

Sedimentation Dynamics and Sustainable Lake Management: Integrating Bathymetric Analysis and Tri Hita Karana in Lake Tamblingan

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ABSTRACT

Lakes play an important role in supporting freshwater resources, ecosystems, and socio-cultural activities. However, increasing sedimentation has become a major environmental issue that can affect lake morphology and ecological functions. This study aims to analyze sediment accumulation in Lake Tamblingan and interpret its implications using the Tri Hita Karana framework. Bathymetric surveys were conducted using a Midas Valeport single-beam echosounder with 200 m transect spacing. The data were processed using Civil 3D and ArcGIS to generate bathymetric maps for 2023 and 2024, and sediment thickness was estimated through depth comparison. The results show that Lake Tamblingan experienced sediment accumulation reaching approximately 1,56 m, indicating a significant lake shallowing process. This condition may reduce lake storage capacity, increase turbidity, and potentially affect ecological stability as well as socio-cultural activities surrounding the lake. Integrating bathymetric analysis with the Tri Hita Karana perspective highlights the importance of holistic lake management that considers environmental, social, and spiritual dimensions.

Keywords: Bathymetric Survey; Lake Sedimentation; Lake Tamblingan; Sustainable Lake Management; Tri Hita Karana

Article Info

Received : 10-01-2026

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Revised : 19-03-2026

Accepted : 30-04-2026



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1. INTRODUCTION

Lakes play an important role in maintaining environmental balance and providing freshwater resources for surrounding communities. In addition to functioning as natural water reservoirs, lakes support various ecological processes and biodiversity. However, many lake ecosystems are currently facing environmental pressures due to both natural processes and human activities. One of the most significant issues affecting lake sustainability is sedimentation. Continuous sediment accumulation can gradually reduce lake depth and water storage capacity, potentially affecting water quality, aquatic ecosystems, and the overall ecological balance of the lake environment[1][2][3][4][5].

In Bali, several lakes located in the Bedugul highland area, including Lake Beratan, Lake Buyan, and Lake Tamblingan, play an important role in supporting environmental and socio-economic activities. These lakes function not only as freshwater resources but also as important landscapes that support tourism, cultural activities, and local livelihoods. However, changes in land use within the surrounding catchment areas,

combined with natural erosion processes, may increase sediment input into the lakes. Bathymetric surveys conducted in recent years indicate that these lakes have experienced varying levels of depth changes, suggesting the occurrence of sediment deposition and gradual lake shallowing [6][7].

Previous bathymetric analysis of these lakes indicates that Lake Tamblingan shows the highest sediment accumulation among the lakes studied. Based on bathymetric data collected between 2023 and 2024, the lake experienced an estimated sediment increase of approximately 1,56 m [8]. This condition suggests that Lake Tamblingan may be undergoing relatively rapid sedimentation compared to the other lakes in the region. Such environmental changes have the potential to influence the ecological condition of the lake and the sustainability of its functions for surrounding communities.

Most studies on lake sedimentation primarily focus on the physical and geomorphological aspects of sediment accumulation, including sediment thickness, bathymetric changes, and sediment distribution patterns. While these approaches are essential for understanding lake dynamics, they often overlook the broader social and cultural dimensions associated with lake environments. In regions such as Bali, where natural landscapes are closely connected with cultural and spiritual values, environmental changes in lakes may also have implications beyond ecological aspects. The Balinese philosophy of Tri Hita Karana, which emphasizes harmony between humans, nature, and the spiritual realm, provides a relevant framework for understanding the relationship between environmental conditions and socio-cultural practices [9][10][11]. Figure 1 illustrates a conceptual framework Tri Hita Karana in this study.

