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ORIGINAL RESEARCH

# Morphometric characteristics of Lake Limboto as critical lake in Gorontalo Province, Indonesia

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***Abstract.*** This research aims to investigate the factors leading to siltation in Lake Limboto by analyzing its morphometric characteristics gathered through direct field measurements and remote sensing using Geographic Information System (GIS). Lake Limboto covers an approximate surface area of 26.09 square kilometers, boasts a maximum depth of 4 meters, and maintains an average depth of 2.83 meters. The Shoreline Development Index (SDI) stands at approximately 2.57, indicating an irregular shape of the lake's water body, while the Lake Volume Development (VD) index, at 2.12, suggests a generally flat lake bottom. The Relative Depth (Zr) registers at around 0.69%, as observed from the water turbidity level. The lakebed relief in the vicinity of the lake's periphery is predominantly flat and shallow, particularly in the western, northern, and southern regions, with depths measuring less than 2 meters. In contrast, the lakebed relief in the central and eastern sections tends to be less flat but still features depths of less than 4 meters. Siltation in Lake Limboto primarily results from high sediment input originating from erosion processes, agricultural activities, and settlements in the surrounding area.

**Keywords**: Lake Limboto, morphometric, horizontal and vertical, sedimentation, environment

## INTRODUCTION

Limboto Lake is a natural lake formed through tectonic processes that created a graben in northern Sulawesi, within Gorontalo Province [1;2]. This graben serves as a basin for rainwater to collect, giving rise to approximately 23 rivers that converge to create Lake Limboto [3;4]. This lake plays a crucial role in maintaining a balanced hydrological system in Gorontalo. Its significance extends beyond being a freshwater reservoir; it also functions as an ecological system controller, helping to balance various ecosystem components, manage floods and droughts, and provide a habitat for biodiversity.

In fact, Lake Limboto represents a valuable natural resource for the people of Gorontalo, serving as a source of livelihood that supports many families' economies. According to [5;6] that around 70% of the Limboto Lake area is in Gorontalo Regency and 30% in Gorontalo City. However, this lake is an icon and a source of pride for all people in Gorontalo province. Nevertheless, the

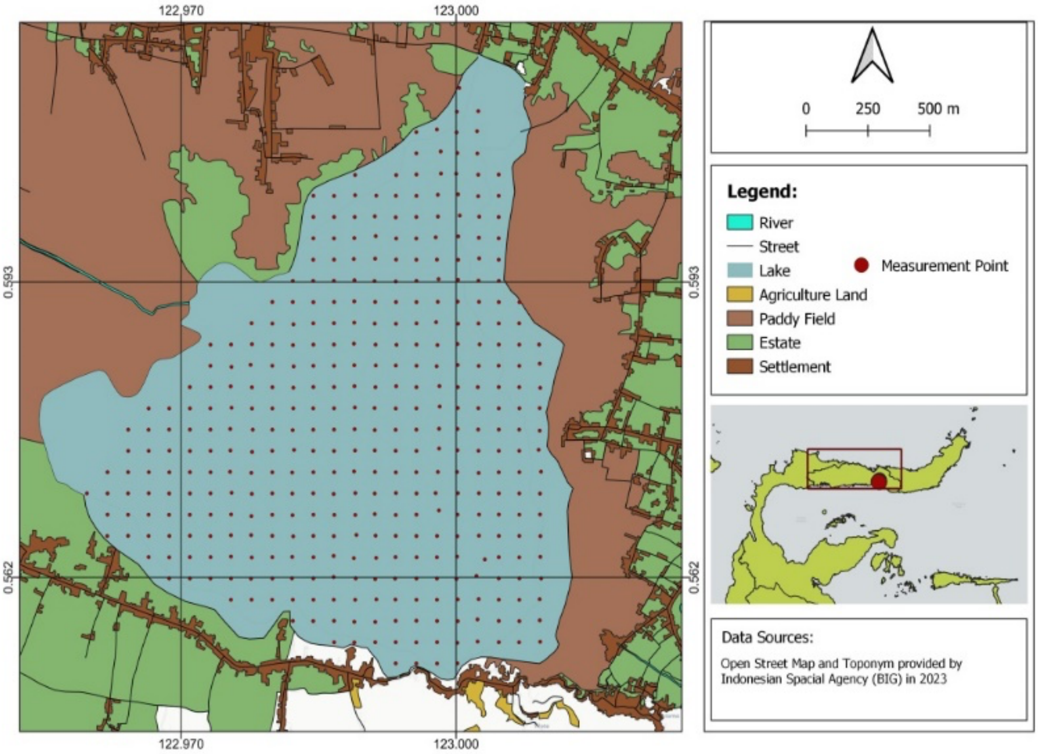


**Figure 1.** The research location in Limboto Lake

magnificence and purpose of Lake Limboto have suffered from a range of issues, encompassing physical, functional, biochemical, and ecological degradation. This is evident through the diminishing size and depth of the lake. Historical data [3;7] indicates that in 1932, Lake Limboto spanned approximately 7,000 hectares with a depth of 30 meters. However, around five decades later, in 1982, the lake's area had dwindled to roughly 3,000 hectares or 30 km$^2$, with an average depth of only 3 meters.

