Bathymetry and morphometry of Siais Lake, South Tapanuli, North Sumatra Province, Indonesia

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Abstract. Siais Lake is the second largest Lake in North Sumatra Province. However, basic and essential information about this lake does not yet exist. Therefore, this study aims to describe the necessary information regarding bathymetry and morphometry of the Siais Lake. Data was collected in June (dry season) and December (rainy season) 2019. Map analysis used the Quantum GIS 1.8 program. Siais Lake is a shallow lake with a maximum depth of 11.8 m and an average depth of 5.81 m. The total area of Siais Lake reaches 17 km^2, with a total volume of 46–64 million m^3. Some 7 km^2 (41%) of the lake's surface are covered by aquatic macrophyte species, dominated by lily plants (Amaryllidaceae). Lake Siais is very suitable for the littoral zone development and rooted aquatic plants cultivation.
Key Words: Batangtoru, depth, limnology, shoreline development index.

Introduction. Lakes have unique morphology and structure determined by the shape of the basin (Wetzel & Gene 2000; Wetzel 2001; Löffler 2007; Cole & Weihe 2016), physical-chemical properties (Wetzel 2001; Cole & Weihe 2016; Dodds & Whiles 2020), biological interactions (Cole & Weihe 2016; Dodds & Whiles 2020) and their interactions with the environment (Hakanson 1981; Staehr et al 2012; Dodds & Whiles 2020). Morphologically, lakes' shape and formation can be determined by bathymetry and morphometry (Håkanson 1981; Wetzel & Gene 2000). Bathymetry and morphometry are branches of limnology that examine the physical form of inland waters (Welch 1948; Håkanson 1981; Wetzel & Gene 2000; Wetzel 2001; Cole & Weihe 2016).

Bathymetry can be interpreted as a measurement and mapping of water's floor topography. It is a collection of imaginary lines connected at the same depth. The imaginary lines will form a bathymetry map that shows the depth and shape of the lake's bottom reliefs (Soeprobowati 2012; Zhu et al 2019). The bathymetry map serves to provide additional information for surface navigation (Ridoan et al 2016). Bathymetry is also necessary concerning the hydrodynamics of water (Muhtadi et al 2017a, 2020). Therefore, bathymetry maps are very important in the context of lake use and management (Soeprobowati 2012; Ridoan et al 2016).

Morphometry is a measurement and mapping of the lake's shape in subsurface and surface dimensions (Håkanson 2005a,b). In other words, lake morphometry is a form of lake water body which includes the length of the lakeside, surface area (A), volume (V), depth (Z) (Wetzel 2001; Håkanson 2005b). So, bathymetry and morphometry are related: bathymetry data will support morphometric information (Alcocer et al 2016; Zhu et al 2019).

Lake morphometry is needed to get a comprehensive picture of a lake's physical condition. Morphometry plays an essential role in determining the factors that cause changes in the biological and physical-chemical processes of a lake (Wetzel 2001; Hakanson 2005a,b; Barroso et al 2014; Cole & Weihe 2016). Morphometry can also describe the potential for biological production (Azzella et al 2014; Seekell et al 2018) and determine the level of sensitivity to the influence of material loads from the surrounding area (Håkanson 2005a; Ptak et al 2018). Thus, for a sustainable use and management of lakes' aquatic resources use, it is necessary to determine morphometric data (Wetzel 2001; Cole & Weihe 2016; Siddiq et al 2019).

Siais is the second-largest lake after Toba Lake in North Sumatra Province. The lake is located in the Batangtoru watershed in South Tapanuli Regency. Based on the author's search, to date, research conducted on this lake is very limited in the form of scientific writing and reports from related government agencies, particularly those related to lake's bathymetry and morphometry. Thus, data about this lake is not yet available, so it is hoped that this study's results can be an initial reference for subsequent research. Besides, data related to the lake's physical conditions such as the area, circumference, and depth of the lake are needed for more appropriate management. Thus, studying the morphometry and making bathymetry maps of Siais Lake are indispensable for its sustainable management. Therefore, this study aims to determine the condition of the relief of the lake floor and morphometric aspects of the Siais Lake.

