

Hydrodynamics of tropical tidal lake waters, Lake Siombak, Medan, Indonesia

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Abstract. Lake Siombak is one of the tidal lakes found in Indonesia. This lake is unique because it is affected by sea tides, 6 km from the coast. This study aims to provide a detailed picture of the hydrodynamic characteristics and profiles of temperature and salinity of the lake Siombak. The primary data collected were tidal data measured every hour for 15 days at the mouth of the lake. The depth measurements were performed using the Garmin 585 echosounder. Measurements of temperature and salinity were conducted using a thermometer and refractometer at depths decreasing by 1 m, perpendicular to the mouth of the lake to the east. The temperature and salinity data were representing the rainy and dry seasons. Tidal measurements at Lake Siombak were diurnal mixed. From the tidal measurement results in Lake Siombak, the highest water level elevation (HAT) obtained was 2.66 m during the rainy season and 2.23 m during the dry season. The lowest water level (LAT) was -0.43 m during the rainy season and -0.04 m during the dry season. Mean Sea Levels (MSL) measured were 1.12 m during the rainy season and 1.1 m during the dry season. The highest water level at full moon or neap tide (HHWL) was 2.34 m during the rainy season and 1.95 m during the dry season, with the lowest water level at full moon (LLWL) of -0.11 m during the rainy season and 0.24 m during drought. This difference in elevation results in differences in lake depth, and other morphometric parameters, but also in temperature and salinity. Thus, there are dynamics and fluctuations in the characteristics of the lake waters on a daily or monthly basis (tidal cycle), and even seasonal fluctuations (rain and dry seasons).

Key Words: bathymetry, coastal lake, Medan, morphometry, water level.

Introduction. A tidal lake is a coastal lake with water conditions influenced by the dynamics of tides. However, in Indonesia, the term is very rare to find because related publications are hardly found, and this type of lake is rare. 'Tidal lake' is another term for a coastal lake or coastal lagoon (Kjerfve 1994; Tagliapietra et al 2010). The coastal lagoon is a lake with waters directly connected to the sea by the effects of tides, waves, rivers, and wind (Kjerfve 1994; Tagliapietra et al 2010). Furthermore, Kjerfve (1994) states that the body of water is connected to the ocean through a narrow door/channel (inlet), which is choked, restricted, and 'leaky'. Thus, the condition of the aquatic environment is very dynamic and fluctuating due to the influence of tidal dynamics (Tagliapietra et al 2010; Muhtadi et al 2017).

Some tidal lakes in the world include Lagoa dos Patos and Lagoa de Araruama, Brazil, Lake St. Lucia, South Africa, the Coorong, Australia, Lake Songkla, Thailand, Laguna de Terminos, Mexico, Pontchartrain Lake, USA, Mississippi Sound, USA, and Wadden Zee, The Netherlands-Denmark (Kjerfve 1994). Some tropical tidal lakes examples are Lake Chilika, India (Mahanty et al 2016), Nokue Lagoon, Benin (Zandagba et al 2016), Teluk Belukar Lagoon (Nias-Indonesia) (Hasudungan et al 2008), and Lake Siombak, in Medan City, North Sumatra Province (Muhtadi et al 2017).

Lake Siombak is a tidal lake located on the coast of Medan City, North Sumatra Province, Indonesia. The lake was formed from the sand dredging construction of the Belawan-Medan-Tanjung Morawa (Belmera) toll road in the late 1980s (Muhtadi et al 2016). This lake is unique because the flow of rivers entering the lake through the Belmera River along 7.5 km from Belawan (Malacca Strait) is still affected by tides. The existence of tidal dynamics certainly affects the dynamics of the lake water level (discharge/volume), water quality (physics and chemistry) (Kjerfve 1994; Elshemy et al 2016; Zandagba et al 2016; Muhtadi et al 2017), and aquatic organisms (flora and fauna) (Jaikumar et al 2011; Reis-Filho et al 2011; Muhtadi et al 2016; Pérez-Ruzafa et al 2019). Therefore, aquatic organisms that inhabit Lake Siombak are unique and distinctive. The uniqueness of Lake Siombak ecosystem can be seen from the presence of mangroves growing on various sides of the lake border, such as Nipah (*Nypa fruticans*), mangrove apple (*Sonneratia caseolaris*), and others, with a total of 14 species (Leidonald et al 2019; Muhtadi et al 2020a). Some aquatic organisms found in Lake Siombak include brackish organisms, such as mullet (*Osteomugil engeli*), striped-nose halfbeak (*Zenarchopterus buffonis*), Indo Pacific tarpon (*Megalops cyprinoides*), rice fish (*Oryzias javanicus*), mudskipper (*Periophthalmonodon schlosseri*), milkfish (*Chanos chanos*), shrimp (*Parapenaeopsis coromandelica*), and mangrove crabs (*Scylla serrata*), while freshwater fish found consist of tilapia (*Oreochromis niloticus* and *Oreochromis mossambicus*), Panchax minnow (*Aplocheilichthys panchax*), catfish (*Clarias bathracus*), snakehead (*Channa striata*), and shortfin eel (*Anguilla bicolor*) (Muhtadi et al 2016; Leidonald et al 2019).

Thus, the uniqueness of the lake has the potential to be developed for fisheries and ecotourism. Therefore, to maintain the preservation of the tidal lake, proper management efforts are needed. In the framework of planning and implementing management strategies, it is necessary to study an understanding of the physical, chemical, geological, and ecological dynamics of the tidal lake (Kjerfve 1994). The study related to water dynamics is the first step in determining appropriate and sustainable management. For this reason, this study aims to describe in detail the characteristics of the dynamics of the waters of Lake Siombak, based on the influence of tides.

Material and Method

Study sites. The research was carried out in Lake Siombak, Medan City, North Sumatra Province, Indonesia (Figure 1). The tools used in this study were GPS Garmin Oregon 65 with an accuracy up to 3 m, Garmin 585 echosounder, and a boat. Tidal data collection was carried out in February 2019 (representing the dry season) and compiled from the results of the study done by Muhtadi et al (2017). Furthermore, temperature, salinity and discharge data were conducted from September 2018 to August 2019.

Data collection and processing. Tidal data retrieval was done by reading the scale on the tide staff submerged in seawater once every hour, within 15 days. The tide staff can reach the highest and lowest tide levels. They were easily observed and still flooded at minimum ebb tides. The tidal staff installation must be perpendicular and unchanging (fixed) (Lisnawati et al 2013).

Lake mapping was done by tracking the edge of the lake using the Global Positioning System (GPS), assisted with digitization from Google Earth. Bathymetry survey was done by measuring depth using an echo sounder placed in the hull of the boat. Mapping was done by making a path that could represent all waters. On this track, depth data were recorded at a distance of 3 m. The measurements were tabulated.

Temperature and salinity are measured from the surface to the bottom of the water at 1 m intervals. Temperature was determined using a thermometer and salinity was measured with a refractometer. Water sampling for temperature and salinity measurements was done using Van Dorn water samples. 9 sampling points of temperature and salinity were established from the west (inlet/outlet) to the east (Figure 1). The water discharge was determined by measuring the current in and out at the inlet/outlet of the lake. The instrument used to measure the current was a flow meter. Flow measurements

were carried out on the surface, middle and bottom of the waters and on the edges and middle of the mouth of the lake.

