Land Use Analysis of Lake Toba's Lakeside Area in Toba Regency Before and After Geopark Designation

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. The lakeside areas of Lake Toba play a vital ecological role but face challenges due to human activities such as deforestation, residential development, and uncontrolled intensive fish farming. This research employs a spatial approach using the Simple Additive Weighting (SAW) method and overlay techniques on satellite imagery data to identify land cover changes from 2015 to 2023. The results show that prior to the Geopark designation, the lakeside areas experienced significant degradation, including erosion reaching 3–20 meters in certain locations and a reduction in natural vegetation cover. After the Geopark designation, there has been an increase in conservation awareness, marked by vegetation rehabilitation programs and stricter zoning policies. Post-Geopark management of lakeside areas successfully reduced water pollution levels and improved ecosystem conditions, as indicated by a decrease in phosphate concentrations and an increase in dissolved oxygen levels in the lake. This study highlights the importance of collaboration among governments, communities, and private sectors to ensure sustainable management of lakeside areas. The findings provide a basis for strategic policy recommendations on spatial planning and adaptive environmental management in Lake Toba, which can serve as a model for other tourism regions in Indonesia.

Keywords: Lake Toba, UNESCO, Geopark, Rehabilitation, Sustainability, Spatial

I. INTRODUCTION

Land use reflects human activities that physically alter the Earth's surface. Urban areas often experience faster dynamics in land use changes than rural regions, although rural areas also undergo significant transformations due to unsustainable land-use practices (Friedman & Alonso, 2008). The increasing population and human activities drive higher land demands, which frequently misalign with the available land resources (Ministry of Agrarian Affairs and Spatial Planning, 2007).

Lakeside zones, serving crucial ecological functions, often face pressures from land conversion for buildings or other activities that deviate from their intended purposes (Bappenas, 2017). Such unregulated exploitation harms the environment and poses risks to communities relying on lake resources for their livelihoods (Barry & Richard, 2003).

Lake Toba, one of Indonesia's natural treasures, plays a pivotal role in the regional ecosystem and has been designated as the Toba Caldera Geopark by UNESCO. This designation aims to preserve the area's geological, ecological, and cultural functions while enhancing public awareness of sustainable natural resource management (UNESCO, 2015). However, land-use changes surrounding Lake Toba after its Geopark designation have posed significant challenges to environmental preservation (Santoso et al., 2020).

Ecologically, lakeside zones act as buffer areas, protecting the lake from erosion, sedimentation, and water quality degradation caused by human activities (Simamora, 2018). This function is particularly critical for Lake Toba, where the lakeside area also contributes to rainwater absorption, preventing floods and landslides (Susetyo, 2014). Nevertheless, violations of lakeside zoning regulations, such as residential developments, persist, threatening the area's ecological balance (Hutabarat, 2017).

The designation of Lake Toba as a Geopark has had positive impacts, such as fostering local economic growth and raising conservation awareness. However, uncontrolled developments in the lakeside areas have led to spatial planning mismatches, adversely affecting both the environment and local communities (Pakpahan et al., 2023). Therefore, an integrated approach is required for lakeside management, involving the government, communities, and other stakeholders (Harsono, 2019).

Previous studies have highlighted land-use changes around Lake Toba and its surroundings. Research by Sitindaon & Iskandar (2020) revealed land cover transformations in the National Strategic Area of Lake Toba, while Naibaho (2023) examined the legality of land title certificates issued for lakeside areas. However, these studies primarily focus on legal or general land dynamics without providing a comprehensive analysis linking Geopark designation to specific land-use changes in lakeside zones.

This study offers a novel contribution by integrating spatial analysis and regulatory reviews to explore the impact of the Geopark designation on land-use changes in Lake Toba's lakeside areas. The approach aims to identify land-use transformations and provide strategic recommendations for sustainable regional management.

This research aspires to offer policy recommendations for sustainable management of Lake Toba's lakeside areas, particularly in supporting the implementation of the Toba Regency Spatial Plan (Presidential Regulation No. 81 of 2014). Additionally, the findings can serve as a reference for future studies and support environmentally friendly development planning.

II. RESEARCH METHODOLOGY

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.

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.