Material and Method

Study sites. The research was carried out in the Siais Lake, Raniate Village, Angkola Sangkunur District, South Tapanuli Regency, North Sumatra Province (Figure 1). Data was collected in June (dry season) and December (rainy season) 2019. The main equipment used was a Garmin GPS Map 585 echo sounder, a Garmin Montana GPS, a boat and stationery. Lake bathymetry data can be obtained by the acoustic method, known as hydroacoustic (underwater acoustic), using underwater detection technology. Determination of the Lake's bathymetry was performed using an active acoustic system, in the form of acoustic signals emitted and reflected by the bottom of the lake. An echo sounder device, the Garmin GPS Map 585, placed under the boat's hull, sent an acoustic wave vertically to the bottom of the lake. The time needed to move the acoustic waves vertically to the bottom of the lake and back to the surface is data that is processed to determine the depth of the lake.

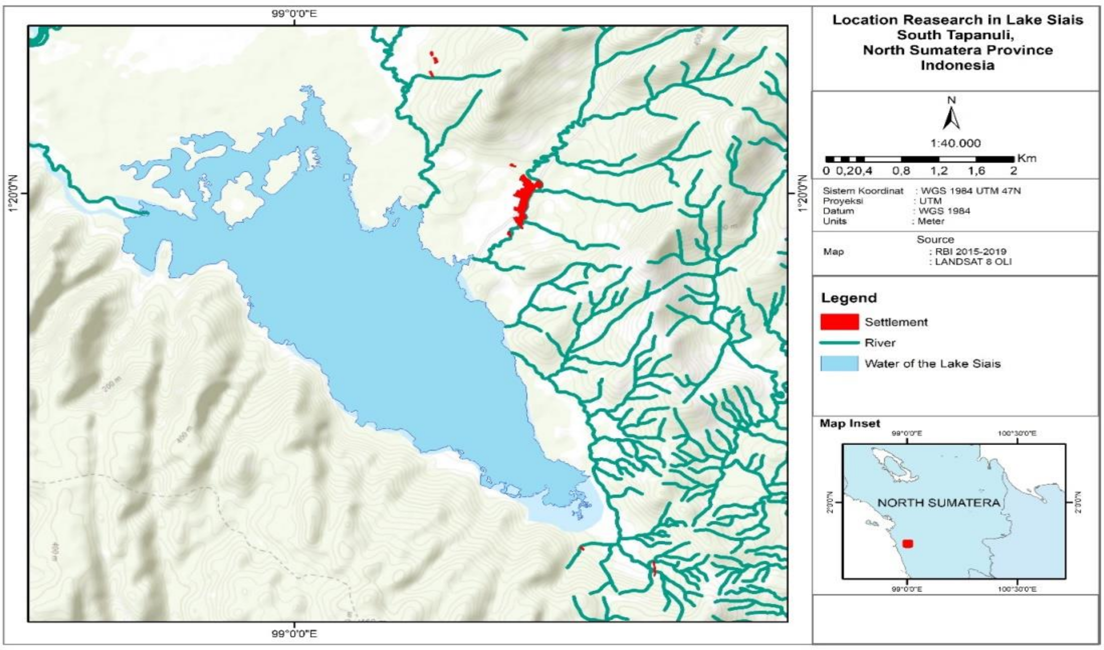

Figure 1. Research location, Lake Siais, South Tapanuli, Indonesia.

Data collection and processing. To get a good bathymetry map, it takes many points that represent every bottom water form. Therefore a cross-sectional sweeping of the body of water is performed and the shoreline of the lake was traced. Coordinate and depth data were recorded every 30 seconds, downloaded through the Map source program and converted to a format compatible with the Quantum GIS 1.8 software.

Lake bathymetry’s trace can only be carried out in areas where there are no water lilies (aquatic macrophytes), which prevent boats navigation through the area. In general, in a location full of water lilies, the depth of the waters is only about 1-2 m. The bathymetry track route can be carried out around 2/3 of the lake area, because in the western side (pictured) and partially in the eastern side, the density of the water lily is almost permanently very high, therefore it cannot be passed by boats.

