Indonesian Journal of Agricultural Research Vol. 07, No. 03, 2024 | 191 – 202

InJAR
Indonesian Journal of Agricultural Research

Morphometric and Bathymetric Characteristics and Trophic Status of Silosung Lake, Lintong Nihuta District, Humbang Hasundutan Regency, North Sumatra Province

Ahmad Muhtadi*, Matthew Federich Willyam Silaban, Rusdi Leidonald, and Astrid Fauzia Dewinta

Program Study in Aquatic Resource Management, Faculty of Agriculture, Universitas Sumatera Utara, Indonesia

Abstract. Lakes can form naturally through natural events or artificially through human activities. Silosung Lake is a natural lake in Siponjot Village, Lintong Nihuta District, Humbang Hasundutan Regency. Lake morphometry refers to the physical characteristics of the lake body, while bathymetry refers to the measurement and mapping of the topographic conditions of the lake bottom. It is essential to know the morphometric and bathymetric characteristics and trophic status of the lake to achieve sustainable lake management. This study aims to determine the characteristics of bathymetry, morphometry, and tropic status of Lake Silosung. This research was conducted in July 2023. The data collection in this study includes lake perimeter data, lake depth data, lake length and width data, and lake water quality data. This research indicates that Silosung Lake has an area of 104,806.6 m² with a lake perimeter length of 1,573.5 m, a maximum length of 474.53 m, and a maximum width of 420.62 m. The maximum depth is 17 m, the average depth is 10.09 m, the relative depth is 7.9% with an average slope of 15.9%, the compensation depth is 4.32 m, and the Shoreline Development Index (SDI) value is 2.74. The Morpho Edapic Index (MEI) value is 2.88. Silosung Lake has a lake water volume of 1,057,108.6 m³. The average Tropic State Index (TSI) value is 15.71, indicating that the trophic status of Silosung Lake is oligotrophic, meaning its productivity is low.

Keywords: lake morphometry, Silosung Lake, trophic status

Received 19 February 2024 | Revised 11 October 2024 | Accepted 07 November 2024

1. Introduction

Lakes are basins filled with water and are inundated throughout the year. Lakes can form naturally or artificially [1], [2]. Lake ecosystems are part of freshwater ecosystems that occupy the smallest surface area on Earth compared to other ecosystems [3], [4]. Lakes have different and unique structures determined by basin shape, topography, physical and chemical properties, and biological interactions [3], [4], [5], [6]. Lake ecosystems are crucial for human life in meeting

*Corresponding author at: Program Study in Aquatic Resource Management, Faculty of Agriculture, Universitas Sumatera Utara. Jl. Prof A. Sofyan No. 3 Kampus USU, Medan 20155

E-mail address: ahmad.muhtadi@usu.ac.id

p-ISSN: 2622-7681 | e-ISSN: 2615-5842 | DOI 10.32734/injar.v7i3.15715
Journal Homepage: https://talenta.usu.ac.id/InJAR

present and future needs because they provide productive natural resources such as raw drinking water, daily necessities, protein sources, minerals, and energy, as well as serving as transportation routes and tourist destinations [1], [4], [5],[6].

Morphometric data are crucial in determining lake layers and can also reveal the extent of a lake's utilization by humans. They help in assessing sedimentation and several indices of water fertility, providing information on water depth, lake shape, light penetration, and changes in lake volume [4], [5], [6], [7]. In other words, lake morphometry refers to the physical characteristics of a lake, including surface area (A), volume (V), and average depth (Z). The topography of the surrounding area can also influence lake morphometry. The lake's bottom structure can form underwater relief known as bathymetry. Bathymetric maps depict the lake's bottom relief with depth contour lines, providing additional information for surface navigation. Bathymetry is essential for understanding the hydrodynamics of a water body. Furthermore, bathymetric data is also crucial for the sustainable management and utilization of water bodies [6], [7], [8], [9], [10], [11].

Data on Lake Silosung are still limited, necessitating basic research on morphometry and bathymetry in Lake Silosung aimed at determining the maximum length and effective maximum length of the lake, maximum width and effective maximum width of the lake, average width of the lake, lake surface area, lake shoreline length, lake depth, contours, and total volume of lake water. Testing of the physical, chemical, and biological parameters of Lake Silosung water is also needed to determine the trophic status of the lake. This research aims to understand the morphological characteristics in terms of morphometry and bathymetry aspects in the waters of Lake Silosung, Lintong Nihuta District, Humbang Hasundutan Regency, and to determine the trophic status in the waters of Lake Silosung, Lintong Nihuta District, Humbang Hasundutan Regency.