Even more disconcerting, data from a study [2] reveals that the lake's area continued to decline, reaching approximately 20.44 km$^2$ in 2019, representing a significant reduction of around 68.13% since 1982. This deteriorating condition has had profound implications for Lake Limboto's function and ecology, raising concerns about the potential for hydrometeorological disasters that pose an increasing threat to public safety.

In response to these challenges, the government took action in 2009 by designating Lake Limboto as one of Indonesia's critical lakes and a national priority in the critical lake conserve program. This commitment was reaffirmed in 2021, emphasizing Lake Limboto's status as one of 15 national priority lakes in need of preservation [8]. Changes in the size and quality of Lake Limboto, driven by factors such as sedimentation [3;2], the proliferation of water hyacinth, and various anthropogenic activities within the community [1;9;10], have further exacerbated the degradation of the lake. Research by [11;12] indicates that environmental alterations from upstream to downstream can significantly impact the morphometric dynamics of the lake, affecting both its physical structure and hydrodynamics.

Moreover, [13;14] explain that changes in the lake's surrounding environment can influence its morphometry, and conversely, an analysis of lake morphometrics can provide insights into the biological and chemical processes within the lake. Therefore, morphometric data plays a crucial role in formulating strategies to rescue critical lakes like Lake Limboto.

Lake morphometry encompasses the shape and dimensions of the lake, including surface area (A), volume (V), average depth (Z), and the examination of water characteristics both vertically (subsurface dimensions) and horizontally (surface dimensions) [14;15]. Morphometric data provides valuable insights into water depth, the underlying structure of the lakebed, water area, volume, light penetration, lake development, and the topography of the lake shoreline area [16]. Additionally, [17] elaborates that bathymetry measurements employing depth contour lines can delineate the structure of the lake bottom, shedding light on its potential for biological production and sensitivity to material loads from its surrounding areas [13;18].

Understanding the morphometric characteristics of a lake is instrumental in determining its layers and assessing its usability by humans. This knowledge forms the foundation for crafting sustainable conservation strategies that encompass the entire lake ecosystem, from upstream to downstream [19;20]. It also allows for the simulation of lake management based on morphology, facilitating efforts to mitigate undesirable impacts associated with severely degraded lakes. Unfortunately,