Data Collection Methods

1. **Primary Data Collection**
    - Conducted via field surveys to:
        - Identify current land cover.
        - Document conditions in lakeside areas affected by land-use conversion.
        - Map locations using GIS and drone technology.
2. **Secondary Data Collection**
    - Includes information from RTRW documents (2017–2037), thematic maps, and government agency reports.

Data Analysis

1. **Lakeside Area Analysis Using Simple Additive Weighting (SAW)**
    - The SAW method integrated spatial parameters such as elevation, distance from the shoreline, and spatial plan compliance. Weighting was applied to each parameter and processed using GIS software to produce a map of land-use changes.
2. **Lakeside Zoning Analysis**

- Overlay techniques identified land-use suitability and violations within Lake Toba's lakeside areas. This analysis utilized thematic data such as geological and spatial planning maps (RTRW).

3. **Population Growth and Housing Demand Projections**
    - Population projections were conducted using exponential methods to predict future housing needs. This analysis evaluated the impact of population growth on land-use conversion.

Operational Definitions

The operational definitions in this study are as follows:

- **Study Area**: Lakeside areas of Lake Toba encompassing nine sub-districts in Toba Regency.
- **Spatial Data**: Base and thematic maps illustrating land-use changes from 2017–2022.
- **ArcGIS**: Spatial analysis software used for mapping and data processing.
- **Overlay Analysis**: Thematic map integration technique for generating zoning maps.

Research Framework

The methods were designed to provide a comprehensive overview of land-use dynamics in Lake Toba's lakeside areas before and after the Geopark designation. The data and analysis results are intended to support.

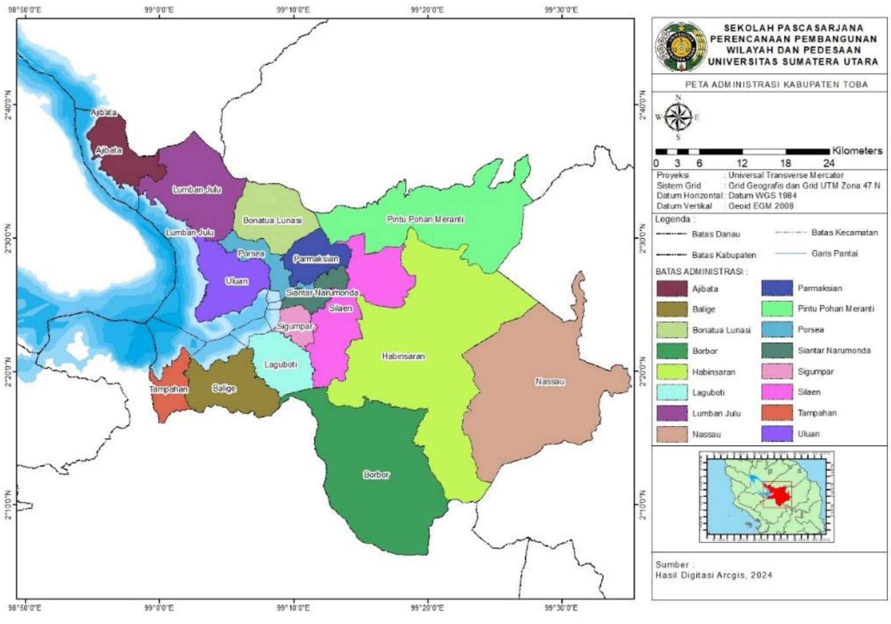
III. RESULTS AND DISCUSSION

3.1 Result

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.

Figure 1. Administrative Map of Toba Regency



Source: ArcGIS Digitization, 2024

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.