2. Materials and Methods

2.1. Study Area

This research was conducted in July 2023 at Lake Silosung, Siponjot Village, Lintong Nihuta District, Humbang Hasundutan Regency, North Sumatra Province. The tools used in this research included a small boat, GPS device, Secchi disk, echosounder (GPS Map Garmin 585), sampling bottles, laptop, smartphone camera, writing utensils, DO meter, pH meter, styrofoam box, car battery, and a life jacket. The materials used in this research included Microsoft Excel, Google Earth software, ArcMap software, Surfer 13 software, and the coordinates of Lake Silosung.

2.2. Data Collection

The bathymetric data was collected using an acoustic method known as hydroacoustics or underwater acoustic detection technology. The echosounder device, Garmin GPS Map 585, placed beneath the boat's transom, emits vertical acoustic waves to the lake bottom, and the waves reaching the bottom are reflected to the receiving signal. Numerous points representing various bottom conditions are required to obtain an excellent bathymetric map. Hence, the lake body was surveyed as cross-sections, and the lake shore was surveyed by tracing the lake's edge. Coordinates and depths were recorded every 30 seconds and then downloaded using the Mapsource program, followed by format conversion to be compatible with Quantum GIS 1.8 software. Morphometric data were derived from the bathymetric map. The lake perimeter or boundary data were obtained from the Digital Indonesia Topographic Map 2015-2019 analysis from the Indonesian Geospatial Information Agency. This map can be accessed at: http://tanahair.indonesia.go.id/portal-web/

2.3. Data Analysis

The bathymetric map of the lake was created using interpolation principles with the assistance of Quantum GIS 1.8 software (free). Gradual color shading indicates changes in depth, with darker colors representing deeper waters. The Digital Indonesia Topographic Map 2015-2019 from the Indonesian Geospatial Information Agency was used as the base map. The analysis of lake morphometry data consists of lake size metrics, lake form metrics, and special metrics for lake morphometry [6].

2.3.1. Lake size metrics

Lake size is directly measured using ArcMap software within the Lake Silosung map. Lake size metrics consist of Lmax, Le, Wmax, We, SL, Ao, Zmax, and V [6]. The total volume is calculated using the equation:

$$V = \frac{h}{3} \text{ x } [\sum_{i-1}^{n}\{(Ai - 1 + Ai) + \sqrt{(Ai - 1) \text{ x } Ai}\}] \quad (1)$$

where: V = Total volume (m^3), h = Contour interval (m), A = Area per contour (m^2), n = Number of contours

2.3.2. Lake form metrics

The average width of the lake is calculated in the form of an equation:

$$\bar{W} = \frac{Ao}{Lmax} \quad (2)$$

where: $\bar{W}$ = Average width (m), Ao = Lake surface area (m^2), Lmax = Maximum length (m)

SDI is calculated in the form of an equation:

$$SDI = \frac{SL}{2\sqrt{\frac{22}{7} Ao}} \quad (3)$$

where: SDI = Shoreline Development Index (dimensionless), SL = Shoreline length (m), Ao = Lake surface area (m^2)

To measure the average depth, it is calculated using the equation:

$$\bar{Z} = \frac{V}{Ao} \quad (4)$$

where: $\bar{Z}$ = Average depth (m), V = Volume (m^3), Ao = Lake surface area (m^2). Relative depth is calculated in the form of an equation

$$Zr = \frac{Zmax}{2 \times \frac{\sqrt{Ao}}{\sqrt{n}}} \times 100\% \quad (5)$$

where: Zr = Relative depth (m), Zmax = Maximum depth (m), Ao = Lake surface area (m^2), n = Number of contours

Lake volume development is calculated in the form of an equation:

$$VD = \frac{Ao \times \bar{Z}}{\frac{1}{3} \times (Zmax \times Ao)} \quad (6)$$

where: Ao = Lake surface area (m^2), $\bar{Z}$ = Average depth (m), Zmax = Maximum depth (m)

2.3.3. Special metrics for lake morphometry

Particular metrics for lake morphometry, one of which involves calculating the fisheries potential using the morpho-edaphic index model with the formula [12]:

$$MEI = \frac{Electrical\ Conductivity}{average\ depth} \quad (7)$$

where: MEI = the morpho-edaphic index

The determination of compensation depth is done using the Beer-Lambert Law equation with the formula [13]:

$$Zc = \frac{4.6}{Kd} \quad (8)$$

This approach calculates the attenuation coefficient based on the Secchi depth. The attenuation coefficient is calculated by:

$$Kd = \frac{1,7}{Zs} \quad (9)$$

where: Kd = Attenuation coefficient of sunlight, Zc = Compensation depth, Zs = Secchi depth. Next, the Basin Permanence Index (BPI) is calculated using the formula [14]:

$$\text{BPI} = \frac{V}{SL} \quad (10)$$

where: BPI = Basin permanence index, V = Lake volume, SL = Lake shoreline length.