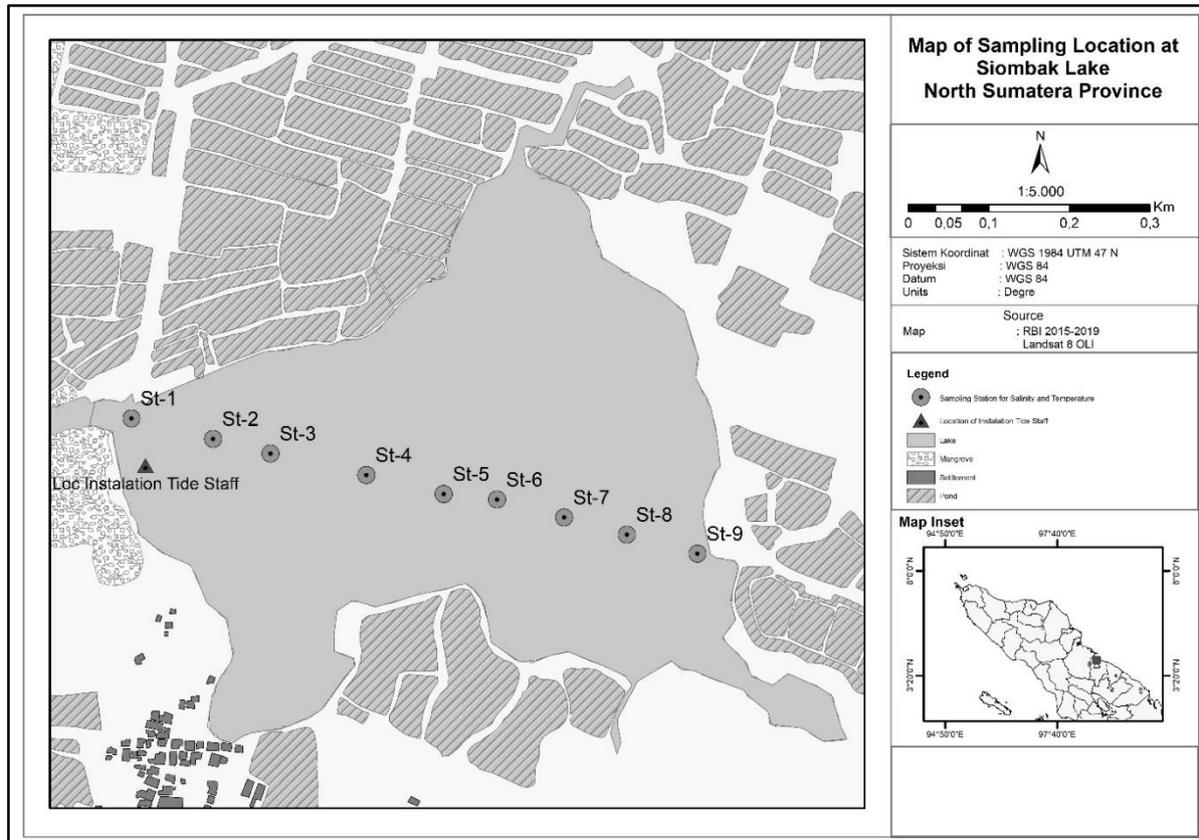


Figure 1. Research Location, Lake Siombak, Medan Indonesia

Data analysis. Data analysis includes tide and water level measurements, bathymetry, morphometry, water discharge and water retention time, spatial and temporal distribution, vertical salinity and temperature.

To find out the type of tides, calculations to obtain the numbers or tidal constants (Tidal Constant/Formzahl) were performed by using the admiralty method formula as follows (Dietrich 1963):

$$F = \frac{AK1 + A01}{AM2 + AS2}$$

Where: F - Formzahl or tidal constants; AK1 - amplitude from the average small single tidal waves affected by moon and sun declination; A01 - amplitude from a small single daily tidal wave affected by solar declination; AM2 - amplitude from the average small double daily tidal wave influenced by the moon; AS2 - amplitude of the average small double daily tidal wave of affected by the sun.

For bathymetry, data rows were represented by measurement stations, while data columns were represented by data identity (ID), time of collection, coordinates, altitude, and water depth. Table data were converted into a spatial form and processed using the ArcMap Geographic Information System (GIS) program equipped with the 3D Analyst extension (Ridoan et al 2016). The basic map used the Indonesian Fine Map of Indonesia from 2018. Furthermore, the analyzed data included lake morphometry representing surface and subsurface (Hakanson 1981).

Lake morphometry was measured following Hakanson (1981), by surface and subsurface dimensions. The surface dimensions consist of: maximum length (L_{max}), expressed in meters and obtained by measuring the farthest distance between two lakeside stations;

the effective maximum length (L_e), expressed in meters and obtained by measuring the farthest distance between two stations on the surface of the lake without crossing the island; the maximum width (W_{max}), expressed in meters and obtained by measuring the distance of the two furthest stations on the edge of the surface of the lake that are drawn perpendicular to L_m ; the maximum effective width (W_e), expressed in meters and obtained by measuring the distance of the two furthest stations on the edge of the lake surface that is drawn perpendicular to L_e ; surface area (A_o), expressed in hectares is the surface area of the lake. The surface area on the bathymetry map is the area of the polygon using the ArcMap program. The shoreline length (SL), expressed in meters or kilometers is the circumference of the lake. SL is measured from a bathymetry map using ArcMap software. The average width (\bar{W}) is expressed in meters, and it is the ratio between the surface area of the lake (A_o) with the maximum length, presented in the following formula:

$$\bar{W} = A_o/L_{max}$$

Where: \bar{W} - average width (m); A_o - lake surface area (m^2); L_{max} - maximum length (m).

The shoreline development index (SDI) is an index illustrating the relationship between SL and surface area. If SDI is higher than 2, then the shape of the water body is irregular. If SDI is between 1 and 2, the shape of the water body is an ellipse (subcircular) and if the SDI is close to 1, it indicates a regular circle shape. The SDI is calculated as follows:

$$SDI = \frac{SL}{\sqrt{\frac{22}{7} \times A_o}}$$

Where: SDI - shoreline development index; SL - the length of coastline (m); A_o - the lake surface area (m^2).

The subsurface dimension values, including the total volume of lake water (V), expressed in m^3 , are represented by the amount of water held by the lake. The volume calculated using the Maximum Depth (Z_{max}) feature expressed in meters is the depth of the lake at the deepest station. Direct measurement was done by echosounder. The average depth (\bar{Z}) is obtained from the average depth measurement in the lake. The relative depth is calculated in terms of the equation:

$$Z_r = \frac{Z_{max} \times \sqrt{n}}{20 \times \sqrt{A_o}} \times 100\%$$

Where: Z_r - relative depth (m); Z_{max} - maximum depth (m); A_o - lake surface area (m^2); n - number of contours.

Average slope (\bar{S}) is expressed in % and describes the extent of shallow water:

$$\bar{S} = \frac{1}{n} \times \left(\frac{1}{2} \times L_o + L_1 + \dots + L_{n-1} + \frac{1}{2} \times L_n \right) \times \frac{Z_{max}}{A_o} \times 100$$

Where: \bar{S} - average slope (%); L - length of the circumference of each contour (m); n - number of contours in the map; Z_{max} - maximum depth (m); A_o - lake surface area (m^2).

The development of lake volume (Volume Development/VD) is a measure that describes the basic shape of a lake in general. If the value is less than 1, the lake has a somewhat conical shape, while if it is higher than 1, the shape is flattened. The development of lake volume is calculated in the form of an equation:

$$VD = \frac{A_o \times \bar{Z}}{\frac{1}{3} \times (Z_{max} \times A_o)}$$

Where: A_0 - lake surface area (m^2); \bar{Z} - average depth (m); Z_{max} - maximum depth (m).

Water discharge (Q) is the volume of water that flows during a specified time interval. Discharge measurements are made at high tide (water in) and at low tide (water out) in the same channel, at a door for water that permits circulation in and from the Waterfall River. Discharge (Q), expressed in $m^3 s^{-1}$, is the volume of water that flows during a specified time interval. Discharge is calculated by the following formula (Wetzel 2001):

$$Q = A \times V$$

Where: Q - water discharge ($m^3 \text{ hour}^{-1}$); A - area of cross section of water channel (m^2); V - current speed ($m s^{-1}$).

Water retention time (Rt), expressed in days, is the retention time of water in a lake. Rt is calculated as follows (Wetzel 2001):

$$Rt = V/Q$$

Where: Rt - water retention time (hours); V - total volume (m^3); Q - water discharge ($m^3 s^{-1}$).