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

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

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**

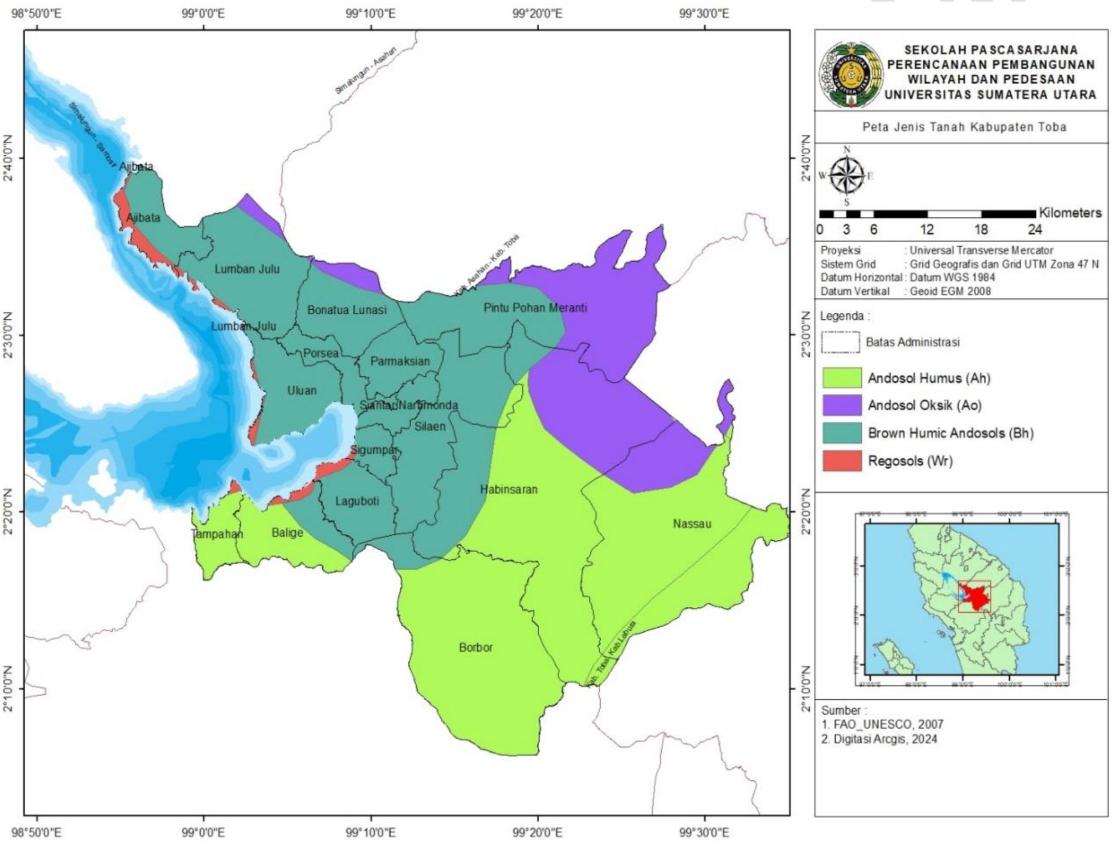
Source: BPS Toba Regency 2019-2024

Analysis of Lakeside Boundary Changes (2015–2023)

Lake Toba, the world's largest volcanic-tectonic lake, spans 87 km in length, 27–31 km in width, and approximately 1,100 km² in area. Its elevation is about 906 meters above sea level, with depths ranging from 400–600 meters. Over time, natural and anthropogenic activities such as erosion, intense rainfall, and uncontrolled development have significantly altered the lake's boundary.

Satellite imagery analysis from 2015 to 2023 reveals erosion of 3 to 20 meters along various points of the lakeside boundary. This erosion results from water currents, heavy rainfall, and unregulated construction. These changes threaten Lake Toba's ecosystem sustainability. The boundary areas are categorized into vegetated and non-vegetated zones. Natural vegetation, including hardwood trees and shrubs, has degraded due to human activities such as land clearing for agriculture and settlements. Conversely, non-vegetated areas show loss of soil cover due to erosion and exploitation.

Figure 2. Soil Type Map of Toba Regency



Source: ArcGIS Digitization, 2024

The morphology and geology of Lake Toba, as illustrated in Figure 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.