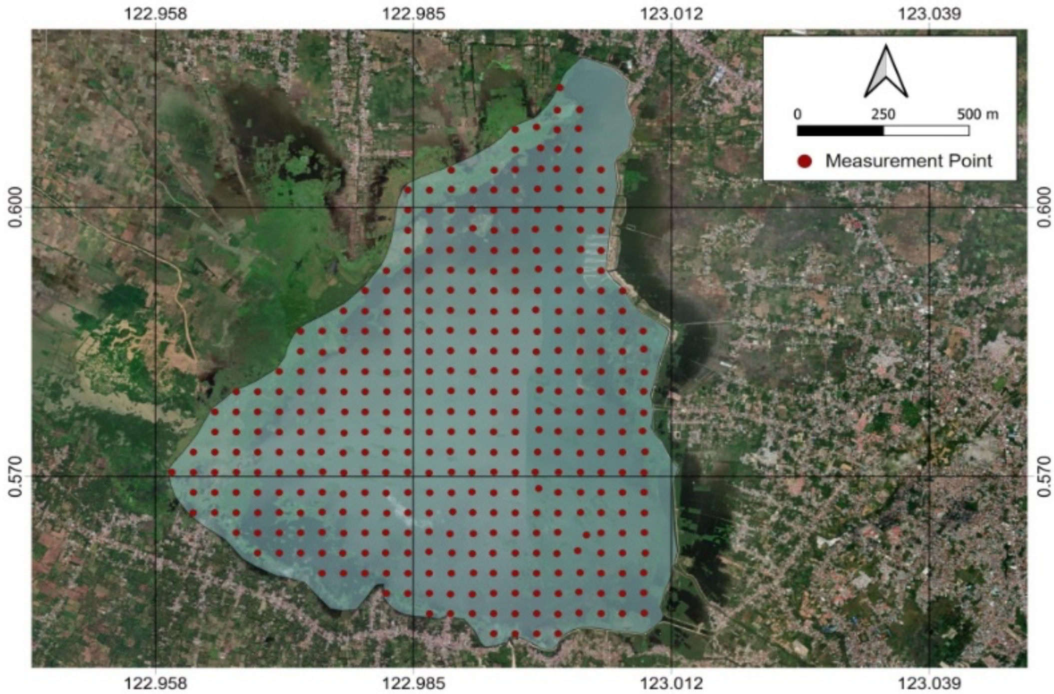


**Figure 2.** Trajectories for measuring the bathymetry of Lake Limboto with approximately 250 meters for each path.

despite the degradation of Lake Limboto, the availability of updated morphometric data, which could serve as a cornerstone for sustainable lake preservation, remains lacking. Therefore, this study aims to analyze the morphometric characteristics of Lake Limboto, currently identified as a critical tropical lake, to inform its conservation and further limnological research concerning critical lakes.

## METHODOLOGY

### Data collection and visualization

This research employed survey and measurement methods conducted in the waters of Lake Limboto during July and August 2023 (refer to Figure 1). To ascertain the lake's surface dimensions, we utilized a boat for circumnavigation (tracking) while referencing a Landsat image map. For subsurface measurements, particularly depth, we employed a measurement technique employing a 7-meter-long wooden apparatus and a global positioning system (GPS). The trajectory for measuring lake depth was meticulously delineated using QGIS LTR 3.22 software, comprising 23 trajectories representing the entire lake's water area. Each trajectory was spaced at intervals of 250 meters, resulting in a total of approximately 415 depth measurement points, as illustrated in Figure 2.

To aid in data analysis and interpretation, this study employed QGIS LTR 3.22 and Surfer 13 software for visualization purposes. QGIS LTR 3.22 was used to create bathymetry color contours for depicting the depth of Lake Limboto through spatial interpolation techniques. It also generated contour lines, calculated the lengths of these contour lines at various depths, and determined the overall area of the lake.

On the other hand, Surfer 13 software was utilized to construct a 3D dimensional model of Lake Limboto using latitude, longitude, and depth parameters obtained from the data. Additionally, this study employed Surfer 13 to map the depth profile model of Lake Limboto by employing a slice model or cross-sectional depth contour method.

### Surface dimensional morphometric analysis techniques

The analysis of the lake's morphometric parameters adhered to an analytical system as described in [21;22;14]. This system encompassed both surface and subsurface dimensions, which were derived through mathematical calculations and employed the QGIS software.

1. Maximum length (Lmax): This parameter was determined by measuring the greatest distance between two points on the lake's edge.
2. Maximum effective length (Le): Le was ascertained by measuring the farthest distance between two points on the lake's surface edge, excluding any passage through islands.
3. Maximum width (Wmax): Wmax was established by measuring the distance between the two farthest points on the lake's surface, drawn perpendicular to Lmax.
4. Maximum effective width (We): Similar to Le, We was determined by measuring the distance between the two farthest points on the lake's surface, drawn perpendicular to Le, and avoiding any islands.

**Table 1.** Morphometric Data of Limboto Lake

| No | Parameters | Unit | Value |
|---|---|---|---|
| **A. Surface Dimensions Data** | | | |
| 1. | Maximum length (Lmax) | km | 7,53 |
| 2. | Maximum effective length (Le) | km | 7,53 |
| 3. | Maximum width (Wmax) | km | 6,15 |
| 4. | Maximum effective width | km | 6,15 |
| 5. | Surface area (Ao) | $km^2$ | 26,09 |
| 6. | Average width (W) | km | 3,46 |
| 7. | Shore line (SL) | km | 23,30 |
| 8. | Shoreline development index | | 2,57 |
| **B. Subsurface Dimensions Data** | | | |
| 1. | Average depth (Z) | m | 2.83 |
| 2. | Maximum depth (Zm) | m | 4.0 |
| 3. | Relative depth (Zr) | % | 0.69 |
| 4. | Volume development (VD) | | 2.12 |
| 5. | The total volume of lake water (V) | $km^3$ | 0,07 |
| 6. | The mean slope ($\bar{S}$ ) | % | 1.7 |