2.3.4. Trophic status of water

The trophic status of water is calculated using the Trophic State Index (TSI) Carlson model with the formula [15]:

$$\text{TSI (SD)} = 60 - 14{,}41 \text{ In(SD)}$$

$$\text{TSI (CHL)} = 30{,}6 + 9{,}81 \text{ In(CHL)}$$

$$\text{TSI (TP)} = 4{,}15 + 14{,}42 \text{ In(TP)}$$

$$\text{TSI rata-rata} = \frac{TSI(SD) + TSI(CHL) + TSI(TP)}{3} \quad (11)$$

where: SD = Water transparency (m), CHL = Chlorophyll-a (mg/l), TP = Total Phosphate (mg/l) The criteria for determining the trophic status of water based on TSI values, as proposed by Carlson [15], can be seen in Table 1.

Table 1. Categories of Fertility Status Based on Carlson's TSI.[15]

TSI	Chl-a	P	SD	Trophic status
<30-40	0-2.6	0-12	>8-4	Oligotrophic
40-50	2.6-7.3	12-24	4-2	Mesotrophic
50-70	7.3-56	24-96	2-0.5	Eutrophic
70-100+	56-155+	96-384+	0.5-<0.25	Hypereutrophic

3. Results and Discussion

3.1. Bathymetric Map

The results of the bathymetric data processing of Lake Silosung show that the most profound area is located in the middle of the lake, which has a depth of 17 m. The processed bathymetric data of Lake Silosung using ArcMap software can be seen in Figure 1. The bathymetric map of Lake Silosung shows the depth at each lake layer with a depth interval of 2 meters per layer. The bathymetric map of Lake Silosung consists of nine layers, and the color variations on the bathymetric map indicate differences in depth at each layer of the lake. The first layer is at a depth of 0-2 m, the second layer is at a depth of 2.1-4 m, the third layer is at a depth of 4.1-6 m, the fourth layer is at a depth of 6.1-8 m, the fifth layer is at a depth of 8.1-10 m, the sixth layer is at a depth of 10.1-12 m, the seventh layer is at a depth of 12.1-14 m, the eighth layer is at a depth of 14.1-16 m, and the ninth layer, shown in the darkest color on the bathymetric map, indicates the deepest part of Lake Silosung with a depth of 16.1-17 m. The transverse lines on the bathymetric map indicate the maximum length and width of Lake Silosung.

The layout of the contour map of Lake Silosung processed using Surfer 13 software can be seen in Figure 2. Based on the contour map layout of Lake Silosung obtained shows the depth of each contour. The density of contour lines indicates the shape of the lake bed relief. The denser the contour lines, the steeper Lake Silosung's bed relief slope. Conversely, the more widely spaced contour lines, the gentler the lake bed relief. This is explained and stated by the results of previous research: the denser the contour, the deeper the lake; conversely, the lighter the contour, the shallower the lake [6], [8], [9], [10], [16].

The layout of the 3D map of Lake Silosung further clarifies the differences in depth and the shape of Lake Silosung's bed relief. This 3D map layout shows that the lake bed relief of Lake Silosung is relatively flat in the middle and tends to slope on the edges. Darker colors on the map indicate deeper parts of the lake. The green color on the 3D map of Lake Silosung represents the land surrounding Lake Silosung, which is higher in elevation than the lake's surface. The layout of the 3D map of Lake Silosung can be seen in Figure 3.

