Bathymetric-Based Sedimentation Assessment in Bali's Volcanic Lakes

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ABSTRACT

The volcanic lakes of Bali, such as Batur, Beratan, Buyan, and Tamblingan, play a critical role in water provision, ecosystem services, and socio-cultural values. In addition to serving as raw water sources for irrigation, domestic use, dan tourism, these lakes also carry important conservation and spiritual functions embedded in Balinese cultural life. However, land-use changes, agricultural intensification, and tourism development within their catchments have accelerated erosion and sediment transport into the lakes. This sediment accumulation has resulted in lakebed shallowing and reduced storage capacity, thereby threatening the long-term sustainability of their hydrological and ecological functions. This study aims to examine sedimentation processes and potential shallowing through a 2024 bathymetric survey of Bali's four main volcanic lakes. The analysis indicates an increase in sediment deposition between 2023 and 2024, with average thicknesses of 0.12 m in Lake Batur, 0.24 m in Lake Beratan, 0.49 m in Lake Buyan, and 1.56 m in Lake Tamblingan. Among these, Lake Tamblingan recorded the greatest thickness of sediment accumulation. These findings highlight the importance of regular monitoring of lake conditions. Bathymetric analysis can serve as a scientific basis for technical conservation planning, including dredging, upstream erosion control, and zoning of lake areas according to their vulnerability to sedimentation.

Keywords: Civil 3D, Echosounder, Endorheic Lake, Sedimentation Rate.

1. INTRODUCTION

The lakes in Bali Province, such as Batur, Beratan, Buyan, and Tamblingan, play a vital role in the region's hydrological systems, ecology, and local culture. In addition to functioning as raw water sources for irrigation, domestic needs, and tourism, these lakes also serve as conservation areas and sacred spaces for Balinese communities, as reflected in religious practices conducted around them. Morphologically, the four lakes are volcanic in origin, formed in highland regions and characterized by distinct hydrological features. Furthermore, Buyan, Tamblingan, and Batur are also classified as endorheic lakes, which are closed-basin systems without inlets or outlets and rely primarily on rainfall as their water source.[1][2][3][4].

However, the physical condition of these lakes is under significant pressure due to land-use changes, intensive agricultural activities, and the expansion of tourism areas within their catchments. These activities accelerate soil erosion, resulting in sediment being transported into the lakes. Over time, this process leads to sediment accumulation on the lakebed, progressively causing shallowing and a reduction in the lakes' storage capacity [4][5][6].

This cumulative sedimentation phenomenon not only threatens the hydrological functions of the lakes but also poses risks to water quality, the sustainability of aquatic ecosystems, and the socio-cultural values associated with the lakes. In Lake Buyan and Lake Tamblingan, for instance, recent studies have reported changes in sediment quality resulting from human activities, including increased concentrations of heavy metals and anthropogenic compounds in areas surrounding temples and riparian zones [7].

To support effective lake maintenance and conservation efforts, regular monitoring of lake conditions is essential, one of which can be carried out through bathymetric surveys. A study by Wang et al. [8] demonstrated the importance of long-term monitoring of lake volume changes using satellite imagery and digital elevation models (DEM), particularly in endorheic basins. Complementing this approach, bathymetric data can be utilized to evaluate sediment accumulation in greater detail in Bali's volcanic lakes. Through bathymetric analysis, changes in lakebed morphology can be identified, deposited sediment volumes can be estimated, and sediment accumulation zones can be spatially mapped [9][10]. This information is crucial for supporting technical conservation planning, including dredging activities, upstream erosion control, and zoning of lake areas based on their vulnerability to sedimentation. This study was conducted to assess sedimentation conditions and the potential for shallowing in four main volcanic lakes in Bali based on a 2024 bathymetric survey. Its primary objective is to provide a scientific foundation for sustainable lake management strategies amid increasing environmental and social pressures.

2. THEORY AND METHODS

2.1 Study Area

This study was conducted in four main volcanic lakes located in Bali, namely Lake Batur, Lake Beratan, Lake Buyan, and Lake Tamblingan. The spatial distribution of these lakes is presented in Figure 1.