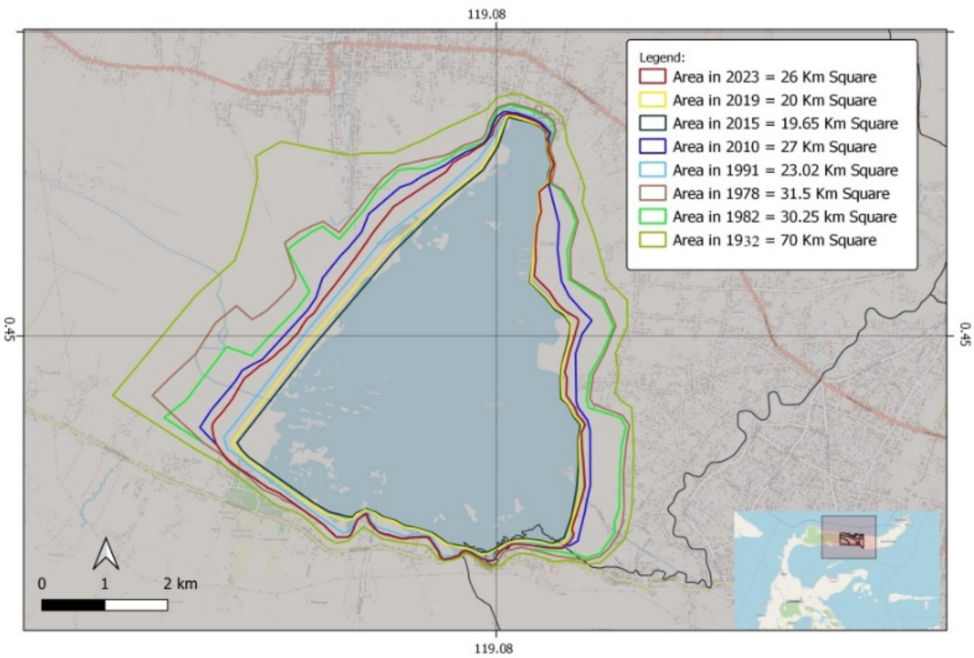


**Figure 3**. Map of changes in the surface area of Lake Limboto from 1932 to 2023

5. Surface area (Ao): This parameter was calculated using QGIS LTR 3.22 software and administrative maps sourced from the Indonesia Geospatial Information Agency (BIG), as well as an image map from Esri Imagery.
6. Average width (W) uses equation (1),

$$W = \frac{A_o}{L_{max}} \qquad (1)$$

7. Shore line (SL) is also measured, which can be measured from the bathymetry map using QGIS LTR 3.22 software.
8. Shoreline Development Index (SDI): SDI, a unitless index, was determined based on SL and surface area Ao, using equation (2):

$$SDI = \frac{SL}{2\sqrt{\frac{22}{7}A_o}} \qquad (2)$$

If SDI > 1, the water body's shape is considered irregular, while if SDI ≤ 1, the shape is considered regular.

**Subsurface Dimensional Morphometric Analysis Techniques**

1. Average depth (Z) using equation (3),

**Table 2.** Lake area adopted from several literatures.

| Years | Surface Area ($km^2$) | Source data |
|---|---|---|
| 1932 | 70,00 | [1;2] |
| 1982 | 30,25 | [3] |
| 1978 | 31,50 | [3] |
| 1991 | 23,02 | [3] |
| 2010 | 27,00 | [20] |
| 2015 | 19,65 | [3] |
| 2019 | 20,00 | [3] |
| 2023 | 26,09 | results of this study |

