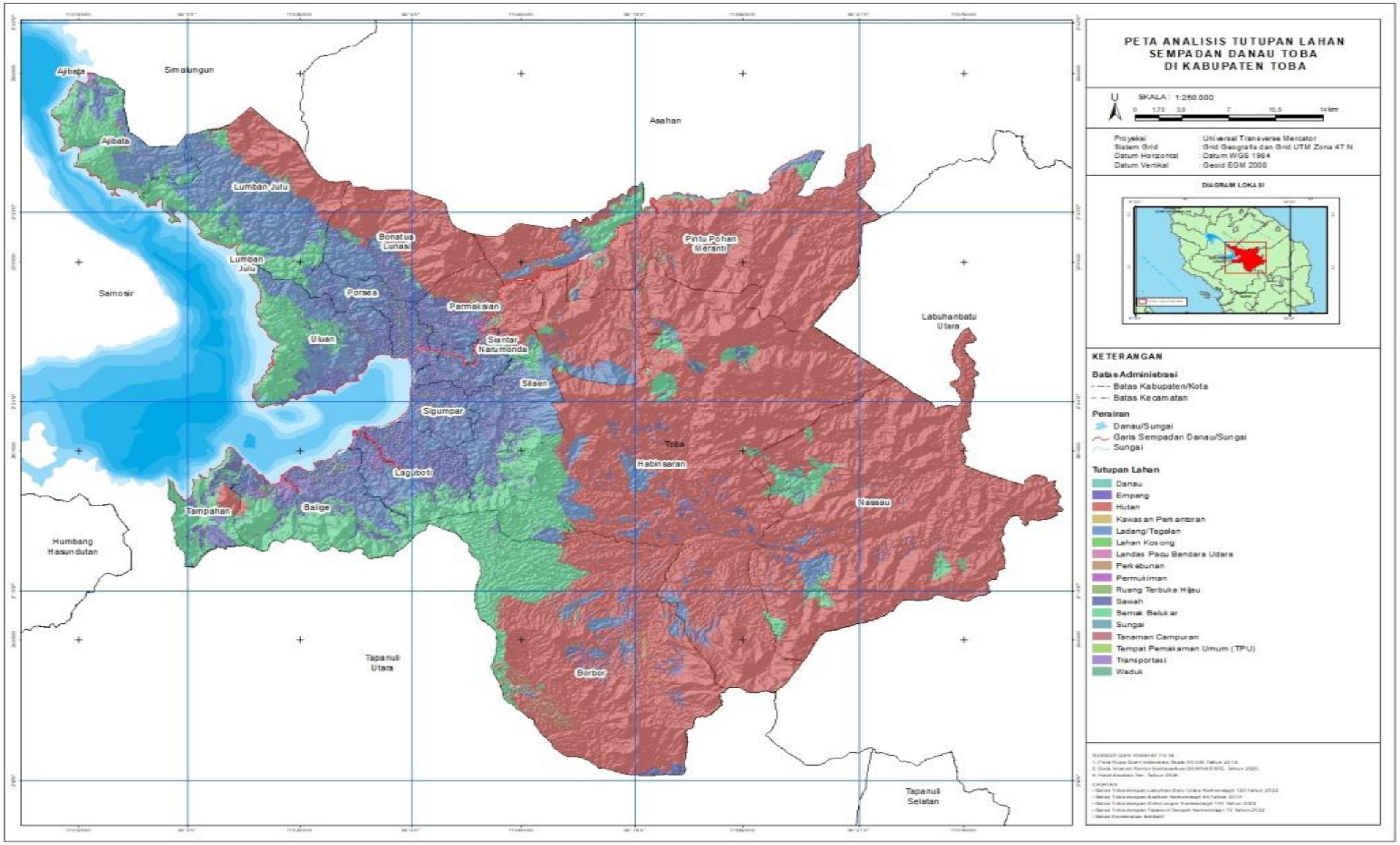

Fig. 4. Land cover map of lake toba in 2023
Source: Research Analysis, 2024

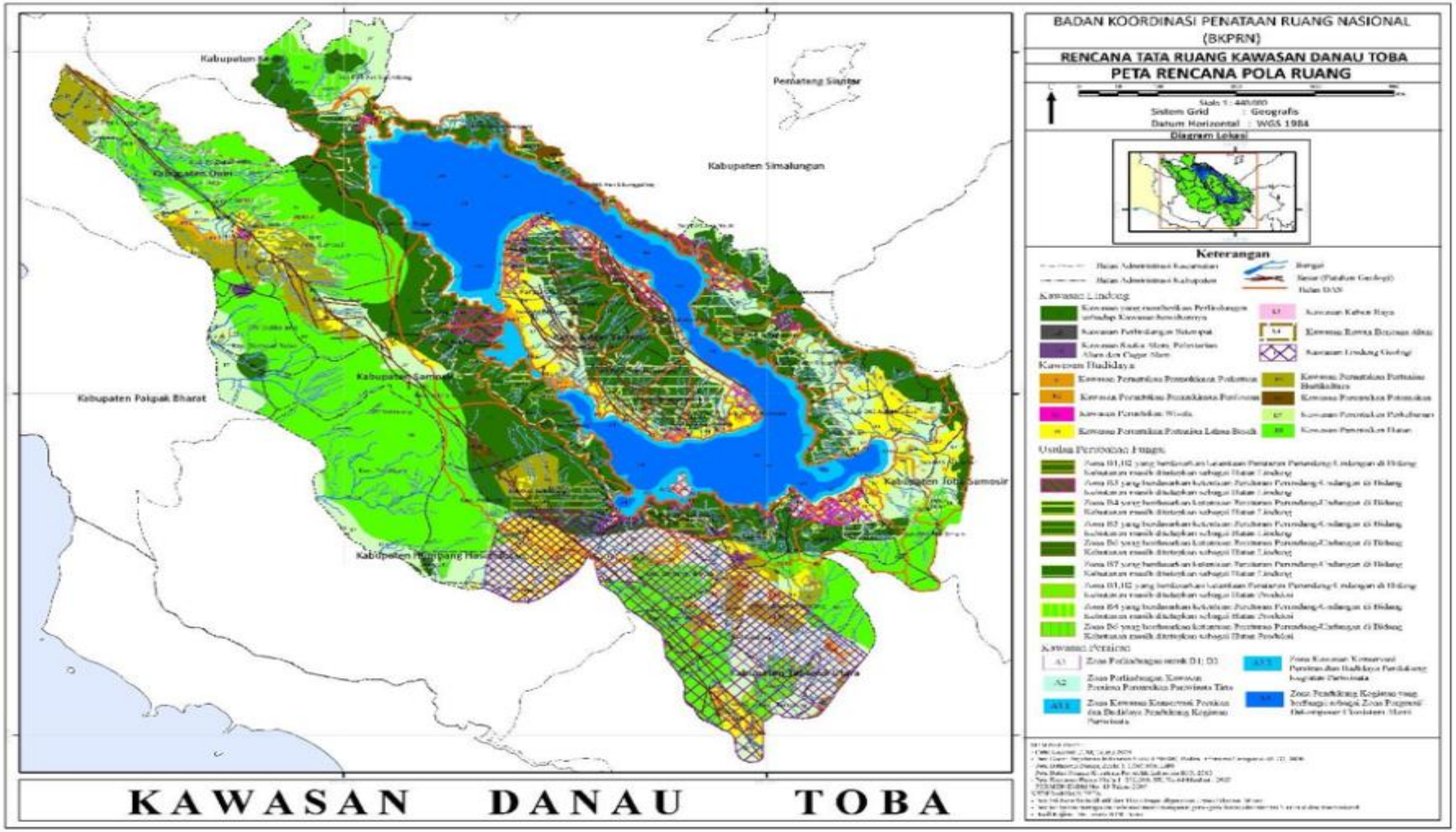

Fig. 5. Zoning map of lake toba land use

Source: Ministry of Environment and Forestry, 2023

Table 2. Population by sub-district in toba regency (2019–2023)