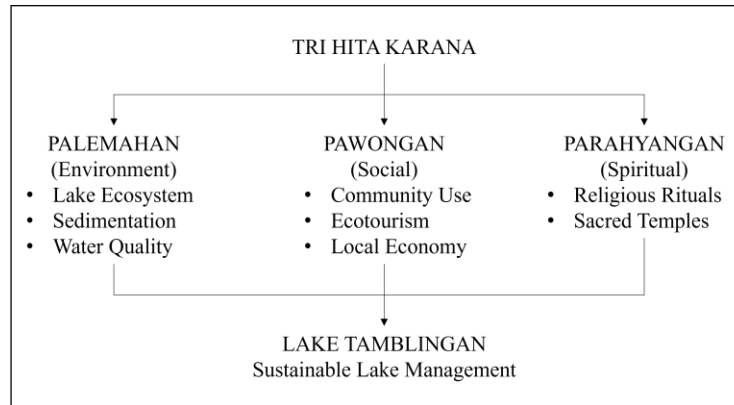


Figure 1. Conceptual framework Tri Hita Karana

Therefore, this study aims to analyze sedimentation changes in Lake Tamblingan and to interpret their environmental and socio-cultural implications using the Tri Hita Karana framework. By integrating bathymetric analysis with local cultural perspectives, this study seeks to provide a more comprehensive understanding of lake sustainability and highlight the importance of incorporating cultural values into environmental management strategies. This study integrates bathymetric sedimentation analysis with the Tri Hita Karana cultural framework to interpret environmental changes in Lake Tamblingan. Unlike previous studies that focus primarily on physical sediment dynamics, this research incorporates ecological, social, and spiritual perspectives in evaluating lake sustainability.

2. RESEARCH METHOD

2.1. Study Area

Lake Tamblingan is located in the northern highland region of Bali, Indonesia, and forms part of the Bali volcanic lake system together with Lakes Beratan and Buyan. The lake is situated at an elevation of approximately 1,200 meters above sea level and is surrounded by protected forest areas. Compared to other lakes in Bali, Lake Tamblingan remains relatively natural with limited tourism infrastructure and strong cultural and spiritual significance for local communities. Several sacred temples are located around the lake, and the area is frequently used for religious ceremonies. These environmental and cultural characteristics make Lake Tamblingan an important site for examining sedimentation processes and their potential implications within the framework of Tri Hita Karana [12][13][14].



Figure 2. Location of Lake Tamblingan in Bali, Indonesia

2.2. Data Processing

The bathymetric data obtained from the field survey were processed using Autodesk Civil 3D and ArcGIS software. Initially, the depth data were input into Civil 3D to generate bathymetric contour maps representing the lakebed topography. Subsequently, spatial interpolation techniques were applied to produce continuous bathymetric surfaces from the discrete survey points. The interpolated bathymetric data were then exported to ArcGIS to facilitate spatial visualization and mapping of depth distribution across Lake Tamblingan [6][15].

To improve the consistency of depth measurements, water level correction was applied during data processing. However, this study did not include a detailed quantitative uncertainty analysis of depth measurements and spatial interpolation. Potential sources of uncertainty may arise from instrument accuracy, GPS positioning errors, and interpolation processes used to generate continuous bathymetric surfaces. Despite these limitations, the applied methodology is considered sufficient to represent general bathymetric patterns and sedimentation trends in Lake Tamblingan [16][17].

2.3. Sedimentation Analysis

Sedimentation analysis was conducted by comparing bathymetric data collected in 2023 and 2024. The two datasets were overlaid using Autodesk Civil 3D to identify differences in lakebed elevation between the two survey periods. This comparison allowed the estimation of sediment accumulation by calculating the change in depth across the lake area. The resulting analysis provided information on the magnitude and spatial distribution of sediment deposition occurring in Lake Tamblingan during the observation period [8].

2.4. Cultural Interpretation Based on Tri Hita Karana

To complement the physical analysis of sedimentation, the results were interpreted using the Tri Hita Karana framework, a traditional Balinese philosophy that emphasizes harmony among humans, nature, and the spiritual realm. This framework consists of three interconnected elements: palemahan (human relationship with nature), pawongan (human relationship with other humans), and parahyangan (human relationship with the divine). By applying this perspective, the environmental changes observed in Lake Tamblingan were interpreted not only from an ecological standpoint but also in relation to their potential social and cultural implications for the surrounding community [9][18].