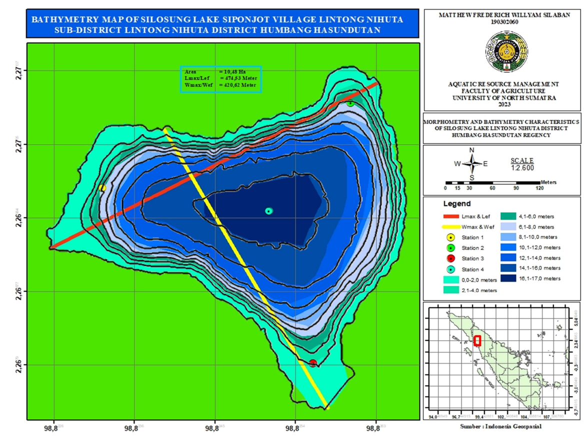

Figure 1. Bathymetry Map of Silosung Lake

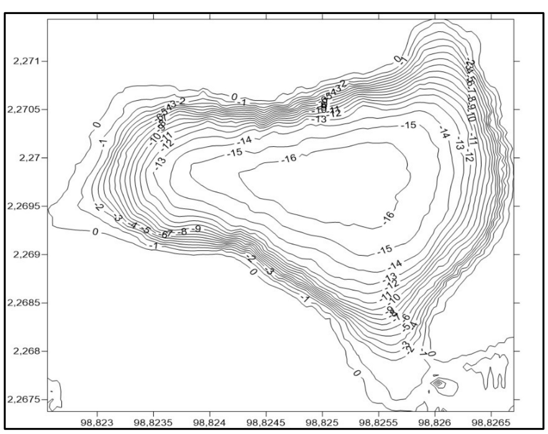

Figure 2. Contour Map Layout of Silosung Lake

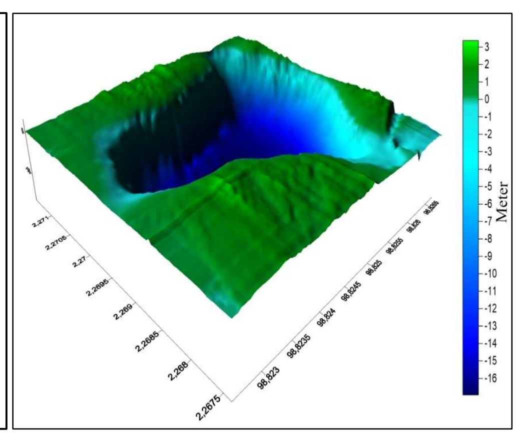

Figure 3. 3D Map Layout of Silosung Lake

3.2. Lake Size Metrics

The measurement results of the lake size metrics parameters using ArcMap software indicate that Lake Silosung has an area of 104,806.6 m². Silosung Lake also has a lake boundary line length of 1,573.5 m. Lake Silosung has a maximum and effective maximum length of 474.53 m, with a maximum width and effective maximum width of 420.62 m. The measurement results show that Lake Silosung has a water volume of 1,057,108.9 m³. The complete data of the lake size metrics parameters can be seen in Table 2.

Lake Silosung falls into the category of small lakes. Lake Silosung is still considered small compared to other natural or artificial lakes, such as Ranu Grati Lake in Pasuruan Regency, which has an area of 1,734,223.07 m² [17], and Siombak Lake (artificial lake) on the coast of Medan City, which has an area of 28.5 hectares [18]. However, Lake Silosung is still larger than Pondok Lapan Lake (artificial lake) in Langkat Regency, which has an area of 63,472.78 m² [11], and Kelapa Gading Lake and Teratai Lake (artificial lakes) in Asahan Regency, which have areas of 11,931.37 m² and 46,236.85 m² respectively [16], [19]. Meanwhile, Palas Asri Lake (Lake A and Lake B) in Batubara Regency has areas of 33,231 m² and 26,544 m² respectively [20].

The maximum width of Lake Silosung is 420.62 m with an effective maximum width of 420.62 m. The values of the maximum length and maximum width of Lake Silosung are the same as the values of its effective maximum length and effective maximum width. Similar results were obtained at Pondok Lapan Lake (Langkat), where the effective length and effective width of the lake have the same values because there are no islands or land within the lake [11].

Table 2. Lake Size Metrics Parameters of Silosung Lake

No	Parameter	Unit	Value
1.	Maximum Length (Lmax)	m	474.53
2.	Effective Maximum Length (Lef)	m	474.53
3.	Maximum Width (Wmax)	m	420.62
4.	Effective Maximum Width (We)	m	420.62
5.	Shoreline Length (SL)	m	1,573.50
6.	Lake Surface Area (Ao)	m²	104,806.60
7.	Maximum Depth (Zmax)	m	17.00
8.	Total Lake Water Volume (V)	m³	1,057,108.60

The maximum depth of Lake Silosung obtained in this study is 17 m. The depth of Lake Silosung is still considered shallow compared to large lakes such as Lake Toba, which has a maximum depth of 508 m [21], and Lake Maninjau in Agam Regency, which has a maximum depth of 107 m [16]. However, the depth of Lake Silosung is more profound compared to other small lakes, such as Kelapa Gading Lake in Asahan Regency, with a maximum depth of 2.15 m [16], Pondok Lapan Lake with a maximum depth of 4.15 m [11], and Palas Asri Lake with maximum depths of 2.5 m and 2.8 m respectively [20], included Siais Lake with maximum depth is 11.8 m [10].