District	2019	2020	2021	2022	2023
Balige	38.972	44.635	45.276	46.100	46.568
Tampahan	4.556	5.141	5.207	5.293	5.339
Laguboti	19.500	22.397	22.724	23.141	23.379
Habinsaran	16.364	17.869	18.036	18.272	18.365
Borbor	7.181	8.299	8.422	8.578	8.668
Nassau	7.631	9.173	9.344	9.553	9.689
Silaen	12.813	14.143	14.289	14.491	14.579
Sigumpar	7.881	8.599	8.683	8.800	8.849
Porsea	14.220	14.669	14.732	14.850	14.875
Pintu Pohan Meranti	7.478	7.346	7.375	7.433	7.442
Siantar Narumonda	6.066	7.435	7.591	7.778	7.848
Parmaksian	10.908	11.556	11.594	11.675	11.701
Lumban Julu	8.633	9.953	10.099	10.286	10.393
Uluan	8.501	9.680	9.735	9.826	9.840
Ajibata	7.668	9.420	9.620	9.860	10.026
Bonatua Lunasi	5.340	5.884	6.027	6.197	6.289
Total	183.712	206.199	208.754	212.133	213.850

Source: BPS Toba Regency 2019-2024

Table 3. Soil types in lake toba's lakeside area

No.	Soil Type	Landform Variation	Erosion Sensitivity	Area (Ha)
1	Andosol Humus (AH)	Flat to sloping lands	Not sensitive	89,602
2	Andosol Oxic (AO)	Hilly lands	Sensitive	33,655
3	Brown Humic Andosols	Mountainous lands	Sensitive	82,024
4	Regosol	Flat lands	Highly sensitive	2,907

Table 4. Land cover of lake toba's lakeside in 2023

No.	Land Cover	Area (Ha)	Percentage (%)
1	Forest	127,746.64	56
2	Lake	20,788.30	9
3	Shrubland	31,132.98	14
4	Fields	25,890.05	11
5	Rice Fields	18,669.15	8

Table 5. Zoning regulations for lake toba's water and lakeside areas

Zone	Permitted Activities	Prohibited Activities
Conservation Zone	Research, ecotourism	Intensive fish farming, industrial waste
Aquatic Tourism Zone	Water recreation, festivals	Permanent construction, pollution
Riparian Zone	Conservation, reforestation	Land excavation, vegetation clearance

Through strict supervision, rehabilitation programs, and the active participation of local communities, land conditions in Lake Toba's lakeside zones have shown positive recovery trends since the Geopark designation. With continuous strengthening of sustainability-based policies, the area has great potential to serve as a model for integrated environmental management that can be replicated in other regions in Indonesia and beyond.

3.1.6 Analysis of zoning and policies

In accordance with Government Regulation No. 13 of 2017, Lake Toba is divided into several zones based on their designated functions, such as conservation zones, aquatic tourism zones, and riparian zones.

3.1.7 Impact of geopark designation on land use

The designation of Lake Toba as a UNESCO Global Geopark brought significant changes to policies, management, and land utilization. These changes aim to balance socio-economic development with environmental preservation.

3.2 Restrictions on Lakeside Activities

Post-Geopark designation, various activities that could potentially harm Lake Toba's lakeside areas faced stringent restrictions. Activities such as residential development, land-use conversion into commercial areas, and fish farming using floating net cages (FNCs) were regulated to prevent pollution and environmental degradation.

3.3 Vegetation Recovery and Reforestation

Vegetation recovery and reforestation in Lake Toba's lakeside zones represent key strategies for ensuring the sustainability of ecosystems in this region. Rehabilitation programs focus on areas degraded by human activities, such as land-use conversion for settlements, agriculture, and unplanned tourism activities. These efforts aim to restore the ecological functions of the lakeside, prevent erosion, and improve overall environmental quality.

Reforestation efforts utilize local plants with high environmental resilience, such as pine trees, which function as erosion barriers, along with other hardwood species capable of improving soil structure. Furthermore, these programs actively involve local communities to raise awareness of environmental conservation and foster a sense of ownership over rehabilitated areas.

