# The hydrodynamics of Anak Laut coastal lake, Aceh Singkil Regency, Indonesia

Rusdi Leidonald, Ahmad Muhtadi, Zulham Apandy Harahap

Department of Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara. Jl. Prof. A. Sofyan No. 3 Medan, Indonesia. Corresponding author: R. Leidonald, rusdi.leidonald@usu.ac.id

**Abstract**. Anak Laut Lake is one of the coastal lakes found in Indonesia. This lake is very unique because tides from the Indian Ocean influence it. This study aims to describe the physical conditions and dynamics of coastal lake waters, including water level conditions, bathymetry, and lake morphometry. Tidal and water level data were obtained from Geospatial Information Agency real-time measurements from January - December 2022. Depth measurements were performed using a Garmin 585 echosounder. Spatial data processing was conducted using Quantum GIS 1.8 program. Anak Laut Lake is a shallow lake (depth < 10 m) with an area of 10.55 $km^2$ at mean sea level, 11.26 $km^2$ at high tide, and 9.84 $km^2$ at low tide. This lake is prone to water mixing because it has a low relative depth (0.03%) and a low area/volume (A/V) ratio (0.15-0.24) and a high wave base depth (> 2 m). The results of tidal measurements at the study site obtained that the highest water level at the highest astronomical tide (HAT) value was 1.92 m in May 2022. The lowest water level at the lowest astronomical tide (LAT) was 0.62 m in February 2022. This difference in water level results in differences in the hydro-morphometry of the lake.

**Key Words**: bathymetry, morphometry, tidal, water level.

**Introduction**. Anak Laut coastal lake is a unique and distinctive lake which is located in the coastal area of Aceh Singkil Regency, Indonesia. The characteristics of coastal lake waters are directly related to the sea either by the influence of tides, waves, rivers, or wind (Muhtadi et al 2020a; Tagliapietra et al 2009). Coastal lakes are generally connected to the ocean through narrow inlets, such as: choked, restricted, and leaky inlets (Kjerfve 1994). Coastal lakes have different water environment characteristics from lakes in general, especially high salinity and TDS content compared to "inland lakes". Coastal lakes are very dynamic and fluctuate due to the influence of tides (Muhtadi et al 2020a).

Some coastal lakes in the world include Lagoa dos Patos and Lagoa de Araruama in Brazil, Lake St. Lucia in South Africa, the Coorong in Australia, Lake Songkla in Thailand, Laguna de Terminos in Mexico, and Lake Pontchartrain and Mississippi Sound in the USA, and Wadden Zee in the Netherlands, Germany, and Denmark (Kjerfve 1994). Examples of tropical coastal lakes are Chilika Lake in India (Mahanty et al 2019) and Nokue Lagoon in Benin (Zandagba et al 2016). There are very few coastal lakes in Indonesia, including Teluk Belukar Lagoon (Nias) (Hasudungan et al 2008) and Siombak Lake (Medan) (Muhtadi et al 2020a) in North Sumatra Province. Anak Laut Lake in Singkil, Aceh Province is another coastal lake identified in Indonesia.

Anak Laut Lake is a coastal lake located on the west coast of Sumatra, precisely in Singkil, Aceh Province. This lake is formed naturally where its waters are directly connected to the Indian Ocean on the west coast of Sumatra. The existence of tidal dynamics in the Indian Ocean, which is directly connected to Anak Laut Lake, will certainly affect the dynamics of lake water levels and water quality (physicochemical parameters) (Elshemy et al 2016; Zandagba et al 2016; Muhtadi et al 2020a, 2023b), as well as aquatic organisms (flora and fauna) (Pérez-Ruzafa et al 2019; Yulianda et al 2020; Muhtadi et al 2020b, 2022). The biota that inhabits this lake are marine organisms (Muhtadi et al 2023a), although there are several rivers that enter the lake which provide freshwater input. These marine organisms have the potential to use this lake as a spawning, nursery, and feeding ground. In order to preserve this lake, appropriate management efforts are needed.

Lake management must begin with accurate information about the characteristics of the lake (Cole & Weihe 2016; Muhtadi 2022). Lake characteristics are closely related to the lake's hydro-morphometry, namely its physical form (morphology) and the influence of its environment (Håkanson 2005a; Barroso et al 2014; Muhtadi 2022). Morphologically, the shape of the lake can be determined through morphometry (Håkanson 1981; Wetzel & Gene 2000; Cole & Weihe 2016). Lake morphometry determines the nutrient loading, primary production, and secondary production of the lake. Lake morphometry also plays an important role in the dynamics of water quality and lake biology (Muhtadi et al 2020b; Muhtadi 2022; Muhtadi et al 2023b). Studies related to water hydrodynamics are the first step to determining appropriate and sustainable management. For this reason, this study aims to describe in detail the hydro-morphometric characteristics of the waters of Anak Laut Lake.

## Material and Method

***Description of the study site***. Anak Laut Lake is an open coastal lake that is influenced by tides from the Indian Ocean (Figure 1). This research was conducted at Anak Laut Lake, Aceh Singkil Regency, Indonesia (Figure 1).