Figure 1. Study Area

Table 1 presents information on the four volcanic lakes, including their location, surface area, dominant land cover, and water utilization by the surrounding communities.

Table 1. Summary of Physical Conditions and Water Utilization of Batur, Beratan, Buyan, and Tamblingan Lakes

Lake	Location	Surface Area (m^2)	Dominant Land Cover	Water Utilization
Lake Batur	Kintamani, Bangli	13479528.95	Mixed dryland with shrubs/gardens (32,64%)	Dources of irrigation water, fisheries, water-based tourism, and hydropower (PLTA)
Lake Beratan	Baturiti, Tabanan	3135582.69	Primary and secondary dryland forest	Provider of piped water supply (PDAM), irrigation, water-based tourism, and cultural activities
Lake Buyan	Sukasada, Buleleng	3738904.24	Primary forest (57,07%), dryland agriculture	Provider of irrigation water, fisheries, and nature-based tourism
Lake Tamblingan	Sukasada, Buleleng	1271237.23	Primary forest, nature serve, protected forest	Religious ritual activities, limited nature tourism, and local water source

2.2 Theory

Erosion and Sedimentation Processes in The Catchment Area

The erosion processes occurring in the catchment area are the primary contributors of sediment material entering the lakes. Human activities such as land conversion, deforestation, and agricultural intensification accelerate erosion rates, thereby increasing the volume of sediment transported into the water bodies. In addition, climatic factors, particularly extreme rainfall intensity, also play a significant role in accelerating sediment transport into the lakes. [11][12][13].

Impacts of Lakebed Morphological Changes

Sediment accumulation in lakes has significant implications for their capacity and hydrological functions. Shallowing caused by sedimentation leads to a reduction in storage capacity, thereby decreasing the ability of lakes to provide raw water, support irrigation, and regulate floods. On the other hand, increased turbidity resulting from sediment input can reduce water quality, limit light penetration, and damage aquatic habitats, including phytoplankton and zooplankton, which play essential roles in the aquatic food chain [14][15].

Bathymetric Survey

To accurately understand and monitor changes in lakebed morphology, bathymetric surveying is one of the primary methods employed. The single-beam echosounder technology currently allows for high-resolution data acquisition with near-complete coverage of the waterbed. The echosounder used operates with dual frequencies: a low frequency (for measuring lakebed depth capable of penetrating soft sediment deposits) and a high frequency (for measuring the uppermost water depth)[9]. The working principle of the echosounder involves emitting sonar pulses downward from a transducer toward the lakebed, as illustrated in Figure 2.