Rehabilitation efforts not only involve tree planting but also include soil and water conservation strategies such as terracing on slopes, planting erosion-resistant grasses, and installing protective structures to prevent landslides in critical areas. These steps are crucial to ensuring the growth and optimal ecological functions of newly planted vegetation.

Additionally, these programs adopt ecosystem-based approaches by introducing plant species that are not only environmentally beneficial but also economically valuable to local communities. For instance, planting fruit-bearing trees provides supplementary income for residents without harming existing ecosystems.

Although the outcomes of these efforts may not be immediately visible, their long-term impacts are expected to be substantial. Restored vegetation will act as natural filters for pollutants, balance the microclimate, and serve as habitats for various flora and fauna. Moreover, well-maintained green lakeside zones will enhance tourism appeal, supporting sustainable tourism concepts at Lake Toba.

Through an integrated approach and active participation from various stakeholders, the rehabilitation and reforestation of Lake Toba's lakeside zones are anticipated to become a model for sustainable environmental management in other tourism regions. This initiative also demonstrates that environmental preservation can coexist with improved livelihoods for local communities.

The Geopark designation has also encouraged the development of sustainable tourism activities. Major tourist areas such as Ajibata, Balige, and Muara have become centers for community-based ecotourism development.

Table 6. Permitted and prohibited activities in lake toba's lakeside areas

Activity	Status (Permitted/Prohibited)	Details
Tree planting	Permitted	Must use local and environmentally friendly species
Water-based tourism management	Permitted	Must align with environmental carrying capacity
Intensive fish farming	Prohibited	FNCs limited to preserve water quality
New residential development	Prohibited	Restricted to designated zones outside lakeside areas

Table 7. Comparison of water quality before and after geopark designation

Water Quality Parameter	Before Geopark	After Geopark	Quality Standard (PP No. 22/2021)
Total Suspended Solids (mg/L)	50	20	≤25
Phosphate (mg/L)	0.5	0.2	≤0.2
Dissolved Oxygen (DO) (mg/L)	4.5	6.0	≥5.0