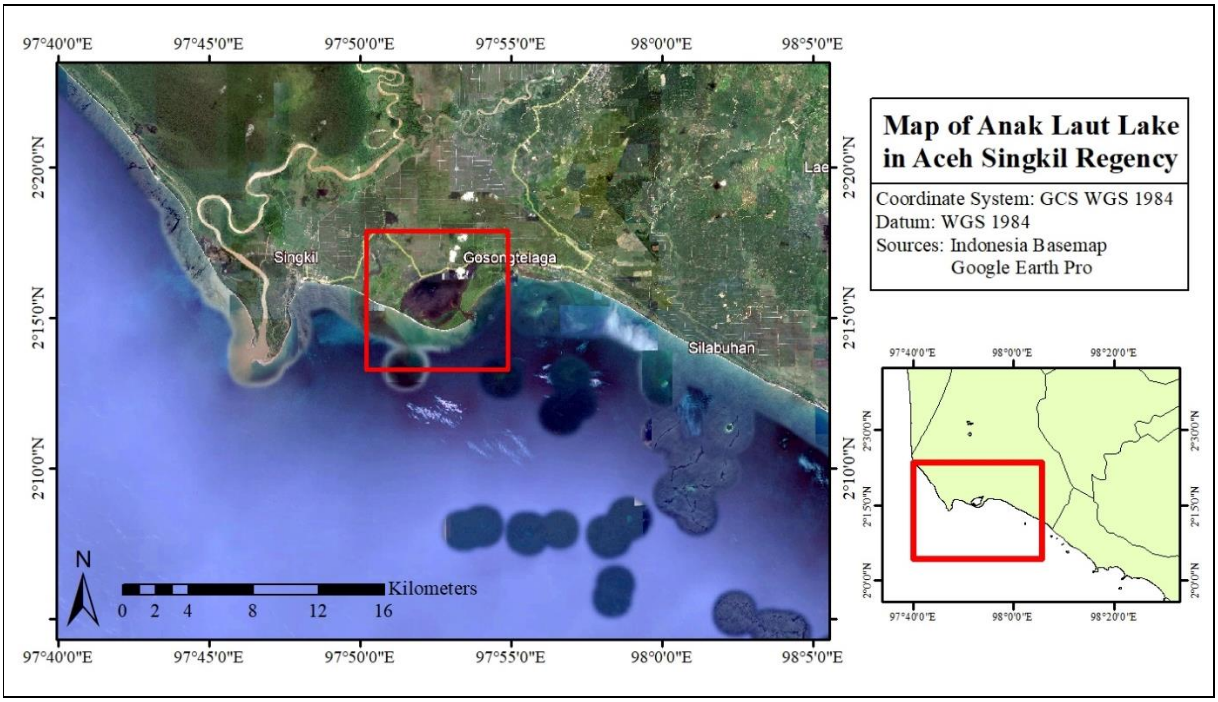


Figure 1. Map of research locations in Anak Laut Lake (map generated using Indonesian Earth Shape Map 2022).

***Data gathering and measurements***. The tidal data was taken from the Geospatial Information Agency's Singkil tidal observation station, which is located 9 km from Anak Laut Lake, from January to December 2022. Lake bathymetry surveys can be taken by acoustic methods or known as hydroacoustics (underwater acoustic) using underwater detection technology. Determination of lake bathymetry uses an active acoustic system, in the form of acoustic signals that are emitted and reflected by the lake bottom. A tool in the form of an echosounder, namely the Garmin GPS Map 585, which is placed under the boat will provide acoustic waves vertically to the bottom of the lake and then reflect to the Garmin GPS Map 585 sensor. Bathymetry data was collected in October 2022.

***Data analysis***. Data analysis includes tide and water level measurements, bathymetry and morphometry. To determine the type of tide, this is calculated by obtaining the number or tidal constant (Formzahl number, F) calculated by the admiralty method using the following formula (Dietrich 1963):

$$\mathbf{F} = \frac{AK1 + AO1}{AM2 + AS2}$$

Where, Formzahl (F) is the tidal constant, AK1 is the amplitude of the average single daily tidal sub-wave affected by lunar and solar declination, AO1 the amplitude of the single daily tidal sub-wave affected by solar declination, AM2 the amplitude of the average double daily tidal sub-wave affected by the moon, AS2 the amplitude of the average double daily tidal sub-wave affected by the sun.

To obtain a good bathymetric map, a large number of points are required and represent each water bottom condition. Therefore, sweeping the water body as a cross-section and sweeping the shoreline of the lake is done by tracing the edge of the lake. Coordinate and depth data were recorded every 30 seconds and then downloaded through the Mapsource program and changed the format to be compatible with the Quantum GIS 1.8 program.

The measurement data were then organized in a table. The data rows are in the form of measurement stations and the data columns are data identity (ID), data collection time, coordinates, altitude, and water depth. Furthermore, the table data was converted into spatial form and processed using the Quantum GIS 1.8 program equipped with the 3D Analyst extension (Muhtadi et al 2020a, 2020c). The base map used the Indonesian Earth Shape Map (2022). Furthermore, the data were analyzed including lake morphometry data.

Morphometric analysis of the lake, referring to Håkanson (2005a, 2005b) and Barroso et al (2014) consist of: 1) lake size metrics, 2) lake form metrics, and 3) special metrics for lake morphometry. Lake size metrics parameters were directly analyzed and calculated on the bathymetry map of Anak Laut Lake using Quantum GIS 1.8. Lake size metrics consisted of maximum length ($L_{max}$), effective length (Le), maximum width ($W_{max}$), effective width (We), shoreline length (SL), total surface area (Ao), maximum depth ($Z_{max}$), and volume (V). Lake form metric parameters were calculated by referring to Hakanson (2005a, 2005b) and Barroso et al (2014). Lake size metrics consists of average width ($\overline{W}$), shoreline development index (SDI), average depth ($\overline{Z}$), relative depth (Zr), average slope ($\overline{S}$) and the lake volume development (VD). Meanwhile, special metrics for lake morphometry (Barroso et al 2014) consist of wave base depth (Zwb), basin permanence index (BPI), dynamic ratio (DR), and morphometric index (MI).

## Results

***Tide and water level***. The tidal type of Singkil waters is mainly semidiurnal mixed tide, which means that in one day there are two high tides and two low tides with different periods and heights (tidal graph). This refers to the Formzahl value obtained in Singkil which is 0.43. The mean sea level was 1.27 m (Table 1 and Figure 2). The tides in this lake are tidal propagation from the double-type Indian Ocean that propagates to the west coast of Sumatra Island (Wyrtki 1961).

The highest water level at the hihghest astronomical tide (HAT) around Singkil was 1.92 m in May 2022 (Table 1 and Figure 2). The lowest water level at the lowest astronomical tide (LAT) was 0.62 m in February 2022 (Table 1 and Figure 3). The measured mean sea level (MSL) was 1.27 m. Daily and monthly (tidal cycle) changes in the elevation (water level) of the Anak Laut Lake occur. This also occurs in Siombak Lake where as far as 6 km from the seafront, tidal dynamics affect the water level in Siombak Lake. The results of tidal measurements at Siombak Lake obtained the highest water level elevation (HAT) value is 2.66 m during the rainy season and 2.23 m during the dry season. The lowest water elevation (LAT) is -0.43 m during the rainy season and -0.04 m during the dry season. The measured MSL was 1.12 during the rainy season and 1.10

during the dry season (Muhtadi et al 2020a). The existence of these tidal dynamics, in addition to affecting water levels, will also affect water quality (Elshemy et al 2016; Ratnayake et al 2018; Muhtadi et al 2023b) and also the composition and distribution of aquatic biota in tidal lakes (Pérez-Ruzafa et al 2019; Yulianda et al 2020; Muhtadi et al 2020b, 2022).