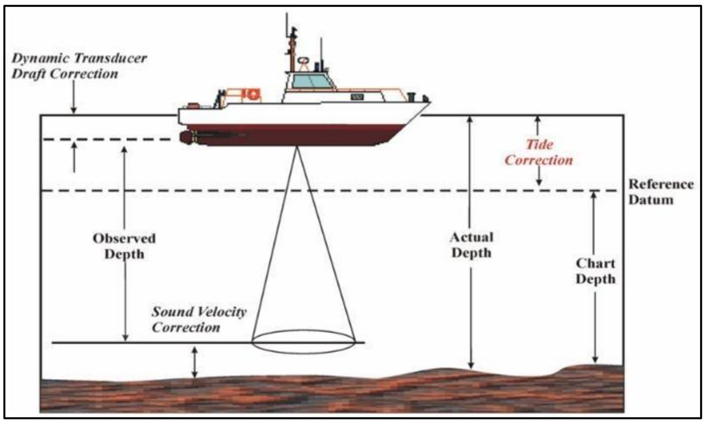
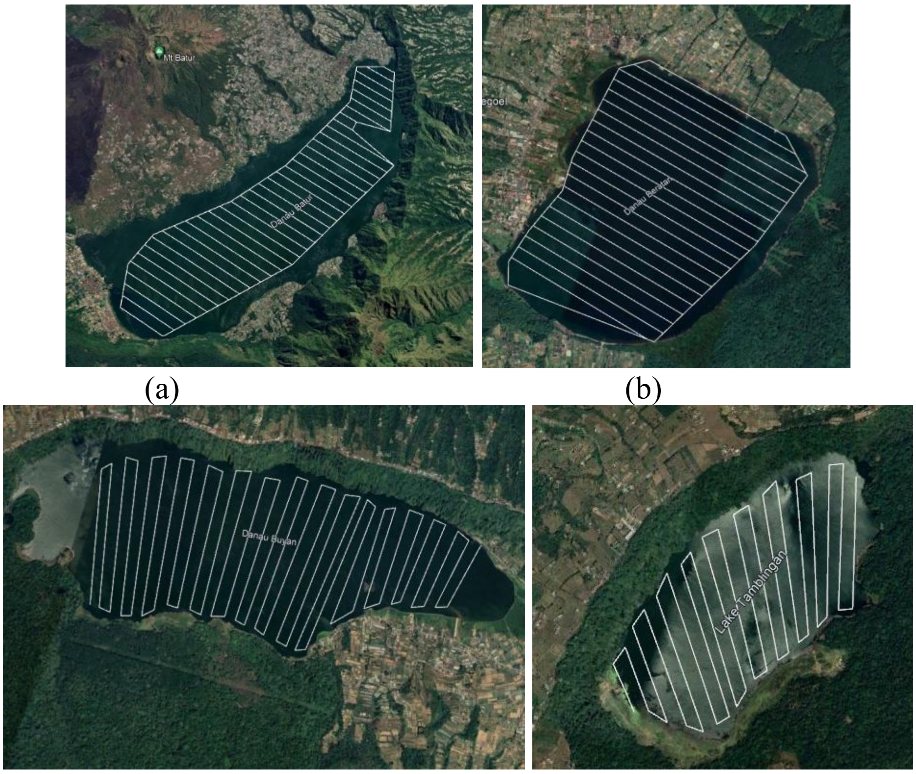


Figure 2. The Working Principle of the Echosounder

2.3 Methods

Bathymetric measurements included recording water depths and positioning measurement points. The survey was carried out using a Midas Valeport single-beam echosounder. Simultaneously, observations of lake water surface elevation were conducted by referencing the elevation to a benchmark (BM). These water surface elevation data were used for correcting the bathymetric results.

The initial stage of the bathymetric survey involved determining the measurement transects. In this study, measurements were conducted at 200-meter intervals. After the transects were established, their coordinates were input into the GPS device to serve as navigation during the survey. Figure 3 illustrates the determination of bathymetric transects for each lake.



(a) (b) (c) (d)

Figure 3. Planned Bathymetric Survey Transects 200-meter Intervals: (a) Lake Batur, (b) Lake Beratan, (c) Lake Buyan, (d) Lake Tamblingan.

Bathymetric data processing was carried out after the completion of field measurements. The initial stage of data processing involved downloading the measurement results from the echosounder. Data retrieval from the MIDAS Valeport echosounder was conducted using the SurveyLog software. The raw survey output contained coordinates and depth readings obtained from the sonar. These data were then transferred from the echosounder to a personal computer for further processing and correction against water level observations.

Tidal (water level) correction was applied to adjust the measured depths by subtracting the observed water surface elevation. The corrected data were subsequently processed to generate contour maps using Autodesk Civil 3D. During this stage, contour refinement and smoothing were performed to produce a comprehensive and reliable representation of the lakebed.

3. RESULTS AND DISCUSSION

Analysis of changes in the lakebed was conducted to identify the sedimentation occurring within the lakes. The analytical process was conducted by overlaying the 2023 measurement data with the most recent 2024 data using Autodesk Civil 3D. Figure 4 presents the contour generated from the overlay of both datasets, illustrating the initial elevation in 2023 and the elevation in 2024, thereby allowing the estimation of the sediment accumulation that has occurred.