The distribution and dynamics of temperature and salinity are presented in a transverse profile. Temperature and salinity profiles are processed using ODV (Ocean Data View).

Results and Discussion

Tide and water level. Tidal characteristics at Lake Siombak refer to semi diurnal tides in the rainy season (F value=0.21) and mixed, mainly semi diurnal tides in the dry season (F value=0.29). Thus, in the rainy season in Lake Siombak, there are 2 high tides and 2 low tides daily, with relatively the same height. In the dry season the mixture of the 2 types is prominent. Tides in this lake are influenced by the tides of the Pacific Ocean, entering from the South China Sea (Wyrtki 1961) through the Belawan coast.

Tidal measurements in Lake Siombak showed a highest water level elevation (HAT) of 2.66 m when it rains and 2.23 m during the dry season. The lowest water level (LAT) is -0.43 m during rainy season and -0.04 m during dry season. MSL measured is 1.12 m when it rains and 1.1 m during the dry season. The highest water level during full tide or dead moon (HHWL) is 2.34 m during rainy season and 1.95 m during dry season. The lowest water during full tide or dead moon (LLWL) is -0.11 m during rainy season and 0.24 m during drought. Thus, on a daily or monthly basis (tidal cycle), including seasonal elevation, changes occur at Lake Siombak. In detail, the water elevation characteristics at Lake Siombak are presented in Table 1 and a description of the daily dynamics for one tidal cycle are presented in Figure 2.

Table 1

Analysis of important tidal elevations on Lake Siombak

Design water level	Symbol	September (rainy season)		February (dry season)	
		LAT (m)	MSL (m)	LAT (m)	MSL (m)
Highest Astronomical Tide	HAT	2.66	1.54	2.23	1.13
Higher High-Water Level	HHWL	2.34	1.22	1.95	0.86
High Water Spring	HWS	2.19	1.08	1.86	0.76
Mean High Water Spring	MHWS	1.95	0.84	1.73	0.63
Mean High Water Level	MHWL	1.92	0.80	1.68	0.58
Mean Sea Level	MSL	1.12	0.00	1.10	0.00
Mean Low Water Level	MLWL	0.31	-0.80	0.52	-0.58
Mean Low Water Spring	MLWS	0.28	-0.84	0.46	-0.63
Chart Datum Level	CDL	0.04	-1.08	0.33	-0.76
Lower Low Water Level	LLWL	-0.11	-1.22	0.24	-0.86
Lowest Astronomical Tide	LAT	-0.43	-1.54	-0.03	-1.13

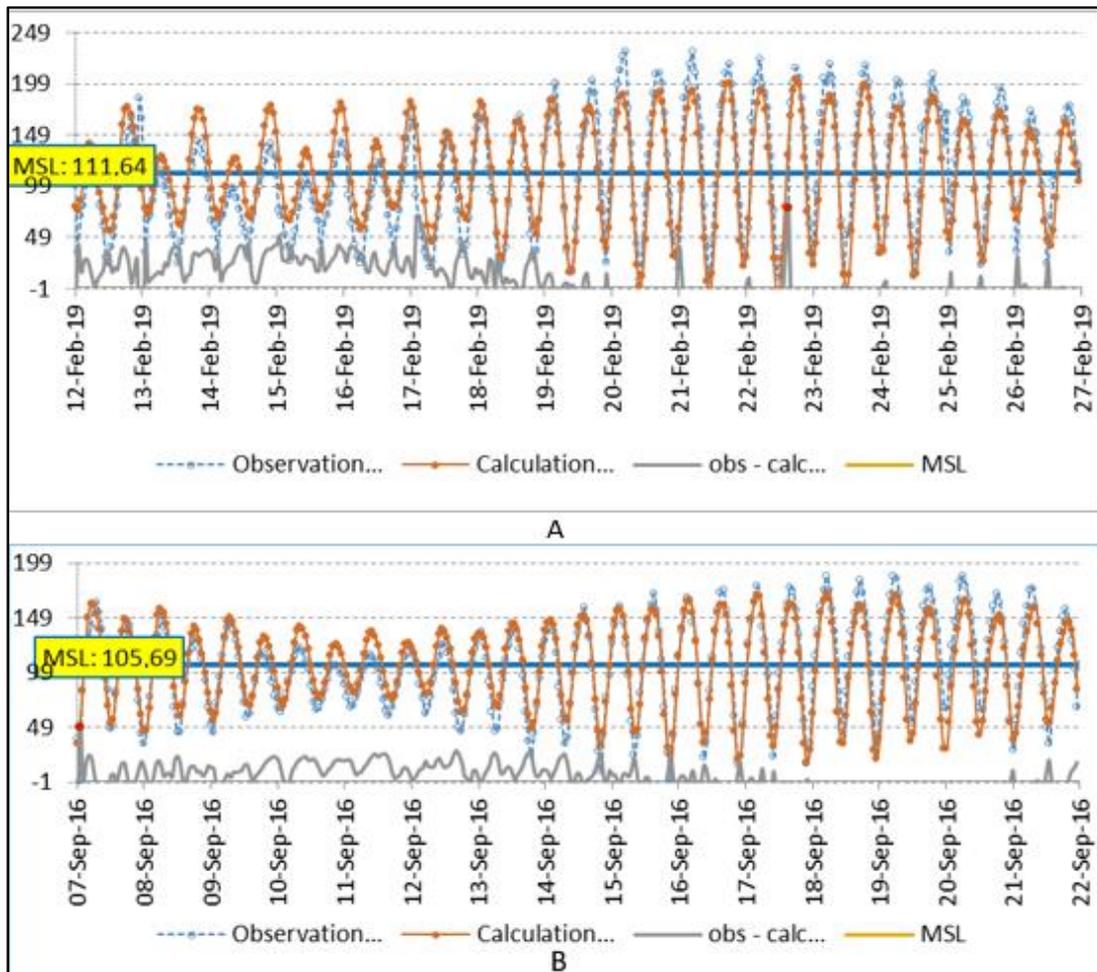


Figure 2. Tides in the study site. MSL - mean sea level; A - dry season; B - rainy season (source: Muhtadi et al 2017).

Bathymetry. Based on the bathymetry map, there are differences in depth in accordance with changes in water elevation. This is clearly due to the tidal dynamics in Lake Siombak. The deepest area is in the middle to the east, and reaches more than 17 m. The innermost locations are marked in dark blue and shallow locations are marked in green (Figures 3, 4, and 5). The shallowest locations (<3 m) are in the southeast and west. In the northern part of the lake, the depth was between 3-6 m, and even reached 6-9 m. In the southwest part, the depth of the lake ranges from 3 to 6 m.

Based on Figures 3, 4 and 5, there is a tidal influence on the bathymetry of the lake at high tide, low tide and MSL. When at high tide, the lowest depth was between 3-6 m. At low tide and MSL, the depth of the lake is lower than at the high tide, ranging between 1-3. Based on the pattern of contour density between high tide, low tide and MSL, the same pattern is in the deep areas in the middle to the east and the shallows in the southeast and west. This can be seen clearly from the increasingly tight contour in the middle to the east. The closer contour lines indicate that the deeper waters reach close from the lake edge (sharp slope), whereas less contour indicates increasingly shallow waters (Ridoan et al 2016). In the southeast and west the contours are clearly seen rarely because at that location is a shallow area with a depth of only up to 3 m.

Based on Figures 3 to 5, the bathymetry of the lake had an irregular pattern. In general, artificial lakes form irregular lake beds (Ridoan et al 2016). This is very different from natural lakes. Moreover, the basic shape of volcanic lakes is regular, a more central location having a bigger depth (Nontji 2017). The irregular shape of the base of Lake Siombak is the impact of lake formation from dredging activities (Muhtadi et al 2016; 2017). In this case the removal of the lake substrate is uneven and tends to be random,

while other coastal natural lakes show a more orderly form of bathymetry (Hasudungan et al 2008; Umgiesser et al 2014; Panda et al 2015; Mahanty et al 2016; Zandagba et al 2016).