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

Land Cover Analysis of Lake Toba's Lakeside

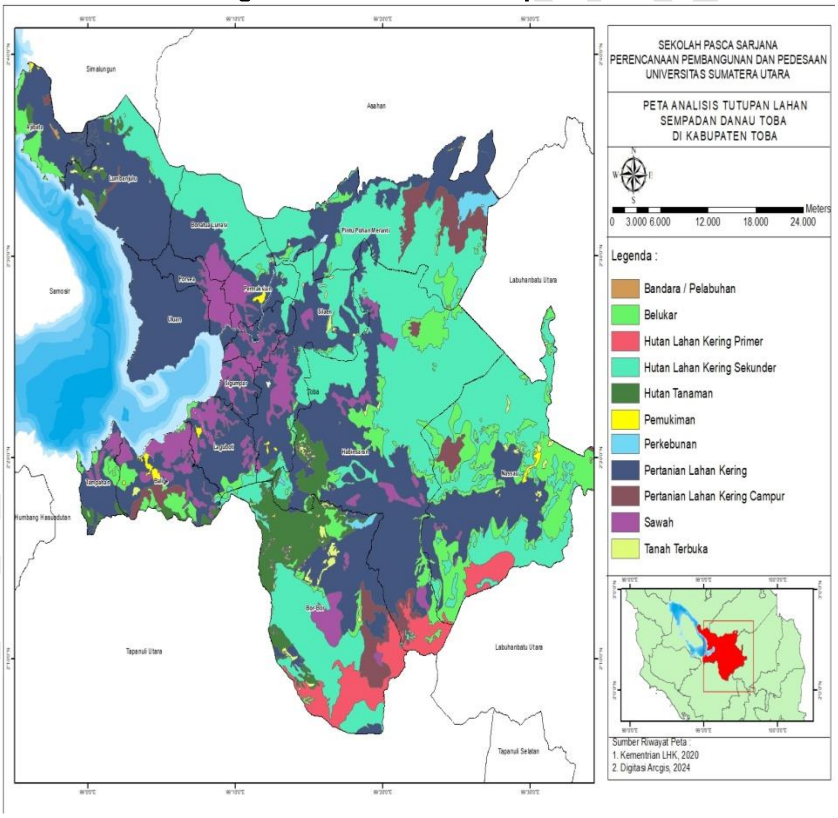
Lake Toba is recognized as a UNESCO Global Geopark for its unique geological, ecological, and cultural values. The designation of Lake Toba as a UNESCO Global Geopark is the result of extensive efforts involving research, policy development, and collaboration among various stakeholders to enhance the 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.

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:

Table 4. Land Cover of Lake Toba's Lakeside in 2023

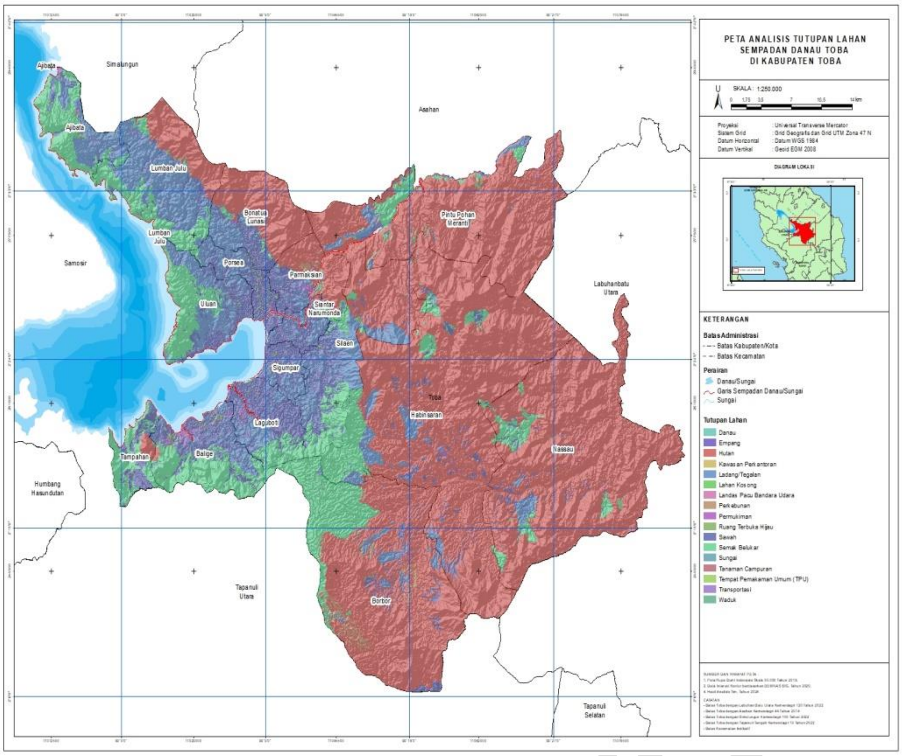
No.	Land Cover	Area (Ha)	Percentage (%)
1	Forest	127,746.64	56
2	Lake	20,788.30	9
3	Shrubland	31,132.98	14
4	Fields	25,890.05	11
5	Rice Fields	18,669.15	8

Figure 3. Land Cover Map of Lake Toba in 2020



Source: Research Analysis, 2024

Figure 4. Land Cover Map of Lake Toba in 2023



Source: Research Analysis, 2024

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.