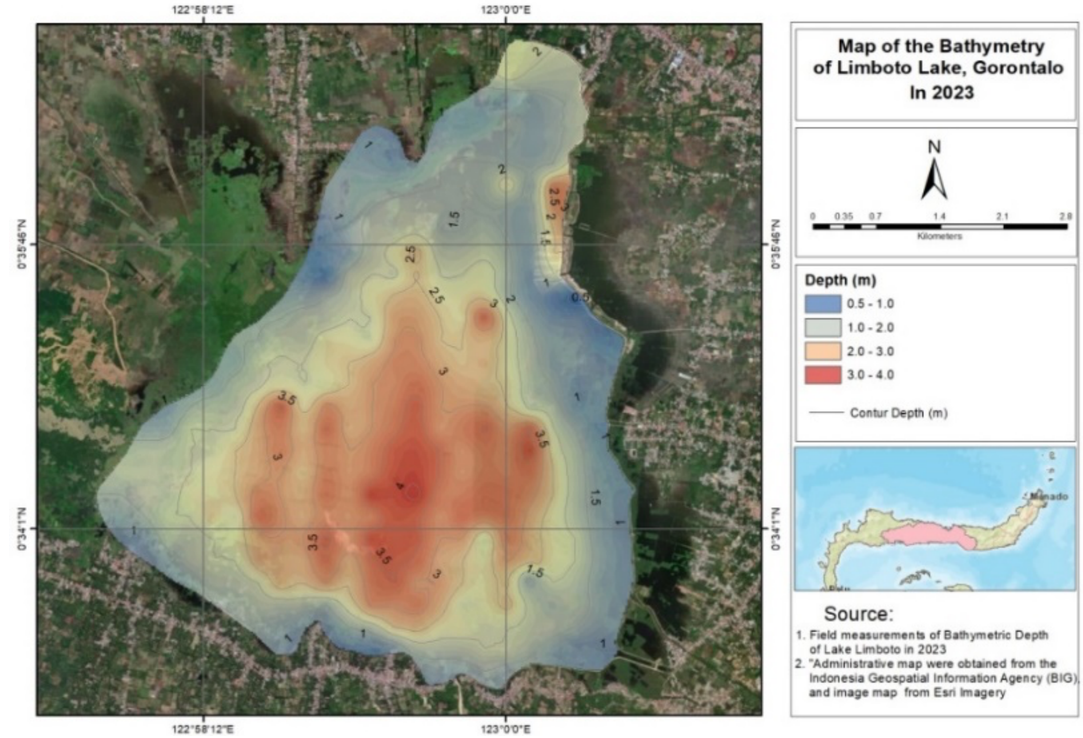


**Figure 4.** Contour of map layout from Limboto Lake bathymetry data in 2023

$$Z = \frac{V}{A} \qquad (3)$$

2. Maximum depth (Zm) is the depth of the lake at the deepest point obtained from direct measurements at the research site.
3. Relative depth (Zr) obtained using equation (4),

$$Zr = \frac{Zm}{2\,x\,\frac{\sqrt{A_O}}{\sqrt{\pi}}}\;x\;100\% \qquad (4)$$

If Zr < 2%: the lake is easily stirred, Zr ≥ 2%: the lake is not easily stirred.

4. Volume development (VD without units) that can describe the general shape of the lake bottom, we use equation (5),

$$VD = \frac{A_O\,x\,Z}{\frac{1}{3}(Zm\,x\,Ao)} \qquad (5)$$

If the VD > 1, the bottom of the water is relatively flat, and if the VD ≤ 1, the bottom of the water is shaped like a cone.

5. The total volume of lake water (V) can use equation (6) by first determining the value of h = interval between contours (m), A = area per layer/contour ($m^2$) and n = the number of contours,

$$V_{tot} = \frac{h}{3}\sum_{i-1}^{n}(Ai - 1 + Ai + \sqrt{(Ai-1\,)x\,Ao} \qquad (6)$$

6. The mean slope ($\bar{S}$ ) of the lake was also determined to illustrate the extent of shallow water using equation (7), which first calculates the length of the perimeter of each contour (L in m), maximum depth (Zm in m) , surface area (Ao in $m^2$), and n is the number of contours on the map.

$$\bar{S} = \frac{1}{n}\left({}^{1}\!/_{2}\,Lo + L1 + \cdots + Ln - 1 + {}^{1}\!/_{2}\,Ln\right)\frac{Zm\,x}{Ao}\;x\;100\% \qquad (7)$$