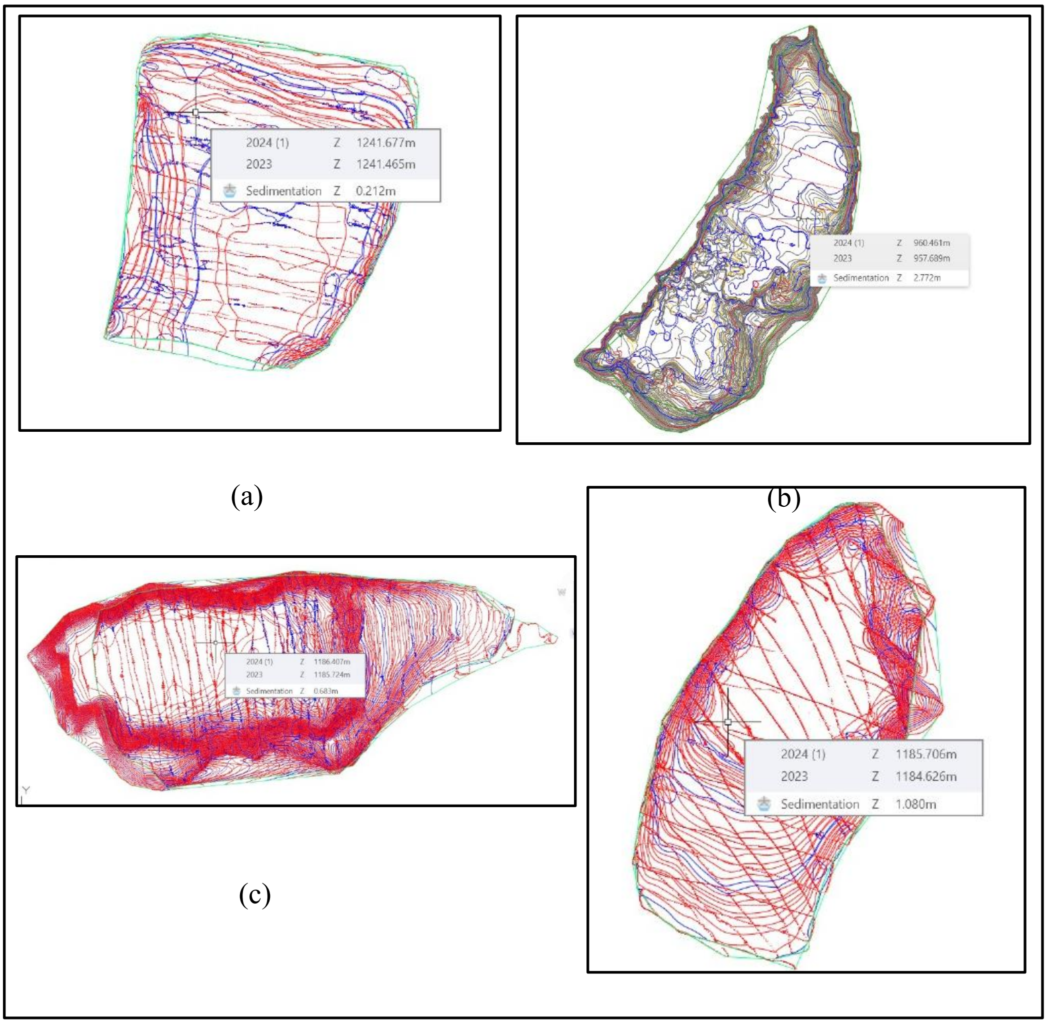


Figure 4. Contour Maps of (a) Lake Batur, (b) Lake Beratan, (c) Lake Buyan, (d) Lake Tamblingan derived from Overlay Analysis using Autodesk Civil 3D