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.

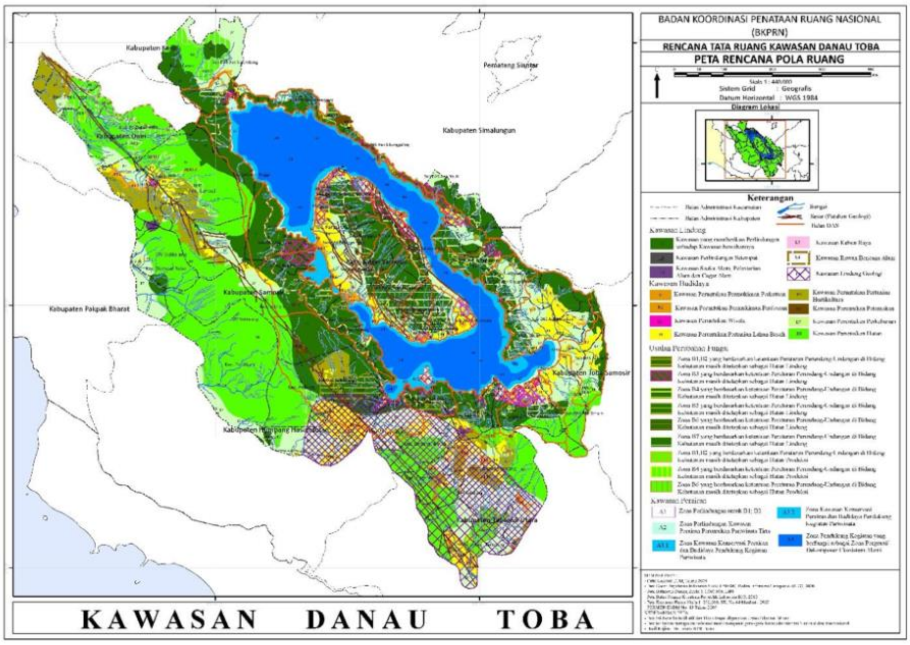
Analysis of Zoning and Policies

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.

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

Figure 5. Zoning Map of Lake Toba Land Use



Source: Ministry of Environment and Forestry, 2023

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.

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.

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

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.

Environmental and Societal Impacts of Geopark Designation

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.

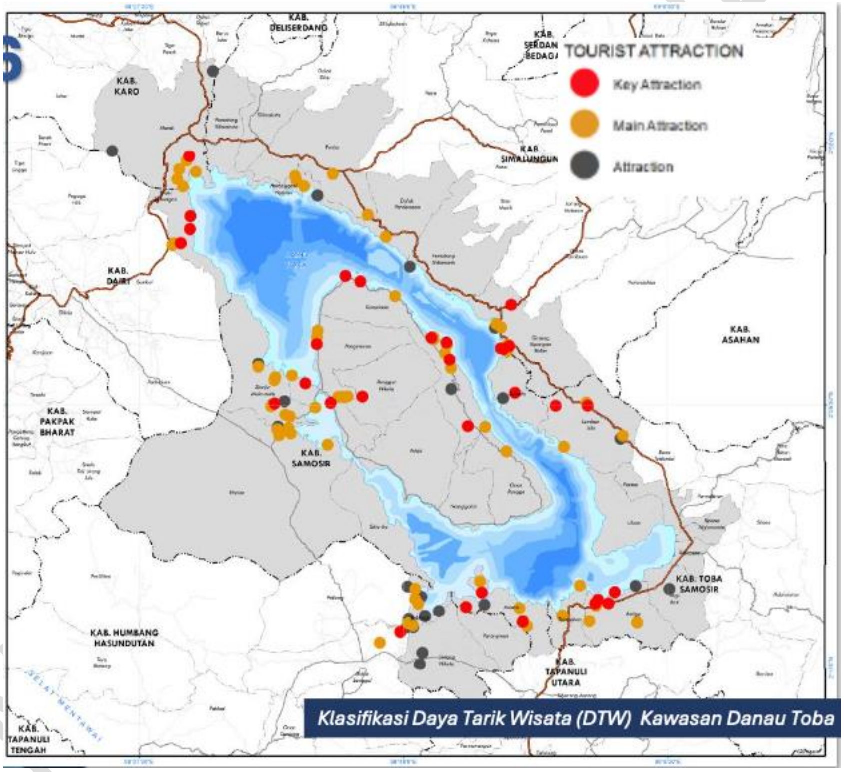
Table 7. Comparison of Water Quality Before and After Geopark Designation