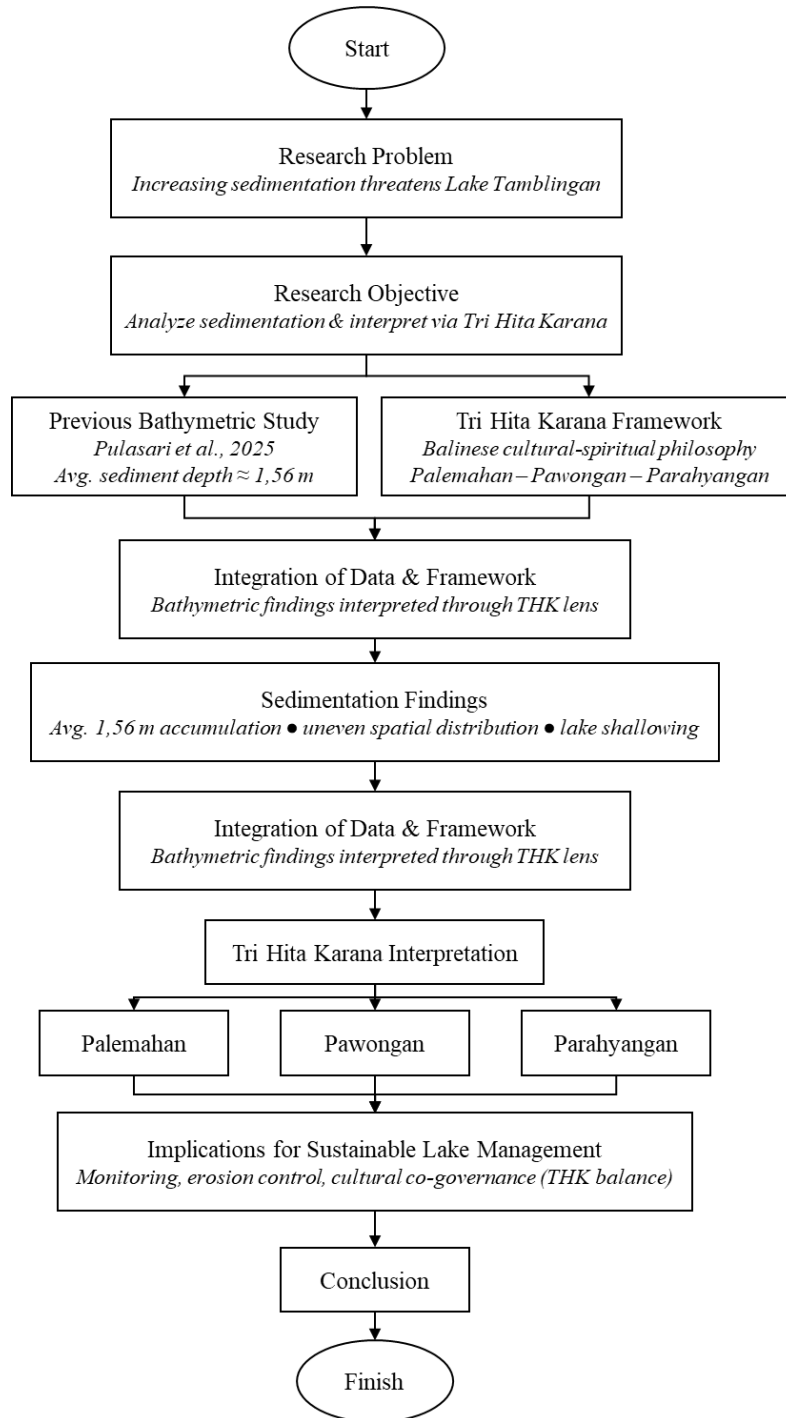


Figure 3. Flowchart

3. RESULTS AND DISCUSSION

3.1. Bathymetric Changes in Lake Tamblingan (2023–2024)

The previous bathymetric analysis was conducted by comparing depth data obtained from surveys carried out in 2023 and 2024 [8]. The overlay of bathymetric contours from the 2023 and 2024 surveys in Figure 4 illustrates differences in lakebed elevation across Lake Tamblingan. Variations between the two contour datasets indicate changes in depth values, suggesting the occurrence of sediment accumulation during the observation period. The comparison between these bathymetric datasets provides the basis for estimating sediment thickness and evaluating lakebed changes over time.