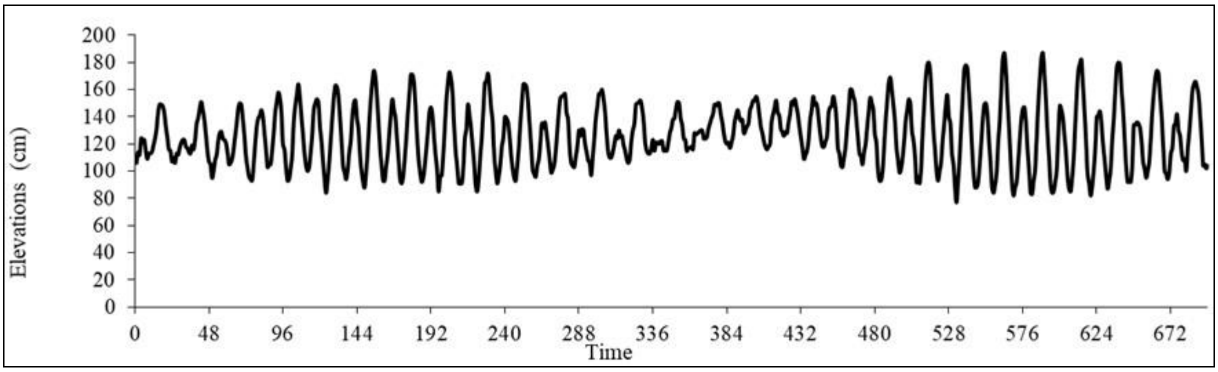

Figure 2. Graph of the tide in location site.

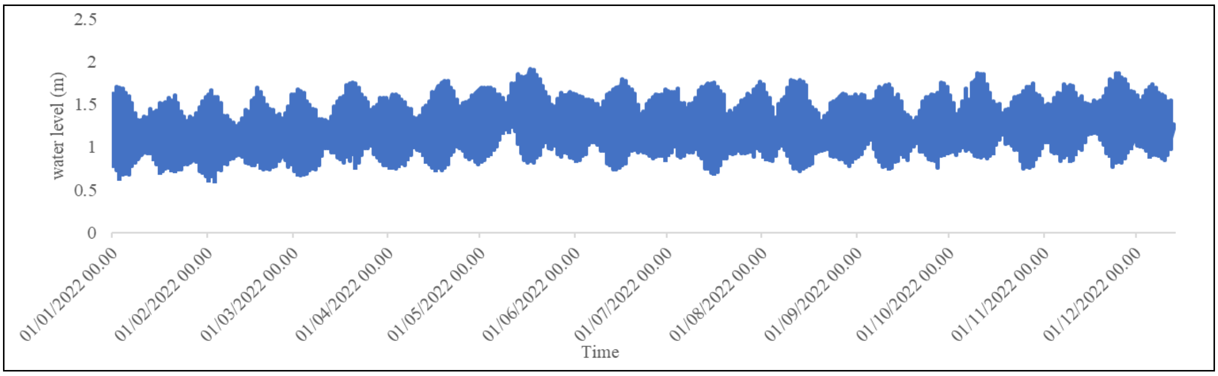

Figure 3. The water level Anak Laut coastal lake (January – December 2022).

***Bathymetry***. The bathymetry map of Anak Laut Lake shows that the deepest area is in the center towards the southwest (Figures 4, 5, 6). The deepest areas are marked in blue on the map and the shallowest areas along the periphery of the lake are in green. Based on Figures 4, 5 and 6, it can be seen that there is a tidal influence on the bathymetry condition of the lake at high tide, low tide, and MSL. At high tide, the highest depth is seen in the range of 7-9 m. At low tide and MSL conditions, the highest depths are seen in the range of 6-8 m.

The bathymetry contour shape of Anak Laut Lake is deeper in the centre part of the lake. In general, natural lakes have a more regular bottom shape (Muhtadi et al 2020a). Other natural coastal lakes show a regular lake bathymetry shape (Hasudungan et al 2008; Umgiesser et al 2014; Panda et al 2015; Zandagba et al 2016; Mahanty et al 2019). Artificial lakes generally have an irregular lakebed shape (Ridoan et al 2016; Muhtadi et al 2020c). The irregularity of artificial lakes bottom shape is generally caused by the formation of the lake from dredging activities (Muhtadi et al 2020b).