Morphometric data in the form of subsurface dimensions were obtained from bathymetry data. Simultaneously, surface dimension data were obtained from the analysis of the Indonesian Digital Earth Map 2015-2019 from the Geospatial Information Agency of the Republic of Indonesia. Lake boundaries were obtained with Landsat 8 OLI image analysis software. The image was accessed from USGS Earth Explorer with the nominal scene center of path 128 and row 59, in the Worldwide Reference System’s (WRS) notation. Simultaneously, ground check was also carried out, especially in areas with high lilies density.

Data analysis.

1) Bathymetry map: Bathymetry maps are realized based on the principle of interpolation, using Quantum GIS 1.8 software (free). The interpolation results are polygons of different depths with graded values: they are the darker the color, the deeper the zone. Indonesian Digital Earth Map 2015-2019 was obtained from the Geospatial Information Agency of the Republic of Indonesia.

2) Lake size metrics: Lake size was directly measured by Quantum GIS 1.8 on the Siais Lake map. Lake size metric consists of L_{max}, Le, W_{max}, We, SL, Ao, Z_{max}, and V. L_{max} is the maximum length (in meters), obtained by measuring the longest distance between two lakeside stations. Le is the maximum effective length (in meters), obtained by measuring the longest distance between two stations on the lake's surface without crossing an island (if any). W_{max} is the maximum width (in meters), obtained by measuring the distance of the two furthest stations on the edge of the lake surface, drawn perpendicular to L_{max}. W_e is the maximum effective width (in meters), obtained by measuring the distance of the two furthest stations on the edge of the lake's surface, drawn perpendicular to L_e. SL is the length of the coastline (in meters or kilometers) obtained by measuring the length of the circumference of the lake. A_o is the surface area of a lake in ha or km^2. Surface area polygons are drawn on bathymetry maps using the ArcMap program. Z_{max} is the maximum depth of the lake (in meters). Z_{max} is obtained by measuring it directly using an echo sounder and indirectly reading the bathymetry map's depth contours. V is the total volume of lake water (in m^3).

3) Lake form metrics: Lake form metrics relationships refer to Håkanson’s formula (1981; 2005a,b), namely:

- Average width ($\bar{W}$), expressed in meters and is the ratio between lake surface area (Ao) with maximum length:

$$\bar{W} = \frac{Ao}{Lmax}$$

Where:
$\bar{W}$ - average width (m);
Ao - lake surface area (m^2);
Lmax - maximum length (m).

- Shoreline development index (SDI) illustrates the relationship between SL with a surface area. If SDI>1, the water body shape is irregular. If SDI is ≤ 1, the shape of the water body is regular. SDI is calculated based on the equation:

$$SDI = \frac{SL}{2\sqrt{\frac{22}{7} \text{ x } Ao}}$$

Where:
SDI - shoreline development index;
SL - shoreline length (m);
Ao - lake surface area (m^2).

- Average depth ($\bar{Z}$), expressed in meter, is a volume (V) divided by the corresponding lake surface area (Ao):

$$\bar{Z} = \frac{V}{Ao}$$

Where:
$\bar{Z}$ - average depth (m);
V - volume (m^3);
Ao - lake surface area (m^2).

- Relative depth (Zr), expressed in meter, is the ratio between the maximum depth (Zmax) and the lake surface area. Relative depth calculated with the formula:

$$Zr = \frac{Zmax \ x \sqrt{n}}{20 \ x \sqrt{Ao}} x100$$

Where:
Zr - relative depth (m);
Zmax - Maximum depth (m);
Ao - Lake surface area (m^2);
N - total contour (m).