Morphometry. Lake Siombak has a surface area of 29.72 ha, with a shoreline reaching 3.67 km (Table 2). This lake has the same L_{max} and L_e at 694.56 m. W_{max} and W_e are also the same, equal to 610.46 m. The average width of Lake Siombak is 427.92 m. Lake Siombak is classified as a very small lake, in an area of less than 100 ha and a volume of less than 10^6 m³ (Straskraba & Tundisi 1999).

Lake Siombak is much smaller compared to other tidal lakes in Indonesia, like Bay of Belukar Lagoon (Nias), which reaches 47.4 Ha (Hasudungan et al 2008). The area of several other tropical tidal lakes include: 1042 km² for Songkhla Lagoon (Ganasut et al 2005); 100 km² for Lake Laguna (Philippines) (Herrera et al 2014); 815 km² during the dry season and 992 km² during the rainy season for Chilika Lagoon (Mohanty et al 2001); 150 km² for Nokoue Lake (Benin) (Zandagba et al 2106). Some other tidal lakes in the Mediterranean region (sub-tropical) are smaller, reaching no more than 500 km² ha, with the Faro Lagoon (Italy) with an area of only 0.26 km² (Umgiesser et al 2014).

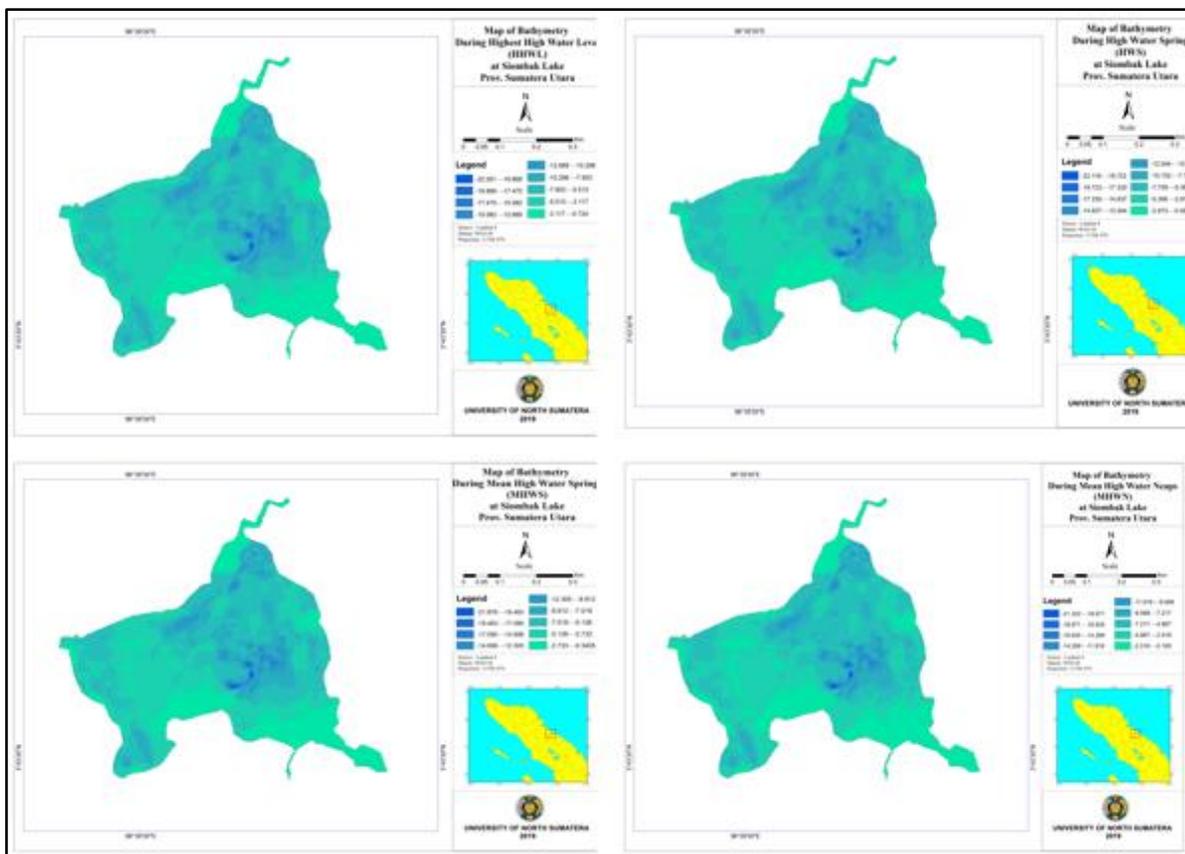


Figure 3. Bathymetry map at high tide.

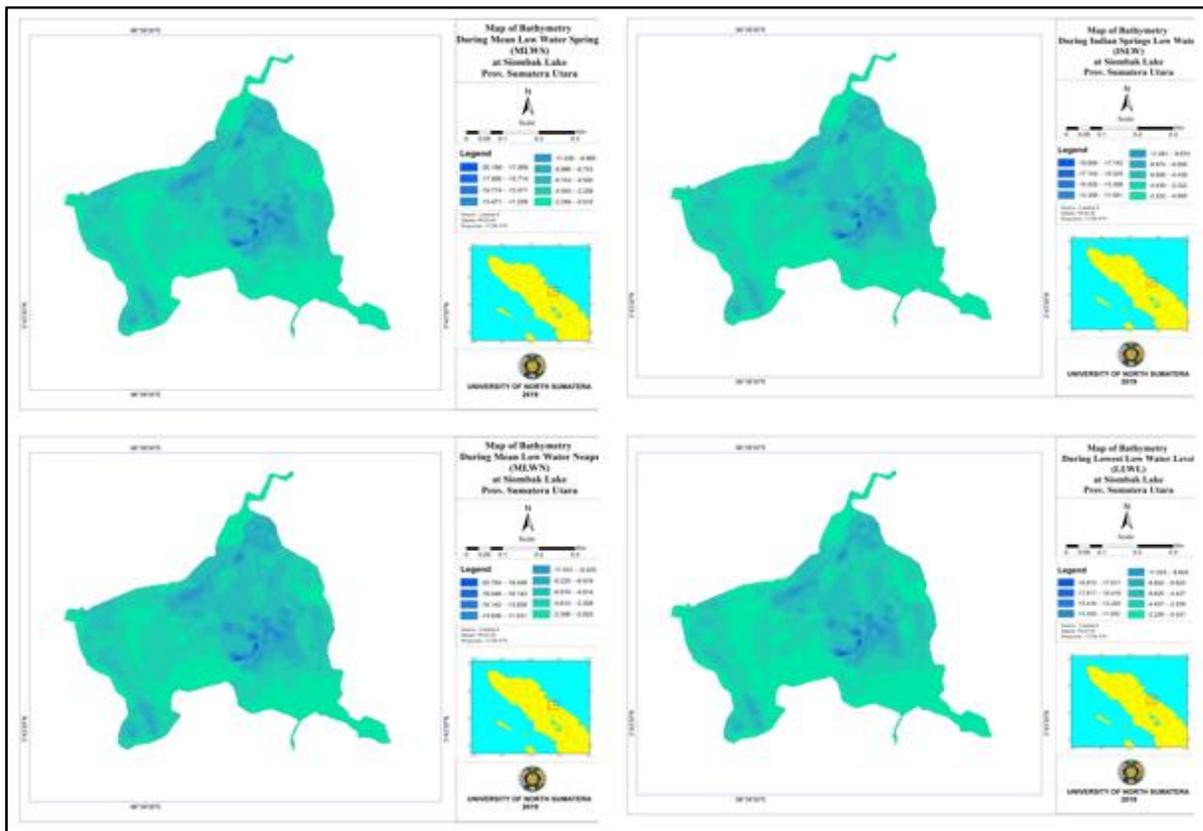


Figure 4. Bathymetry map at low tide.