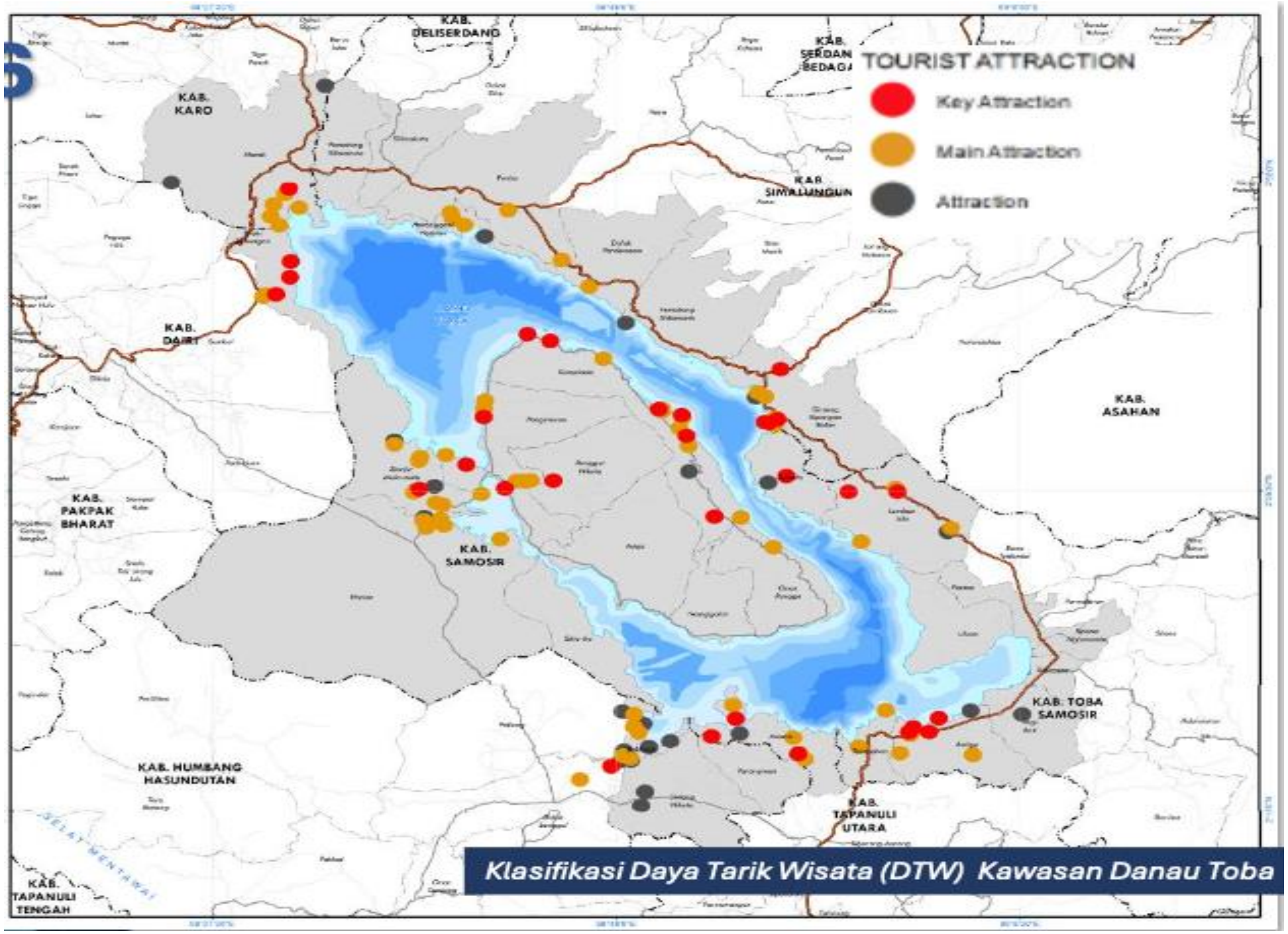

Fig. 6. Classification map of lake toba's tourism attractions
Source: Ministry of Tourism, 2024

3.4 Environmental and Societal Impacts of Geopark Designation

a. Water Quality Improvements

Reduced pollution levels were recorded in key strategic locations such as Ajibata and Parapat after the number of FNCs was reduced. In addition, soil abrasion levels in some regions have decreased due to vegetation planting programs aimed at erosion prevention.

b. Socioeconomic Impact

Community Involvement

Interviews with local stakeholders revealed:

- **Increased Income**: Community income from ecotourism and local goods production grew by 25% post-Geopark designation.
- **Tourism Engagement**: Ecotourism activities, such as homestay management and guided tours, have become significant income sources.

However, gaps remain in community participation. Some residents reported limited awareness of zoning policies and uneven access to tourism opportunities.

c. Challenges in Stakeholder Collaboration

Although the Geopark designation fostered cooperation among governments, private sectors, and communities, enforcement of zoning regulations remains inconsistent. For example, violations such as illegal land clearing persist in remote areas.

d. Alignment with Policy and Sustainability Goals

Zoning and Policy Enforcement:

Analysis revealed that while zoning regulations improved compliance, enforcement gaps persist:

- Conservation zones saw a 10% decrease in violations, but tourism zones experienced sporadic unregulated development.
- Strengthened collaboration frameworks are needed to ensure consistency in enforcement and address local challenges.

3.5 Broader Ecosystem Health

Biodiversity indicators were identified as a critical gap in this study, as requested by reviewers. Future research should incorporate metrics such as species diversity and habitat recovery to evaluate long-term ecosystem health.

3.6 Discussion

This research highlights the significant impact of Lake Toba's designation as a UNESCO Global Geopark on land use and environmental management in its lakeside areas. The analysis demonstrates that the Geopark status has resulted in strengthened zoning policies, measurable reductions in destructive activities, and increased public awareness regarding environmental conservation. These findings align with earlier studies emphasizing the role of geoparks in promoting environmental sustainability and socio-economic development.