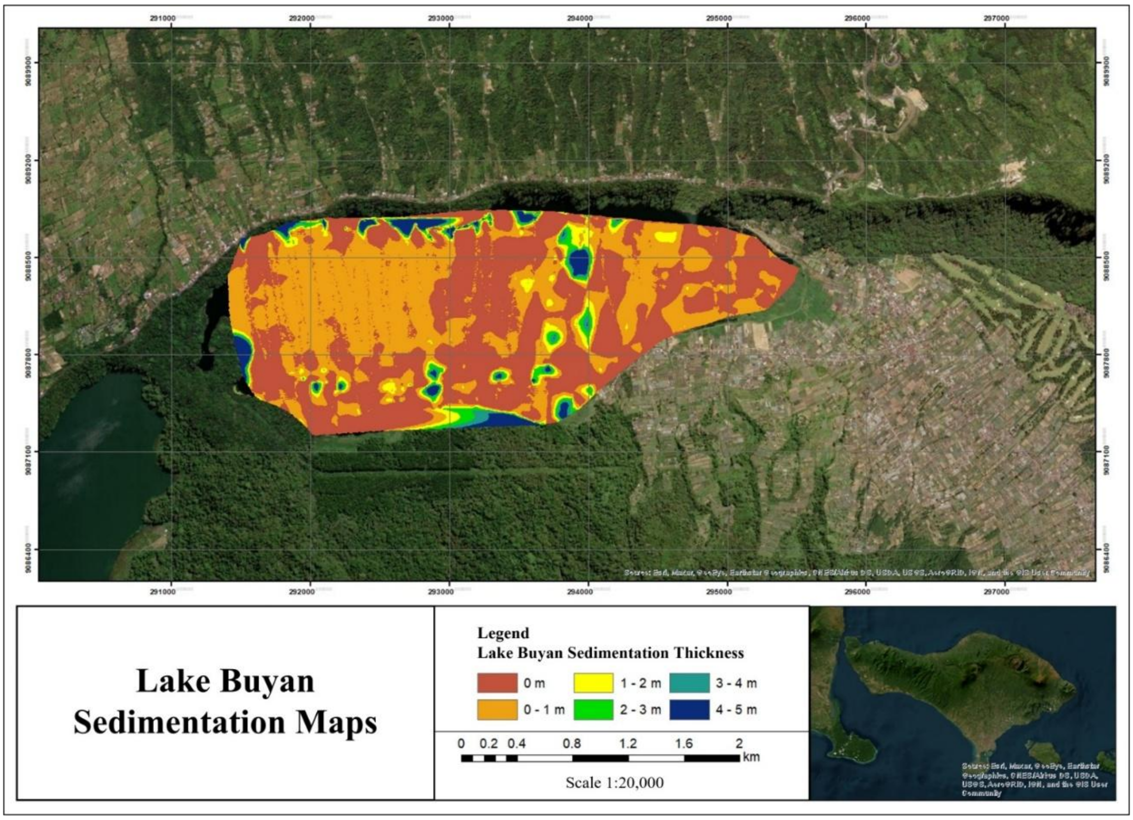
This analysis allows the estimation of sediment accumulation between 2023 and 2024. The sedimentation rates of the four lakes are summarized in Table 2.