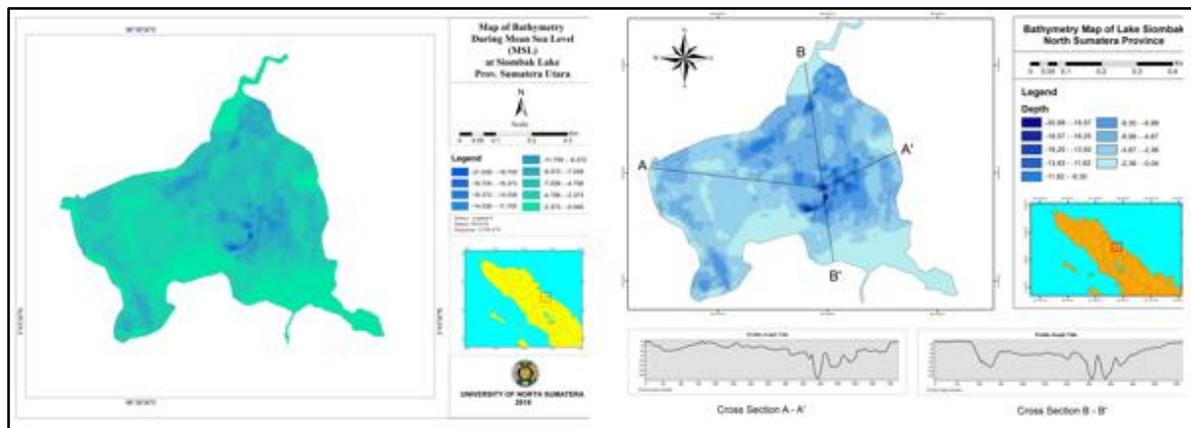


Figure 5. Bathymetry map at mean sea level (left) and cross section of depth profile (right).

The SDI of Lake Siombak is 1.90. This shows that the body shape of Lake Siombak waters approach the regular (ellipse) shape. The SDI value is close to the value in the Teluk Belukar Lagoon, which is 1.6 (Hasudungan et al 2008). The greater SDI value shows the increasingly irregular shape of the lake. The longer is the lake perimeter and the greater the SDI value is, the greater the input received by the lake is. Wetzel (2001) states that SDI can be used to describe the level of productivity of a water. The level of aquatic productivity is closely related to the increasingly irregular shape of the lake. A high SDI value of a lake can indicate a higher lake productivity. The result of the calculation of surface dimensions in the Lake Siombak is presented in Table 2.

Table 2

Surface dimensions of Lake Siombak

<i>Parameters</i>	<i>Unit</i>	<i>Value</i>
Maximum length (L_{\max})	m	694.56
Effective length (L_e)	m	694.56
Maximum width (W_{\max})	m	610.46
Effective width (W_e)	m	610.46
Average width (W)	m	427.92
Shore line development index (SDI)		1.90
Shore line length (SL)	m	3668.68
Cover area (A_0)	m ²	297206.22

Lake Siombak is a shallow lake. The average depth of the lake ranges from 2.96 m to 5.26 m when it rains, and 2.96 m to 4.90 m when it is dry (Tables 3 and 4). However, the maximum depth of Lake Siombak reaches 20.23 m to 22.54 m during the rainy season and 20.36 m to 22.29 m during the dry season. Even though the lake is small and shallow, the depth of Lake Siombak is considered deep compared to other tidal lakes. For example Songkhla Lagoon is only about 1.2-1.8 m deep (Ganasut et al 2005); Lake Laguna (Philippines) is 2.5 m deep (Herrera et al 2014); Chilika Lagoon is 1.7 m deep (Mohanty et al 2001); Lake Nokoue (Benin) is 2.5 m deep (Zandagba et al 2106), while other tidal lakes in the Mediterranean region (sub-tropical) reach a depth of only 0.91-4.84 m, except Faro Lagoon and Taranto (Italy) reaching a depth of 10.75-11.85 m (Umgiesser et al 2014). Therefore, based on tracking various scientific reports, it is indicated that, in general, coastal lakes are shallow, with a depth less than 5 m.

Water discharge and water retention time. Discharge of incoming water (tides) at Lake Siombak is between 18.84 and 67.53 m³ s⁻¹ in the rainy season, and between 34.44 and 43.01 m³ s⁻¹ during the dry season. The flow of water out (ebb) is 15.54-29.31 m³ s⁻¹ when it rains, and 32.6-35.62 m³ s⁻¹ during drought. The flow of water that enters Lake Siombak is affected by tides, so the input of water to Lake Siombak is very dependent on tides. Therefore, the volume of water will depend on tidal conditions in Belawan waters. The volume of Lake Siombak is different between high and low tides (Table 3).

The flow of water that enters and exits Lake Siombak is also affected by the season. In the rainy season, the flow of incoming water is greater than that during the dry season. In addition to the push of tidal water, there is also the influence of a greater river discharge in the rainy season compared to the dry season. However, the discharge of water that comes out in the rainy season is lower than that in the dry season, because the water discharge that comes out of the lake is likely to be obstructed by the large river water discharge in the rainy season.

The retention time of water in Lake Siombak is between 13.37 and 25.22 hours in the rainy season and between 11.00 and 12.03 hours in the dry season. Rt of Lake Siombak is short because of tidal dynamics. Rt in the rainy season is longer than that in the dry season. This is caused by the water discharge that comes out at low tide during the rainy season due to the obstacles of large water discharges (due to rain) in the Falls River. In the dry season, the discharge is higher because the obstacles have diminished (and may no longer exist).

The retention time in Lake Siombak is very much different from natural lakes (inland lake), which can reach years and even decades (Nontji 2017). Lukman & Ridwansyah (2009, 2010) reported that Rt in Lake Poso and Lake Toba were 7.21 years and 81.24 years, respectively. The higher the value of Rt is, the longer the retention time of water in a lake is, so the level of organic matter or nutrients in the water will be greater (Mitchell et al 2017). The Rt of Lake Siombak is considered short because it is affected by tides, so that the opportunity for organic matter to accumulate in Lake Siombak water is only 11 to 25 hours. In addition, the low Rt does not allow the material suspended in the waters to settle. This is also reported by Umgiesser et al (2014), in a coastal lagoon in the Mediterranean Sea with low Rt.

Table 3

Subsurface dimensions of lake Siombak in the rainy and dry seasons

Parameter	Unit	HHWL	HWS	Average depth during elevation						
				MHWS	MHWN	MSL	MLWN	MLWS	ISLW	LLWL
Rainy season										
Mean depth	m	4.37	5.26	5.11	4.87	4.32	4.04	3.75	3.20	2.96
Maximum depth	m	22.68	22.54	22.30	21.74	21.46	21.17	20.62	20.38	20.23
Relative depth	%	0.62	0.62	0.61	0.60	0.59	0.58	0.57	0.56	0.56
Average slope	%	0.39	0.46	0.15	0.75	0.74	0.73	0.71	0.70	0.69
Volume development		0.58	0.70	0.69	0.67	0.60	0.57	0.55	0.47	0.44
Total volume	(x10 ⁶) m ³	1.33	1.60	1.60	1.41	1.33	1.26	1.19	1.00	0.97
Dry season										
Mean depth	m	4.90	4.81	4.68	4.31	4.04	3.78	3.41	2.96	3.19
Maximum depth	m	22.29	22.20	22.07	21.70	1.44	21.17	20.80	20.36	20.58
Relative depth	%	0.61	0.61	0.61	0.60	0.59	0.58	0.57	0.56	0.57
Average slope	%	0.38	0.46	0.15	0.74	0.74	0.73	0.71	0.70	0.71
Volume development		0.66	0.65	0.64	0.60	0.57	0.54	0.49	0.44	0.46
Total volume	(x10 ⁶) m ³	1.41	1.41	1.41	1.33	1.26	1.19	1.05	0.97	1.00

Note: HHWL - highest water level at neap tide; HWS - high water spring; MHWS - mean high water spring; MHWN - mean high water level; MSL - mean sea level; MLWN - mean low water at neap tide; MLWS - mean low water spring; ISLW - Indian spring low water; LLWL - lowest low water level.