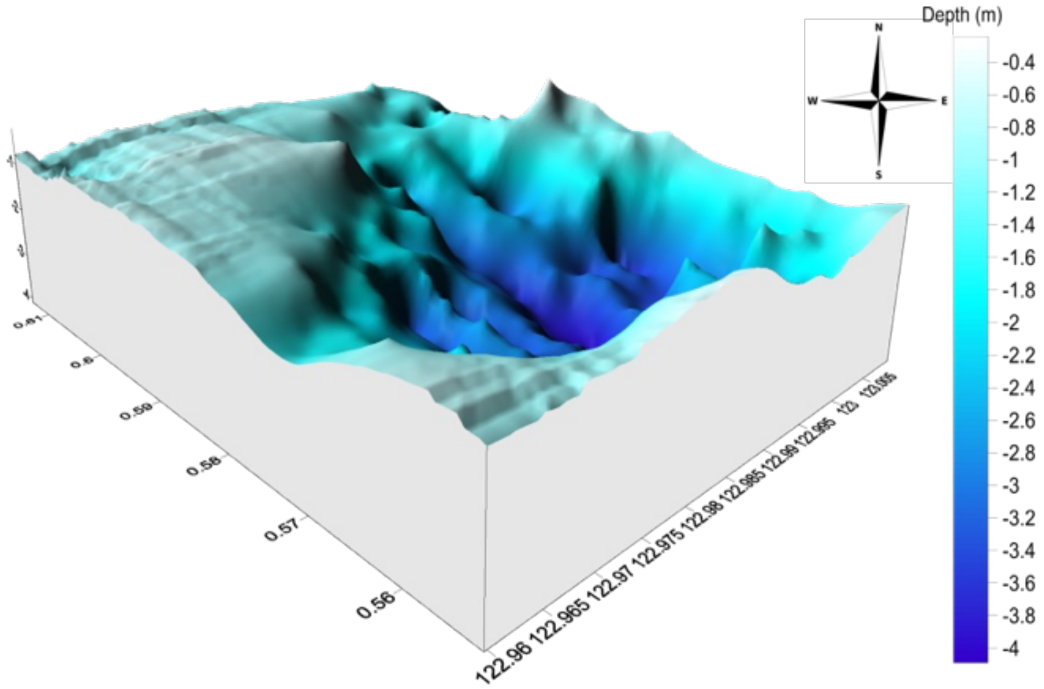


**Figure 5.** Layout 3D bathymetry of Lake Limboto

## RESULTS AND DISCUSSION

The results of this research have provided morphometric measurement data for both surface and subsurface dimensions of Lake Limboto, as detailed in Table 1. The findings indicate that the surface area of Lake Limboto (Ao) is approximately 26.09 km$^2$. When compared to the 2010 data on Lake Limboto's area (27 km$^2$) reported by [23], it becomes evident that the current lake surface area has decreased by approximately 0.91 km$^2$, equivalent to about 91 hectares. However, in contrast to the data on Lake Limboto's area in 2019 (20.44 km$^2$) reported by [2], it appears that the lake's area has increased by about 5.65 km$^2$ or 565 hectares. This expansion is attributed to government initiatives involving water hyacinth removal and dam construction during the measurement period.

Nonetheless, it is crucial to note that the overall area of Lake Limboto in 2023 has experienced a general decline, decreasing by approximately 43.91 km$^2$, which accounts for about 37.27% of its area in 1932, when it spanned approximately 70 km$^2$. Figure 3 provides a visual representation of these area changes in Lake Limboto since 1932, as compiled from multiple sources [2;7;23], with the results from this study highlighted by red lines.

Furthermore, based on the bathymetric measurements conducted in Lake Limboto, it was observed that the maximum depth (Zm) reaches approximately 4 meters at the lake's central point. In contrast, the mathematically calculated average depth (Z) is 2.83 meters, which is closely aligned with the average depth recorded in 2003, approximately 2.99 meters, as reported by [2]. The contour map displayed in Figure 4 illustrates the bathymetry measurements' outcomes, highlighting that the lake's periphery predominantly features depths of less than 2 meters. In contrast, as you move towards the lake's center, the depth gradually increases, evident by the intensifying red contours, ultimately reaching a maximum depth of 4 meters.

A significant morphometric aspect under analysis pertains to the bottom relief shape of Lake Limboto, derived from a volume development (VD) value of approximately 2.12 (VD>1). This value signifies that Lake Limboto's bottom relief tends towards flatness, indicating relatively minimal variation in its bottom contours. As described by [18;19], a VD>1 value suggests that the water body's bottom relief is relatively flat. This assessment is further supported by the average slope ($\bar{S}$) of the lake, which measures around 1.7%, signifying that Lake Limboto predominantly features a flat slope. The slope categories follow the reference provided by [24], classifying slopes into five categories: flat (0-8%), gentle (8-15%), rather steep (15-25%), steep (25-45%), and very steep (>45%).

This analysis is visually confirmed by 3D visualization of bathymetry data using Surfer 13, providing a clear depiction of Lake Limboto's baseline relief, as shown in Figure 4. The flat bottom relief predominantly extends along the lake's periphery, particularly in the west, north, and south. Conversely, towards the lake's center and eastern edge, the relief becomes less flat and slopes gradually, with the dark blue color indicating increasing depth, culminating in a maximum depth of 4 meters.