Table 2. Sediment Increase in the lakes from 2023-2024

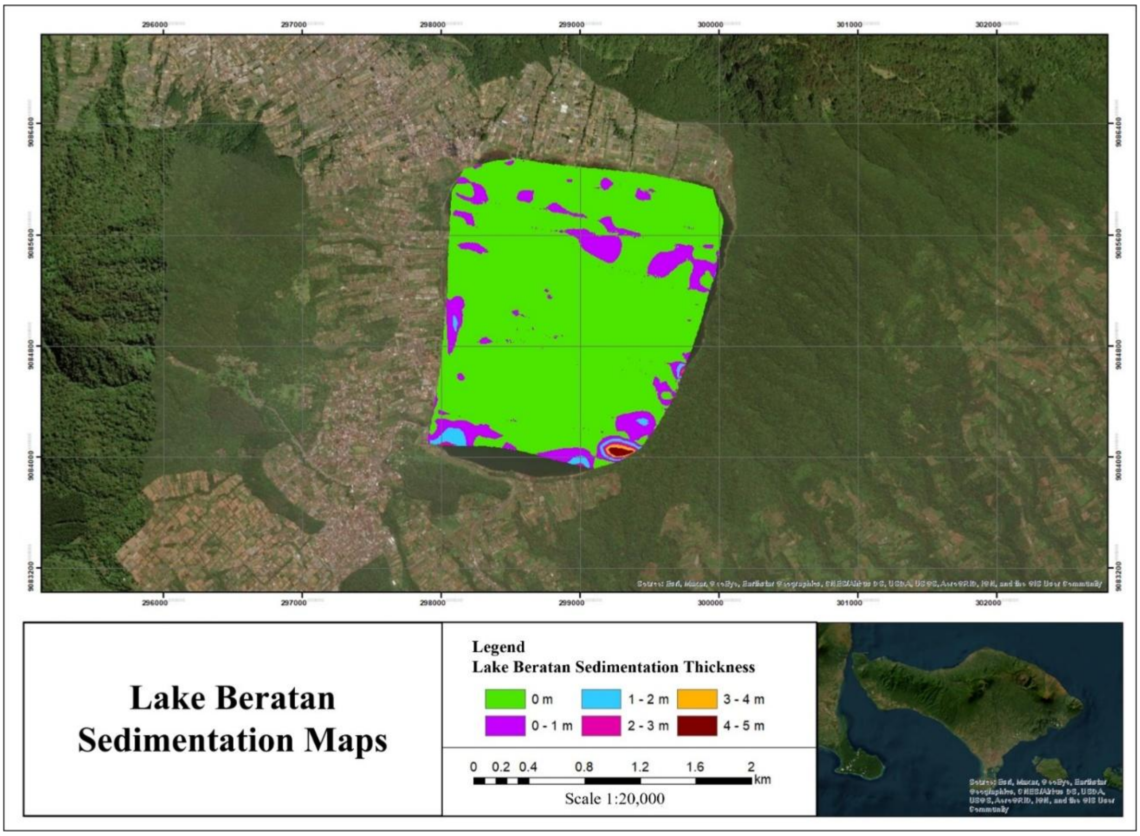
Lake	Sediment Accumulation (m^3)	Surface Area (m^2)	Average Sediment Thickness (m)
Lake Batur	1572807.90	13479528.95	0.12
Lake Beratan	740464.24	3135582.69	0.24
Lake Buyan	1843626.86	3738904.24	0.49
Lake Tamblingan	1630997.09	1271237.23	1.56

Based on Table 2, it can be observed that there has been an increase in sediment deposition on the lakebeds, indicating morphological changes at the lake bottom. The data show that although Lake Tamblingan has a smaller surface area compared to Lakes Batur and Buyan, it records the greatest average sediment thickness, suggesting a relatively higher sedimentation rate.

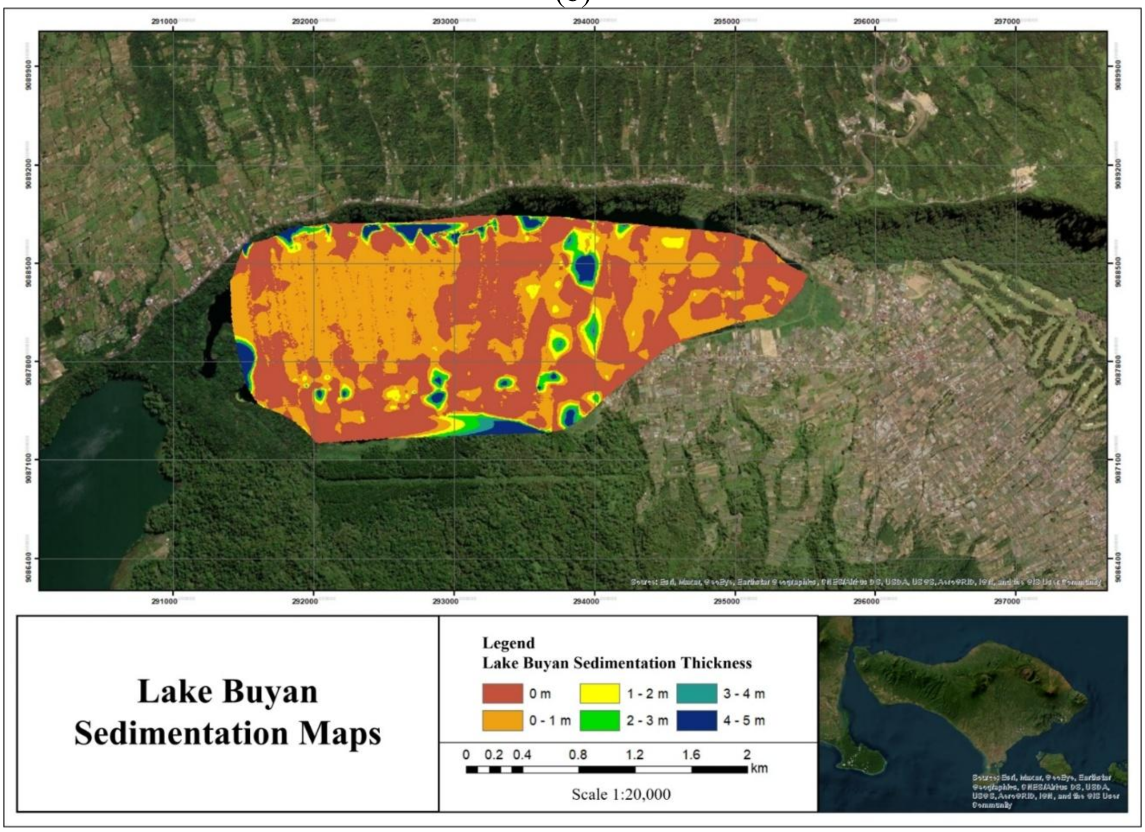
Furthermore, the contour maps obtained were further processed using ArcGIS to generate sedimentation maps for each lake, as presented in Figure 5. These maps visualize the spatial distribution patterns of sediment on the lakebeds according to their thickness.