Spatial and temporal distribution, vertical salinity and temperature. In the rainy season, the surface salinity value (up to 2 m) ranges from 2 to 7 ppt, while at the bottom it reaches 10 (in depths bigger than 5 m) to 20 ppt (11 m depth). Furthermore, in the dry season, the surface salinity can reach 10-12 ppt and at the bottom it can reach 15-24 ppt. This shows that there is a difference in salinity between the surface and the bottom of the water. Although the coastal lakes are shallow (<5 m), salinity stratification occurs between the surface and the bottom.

The difference in salinity between the surface and the bottom can occur due to seawater intrusion (Pessoa de Barros et al 2014; Medina-Gómez et al 2014) or the trapping of salt water at the bottom of the sediment (Furusato et al 2012). Thus, there is stratification in Siombak Lake between the surface (depth <4 m) and bottom (depth >5 m), making layers difficult to mix. The difference in salinity between the rainy season and the dry season is highly due to the presence of large volumes of freshwater input into the lake (Newton & Mudge 2003; Pessoa de Barros et al 2014; Medina-Gómez et al 2014). Vertical salinity profiles in the Lake Siombak can be seen in Figures 6 and 7.

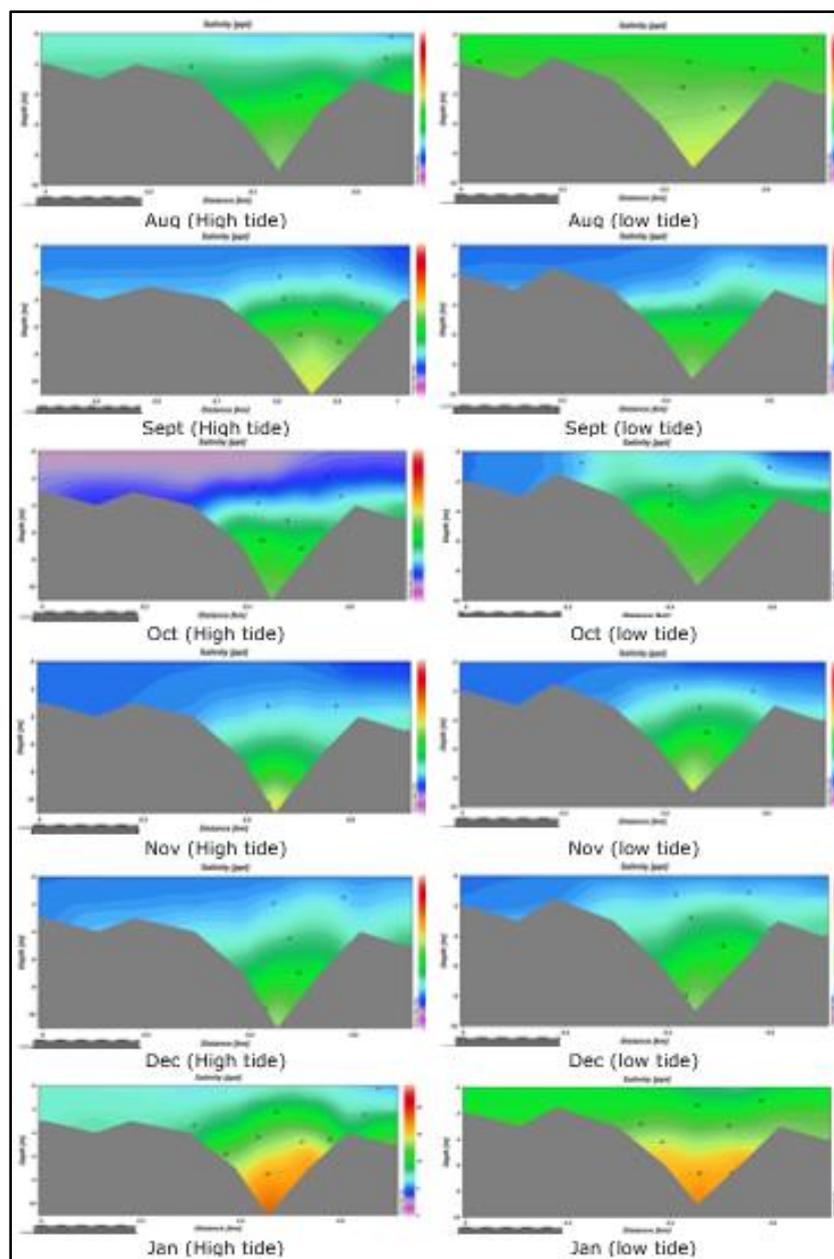


Figure 6. Distribution of salinity in the rainy season.

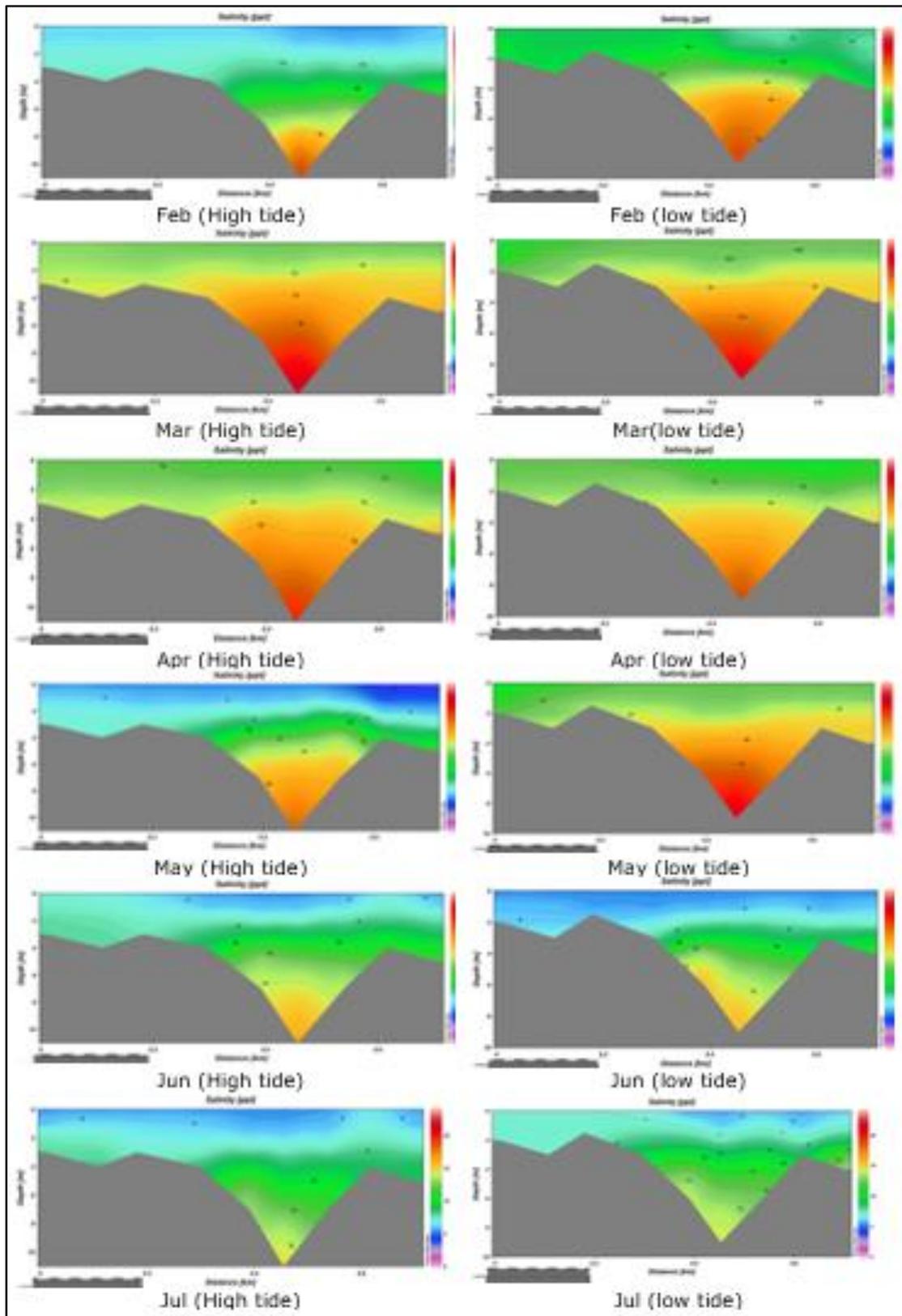


Figure 7. Distribution of salinity in the dry season.