3.6.1 Environmental impact

Before the Geopark designation, Lake Toba’s lakeside areas faced several environmental challenges, including severe erosion, unplanned land-use conversions, and pollution from fish farming using floating net cages (FNCs). This study confirms earlier findings by Sidabutar et al. (2019), which identified weak spatial planning oversight and non-compliance as critical issues. However, post-Geopark initiatives have led to substantial improvements:

- Vegetation cover increased by 8%, driven by reforestation programs utilizing local species like pine trees and erosion-resistant grasses.
- Erosion-prone areas decreased by 12%, demonstrating the effectiveness of targeted rehabilitation strategies.

Water quality improvements were also notable, with phosphate levels decreasing from 0.5 mg/L to 0.2 mg/L and dissolved oxygen levels increasing from 4.5 mg/L to 6.0 mg/L. These findings align with Setiawan et al. (2020), who reported similar trends in volcanic lakes following the adoption of sustainable aquaculture practices and enhanced waste management systems. Nevertheless, the study acknowledges the absence of biodiversity metrics, which are critical for a more comprehensive evaluation of ecosystem health.

3.6.2 Socioeconomic impacts

From a social perspective, the study found that local community involvement in tourism and conservation has increased significantly. Interviews with local residents revealed:

- Community income from ecotourism and local goods production rose by 25%.
- Participation in ecotourism activities, such as homestay management and guided tours, has grown steadily.

These findings support the work of Sitorus et al. (2020), who emphasized the dual benefits of economic empowerment and conservation awareness through community engagement. However, challenges remain, including uneven distribution of economic benefits and limited awareness of zoning policies in certain areas.

3.6.3 Policy and zoning implementation

The Geopark designation has driven improvements in zoning regulation compliance, which increased by 15% in monitored areas. However, enforcement gaps persist, particularly in remote regions where illegal deforestation and unregulated land use continue to pose threats. As highlighted by Hasibuan et al. (2018), weak implementation of spatial planning policies remains a barrier to sustainable management.

3.6.4 Broader implications for geoparks

The study's findings underscore the potential of geoparks to integrate environmental preservation with socio-economic development. Lake Toba’s case demonstrates the value of adopting adaptive management frameworks and fostering collaboration among governments, private sectors, and communities. However, as noted by Arifin et al. (2019), increased tourism activities must be managed carefully to avoid exceeding the region's environmental carrying capacity and causing ecosystem damage.

3.6.5 Recommendations for future action

To address existing challenges, this study recommends:

- **Community-Based Monitoring**: Establishing local monitoring teams to oversee compliance with zoning regulations and conservation efforts.
- **GIS Technology for Surveillance**: Utilizing geospatial tools to improve the accuracy and efficiency of zoning enforcement.
- **Collaborative Frameworks**: Strengthening partnerships between governments, local communities, and private sectors to ensure consistent policy implementation.
- **Broader Metrics**: Incorporating biodiversity and habitat recovery indicators in future studies to provide a holistic assessment of ecosystem health.

These recommendations support the global geopark movement by offering actionable insights into the integration of conservation, economic development, and community participation. Lake Toba’s experience provides a replicable model for other regions facing similar challenges.

4. CONCLUSION AND RECOMMENDATIONS

The lakeside areas of Lake Toba have experienced significant changes in land use and environmental quality, both before and after its designation as a UNESCO Global Geopark. Uncontrolled land utilization, such as conversions for residential use and tourism activities, has led to environmental degradation, including erosion, water quality decline, and the loss of natural vegetation. However, rehabilitation, reforestation, and sustainable management efforts implemented post-Geopark designation have increased public awareness and balanced development needs with ecosystem preservation. These programs demonstrate significant potential for achieving long-term sustainability in the Lake Toba region.

To ensure environmental sustainability and optimize the economic benefits of Lake Toba, more intensive collaboration among governments, local communities, and the private sector is needed. Strengthened regulations and supervision of land use, environmentally friendly natural resource utilization, and community empowerment in maintaining lakeside areas should be prioritized. Furthermore, the development of eco-friendly technologies and increased public awareness through education and training on ecosystem conservation should be continuously pursued. These steps are expected to position Lake Toba as a model for sustainable tourism management meeting international standards.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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