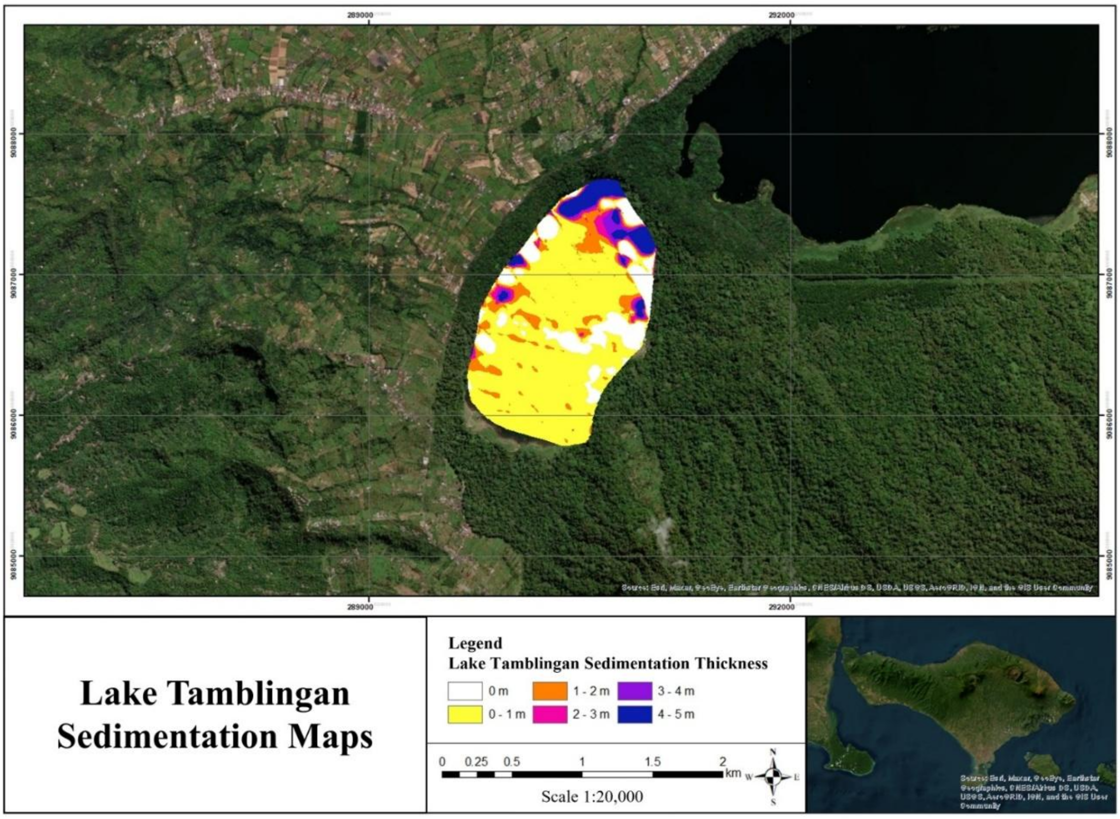
(a)