- Average slope ($\bar{S}$), expressed in %, describes the area with shallow water. The average slope is obtained directly from the processed data in Quantum GIS 1.8.
- The lake volume development (VD), is a non-dimensional measure that describes the shape of a lake bottom, in general. The development of lake volume is calculated with the equation:

$$VD = \frac{Ao \ x \bar{Z}}{\frac{1}{3} x(Zmax \ x \ Ao)}$$

Where:
Ao - lake surface area (m^2);
$\bar{Z}$ - Average depth (m);
Zmax - maximum depth (m).

4) Special metrics for lake morphometry*:* Special metrics for lake morphometry, referred by Håkanson (2005b), consist of: wave base depth (Z_{wb}), Basin Permanence Index (BPI), dynamic ratio (DR), and Morphometric index (MI). Z_{wb} is the depth used to estimate the epilimnion water volume. The epilimnion is the euphotic zone where there is a lot of sunlight and high oxygen content. High epilimnions in shallow lakes are the main habitat for macrophyte. The wave base depth (Z_{wb}) in meters was calculated from the formula:

$$Z_{wb} = \frac{45.7x\sqrt{A}}{21.4x\sqrt{A}}$$

with A in km^2.

The Basin Permanence Index (BPI) ($m^3 \ km^{-1}$) indicates the effect of the littoral zone on basin volume. BPI is the ratio of lake volume (million m^3) to the lake circumference (km):

$$BPI = \frac{V}{SL}.$$

The dynamic ratio (DR) is calculated by the equation:

$$DR = \frac{\sqrt{A}}{z}$$

with A in $km^{2.}$

Results and Discussion

Bathymetry. The results of the bathymetry mapping at Siasis Lake are shown in Figures 2-4. The deepest area is in the middle of the south direction. The deepest locations are marked with dark blue, darker color degradation indicates deeper location. In general, natural lakes have a more regular lake bottom shape, compared to the artificial lakes

(Soeprobowati 2012; Ridoan et al 2016). The irregular shape of the bottom of an artificial lake is generally determined by previous dredging activities (Muhtadi et al 2017a, 2020).

The seasonal influence on bathymetry conditions can be observed in Figure 2: in the rainy season, lake maps show a dark blue color (10-12 m depth) that broadens in the middle. However, both in the rainy and dry seasons, the same bathymetry pattern is shown where the edges are steep, but in the middle it is rather flat, with increasingly tight contours and rapid discoloration at the lake's edges compared to the middle. The more intense the contours, the deeper the lake and conversely, the lighter the contours, the shallower the lake (Ridoan et al 2016). In the northwest and southeast, the contours are very sparse because it is a shallow area with a depth of only up to 5 m.