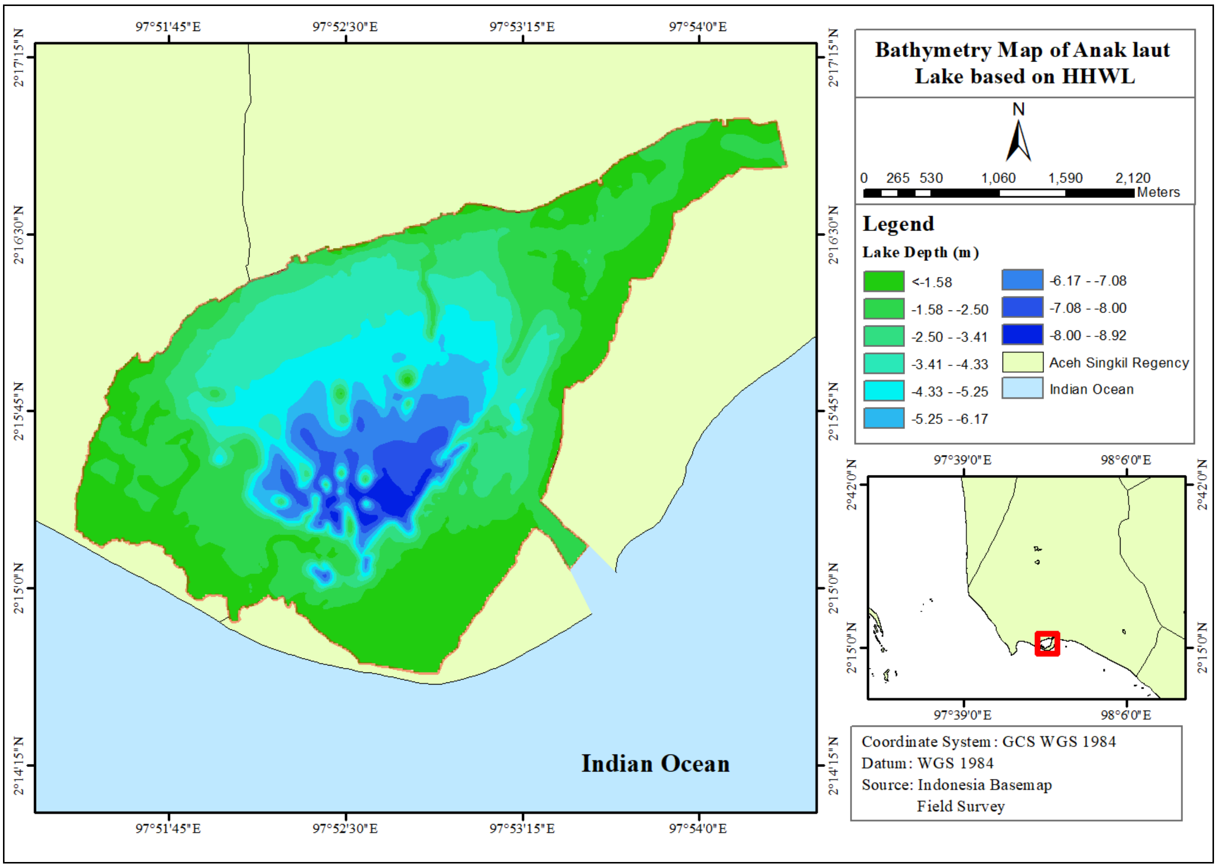


Figure 4. Bathymetry map of Anak Laut Lake at high tide (map generated using Quantum GIS 1.8 software).

***Lake size metrics***. Anak Laut Lake has an area of 10.55 $km^2$ at MSL, 11.26 $km^2$ at high tide, and 9.84 $km^2$ at low tide (Table 1). The total water volume of Anak Laut Lake reaches 16.51 million $m^3$ at MSL, 17.61 million $m^3$ at high tide, and 15.40 million $m^3$ at low tide. The existence of tidal dynamics in Anak Laut Lake causes differences between high tide, low tide and MSL conditions (Tables 1, 2, 3). A small portion of the water body in the south and east are mangroves where during low tide the mangrove roots of *Rhizophora stylosa* species are more clearly visible and covered by water at high tide.

The shoreline length of Anak Laut Lake (SL) reaches up to 11.52 km at MSL, 18.54 km at high tide, and 11.12 km at low tide. The maximum length reaches 6.35 km with a maximum width of 2.64 km at MSL, 3.38 km at high tide, and 2.64 km at low tide, respectively. Anak Laut Lake is categorized as a medium lake with an area of 100-10,000 ha and a volume of less than 100-10,000 million $m^3$ (Mingazova & Galeeva 2016).

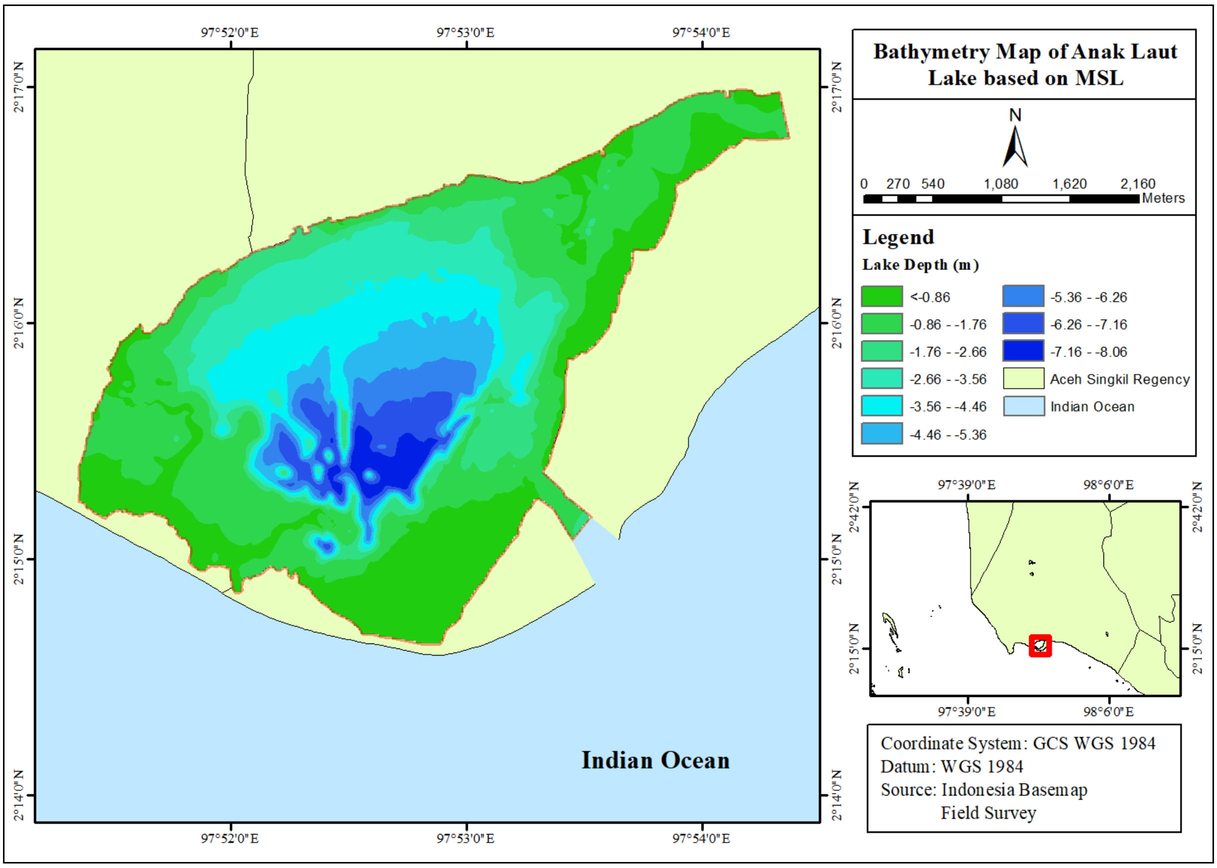


Figure 5. Bathymetry map of Anak Laut Lake at MSL (map generated using Quantum GIS 1.8 software).