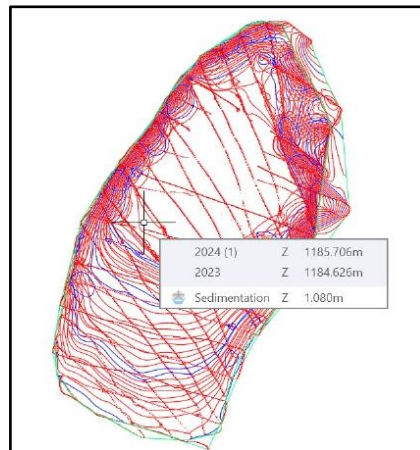


Figure 4. Overlay of bathymetric contours from the 2023 and 2024 surveys showing lakebed elevation changes in Lake Tamblingan

This study focuses on identifying relative changes in lakebed elevation based on comparative bathymetric data. Detailed quantitative analysis such as sediment volume estimation or sedimentation rates was not conducted due to data limitations. However, the observed depth differences provide a useful preliminary indication of sediment accumulation patterns in Lake Tamblingan.

3.2. Sediment Thickness Distribution

Based on the comparison between the 2023 and 2024 bathymetric datasets, sediment thickness was estimated to evaluate the extent of sediment accumulation in Lake Tamblingan. The spatial distribution map shows that sediment deposition is unevenly distributed across the lake basin. Most areas of the lake exhibit sediment thickness ranging from approximately 0–1 m, as indicated by the dominant yellow color on the map. However, several localized zones show thicker sediment deposits reaching 3–4 m in certain parts of the lake.

Based on the previous quantitative analysis of bathymetric differences between the 2023 and 2024 surveys, the average sediment thickness in Lake Tamblingan was estimated at approximately 1,56 m [8]. This value represents the overall sediment accumulation across the lake basin. The sediment thickness distribution provides important information for understanding lake sediment dynamics and evaluating the potential impact of lake shallowing. These findings indicate that sediment accumulation has become an important environmental issue in Lake Tamblingan and may have broader ecological and socio-cultural implications.