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

Community Impacts

Local community involvement in tourism management has increased through ecotourism training, homestay management, and the production of local goods such as food and crafts. Economic benefits are evident from increased community income in major tourist areas.

Figure 6. Classification Map of Lake Toba's Tourism Attractions



Source: Ministry of Tourism, 2024

Discussion

This research highlights the impact of Lake Toba's designation as a UNESCO Global Geopark on land use within lakeside areas and environmental management. The analysis reveals that the Geopark status has driven strengthened zoning policies, reduced destructive activities, and heightened public awareness of the importance of environmental conservation. These findings align with previous studies emphasizing the critical role of geoparks in promoting environmental sustainability and socio-economic development (Farsani et al., 2014; Novelli et al., 2018).

Before the Geopark designation, Lake Toba's lakeside areas faced various challenges, such as erosion, unplanned land-use conversion, and pollution caused by fish farming using floating net cages (FNCs). Previous research by Sidabutar et al. (2019) noted that environmental degradation in the Lake Toba region resulted from weak spatial planning oversight and noncompliance with regulations. This study confirms these findings but also demonstrates improvements following the implementation of stricter policies post-Geopark designation.

Lakeside rehabilitation has emerged as a strategic initiative yielding significant results. The planting of local trees, such as pine, and the use of erosion-control vegetation have proven effective in reducing abrasion. These findings are supported by Mutaqin et al. (2021), who reported that reforestation in lakeside areas effectively reduces soil erosion risk and enhances ecological functionality. However, challenges such as inconsistent funding and uneven community participation remain key obstacles.

A reduction in water pollution levels is another positive indicator of Geopark-based management. Water quality data show significant improvements, including increased dissolved oxygen (DO) levels and decreased phosphate concentrations. These results are consistent with research by Setiawan et al. (2020), which highlighted the role of reduced intensive aquaculture activities and the adoption of environmentally friendly technologies in improving water quality in volcanic lakes.

From a social perspective, increased local community involvement in tourism management has yielded promising results. Ecotourism training, homestay management, and the production of local goods have become new sources of income for residents. Research by Sitorus et al. (2020) suggests that involving local communities in Geopark management not only enhances economic welfare but also strengthens awareness of environmental conservation.

Nevertheless, several challenges require further attention. Violations of zoning regulations and illegal activities, such as deforestation in lakeside areas, persist in certain locations. Previous research by Hasibuan et al. (2018) also highlighted weak spatial planning policy implementation in the Lake Toba region as a major barrier to sustainable management.

The Geopark designation has also positively influenced the region's tourism appeal. The development of main tourism areas (KWU) such as Ajibata and Balige has attracted domestic and international tourists. However, as noted by Arifin et al. (2019), increased tourism activities must be balanced with the region's environmental carrying capacity to avoid over-tourism and ecosystem damage.

As a recommendation, community-based monitoring and the use of GIS technology for zoning surveillance can be strategic steps to ensure the region’s sustainability. Additionally, developing collaborative frameworks among governments, local communities, and private sectors is crucial for addressing policy implementation challenges. These findings support the notion that geoparks can serve as strategic tools for integrating environmental preservation with socio-economic development (Dowling, 2013).

Overall, this study provides important contributions to understanding the impact of geoparks on land and environmental management. It not only confirms previous findings but also offers new insights into the effectiveness of Geopark-based policies in addressing spatial planning and environmental challenges in Lake Toba's lakeside areas. These findings provide a vital foundation for future sustainable policy development.

IV. 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.

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