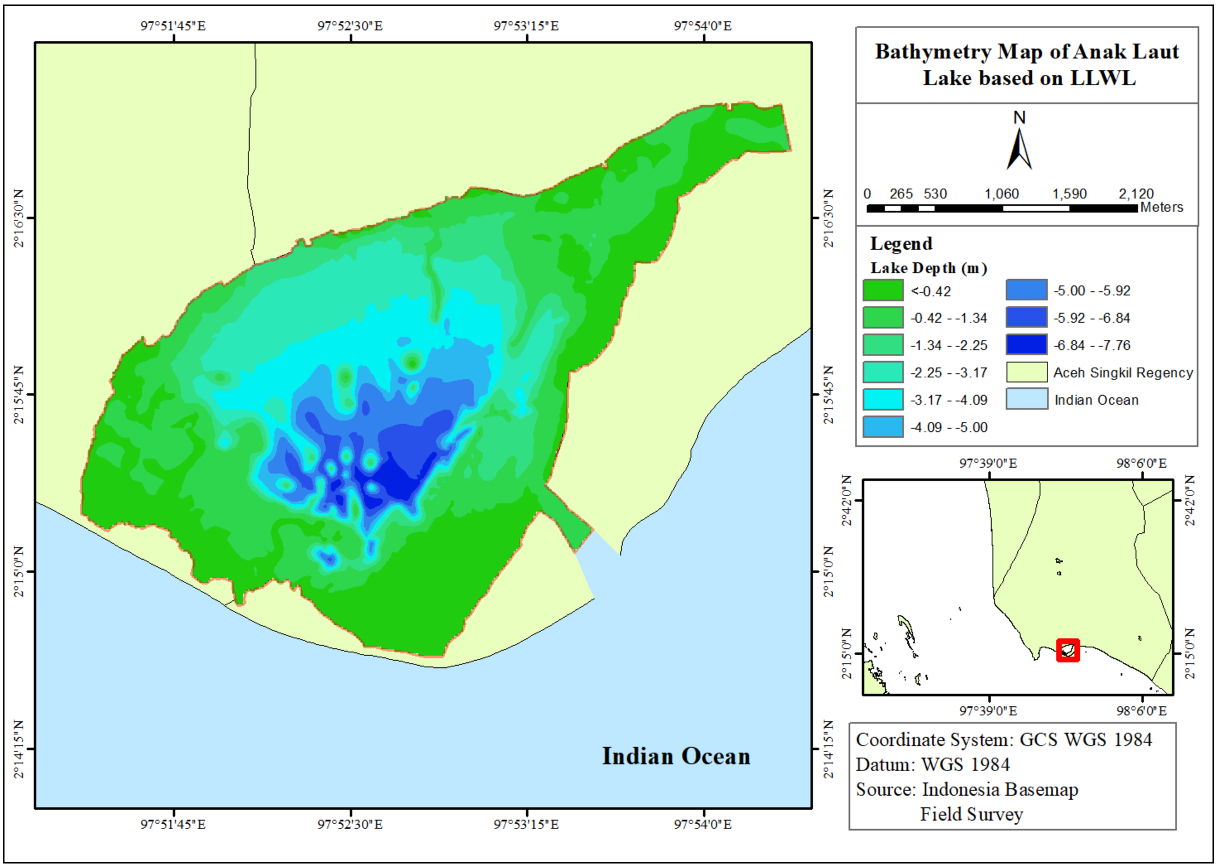


Figure 6. Bathymetry map of Anak Laut Lake at low tide (map generated using Quantum GIS 1.8 software).

Anak Laut Lake is the largest coastal lake in Indonesia. Some other coastal lakes are Teluk Belukar Lake (Nias-North Sumatra) with an area of 47.4 ha (Hasudungan et al 2008), and Siombak Lake (Medan-North Sumatra) which is only 29 ha (Muhtadi et al 2020a). Other coastal lakes surface area: Songkhla Lagoon (Thailand) reaching 1,042 $km^2$ (Ganasut et al 2005); Laguna Lake (Philippines) reaching 100 $km^2$ (Herrera et al 2014); Chilika Lagoon (India) reaches 815 $km^2$ during the dry season and 992 $km^2$ during the rainy season (Mahanty et al 2019); Nokoue Lake (Benin) reaches 150 $km^2$ (Zandagba et al 2016). Coastal lakes in the Mediterranean region (sub-tropical) reach 31-41,500 ha, except Faro Lagoon (Italy) with an area of 26 ha (Umgiesser et al 2014).

Table 1

Lake size metrics of Anak Laut Lake

| *No.* | *Parameter* | *Unit* | *MSL* | *High tide* | *Low tide* |
|---|---|---|---|---|---|
| 1 | Maximum length $(L)_{max}$ | Km | 6.35 | 6.35 | 6.35 |
| 2 | Effective length (Le) | Km | 6.35 | 6.35 | 6.35 |
| 3 | Maximum width $(W)_{max}$ | Km | 2.64 | 3.38 | 2.64 |
| 4 | Effective width (Le) | Km | 2.64 | 3.38 | 2.64 |
| 5 | Total surface area (Ao) | $Km^2$ | 10.55 | 11.26 | 9.84 |
| 8 | Shoreline length (SL) | Km | 11.52 | 18.54 | 11.12 |
| 9 | Volume (V) | $m^3$ | 28,736,505 | 30,662,156 | 26,810,854 |
| 10 | Maximum depth ($Z_{max}$) | m | 8.00 | 8.58 | 7.42 |

***Lake form metrics***. Anak Laut Lake is a shallow lake, with an average lake depth ($\bar{Z}$) ranging between 2.51-3.67 m (Table 2). Shallow lakes usually have high biological productivity potential because the epilimnion layer is thicker than the hypolimnion layer (Barroso et al 2014; Muhtadi et al 2020c, 2020a). The values of ($\bar{Z}$) (2.51-3.67) and $Z_r$ (0.03%) in Anak Laut Lake are low, indicating that this lake will easily experience stirring because the lake has a low level of lake stratification stability. Coastal lakes generally have low $Z_r$ values such as Siombak Lake which has $Z_r$ of 0.59% at MSL, 0.61% at high tide, and 0.57% at low tide (Muhtadi et al 2020a).

The volume development (VD) value of the lake is 0.80 m at MSL, 0.94 m at high tide, and 0.62 m at low tide. VD values > 0.5 m describe a relatively shallow lake with a flat bottom (Wetzel 2001). The shape of the bottom of Anak Laut Lake is not much different between MSL and high tide because the change in water volume is not so significant, but at low tide, it is quite significant because the difference in water volume is quite large between high and low tide. The average slope of Anak Laut Lake is 5%, which is a gentle slope. This value describes relatively flat waters with large littoral areas. Waters with large littoral areas have the potential for high biological productivity (Barroso et al 2014; Muhtadi et al 2020a, 2020c). This is because littoral areas have rooted plants that contribute to organic matter (Welch 1952; Barroso et al 2014). Rooted plants in Anak Laut Lake are found around the lake, especially in the southeast part where mangrove vegetation and seagrass is found.