The total water volume of Lake Silosung (V) is 1,057,108.6 m³. Lake volume is an essential factor in lake management, especially its influence on the dilution capacity of the lake. Lakes with larger volumes will have a greater dilution capacity [1], [4]. The volume of Lake Silosung is still relatively small compared to other lakes in Indonesia, such as Siais Lake (North Sumatra) with an area of 1700 hectares [10], Ranu Grati Lake with a water volume of 124,491,952.55 m^3 [17], Lake Toba with a water volume of 256.6 x 10^9 m^3 [21], Siombak Lake with a volume of 5.8 x 10^8 m^3 [18], and Lake Poso in Central Sulawesi with a water volume of 71,811,599,956 m^3 [22]. However, the water volume of Lake Silosung is larger than Kelapa Gading Lake, with a volume of 15,033.52 m^3 [16], and Teloko Lake in South Sumatra, with a water volume of 58,346.1 m^3 [23]. Palas Asri Lake has a water volume of only 49,938.74 m^3 and 44,062.64 m^3 respectively [20].

3.3. Lake Form Metrics

Based on the calculation results, the average slope obtained is 15.9%. Lake Silosung has a relatively steep bottom contour gradually shallower towards the lake's center. This is supported by the volume development value of Lake Silosung, which is 1.78, indicating a pot-shaped bottom contour. This is further clarified by the contour map of Lake Silosung (Figure 1), where the contour lines become more widely spaced in the middle, and the lake's shape is more evident when viewed on the 3D map of Lake Silosung (Figure 2). This aligns with the statement from [26], where a VD value < 1 depicts a conical lake shape, while a VD value > 1 represents a lake with a flat or pot-shaped bottom. [27] categorizes slope inclination into five classes: very steep (>45%), steep (25-45%), moderately steep (15-25%), gentle (8-15%), and flat (0-8%).

The calculation results for the average width of Lake Silosung show that it is 220.86 m. This is significantly different from the effective maximum width of Lake Silosung, which is 420.62 m. This indicates that Lake Silosung has both narrow and comprehensive sections. Similar results were obtained by [24] at Situ Cilala, which has an average width of 108 m and an effective maximum width of 225 m. The shoreline development index (SDI) of Lake Silosung is calculated to be 2.74. The lake's average depth is 10.09 m, with a relative depth of 7.9%. This indicates that the waters of Lake Silosung are stable and not easily stirred [14]. Similar results were also obtained by [17] at Lake Ranu Grati, which has a relative depth of 8.20%. Lakes with Zr values > 4% generally have high stability and are deep with narrow surfaces [4].

Table 3. Lake Form Metrics Parameters of Silosung Lake

No	Parameter	Unit	Value
1.	Average Width ($\overline{W}$)	m	220.86
2.	Shoreline Development Index (SDI)	-	2.74
3.	Average Depth ($\overline{Z}$)	m	10.09
4.	Relative Depth (Zr)	%	7.90
5.	Average Slope ($\overline{S}$)	%	15.90
6.	Lake Volume Development (VD)	-	1.78

3.4. Special Metrics for Lake Morphometry

The Morpho-Edaphic Index (MEI) value for Lake Silosung is 2.88 (Table 4), indicating that the lake has low fisheries potential. This is supported by the average depth of Lake Silosung, which is 10.09 m. Lakes with shallow average depths (<10 m) tend to have higher MEI values. A higher MEI value indicates a higher potential for fish production. The conductivity of the water also influences the MEI value. High conductivity values lead to higher MEI values, indicating a high potential for fish production in the water body. The MEI value reflects the water's high content of minerals/nutrients [12], [25].

The calculated compensation depth (Zc) for Lake Silosung is 4.32 m. This indicates that photosynthesis processes occur in Lake Silosung up to a depth of 4.32 m. The compensation depth indicates the depth at which light intensity is 1% of the light intensity at the water surface [13]. The compensation depth of Lake Silosung is more profound compared to Lake Kelapa Gading, which has a compensation depth ranging from 0.98 to 1.15 m [16], and Lake Pondok Lapan, which ranges from 2.61 to 2.85 m [11].