A comprehensive examination of Lake Limboto's bottom relief is undertaken through cross-sectional analysis, considering both south-to-north and west-to-east perspectives, as illustrated in Figure 5. The south-to-north cross sections, represented by A-A' and C-C', predominantly exhibit shallow lake depths (< 2 meters) with a flat relief, especially in the northern region. Additionally, cross section F-F', located along the northern shoreline, illustrates that the lake's relief maintains a flat profile from west to east, with depths of less than 2 meters. Meanwhile, cross section D-D', situated in the southern shoreline, also tends to feature shallow lake depths (<3 meters), with a somewhat less flat relief. The middle section of the lake is characterized by cross sections E-E' and B-B', which display a relief that is less flat but gradually sloping, accompanied by relatively shallow depths (<4 meters).

The bottom relief of Lake Limboto exhibits a trend towards flatness in its western and northern sections, featuring an average depth of less than 2 meters. In contrast, the relief becomes progressively less flat as one moves towards the central and eastern regions of the lake. However, despite this variation in relief, the lake is categorized as flat based on the average slope value ($\bar{S}$).

The flat and shallow relief and depth observed in the western and northern parts of Lake Limboto are attributed to several factors. These include the substantial inflow of sediment from river erosion, intensive agricultural activities, and human settlements, all of which contribute to increased siltation within these areas. The rivers that flow into the western and northern segments of the lake include the Alo River, Rombongan River, Pohu River, Alopohu River, Marisa River, and Biyonga River. As reported in research by [2], these rivers collectively account for substantial sediment input, with erosion volumes estimated at 21% for the Alo River, 20% for the Rombongan River, 10% for the Pohu River, 8.3% for the Alopohu River, 9% for the Marisa River, and 7% for the Biyonga River

Based on directly measured bathymetry data collected from the water, Lake Limboto is classified as an extremely shallow lentic water body, falling into the category of lakes with depths of less than 10 meters [25;14]. In fact, both the surface area and depth of Lake Limboto tend to be significantly lower when compared to other tectonic lakes in Sulawesi that have been designated as national priority lakes by the government. For instance, Lake Poso boasts an area of 36,892 hectares and a maximum depth (Zm) of 384.5 meters [26], Lake Matano spans an area of 16,408 hectares with a maximum depth of 540 meters (26), and Tempe Lake covers an area of 20,000 hectares with a maximum depth of 5.5 meters [27].

According to [28;29], shallow lake types are typically more susceptible to rapid eutrophication processes. Additionally, [30] has affirmed that shallow lakes, with an average depth of 5.43 meters, tend to have soft bottoms that easily mix with the water column, resulting in turbid lake water. In line with these observations, the measurement results reveal that Lake Limboto has an