The SDI of Anak Laut Lake is 2.00 m at MSL and low tide and 3.12 m at high tide. At low tide and MSL, the shape of the Anak Laut Lake water body is close to elliptical. However, at high tide, the shape of the lake is more irregular. The shape of a lake water body is strongly related to the opportunity for a water body to have direct contact with land, which can affect the intake of both nutrients and suspended solids from land to water (Wetzel 2001; Håkanson 2005a). At low tide, the MSL of Anak Laut Lake is elliptical, indicating low contact of the lake shore with the surrounding area, resulting in low inputs of both nutrients and suspended solids from land to the water. Inputs of nutrients and other suspended materials come from the lake inlet in the east and a small amount from residential runoff in the north.

At high tide, the lake is irregularly shaped and nutrients can come from seawater carried from the Indian Ocean whereas, in the western part of Anak Laut Lake, there is the Alas-Singkil River estuary. This shows that the shape of the Anak Laut Lake water body is irregular. The level of productivity of these waters is closely related to the more irregular shape of the lake so the more parts that cove and connect with the mainland the possibility of nutrient inputs from the land will also be greater (Muhtadi et al 2020a). In general, both natural and artificial lake water have an SDI greater than 2 m, such as Toba Lake at 3.61 m (Lukman & Ridwansyah 2010), Kelapa Gading Lake at 3.55 m (Ridoan et al 2016), Pondok Lapan Lake by 4.93 m (Muhtadi et al 2017), Siais Lake by 2.83 m (Muhtadi et al 2020c). However, coastal lakes in Indonesia show a regular lake shape (SDI < 2) i.e. 1.6 in Teluk Belukar Lake (Hasudungan et al 2008) and 1.96 in Siombak Lake (Muhtadi et al 2020a).

Table 2

Lake form metrics of Anak Laut Lake

| *No.* | *Parameter* | *Unit* | *MSL* | *High tide* | *Low tide* |
|---|---|---|---|---|---|
| 1 | Average width ($\overline{W}$) | m | 1.66 | 1.77 | 1.55 |
| 2 | Shoreline development index (SDI) | m | 2.00 | 3.12 | 2.00 |
| 3 | Average depth ($\overline{Z}$) | m | 3.11 | 3.67 | 2.51 |
| 4 | Relative depth (Zr) | % | 0.03 | 0.03 | 0.03 |
| 5 | Volume development (VD) | m | 0.80 | 0.94 | 0.62 |
| 6 | Average slope ($\overline{S}$) | % | | 5 | |

Figure 7. Mangroves (left) and seagrass (right) are found growing in the Anak Laut Lake.

***Special metrics for lake morphometry***. The value of wave base depth (Zwb), in Anak Laut Lake is 2.14 m which indicates an indicator of turbulent mixing depth at a depth of 2.14 m (Table 3). The volume of the surface layer (i.e. the mixing layer) is 11-13 million $m^3$ or 43% of the total lake volume. Accordingly, the volume of bottom waters is 15-17 million $m^3$ or 47% of the total lake volume. The compensation depth of Anak Laut Lake is at a depth of 2.98 m. The average compensation depth of the lake is low compared to the sea.

The area/volume (A/V) ratio of Anak Laut Lake is 0.15-0.24, indicating that this lake is a shallow lake with a large littoral zone. The large littoral zone is also supported by the low relative slope and depth values where many mangrove trees are found around the lake. This A/V ratio value also indicates a relatively wide drainage basin and the potential for large discharges from the river into the lake. The dynamic ratio (DR) of Anak Laut lake is 2.62-4.11 m which indicates the dominance of the wind/wave process over the lake is high, so in Anak Laut Lake it is very easy for stirring to occur. Wind entering the lake can come from the Indian Ocean where the lake is directly adjacent to the open sea on the west coast of Sumatra.

The permanent basin index (BPI) of Anak Laut Lake is 2.53 $m^3$ $km^{-1}$ at high tide, 4.73 $m^3$ $km^{-1}$ at MSL, and 5.82 $m^3$ $km^{-1}$ at low tide. BPI values are lower at low tide than at high tide. These BPI values also indicate that Anak Laut Lake has a large littoral zone and potential for the growth of rooted aquatic plants at the edge of the lake where in this case mangroves grow mainly along the east to west of the lake.

The inlet (high tide) water discharge (Q) at Anak Laut lake is 56.5 $m^3$ $sec^{-1}$ and the outlet (ebb) water discharge is 33.75 $m^3$ $sec^{-1}$, while the water discharge at MSL is 0 $m^3$ $sec^{-1}$ because the water position is stagnant. The water discharge in and out of the lake is strongly influenced by sea tides so the dynamics of the lake's water follow the pattern and dynamics of seawater in the Indian Ocean.

The water residence time (Rt) was 5.52-6.31 days. The residence time of Anak Laut Lake's water is short due to tidal dynamics, but it is still shorter in Siombak Lake, which is only 11-25 hours (Muhtadi et al 2020c). However, the Rt in Anak Laut Lake is very much different from an inland lake, which even reaches years (Nontji 2017). The higher the retention time (Rt) value, the longer the residence time of water in a lake, so the opportunity for organic matter or nutrients to be in the water will be greater (Mitchell et al 2017). The retention time (Rt) of Anak Laut Lake is short because it is influenced by tides so the opportunity for organic matter in the waters of Anak Laut Lake is no more than one week. This low retention time (Rt) also causes little opportunity for suspended material in the water to settle.

Table 3

Special metrics for lake morphometry

| *No.* | *Parameter* | *Unit* | *MSL* | *High tide* | *Low tide* |
|---|---|---|---|---|---|
| 1 | Compensation depth | m | 2.98 | 2.98 | 2.98 |
| 3 | Wave base depth (Zwb) | m | 2.14 | 2.14 | 2.14 |
| 4 | A/V ratio | | 0.19 | 0.24 | 0.15 |
| 5 | Basin permanence index (BPI) | $m^3$ $km^{-1}$ | 4.73 | 2.53 | 5.82 |
| 6 | Dynamic ratio (DR) | m | 3.33 | 4.11 | 2.62 |
| 7 | Debit | $m^3$ $sec^{-1}$ | 0 | 56.5 | 33.75 |
| 8 | Water retention time | day | 5.91 | 6.31 | 5.52 |
| 9 | Flushing time | 1/year | 60.88 | 57.06 | 65.26 |

**Discussion**. Anak Laut Lake is categorized as medium (10 to 100 $km^2$) and shallow (<10m) (Mingazova & Galeeva 2016). The lake has relatively flat bottom conditions with large shallow littoral areas. Waters with large littoral areas have the potential for high biological productivity. This is because littoral areas have rooted plants that contribute to the organic matter at the bottom; decomposed organic matter becomes a source of nutrients for phytoplankton and aquatic plants (Figure 7); and the accumulated layer of organic matter at the bottom of the water will be utilized for benthic growth (Welch 1952; Barroso et al 2014; Muhtadi et al 2020a, 2020c).