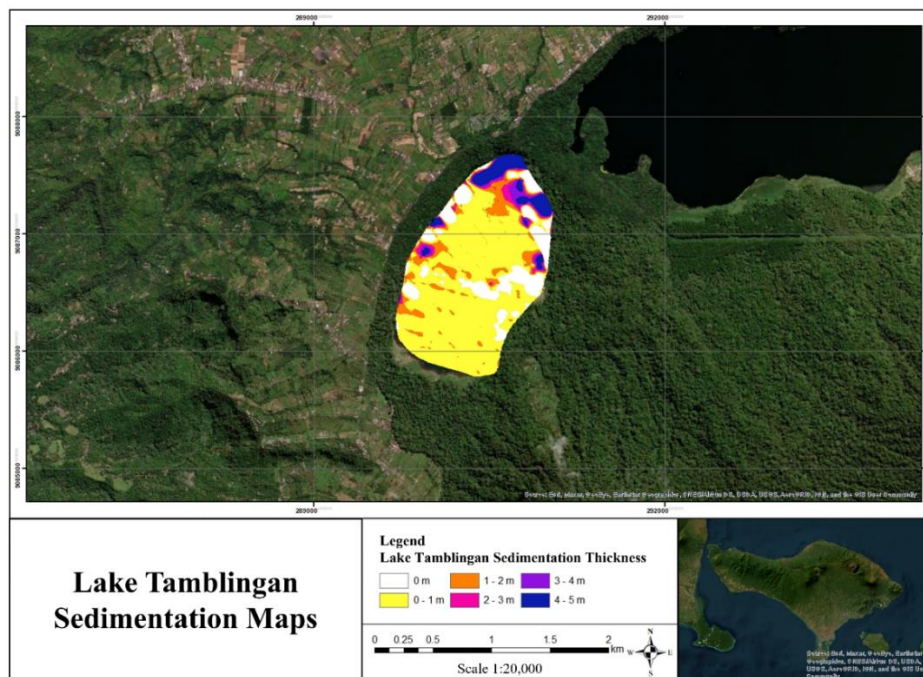


Figure 5. Spatial distribution of sediment thickness in Lake Tamblingan estimated from bathymetric differences between the 2023 and 2024 surveys

In this study, the Tri Hita Karana framework is applied as a conceptual approach to interpret the broader implications of environmental changes observed in Lake Tamblingan. This approach is not intended

as a primary socio-cultural analysis based on quantitative or survey data, but rather as an interpretative framework to understand the interconnections between environmental, social, and spiritual dimensions.

3.3. Palembang: Environmental Implications of Lake Sedimentation

Previous bathymetric analysis reported that Lake Tamblingan has experienced significant sediment accumulation, reaching approximately 1,56 m between 2023 and 2024 [8]. This sediment deposition contributes to the gradual shallowing of the lake, which may reduce the overall water storage capacity. A decrease in lake depth can affect the hydrological function of the lake as a natural water reservoir and potentially alter water circulation patterns within the lake ecosystem. Sediment accumulation may also increase water turbidity, particularly when fine sediments are resuspended by water movement or human activities. Elevated turbidity levels can reduce light penetration into the water column, which may affect photosynthetic processes in aquatic vegetation and phytoplankton. Over time, excessive sediment input combined with nutrient accumulation may increase the risk of eutrophication, a condition characterized by excessive algal growth and declining water quality [19][20][21].

Furthermore, continuous sedimentation may disrupt aquatic habitats and biodiversity within the lake. Changes in the lakebed morphology can influence the distribution of aquatic organisms, including fish and benthic species that depend on stable substrate conditions. Therefore, sedimentation not only represents a geomorphological process but also poses ecological challenges that may affect the long-term environmental sustainability of Lake Tamblingan.

3.4. Pawongan: Socio-Economic Implications for Local Communities

Beyond its ecological functions, Lake Tamblingan also plays an important role in supporting community activities and local livelihoods. The lake and its surrounding forest landscape have become a destination for nature-based and spiritual tourism. Several recreational and cultural activities are commonly carried out in the area, including forest trekking, traditional wooden boat rides across the lake, and spiritual tourism associated with meditation and cultural experiences[22].

The scenic landscape of Lake Tamblingan, characterized by calm waters and natural forest surroundings, contributes significantly to its attractiveness as an ecotourism destination. Local communities often participate in tourism-related activities, such as guiding visitors during trekking routes or operating traditional boats for lake exploration. These activities provide economic opportunities and contribute to local income generation.

However, ongoing sedimentation and environmental degradation may reduce the aesthetic value and ecological quality of the lake environment. Increased turbidity or reduced water depth could potentially affect visitor experiences and limit certain tourism activities. If sedimentation continues without proper management, it may gradually decrease the attractiveness of the lake as a nature-based tourism destination [8], which in turn could influence the local economy that partially depends on tourism activities around Lake Tamblingan.

3.5. Parahyangan: Spiritual and Cultural Significance of Lake Tamblingan

One of the distinctive aspects of Lake Tamblingan is its strong spiritual and cultural significance for Balinese communities. The lake is considered a sacred landscape and is surrounded by several temples that play important roles in local religious traditions. These temples serve as places for various Hindu rituals and ceremonies that maintain spiritual harmony between humans, nature, and the divine. In the context of the Tri Hita Karana philosophy, Lake Tamblingan represents an important element of parahyangan, which emphasizes the relationship between humans and the spiritual realm. The natural environment of the lake is closely associated with sacred values and is often used as a setting for religious activities and spiritual reflection [13].