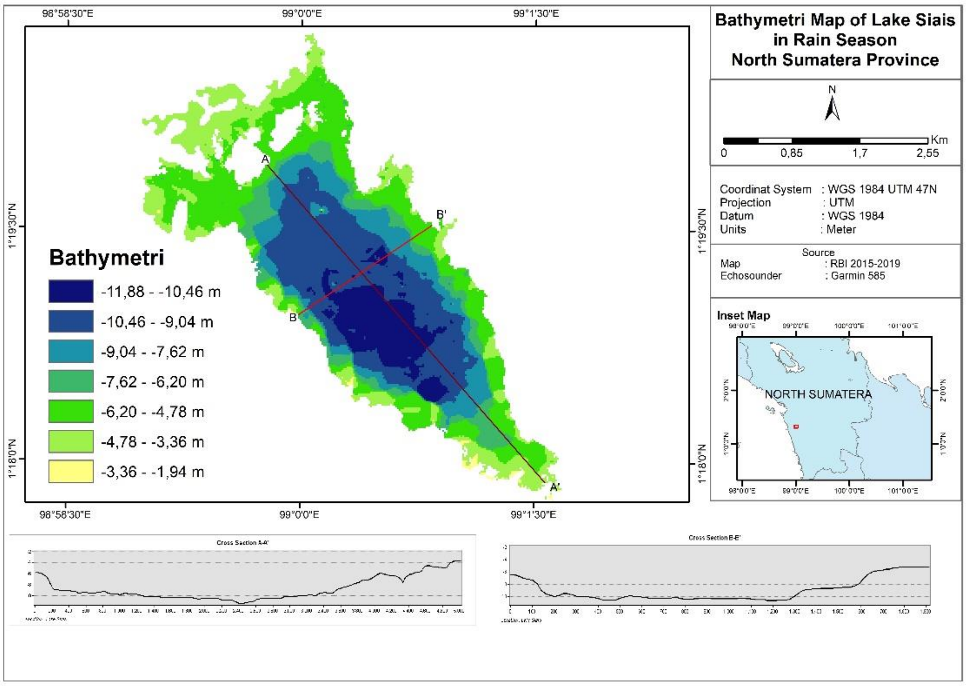

Figure 2. Bathymetry map during the rainy season at Siais Lake.

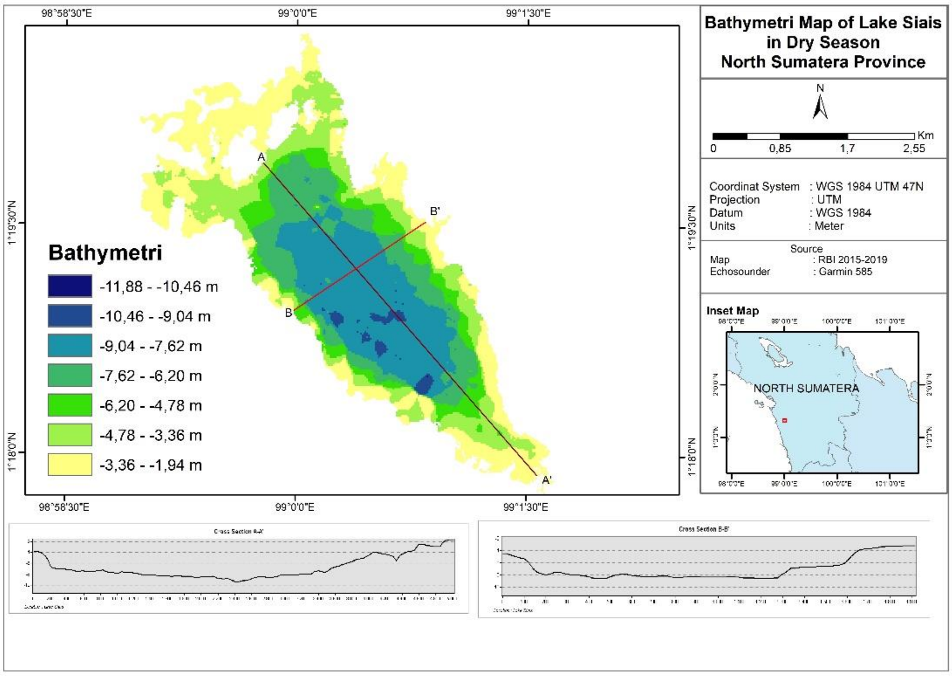

Figure 3. Bathymetry map during the dry season at Siais Lake.