Temperature distribution on the surface of Lake Siombak shows unevenness (Figures 8 and 9). Surface temperature at low tide ranges from 29.1 to 33.2°C, while at high tide the surface temperature ranges between 29 and 33.5°C. The highest temperature at each

station is obtained at the time of measurement in the surface layer of water and occurs when the optimum sunlight is around 12.00 to 14.00 WIB. Consequently, there is no significant difference in surface temperature between high and low tides. The difference in temperature on the surface of the water is highly caused by weather factors and time of measurement. The temperature of a water body is influenced by the season, latitude, altitude from sea level, time of day, cloud cover and water depth (Effendi 2003; Sinaga et al 2016).

More temperature differences occur between the surface and the bottom. The temperature at the bottom of the water, both in high tide and low tide ranges from 28 to 30°C. Thus, there is a 4°C change in temperature between the surface and the bottom of the lake. The low temperature is due to the lower heat content because of lower light intensity as the depth increases (Sinaga et al 2016).

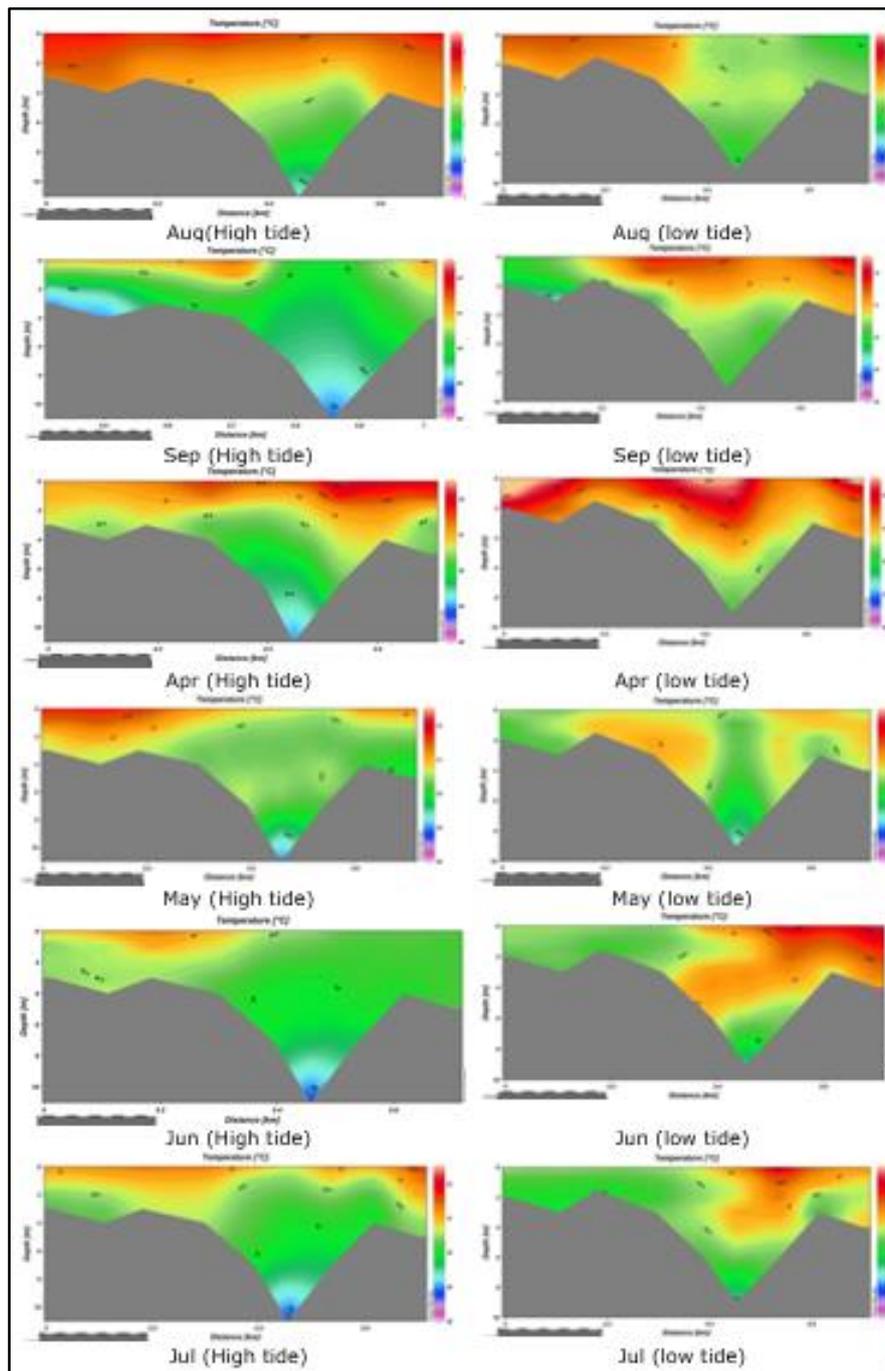


Figure 8. Distribution of temperature during rainy season.