Lake Beratan
Sedimentation Maps
Legend
Lake Beratan Sedimentation Thickness
0 m
1 - 2 m
3 - 4 m
0 - 1 m
2 - 3 m
4 - 5 m
0 0.2 0.4 0.8 1.2 1.6 2 km
Scale 1:20,000

(b)


Lake Buyan
Sedimentation Maps
Legend
Lake Buyan Sedimentation Thickness
0 m
1 - 2 m
3 - 4 m
0 - 1 m
2 - 3 m
4 - 5 m
0 0.2 0.4 0.8 1.2 1.6 2 km
Scale 1:20,000

(c)



(d)

Figure 5. Sedimentation Maps of (a) Lake Batur, (b) Lake Beratan, (c) Lake Buyan, (d) Lake Tamblingan Derived from Overlay Using Autodesk Civil 3D

Based on Figure 5, variations in sediment accumulation patterns are evident across the four lakes:

a. Lake Batur shows significant sediment accumulation zones near the main inlet from the northern catchment area, where surface runoff transports eroded material from agricultural slopes.
b. Lake Beratan exhibits a relatively even distribution of sediment, with thicker deposits concentrated in the southern and southeastern areas, near settlements and recreational water-use zones.
c. Lake Buyan displays high sediment accumulation along its western and southwestern margins, directly adjacent to areas of intensive vegetable farming.
d. Lake Tamblingan demonstrates concentrated sediment deposition in the northern section.

The spatial sedimentation maps enable the identification of priority areas for maintenance, such as dredging or riparian buffer rehabilitation.

Sediment accumulation leads to lakebed shallowing, which directly reduces water storage capacity. This reduction compromises the lakes' functions as sources of raw water, natural flood regulators, and aquatic ecosystem habitats. Lower storage capacity may also accelerate water quality degradation, including increased turbidity and decreased dissolved oxygen levels. From a socio-economic perspective, diminished storage capacity and water quality can affect irrigation supply, disrupt recreational water activities, and reduce the aesthetic and spiritual values of the lakes.

In terms of average sediment thickness, Lake Tamblingan is the most affected, with 1.56 m of accumulated sediment. This finding indicates that smaller surface area does not necessarily correspond to lower sedimentation risk. The shallowing of Lake Tamblingan has the potential to reduce the lake's storage capacity, increase turbidity, and accelerate eutrophication processes that may impair water quality and aquatic biodiversity. As a sacred space, the degradation of lake quality also poses risks to religious rituals that hold profound spiritual significance for the Balinese community. In addition, Lake Tamblingan functions as a destination for eco and spiritual tourism, with limited activities such as forest trekking and traditional non-motorized boating. Continued shallowing may diminish the comfort of these tourism activities, reduce the aesthetic appeal of the lake, and affect the local economy that relies on nature-based tourism.

4. CONCLUSIONS

From the 2024 bathymetric surveys conducted on the four main volcanic lakes in Bali, evident sedimentation was observed across all studied lakes. Bathymetric surveys proved effective in assessing the degree of lakebed shallowing. Lakes with endorheic characteristics and smaller surface areas were found to be more vulnerable to sediment accumulation. In this study, Lake Tamblingan is the most affected, with 1.56 m of accumulated sediment. To gain a more comprehensive understanding of sedimentation dynamics in Bali's volcanic lakes, future studies are recommended to include periodic analyses of sedimentation rates. Such information would allow for more accurate estimations of lake shallowing rates and projections of storage capacity in the future. Sediment transport from catchment erosion should be quantified via modeling or field measurement to help identify key sources and supports targeted mitigation.

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