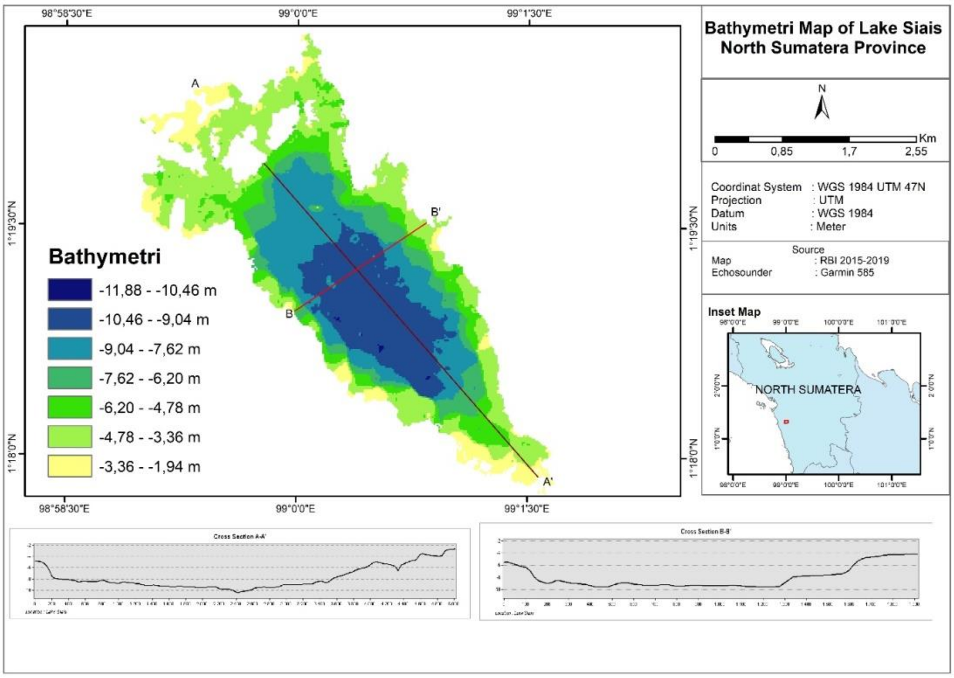

Figure 4. Bathymetry map of the average condition at Siais Lake.

Morphometry. The results of Siais Lake morphometry analysis are presented in Table 1 and Table 2. The total area of Siais Lake reaches 17 km^2, with a total volume reaching 54 million m^3. There is no significant difference between the rainy season and the dry season concerning the area, volume, and other parameters (Table 1). The length of the Siais lake circumference (SL) reaches 41.57 km with the maximum length and maximum width reaching 8.64 km and 2.63 km. Islands do not exist in this lake, so that the maximum length and width equals the effective length and width. Siais Lake belongs to moderate lakes, covering an area of 100-10,000 ha (Straskraba & Tundisi 1999).

Table 1

Lake size metrics of the Siais Lake

Parameter	*Unit*	*Rain*	*Dry*	*Average*
Maximum length (L_{max})	m	8,643.21	8,635.11	8,639.16
Effective length (Le)	m	8,643.21	8,635.11	8,639.16
Maximum width (W_{max})	m	2,642.98	2,634.98	2,638.98
Effective width (Le)	m	2,642.98	2,634.98	2,638.98
Total surface area (Ao)	m^2	17,258,815.35	17,092,552.96	17,175,882.33
Lake area covered by aquatic macrophyte	m^2	9,339,198.76	9,249,229.81	7,881,560.81
Lake area without covered by aquatic macrophyte	m^2	7,919,616.59	7,843,323.15	9,294,321.52
Lake circumference (SL)	m	41,350.43	41,745.70	41,586.08
Volume (V)	m^3	54,504,140	46,851,462	64,783,888
Maximum depth (Z_{max})	m	11.88	11.88	11.88

Siais Lake is the second largest lake in North Sumatra Province after Toba Lake which reaches 110,400 ha (Lukman & Ridwansyah 2010). However, it is much bigger than other lakes in North Sumatra, such as: Teluk Belukar Lake on Nias, with 47.4 ha (Hasudugan et al 2008), Siombak Lake in Medan, with 29 Ha (Muhtadi et al 2020), Pondok Lapan Lake in Langkat, covering an area of 6.34 ha (Muhtadi et al 2017b) and Kelapa Gading Lake on Kisaran, in the Range of 1.19 ha (Ridoan et al 2016).

Siais Lake volume development (VD) value is 0.69-0.95. Wetzel (2001), as well as Cole & Weihe (2016) stated that a VD value >0.5 depicts a flat-shaped bottom. Basically, the shape of the lake's bottom does not show significant differences. Siais lake SDI is 2.81. This shows that the shape of the Siais Lake water body is irregular. The water shape of a lake is closely related to the water body contact the land, which can facilitate the transport of both nutrients and suspended solids from land to water (Håkanson 2005a).