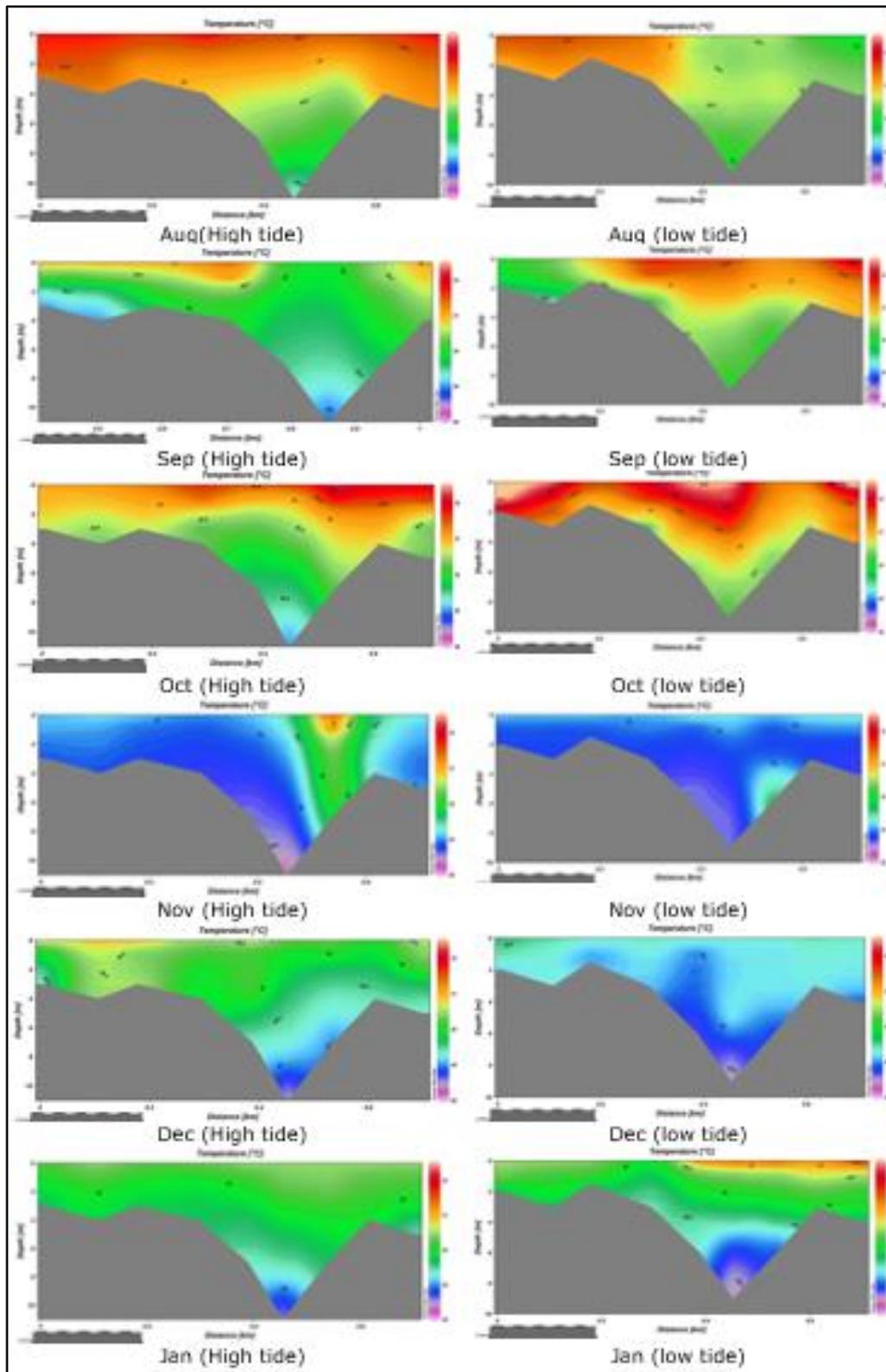


Figure 9. Distribution of temperature in the dry season.

Lake Siombak is one of the tropical tidal lakes in Indonesia. Based on tidal studies, the lake water level elevation is influenced by the tides of Belawan. Tidal elevation differences are high (>2 m), indicating that the lake waters are very dynamic. Referring to Short (1991), the tide in Lake Siombak presents mesotidal characteristics, with tidal ranges of 2-4 m. The elevation difference in Lake Siombak is high (-0.11 to 2.34 m) compared to other tidal

lakes, excepting Lake Laguna (Philippines), which ranges from 0.6 to 4.1 m (Herrera et al 2014). In Lagos and Lekki Lagoons (Nigeria), the difference in elevation is only between 0.3 and 1.3 m (Ahmed 2014), while the elevation in Lake Nokoue ranges between 1.25 m in high tide and 0.15 m in low tide (Zandagba et al 2016). The elevation in Chilika Lagoon (India) ranges from 0.52 to 1.02 m in the dry season and between 0.36 and 0.81 m in the rainy season (Mahanty et al 2016). Ten coastal lagoons in the Mediterranean (sub-tropical) present a tidal range of only 0.13-0.9 m (Umgiesser et al 2014). Thus, the tidal influence is strong in Lake Siombak, even though it is far from the coast (7.5 km).

The difference in elevation is influential on the depth and volume of the lake. The value of the volume development (VD) of Lake Siombak differs between high and low tides, and by season. This shows that tides have an effect on the physical aspects of subsurface dimensions, especially at depth. Likewise, the volume of the lakes will change according to the amount of water entering and exiting. In this case, the volume of Lake Siombak is greater in the rainy season 0.97-1.6 million m³ (MSL=1.33 m³) compared to that in the dry season, of 0.97-1.41 million m³ (MSL=1.26 m³). However, the difference in lake volume can be considered insignificant between rain and drought. This is more due to the dynamics of the waters, especially the elevation of the lake water, which is influenced by the tides, where the elevation of the water level is influenced by the circulation time of the month, and not based on season.

The dynamics of water elevation due to tides also have an impact on water quality, including temperature and salinity. Spatially, the salinity on the surface of Lake Siombak is almost evenly distributed throughout the lake. This indicates that the tidal effect is important, affecting the distribution of salinity in Lake Siombak. However, the distribution of surface temperatures differs spatially based on time of measurement. However, the distribution of temperature and salinity is vertically different between the surface and the base layers. The temperature on the surface is higher than that at the bottom, while the salinity value on the surface is lower than that at the bottom.

Based on temperature stratification in Lake Siombak, there is no thermocline layer. Thus, there is no significant temperature difference between the surface and the bottom of the water. This is due to the low depth of the lake (average depth of 4-6). However, based on salinity stratification, there is a halocline reported at a depth of 5 m. Therefore, there is stratification in Lake Siombak between the surface (depth <4m) and bottom (depth >5 m), making layers difficult to mix. This can be seen from the depth profile (cross section) in Figure 5 (right) showing that not all areas are fully stirred. In the middle (towards the left), the area where the deep waters exist acts like a trough, being not completely stirred. This is clear from the transverse distribution of salinity (Figures 8 and 9), which shows that there is stratification. Thus, the stirring that occurred at Lake Siombak only occurred at a depth of 1-4 m. However, by looking at the deep area (>5 m), narrow in the middle to the east, there is a slight stirring. There is generally low lake stratification, with stirring. This is supported by the low Z_r and Z_r values and data indicating that Lake Siombak has a low level of stability of stratification, so that it will easily experience stirring. A Z_r value less than 2% shows stirring of water mass, characterized by a layer that tends to be homogeneous and decomposition nutrients from the decomposition zone. This will be distributed to the epilimnion layer (Mohanty & Panda 2009). Therefore, the depth of the lake has a very big influence on water quality. This is also related to the presence of stirring in the lake (Newton & Mudge 2003).

Lake Siombak is categorized as a very small lake (<100 ha) and shallow (<10 m) (Straskraba & Tundisi 1999). Lake Siombak has a high biological productivity potential because the epilimnion layer is thicker than the hypolimnion layer. This is supported by the Z_r value below 2% (Tables 3 and 4). This condition is increasingly visible based on bathymetry maps, tending to look at the shape of the relief of a flat bottom of the lake (except the central part to the east). This value illustrates that the waters are relatively flat with large littoral areas. Waters with large littoral areas have high biological productivity potential (Mohanty & Panda 2009; Herrera et al 2014; Elshemy et al 2016). This is due to the fact that the littoral region has rooted plants that contribute to organic matter at the base, decomposed organic material that is a source of nutrients for phytoplankton and aquatic plants, and layers of organic matter in the accumulated water

base, that can be utilized for benthic growth (Welch 1952; Pratiwi et al 2007; Röderstein et al 2014; Specchiulli et al 2016).

The existence of these fluctuations will certainly affect the characteristics of water quality and the biological community structure of Lake Siombak. Therefore, in the future, it is necessary to study the effect of tides on the dynamics of water quality and fish communities in the lake.

Conclusions. Lake Siombak is an open lake with water affected by tides from the sea (Belawan). Tidal measurement results in Lake Siombak showed the highest water level elevation (HAT) of 2.66 m when it rains and 2.23 m during the dry season. The lowest water level (LAT) was -0.43 m during rain and -0.04 m during dry season. MSL measured are 1.12 m when it rains and 1.10 m during the dry season. The highest water level during full tide or dead moon (HHWL) is 2.34 m during rain and 1.95 m during dry season. The lowest water during full tide or dead moon (LLWL) was -0.11 m during rain and 0.24 m during drought. This difference in elevation results in differences in lake depth, and other morphometric parameters, as well as temperature and salinity. Thus, there are dynamics and fluctuations in the characteristics of lake waters on a daily and monthly basis (tidal cycle) and on a seasonal (rain and dry seasons) basis.

Acknowledgements. The authors gratefully acknowledge that the present research is supported by the Ministry of Research and Technology and Higher Education of the Republic of Indonesia. We are for the opportunity given to pursue further study and get awarded a scholarship at IPB University, Bogor Indonesia. Thank you to Ahyar Pulungan, S.Pi for helping me to collect data in the field.

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Received: 11 November 2019. Accepted: 21 January 2020. Published online: 03 August 2020.

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How to cite this article:

Muhtadi A., Yulianda F., Boer M., Krisanti M., Rahmadya A., Santos, 2020 Hydrodynamics of tropical tidal lake waters, Lake Siombak, Medan, Indonesia. *AAFL Bioflux* 13(4):2014-2031.