The Basin Permanence Index (BPI) value for Lake Silosung is 6.9 m^3.km-1. BPI provides information about the vulnerability of a lake to degradation or siltation. The rapid loss rate of a lake is characterized by rapid siltation and vegetation growth. The BPI value also indicates whether a water body is suitable for developing littoral zones and rooted aquatic plants [6], [14], [26].

Table 4. Special Metrics for Lake Morphometry of Silosung Lake

No.	Parameter	Unit	Value
1.	Morpho Edaphic Index (MEI)	-	2.88
2.	Compensation Depth (Zc)	m	4.32
3.	Basin Permanence Index (BPI)	$m^3.km^{-1}$	6.90

3.5. Water Quality

The results of measurements of physical, chemical, and biological parameters of Lake Silosung at four stations are as follows: the temperature values obtained sequentially are 24.0°C, 24.2°C, 24.2°C, and 24.5°C. The clarity values are 1.60 m, 1.67 m, 1.50 m, and 1.62 m. Total Dissolved Solids (TDS) values are 14.26 mg/l; 14.27 mg/l; 14.25 mg/l; and 14.25 mg/l. Total Suspended Solids (TSS) values are 11 mg/l; 25 mg/l; 11 mg/l; and 12 mg/l. Chlorophyll-a values are 1.482 mg/l; 1.587 mg/l; 1.464 mg/l; and 1.622 mg/l. The complete data of the results of measurements of physical, chemical, and biological parameters of Lake Silosung can be seen in Table 4.

Table 5. Water Quality Parameters of Silosung Lake

Parameter	Unit	Stations				Average
		I	II	III	IV	
Temperature	°C	24.0	24.20	24.20	24.50	24.23
Water transparency	m	1.60	1.67	1.50	1.62	1.60
TDS	mg/l	14.26	14.27	14.25	14.25	14.23
TSS	mg/l	11.00	25.00	11.00	12.00	14.75
EC	µs/cm	29.20	29.50	28.80	29.00	29.13
pH	-	7.60	7.50	7.70	7.50	7.58
PO4	mg/l	0.46	0.04	0.02	0.01	0.133
DO	mg/l	6.60	6.60	6.50	6.70	6.60
Chlorophyll-a	mg/l	1.48	1.59	1.46	1.62	1.54

3.6. Water Trophic Status

The analysis of the trophic status of Lake Silosung, conducted using the TSI Carlson 1977 method, yielded TSI values ranging from 8.71 to 26.88 (Table 6), with an overall average TSI for Lake Silosung of 15.71. Based on these TSI values, the trophic status of Lake Silosung is classified as Oligotrophic, indicating a low level of water fertility. The low fertility of the lake suggests that nutrient inputs into Lake Silosung are relatively low. Geographically, Lake Silosung has a small catchment area, resulting in minimal nutrient input from its surroundings. Although agriculture is present in the surrounding area of Lake Silosung, the catchment area from these agricultural activities could be more prominent. Thus, the nutrient input into Lake Silosung will likely come mainly from autochthonous sources. Additionally, it is observed that there are no surface water inputs (rivers) into Lake Silosung; instead, its water source is groundwater.

Other lakes with similar trophic statuses to Lake Silosung include Lake Palas Asri in Batu Bara Regency, which has TSI values ranging from 16.05 to 21.10 [20], and Laguna Lake in North Maluku, which has a TSI value of 23.28 [27]. Other small lakes in North Sumatra, such as Lake Pondok Lapan, remain relatively unpolluted and suitable for aquatic life [11]. At the same time, Lake Kelapa Gading is classified as eutrophic, with TSI values ranging from 72.71 to 79.21 [28], and Lake Siombak is classified as eutrophic [25], including Lake Toba [29].

The highest TSI in Lake Silosung is found at station I, with a value of 26.88 due to the highest total phosphorus (P) value at this station, namely 0.46 mg/l. The high concentration of total phosphate at this station is caused by inputs from domestic waste such as leftover detergent, soapy water, agricultural activities, and also the local habit of allowing buffalo to graze near the lake, resulting in buffalo dung entering the depths of Lake Silosung. This is consistent with [11], [29], which states that the concentration of P is highly dependent on activities around the lake as a source of input, including agricultural activities, organic waste, and other waste containing N and

P, potassium oxide, as well as circulation and mass exchange of water from the bottom of the lake.