Anak Laut Lake is a tropical coastal lake, categorized as a tidal lake in Indonesia. This can be seen from the tidal dynamics that affect the lake water level where the tidal range difference (0.62-1.92 m) is included in the micro-tidal group (< 2 m) (Short 1991). The difference in the tidal range of this lake is not much different than in other coastal lakes, such as in Lagos and Lekki Lagoons (Nigeria), with only 0.30 - 1.30 m (Sayed & Ahmed 2014), Nokoue Lake ranges between 0.15 - 1.25 m (Zandagba et al 2016), in Chilika Lagoon (India) it ranges between 0.52 - 1.02 m in the dry season and 0.36 - 0.81 m in the wet season (Mahanty et al 2016) and some coastal lagoons in the Mediterranean (sub-tropical) have a tidal range of only 0.13 - 0.90 m (Umgiesser et al 2014). However, the difference in tidal range in Siombak Lake (east coast of Sumatra) is quite wide, namely -0.11 - 2.34 m (Muhtadi et al 2020a) and in Laguna Lake (Philippines) ranges between 0.60 - 4.10 m (Herrera et al 2014).

The tidal dynamics that occur in Anak Laut Lake certainly affect the hydro morphometric conditions of the lake. This is seen in the depth and volume of lake water (Figures 1, 2, 3 and Table 1). The depth and volume of the lake change according to the incoming and outgoing water fit to the tidal cycle. These fluctuations will certainly affect the water quality characteristics and biological community structure of Anak Laut Lake.

Therefore, in the future, it is necessary to study the influence of tides on the dynamics of water quality and biological communities in the lake.

**Conclusions**. Anak Laut Lake is an open lake whose waters are influenced by tides from the Indian Ocean. The highest water level (HAT) of Anak Laut Lake is 1.92 m in May 2022. The lowest water level (LAT) was 0.62 m in February 2022. The measured MSL was 1.27 m. The difference in water level results in differences in lake morphometry. This difference in elevation results in differences in lake depth and lake volume. Anak Laut Lake is a shallow lake (depth < 10 m) with an area of 10.55 $km^2$ at mean sea level, 11.26 $km^2$ at high tide, and 9.84 $km^2$ at low tide. This lake is surrounded by mangrove trees as macrophytes that grow on the outskirts of the lake. This lake is prone to mixing because it has a low relative depth (0.03%) and a low A/V ratio (0.15-0.24) and a high wave base depth (> 2 m). In general, Anak Laut Lake is very dynamic with fluctuating condition, following the dynamics of the tidal cycle in the Indian Ocean.

**Acknowledgements**. We thank the Universitas Sumatera Utara for funding this research through the USU Talenta Research scheme, Basic Research Scheme in 2022 with Agreement/Contract Letter Number: 002 / UN5.1.2.3.1 / SPP.TALENTA USU / 2022 dated 1 September 2022. We also thank to the Aquatic Resource Management students in the Merdeka Learning Campus 2022 activity programme. We appreciate Ade Septiya Jumiani Rambe and Arnita Sari Siagian who helped with data processing.

**Conflict of interest**. The authors declare that there is no conflict of interest.

**References**

Barroso G. F., Gonçalves M. A., Da Garcia F. C., 2014 The morphometry of Lake Palmas, a deep natural lake in Brazil. PLoS One 9(11):e111469. https://doi.org/10.1371/journal.pone.0111469.

Cole G. A., Weihe P. E., 2016 Textbook of limnology, 5th ed. Waveland Press, Inc, Illinois (US). 440 pp.

Dietrich G., 1963 General oceanography: an introduction. Interscience Publishers, New York (US). 588 pp.

Elshemy M., Khadr M., Atta, Y., Ahmed A., 2016 Hydrodynamic and water quality modeling of Lake Manzala (Egypt) under data scarcity. Environ. Earth Sci. 75(19):1329. doi: 10.1007/s12665-016-6136-x.

Ganasut J., Weesakul S., Vongvisessomjai S., 2005 Hydrodynamic modeling of Songkhla Lagoono Thailand. Thammasat Int. J. Sc. Tech. 10 (1):32–46.

Håkanson L., 2005a The importance of lake morphometry and catchment characteristics in limnology - Ranking based on statistical analyses. Hydrobiologia 541(1):117–137.

Håkanson, L., 2005b The importance of lake morphometry for the structure and function of lakes. Int. Rev. Hydrobiol. 90(4):433–461.

Håkanson L., 1981 A manual of lake morphometry. Spinger-Verlag, Berlin. 80 pp.

Hasudungan F., Sutaryo D., Giyanto, Sualia I., Wibisono I., Ilman M., Muslihat L., 2008 [Belukar Bay Lagoon Ecosystem]. Wetlands International - Indonesia Programme, Bogor. 111 pp. [In Indonesian].

Herrera E. C., Nadaok K., Blanco A. C., Hernandez E. C., 2014 Hydrodynamic investigation of a shallow tropical lake environment (Laguna Lake, Philippines) and associated implications for eutrophic vulnerability. ASEAN Eng. J. 4(1):48-62.

Kjerfve B., 1994 Coastal lagoons, in: Kjerfve, B. (Ed.), Coastal Lagoon Processes. Elsevier Science, 1–8 pp. https://doi.org/10.2307/634562.

Lukman, Ridwansyah I., 2010 [Study of morphometric conditions and several stratification parameters of Lake Toba waters]. Limnotek Perair. darat Trop. di Indones. 17(2):158–170 [In Indonesian].

Mahanty M. M., Mohanty P. K., Pradhan S., Samal R. N., Ranga Rao V., 2019 Spit and inlet morphodynamics of a tropical coastal lagoon. Mar. Geod. 42(2):130–165.

Mahanty M. M., Mohanty P. K., Pattnaik A. K., Panda U. S., Pradhan S., Samal R. N., 2016 Hydrodynamics, temperature/salinity variability and residence time in the Chilika Lagoon during dry and wet period: measurement and modeling. Cont. Shelf Res. 125:28–43.

Mingazova N. M., Galeeva A. I., 2016 The original method of classification of world lakes based on formulas and results of its application, in: Maghfiroh, M., Dianto, A., Jasalesmana, T., Melati, I., Samir, O., Kurniawan, R. (Eds.), Proceedings of the 16th World Lake Conference. Research Center for Limnology, Indonesian Institute of Sciences, Bali, 491–499 p.