Discussion. Siais Lake is a shallow lake, its average depth ranges from 2.74-3.75 m (Table 2). Shallow waters usually have high biological productivity potential because the epilimnion layer is thicker than the hypolimnion layer. This is supported by the Zr value of Siais Lake, of 0.04%, under 2%.Low values of Z and Zr indicate that Siais Lake has a low level of stratification stability, making it easy to experience stirring. Wetzel (2001) reported that water masses with Zr less than 2% will be easily stirred, so the water layer tends to be homogeneous and decomposed nutrients from the decomposition zone will be distributed to the epilimnion layer. This can be seen from the number of aquatic plants (other than macrophytes) that grow at the bottom of the lake. This can also be supported by an average slope data of 0-10%, suggesting a gentle slope. This value illustrates that the waters are relatively flat with broad littoral areas. Waters, with large littoral areas, have high biological productivity potential (Azzella et al 2014; Seekell et al 2018). This is because the littoral region has rooted plants which contribute to the increased concentration of organic matter at the bottom. Decomposed organic material is a source of nutrients for phytoplankton and aquatic plants, and the organic matter layer accumulated at the bottom of the lake supports the benthic biomass growth (Wetzel 2001; Azzella et al 2014; Cole & Weihe 2016).

Among the special metrics for lake morphometry, the A/V ratio's value of 0.27-0.32 (Table 2) indicate that the lake is shallow, with a wide littoral zone. The broad littoral zone is also supported by low slope and low relative depth values. This is evidenced by the presence of aquatic plants covering 41% of the lake area. This value also indicates a relatively extended drainage basin and a water debit potential for large discharges from rivers into lakes. The value of wave base depth (Zwb) shows the indicator of turbulent mixing at a depth of 2.14 m, with a surface layer volume of 13,816,738.54 m^3, or 25.35% of the lake volume. Thus, the bottom water volume is 40,687,401.11 or 74.65% of the lake's volume. The dynamic ratio (DR) has a value of 2.53-3.55, showing an intense wind/wave process determining the Siais Lake's propensity to experience stirring. Basin Permanent Index (BPI), 1.12-1.57 m^3 km^{-1}, indicates that the Siais Lake is very suitable for the littoral zone development and rooted aquatic plants. As previously explained, 41% (7 km^2) of the lake's water body is covered by aquatic plants, some of which are rooted to the bottom. Most of the aquatic macrophytes are found west to the north of the lake (Figure 5). The depth of the lake in the zones with macrophytes is of 1-2 m, while in other zones the average depth is 4.81-6.81 m, with a maximum depth of 11.8 m.

Table 2

Lake form and special metrics for the Siais Lake morphometry

Parameter	*Unit*	*Rain*	*Dry*	*Average*
Lake form metric				
Average width ($\overline{W}$)	m	1,996.81	1,979.48	1,988.14
Shore line development index (SDI)	-	2.81	2.85	2.83
Average depth ($\bar{Z}$)	m	3.75	2.74	3.17
Relative depth (Zr)	%	0.04	0.04	0.04
Volume development (VD)	m	0.95	0.69	0.80
Average slope ($\overline{S}$)	%		0-10	
Special metric for morphometry				
A/V ratio		0.36	0.27	0.32
Wave base depth (Zwb)	m	2.14	2.14	2.14
Basin permanence index (BPI)	m^3 km^{-1}	1.57	1.12	1.31
Dynamic ratio (DR)	m	2.53	3.55	2.96