Table 6. Trophic Status of Silosung Lake

Stasiun	TSI SD	TSI Chl-a	TSI TP	Average of TSI	Trophic status
I	53.23	34.46	7.05	26.88	Oligotrophic
II	52.61	35.13	42.27	15.16	Oligotrophic
III	54.16	34.34	52.26	12.08	Oligotrophic
IV	53.05	35.34	62.26	8.71	Oligotrophic
Average				15.71	Oligotrophic

4. Conclusion

Lake Silosung covers an area of 10.48 hectares with a circumference of 1.57 kilometers, a maximum length of 474.53 meters, and a maximum width of 420.62 meters. The maximum depth of Lake Silosung is 17 meters, with an average depth of 10.09 meters and a relative depth of 7.9%. The average slope in Lake Silosung reaches 15.9%, and the compensation depth in this lake reaches 4.32 meters. The SDI value of Lake Silosung is 2.74, with an MEI value of 2.88. Lake Silosung has a total volume of 1,057,108.6 cubic meters of water. The trophic status of Lake Silosung is classified as oligotrophic, with a TSI value of 15.71.

REFERENCES

[1] A. Nontji, *Danau-Danau Alami Nusantara*. Cibinong: Pusat Penelitian Limnologi, LIPI, 2017.

[2] J. G. Tundisi and T. M. Tundisi, *Limnology*. Boca Roton: CRC Press, 2011.

[3] E. P. Odum and G. W. Barrett, *Fundamental of Ecology*, 5th ed. Belmont, CA: Brooks/Cole Publishing Co, 2005.

[4] R. G. Wetzel, “Limnology Lake and River Ecosystems”, *3th ed. California: Academic Press*, 2001. doi: https://doi.org/10.1016/C2009-0-02112-6.

[5] G. A. Cole and P. E. Weihe, *Textbook of Limnology*, 5th ed. Illionis (US): Waveland Press, Inc, 2016.

[6] A. Muhtadi and R. Leidonald, *Limnologi: Praktik Dalam Laboratorium dan Lapangan*, 1st ed. Medan (ID): Media Kreasi, 2022.

[7] A. Muhtadi, “Dinamika Perairan Danau Pasang-Surut Dalam Perspektif Pengelolaan Danau Siombak,” *IPB university, Bogor*, 2022. Accessed: Feb. 22, 2023. [Online]. Available: http://repository.ipb.ac.id/handle/123456789/112405

[8] R. Leidonald, A. Muhtadi, and Z. A. Harahap, “The hydrodynamics of Anak Laut coastal lake, Aceh Singkil Regency, Indonesia,” *AACL Bioflux*, vol. 16, no. 5, pp. 2856–2867, 2023.

[9] A. Muhtadi, Z. A. Harahap, and R. Leidonald, “Morphometry Dynamical of Siombak Lake, Medan, Indonesia,” *Omni-Akuatika*, vol. 13, no. 2, pp. 48–56, 2017, doi: http://dx.doi.org/10.20884/1.oa.2017.13.2.174.

[10] A. Muhtadi, R. Leidonald, A. Rahmadya, and Lukman, “Bathymetry and morphometry of Siais Lake, South Tapanuli, North Sumatra Province, Indonesia,” *AACL Bioflux*, vol. 13, no. 5, pp. 2647–2656, 2020, [Online]. Available: http://www.bioflux.com.ro/aacl

[11] A. Muhtadi, Yunasfi, M. Ma'rufi, and A. Rizki, "Morphometry and Pollution Load Capacity of Lake Pondok Lapan in Langkat Regency, North Sumatra," *Oseanologi dan Limnologi di Indonesia*, vol. 2, no. 2, pp. 49–63, 2017, doi: 10.14203/oldi.2017.v2i2.51.

[12] H. F. Henderson and R. L. Welcomme, "The relationship of yield to morphoedaphic index and numbers of fishermen in African inland fisheries," *Roma, CIFA Occasional Paper*, 1974.

[13] H. Effendi, *Telaah Kualitas Air Bagi Pengelolaan Sumberdaya dan Lingkungan Perairan*. Yogyakarta: PT. Kanisius, 2003.

[14] G. F. Barroso, M. A. Gonçalves, and F. C. Da Garcia, "The morphometry of Lake Palmas, a deep natural lake in Brazil," *PLoS One*, vol. 9, no. 11, 2014, doi: 10.1371/journal.pone.0111469.

[15] R. E. Carlson, "A trophic state index for lakes," *Limnol Oceanogr*, vol. 22, no. 2, pp. 361–369, 1977, doi: 10.4319/lo.1977.22.2.0361.

[16] R. Ridoan, A. Muhtadi, and P. Patana, "The morphometry of Kelapa Gading Lake in Kisaran City, Asahan District , North Sumatera Province," *Depik*, vol. 5, no. 2, pp. 77–84, 2016, doi: https://doi.org/10.13170/depik.5.2.4913.