Environmental changes such as lake shallowing and sediment accumulation may indirectly affect the spiritual landscape of the area. Significant alterations to the lake's physical condition could influence the visual and environmental integrity of the sacred site. If the ecological quality of the lake declines, it may also affect the atmosphere and spatial conditions required for certain ritual practices [12]. Therefore, maintaining the environmental sustainability of Lake Tamblingan is not only important from an ecological and socio-economic perspective but also essential for preserving the spiritual and cultural values associated with the lake.

The findings of this study demonstrate that sedimentation in Lake Tamblingan does not only represent a physical environmental process but also has broader implications when viewed through the Tri Hita Karana perspective. Sediment accumulation contributes to lake shallowing, reduced water storage capacity, and increased turbidity, which reflect disturbances in the Palembang aspect, referring to the harmony between humans and the natural environment. Environmental degradation in a sacred landscape such as Lake Tamblingan may further influence the parahyangan dimension, which relates to the spiritual relationship between humans and the divine. The lake and its surrounding area function as an important spiritual landscape where several temples and religious rituals are conducted. Therefore, maintaining the ecological integrity of the lake is essential not only for environmental sustainability but also for preserving the spiritual values and

sacred atmosphere associated with the site. In this context, sedimentation management becomes an important effort to sustain the balance among environmental, social, and spiritual dimensions as emphasized in the Tri Hita Karana philosophy [12][23][24].

This study contributes to the growing body of research on lake sedimentation by integrating physical environmental analysis with a cultural sustainability perspective. While most sedimentation studies primarily focus on geomorphological changes and hydrological impacts, this research highlights the importance of interpreting environmental changes within the local socio-cultural context. By applying the Tri Hita Karana framework, this study demonstrates that sedimentation in Lake Tamblingan should not only be understood as a physical process affecting lake morphology, but also as a phenomenon that may influence social activities and the spiritual landscape surrounding the lake. This integrative approach provides a broader understanding of lake management in culturally significant environments and suggests that environmental conservation strategies should consider not only ecological factors but also the cultural and spiritual values embedded within the landscape.

3.6. Implications for Sustainable Lake Management

The findings of this study highlight the importance of integrating environmental monitoring with local cultural values in managing Lake Tamblingan. Continuous bathymetric monitoring is essential to detect sediment accumulation and evaluate lake shallowing over time, as periodic bathymetric surveys provide important information for assessing sediment dynamics in lakes and reservoirs [19]. In addition, management strategies should consider controlling sediment inputs from the surrounding catchment area through improved land management and erosion control, since soil erosion and land-use changes are major contributors to sediment delivery into lake systems [25].

From the perspective of the Tri Hita Karana philosophy, sustainable lake management should maintain the balance among environmental conservation (palemahan), community well-being (pawongan), and spiritual values associated with the sacred landscape (parahyangan). Therefore, conservation efforts in Lake Tamblingan should involve collaboration between local communities, traditional institutions, and environmental authorities to ensure the long-term sustainability of the lake ecosystem.

4. CONCLUSION

The findings confirm that Lake Tamblingan experienced the highest sediment accumulation among the studied lakes in a previous study, reaching approximately 1.56 m, indicating relatively more intensive sedimentation compared to other lakes in the region. Such sedimentation processes may gradually reduce lake storage capacity and affect water quality, which in turn could influence both ecological functions and socio-cultural activities surrounding the lake. However, this study did not include quantitative estimation of changes in lake volume and storage capacity due to data limitations. Future research is recommended to incorporate volumetric analysis to provide a more comprehensive assessment of sedimentation impacts.




Furthermore, this study demonstrates that understanding lake sedimentation through the Tri Hita Karana framework provides a broader perspective for sustainable lake management. By considering the interconnected dimensions of palemahan (environment), pawongan (community), and parahyangan (spiritual values), lake conservation efforts can be approached in a more holistic manner that integrates environmental sustainability with cultural and spiritual preservation. This integrative perspective may support the development of more culturally sensitive and sustainable management strategies for Lake Tamblingan.

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