Mitchell S., Boateng I., Couceiro F., 2017 Influence of flushing and other characteristics of coastal lagoons using data from Ghana. Ocean Coast. Manag. 143:26–37.

Muhtadi A., Leidonald R., Yolanda O., Harahap R., Matondang N. P., Putri K., Simamora L. F. M., Sitompul G., 2023a Short communication: the biodiversity of aquatic organisms in Anak Laut Lake, Aceh Singkil District, Indonesia. Biodiversitas 24(9):4837-4844.

Muhtadi A., Yulianda F., Boer M., Krisanti M., Riani E., Leidonald R., Hasani Q., Cordova M. R., 2023b Assessment of pollution status of tropical coastal lakes using modified water quality index (WQI) based on physio-chemical parameters. AACL Bioflux 16(1):356–370.

Muhtadi A., 2022 [Dynamics of tidal lake waters in the perspective of Lake Siombak management]. Disertation. IPB University, Bogor. 127 pp. https://repository.ipb.ac.id/handle/123456789/112405 [In Indonesian].

Muhtadi A., Yulianda F., Boer M.F., Krisanti M., 2022 Spatial distribution management of Crustacea (Decapoda) based on conservation in tropical tidal lake. Biodiversitas J. Biol. Divers., 23 (8): 4064–4072.

Muhtadi A., Yulianda F., Boer M., Krisanti M., Rahmadya A., Sontos, 2020a Hydrodynamics of tropical tidal lake waters Lake Siombak, Medan, Indonesia. AACL Bioflux 13(4):2014–2031.

Muhtadi A., Pulunga A., Maiyah N., Fadhlin A., Melati P., Sinaga R. Z., Uliya R., Rizki M., Ifanda D., Leidonald R., Wahyuningsih H., Hasani Q., 2020b The dynamics of the plankton community on Lake Siombak, a tropical tidal lake in North Sumatra, Indonesia. Biodiversitas J. Biol. Divers. 21(8):3707–3719.

Muhtadi A., Leidonald R., Rahmadya A., Lukman, 2020c Bathymetry and morphometry of Siais Lake, South Tapanuli, North Sumatra Province, Indonesia. AACL Bioflux 13(5):2647–2656.

Muhtadi A., Yunasfi, Ma’rufi M., Rizki, A., 2017 [Morphometry and pollution load capacity of Lake Pondok Lapan in Langkat Regency, North Sumatra]. Oseanologi dan Limnol. di Indones. 2(2):49–63 [In Indonesian].

Nontji A., 2017 [Natural lakes of the archipelago]. Pusat Penelitian Limnologi, LIPI, Cibinong (ID), 285 p. [In Indonesian].

Panda U. S., Mahanty M. M., Ranga Rao V., Patra S., Mishra P., 2015 Hydrodynamics and water quality in Chilika Lagoon - a modelling approach. Procedia Eng. 116:639–646.

Pérez-Ruzafa A., Pérez-Ruzafa I. M., Newton A., Marcos C., 2019 Coastal lagoons: environmental variability, ecosystem complexity, and goods and services uniformity. In: Wolanski E., Day J. W., Elliott M., Ramachandran R. (Eds.), Coasts and Estuaries. 253–276 p.

Ratnayake A. S., Ratnayake N. P., Sampei Y., Vijitha A. V. P., Jayamali S. D., 2018 Seasonal and tidal influence for water quality changes in coastal Bolgoda Lake system, Sri Lanka. J. Coast. Conserv. 22:1191–1199.

Ridoan R., Muhtadi A., Patana P., 2016 [The morphometry of Kelapa Gading Lake in Kisaran City , Asahan District , North Sumatera Province]. Depik 5(2):77–84 [In Indonesian].

Sayed A., Ahmed M., 2014 Hydrodynamic modeling of Lagos and Lekki Lagoons. International Journal of Advanced Biological Research 4(4):416–427.

Short A. D., 1991 Macro-meso tidal beach morphodynamics: an overview. J. Coast. Res. 7(2):417–436.

Tagliapietra D., Sigovini M., Ghirardini A.V., 2009 A review of terms and definitions to categorise estuaries, lagoons and associated environments. Mar. Freshw. Res. 60(6):497–509.
Umgiesser G., Ferrarin C., Cucco A., De Pascalis F., Bellafiore D., Ghezzo M., Bajo M., 2014 Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling. J. Geophys. Res. Ocean. 119(4):2212–2226.
Welch P. S., 1952 Limnology, 2nd. ed. McGraw-Hill Book Company, Inc, New York. 538 pp.
Wetzel R. G., 2001 Limnology. Lake and river ecosystems, 3rd. ed. Academic Press, California. 1024 pp.
Wetzel R. G., Gene E. L., 2000 Lake basin characteristics and morphometry. In: Limnological analyses. Springer, New York. 1-14 p.
Yulianda F., Muhtadi A., Boer M., Krisanti M., Wardiatno Y., 2020 Biological conservation of molluscs based on spatial & temporal distribution in tropical tidal lake, Medan-Indonesia. HAYATI J. Biosci. 27(4):273–282.
Zandagba J., Moussa M., Obada E., Afouda A., 2016 Hydrodynamic modeling of Nokoué Lake in Benin. Hydrology 3(4):1–17. doi: 10.3390/hydrology3040044.
*** Indonesian Earth Shape Map, 2022 www.basemap.big.go.id/rbi [Last accessed on 30 November 2022].

Received: 15 April 2023. Accepted: 22 June 2023. Published online: 30 October 2023.
Authors:
Rusdi Leidonald, Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara, Medan, Indonesia, Jl. Prof A. Sofyan No. 3, Medan, 20155 – Indonesia, e-mail: rusdi.leidonald@usu.ac.id
Ahmad Muhtadi, Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara, Medan, Indonesia, Jl. Prof A. Sofyan No. 3, Medan, 20155 – Indonesia, e-mail: ahmad.muhtadi@usu.ac.id
Zulham Apandy Harahap, Aquatic Resources Management, Faculty of Agriculture, Universitas Sumatera Utara, Medan, Indonesia, Jl. Prof A. Sofyan No. 3, Medan, 20155 – Indonesia, e-mail: zulham.apandy@usu.ac.id

How to cite this article:
Leidonald R., Muhtadi A., Harahap Z. A., 2023 The hydrodynamics of Anak Laut coastal lake, Aceh Singkil Regency, Indonesia. AACL Bioflux 16(5):2856-2867.