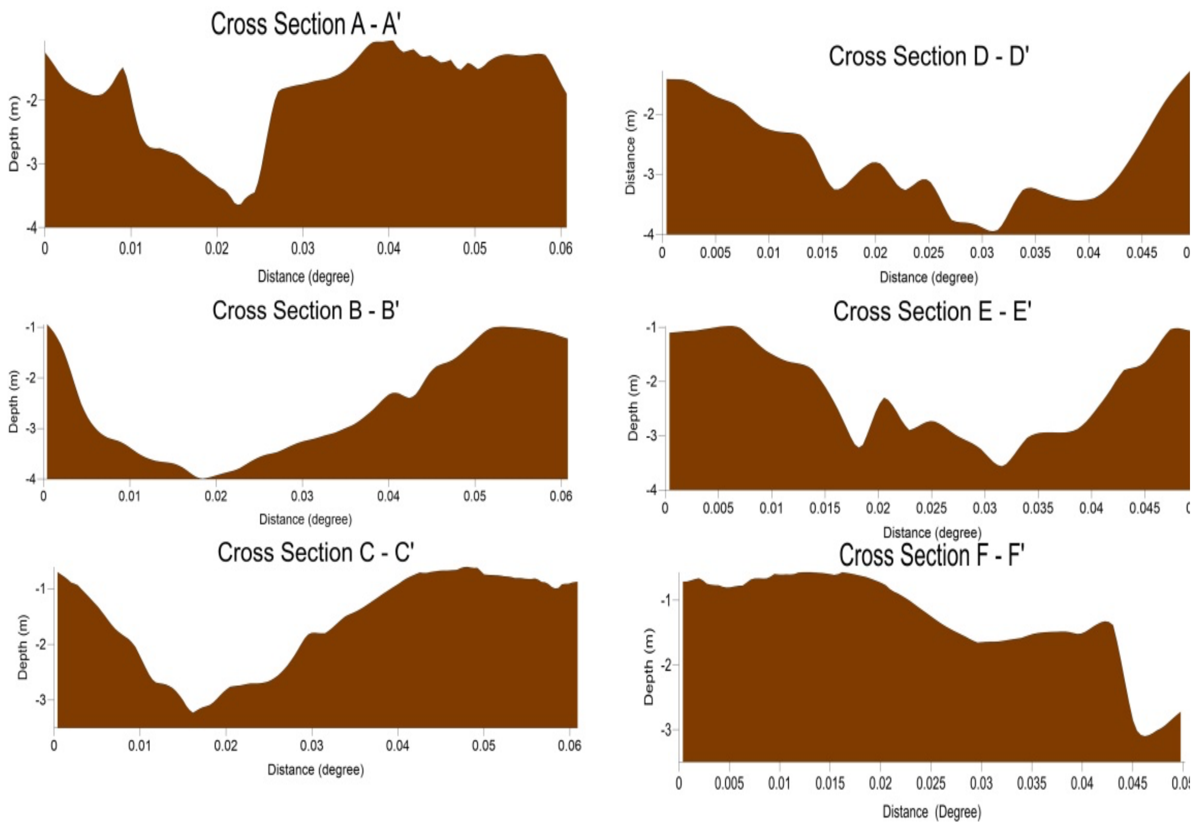


**Figure 6.** Map of the basic relief of Lake Limboto based on cross section from south to north (A-A', B-B' and C-C') and from west to east (D-D', E-E', F-F').

average depth (Z) of 2.82 meters, signifying the presence of a soft bottom that readily undergoes water mixing. This explanation gains further support from the fact that the maximum length (Lmax) of Lake Limboto, approximately 7.53 km, coincides with the maximum effective length (Le), as there are no islands within the lake. Similarly, the maximum width of the lake (Wmax) at about 6.15 km also aligns with the maximum effective width (W). These data points collectively indicate minimal variation in the length and width of Lake Limboto, reflecting its relatively flat bottom contours [19;28;30].

This analysis is corroborated by the lake shoreline development index (SDI) value of 2.57 (SDI > 1), suggesting an irregular shape for Lake Limboto. According to [31], SDI > 1 signifies an irregular lake shape and the potential for increased water productivity. Essentially, the amount of nutrients entering the lake is influenced by the perimeter length and the SDI value of the lake. A greater perimeter length and higher SDI value indicate increased nutrient input from the surrounding land. This is linked to the lake's irregular shape, with more areas connected to the land, which enhances the possibility of nutrient inflow from the land.

In summary, the results of this study on the morphometric characteristics of Lake Limboto, a critical lake, indicate a decrease in both area and depth. Furthermore, it classifies Lake Limboto as a smaller and shallower type of lake when compared to other critical lakes in Sulawesi. The irregular shape of Lake Limboto, coupled with its flat and soft bottom relief, suggests susceptibility to churning and upwelling, affecting water productivity. Notably, the flat and shallow bottom relief in the western, northern, and southern regions contributes to faster sedimentation, driven by substantial sediment inflow from rivers and aquaculture activities employing floating net cages within the lake. These measurement and analysis results on Lake Limboto's morphometric characteristics can serve as a foundation for developing strategies to expedite the rescue of critical lakes and reassess the lake's pollution capacity.

## CONCLUSION

Lake Limboto exhibits distinct morphometric characteristics that categorize it as a shallow lake, featuring a surface area of approximately 26.09 km$^2$, a maximum depth of 4 meters, and an average depth of 2.83 meters. The current area of Lake Limboto has diminished by about 43.91 km$^2$, representing a reduction of approximately 37.27% from its 1932 size of 70 km$^2$. The lake's irregular shape is evident through an SDI value of around 2.57 (SDI > 1), indicating that the more sections of the lake are connected to the mainland, the greater the ease with which nutrients from the land enter the lake. This characteristic aligns with a VD value of approximately 2.12 (VD > 1) and a relative depth of 0.69% (Zr < 2%), highlighting Lake Limboto's tendency towards a flat bottom and a soft substrate that readily mixes with the water column, resulting in cloudy lake water. Furthermore, Lake Limboto boasts an average slope of approximately 1.7%, categorizing it as flat, which promotes the stirring or upwelling of water masses caused by wind. These characteristics amplify the eutrophication process within the lake, significantly impacting its water quality. Along the lake's periphery, especially in the west, north, and south, the bottom topography is flat with depths predominantly less than 2 meters. Conversely, the central part of the lake features a less flat relief characterized by depths of less than 4 meters and a tendency towards sloping terrain. The flatness and shallowness observed in Lake Limboto's western and northern regions are attributed to the substantial sediment influx from river erosion, along with agricultural and settlement activities that accelerate siltation within these areas.

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