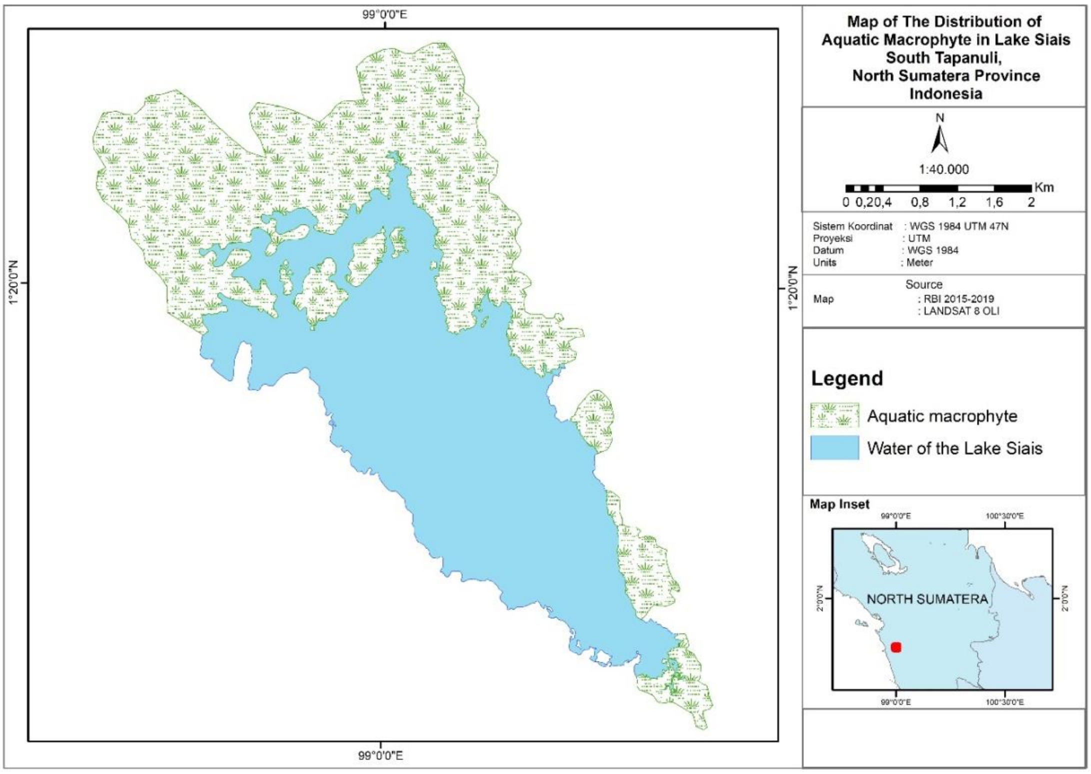

Figure 5. The map of aquatic macrophyte distribution in the Siais Lake.

Based on field surveys and information from in-depth interviews with surrounding communities, it was established that Siais Lake is a fishing area for Raniate Village fishermen. At least 20% of the Raniate community depends on fishing from the Siais Lake. Desrita et al (2020) reported that there were at least 23 species of fish 2 species of shrimp found in the lake, and even eel fish (*Anguilla bicolor*), which demonstrates that Siais Lake is a fish habitat and a destination for the their migration. Currently, Siais Lake has also been designated as a tourist destination, together with Toba Lake, through the North Sumatra Provincial Spatial Plan for 2015-2035. On the surrounding of the lake several lodges and restaurants for visitors have been developed.

The development of lake's use will undoubtedly harm the sustainability of the lake's ecosystem. Therefore, morphometry and bathymetry data can help in this regard. The lake's development for tourism purposes requires more studies related to the lake's carrying capacity of tourist areas, necessary to achieve the sustainability of the lake's ecosystem. Of course, morphometric data is vital in determining the spatial distribution of the lake's carrying capacity. Bathymetry data is also essential in determining tourist areas and routes, especially for boating tourism.

The efforts of the local government to make the Siais Lake available for developing floating fish pond certainly need a particular study. However, through this morphometric data, we suggest that the lake is too shallow to be compatible with aquaculture. This will only increase the nutrients concentration, with a significant risk of the water eutrophication. In the future, more research is required for maintaining the fisheries' sustainability, for example to determine the role of aquatic plants in supporting fisheries, in the context of an expanding area covered by aquatic plants.

Conclusions. Lake Sais has a total area of 17 km^2. This lake is a shallow lake with an average depth of 5.81 meters, while the maximum depth in this lake is 11.8 meters. The shape of the Lake Siais is irregular and part of the water surface is covered by aquatic macrophyte (Amaryllidaceae). At this time Lake Siais is used by the local community as a capture fishery location. Siais Lake is very suitable for the littoral zone development and rooted aquatic plants.

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