[17] A. Darmawan, M. Mahmudi, T. W. Nisa, C. D. S. Putri, G. A. Gurinda, and A. W. Putri, "Kajian Morfometri Ranu Grati Menggunakan GPSMAP 585 dan SIG," *Oseanologi dan Limnologi di Indonesia*, vol. 4, no. 3, pp. 205–213, Dec. 2019, doi: 10.14203/oldi.2019.v4i3.261.

[18] A. Muhtadi, F. Yulianda, M. Boer, M. Krisanti, A. Rahmadya, and Sontos, "Hydrodynamics of tropical tidal lake waters Lake Siombak, Medan, Indonesia," *AACL Bioflux*, vol. 13, no. 4, pp. 2014–2031, Aug. 2020, [Online]. Available: http://www.bioflux.com.ro/aacl

[19] I. Astrika, "Kajian Hidromorfologi Danau Teratai Kecamatan Tinggi Raja Kabupaten Asahan," Skripsi, Universitas Sumatera Utara, Medan, 2022.

[20] R. Leidonald, A. S. J. Rambe, A. Muhtadi, and A. Fadhilah, "Morfometri Dan Batimetri Danau Palas Asri Kecamatan Medang Deras Kabupaten Batubara," *AQUACOASTMARINE: Journal of Aquatic and Fisheries Sciences*, vol. 3, no. 1, pp. 9–20, Apr. 2024, doi: 10.32734/jafs.v3i1.14645.

[21] Lukman and I. Ridwansyah, "Kajian Kondisi Morfometri dan Beberapa Parameter Stratifikasi Perairan Danau Toba," *Limnotek : perairan darat tropis di Indonesia*, vol. 17, no. 2, pp. 158–170, 2010.

[22] Lukman and I. Ridwansyah, "Telaah kondisi fisik Danau Poso dan prediksi ciri ekosistem perairannya," *Limnotek: Perairan Darat Tropis di Indonesia*, vol. 16, no. 2, pp. 64–73, 2009.

[23] A. Catharica, R. Fahleny, and A. Rahim, "Kajian Morfometrik dan Fisika Kimia Air di Perairan Danau Teloko Kecamatan Kota Kayuagung Kabupaten Ogan Komering Ilir," *Jurnal Perikanan Perairan Umum*, vol. 1, no. 2, pp. 112–120, 2023.

[24] N. T. M. Pratiwi, E. M. Adiwilaga, J. Basmi, M. Krisanti, O. Hadijah, and W. K. Pieka, "Status Limnologis Situ Cilala Mengacu pada Kondisi Parameter Fisika, Kimia, dan Biologi Perairan ," *Jurnal Perikanan*, vol. 9, no. 1, pp. 82–94, 2007, Accessed: Oct. 11, 2022. [Online]. Available: https://journal.ugm.ac.id/jfs/article/view/67/77

[25] A. Muhtadi, R. Leidonald, A. Pulungan, N. Rohim, and Q. Hasani, "Trophic States and Fishery Potential of Tidal Lakes, Lake Siombak, Medan, Indonesia," *Indonesian Journal of Limnology* , vol. 4, no. 2, pp. 70–80, 2023.

[26] J. Tylkowski and M. Samołyk, "Meteorological conditions, physiochemical properties, thermal-oxygen stratification, water overturn and water balance of Lake Gardno on Wolin Island," *Limnological Review*, vol. 15, no. 3, pp. 107–118, Sep. 2015, doi: 10.2478/limre-2015-0012.

[27] A. Samman *et al.*, "Status Trofik Perairan Danau Laguna, Kota Ternate Selatan, Maluku Utara," *Jurnal Pengabdian Magister Pendidikan IPA*, vol. 6, no. 2, pp. 434–438, 2023.

[28] A. Muhtadi, H. Wahyuningsih, N. Zaharuddin, and A. Sihaloho, "Status Kualitas Air dan Kesuburan Perairan Danau Kelapa Gading Kota Kisaran Provinsi Sumatera Utara," *Talenta Conference Series: Agricultural and Natural Resources (ANR)*, vol. 1, no. 1, pp. 27–33, Oct. 2018, doi: 10.32734/anr.v1i1.92.

[29] T. A. Barus, H. Wahyuningsih, and A. Hartanto, "Water Quality and Trophic Status of Lake Toba, North Sumatra, Indonesia," *Hydrobiological Journal*, vol. 58, no. 2, pp. 34–43, 2022, doi: 10.1615/HydrobJ.v58.i2.30.