The Dynamics and Water Quality Status of a Tropical Coastal Lake in Anak Laut Lake, Singkil Indonesia

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Abstract

Anak Laut Lake a tropical coastal lake in Singkil, Aceh Province, is directly connected to the Indian Ocean on the northwestern part of Sumatra Island. The existence of oil palm plantations in the northern part of Lake Anak Laut has the potential to pollute the lake waters. Therefore, this research aims to determine the dynamics of water quality which is influenced by the tidal cycle and the level of pollution of Lake Anak Laut. This research was conducted on March and April 2023. Water sampling was conducted in four (4) times, following the tidal cycle, namely new month, first quarter, full moon, and last quarter. The sampling was also carried out at high and low tides. The method for determining water pollution is the Canadian Council of Ministers of the Environment (CCME) and Pollution Index Method (PI). The results of the research show that the current and water level of Anak Laut Lake varies according to the tidal cycle, so the water quality fluctuates greatly following the tidal cycle. The concentration of organic matter and nutrients as well as Total Coliform showed higher in the last quarter phase where the water entering the lake was very low. The high level of organic matter is caused by 'waste' from palm oil plantation activities located north of Anak Laut Lake. The water quality status of Anak Laut Lake is categorized as marginal-poor based on CCME (score 42-66) and moderate based on PI (score 5-8). In general, water quality conditions are "better" at high tide (new month and full moon) than at low tide (first quarter and last quarter).

Keywords: coastal lagoon, Indian Ocean, pollution, Sumatra, tidal lake

Introduction

There are 5,807 lakes in Indonesia totalling 586,871.64 ha; these are made up of 1,022 natural lakes, 1,314 manmade lakes, and 3,471 undetermined lakes (Dianto *et al*., 2020). The majority of the lakes that LIPI reports are inland or semi-inland lakes; reports of coastal lakes are extremely rare. Coastal lakes are those that are situated near the coast or have a direct connection to the ocean. Seawater intrusion, wind, or tides are the main ways that the ocean affects coastal lakes (Kjerfve, 1994; Tagliapietra *et al*., 2009).

Information and research on coastal lakes remain relatively scarce. However, notable studies have been conducted to address this gap. Muhtadi *et al.* (2016; 2017; 2020), undertook pioneering research on coastal lakes, focusing particularly on Lake Siombak in Medan City, North Sumatra Province. Lake Siombak, an artificial lake resulting from dredging activities associated with the construction of the Belawan-Medan-Tanjung Morawa toll road, served as a primary subject for in-depth analysis. Additionally, Leidonald *et al.* (2023) and Muhtadi *et al.* (2023b), contributed to the body of knowledge through their research on bathymetry and aquatic biodiversity in Lake Anak Laut, situated in Singkil, Aceh Province. Lake Anak Laut is a natural coastal lake located in West Gosong Telaga Village, North Singkil District, Aceh Singkil Regency, Aceh Province. Its direct proximity to the open sea, specifically the Indian Ocean, exposes it directly to the influences of tides and ebbs from the ocean, as highlighted by Leidonald *et al*. (2023).

Anak Laut Lake plays a crucial role in providing various benefits to the surrounding community (Muhtadi *et al*., 2023b). It serves as a significant tourist attraction in both Aceh and North Sumatra provinces, drawing visitors to its scenic beauty and diverse ecosystems. Additionally, the lake supports fisheries activities, serving as a fish landing base and providing areas for floating net cages and fishing grounds. Given that a majority of the local residents rely on fishing for their livelihoods, the lake holds immense economic importance to the community. Moreover, Anak Laut Lake is home to valuable

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mangrove ecosystems and adjacent residential areas, further enhancing its ecological and social significance. However, the presence of multiple human activities around the lake, such as tourism, fisheries, and residential development, can potentially impact water quality through the generation of pollutants and waste.

Considering the substantial benefits associated with activities around Anak Laut Lake, effective lake management is imperative. The initial step involves conducting comprehensive water quality studies to assess the current state and condition of the lake's water resources. Such studies are essential for identifying potential sources of pollution, evaluating ecological health, and formulating strategies for sustainable water resource management. By prioritizing the conservation and preservation of water quality in Anak Laut Lake, stakeholders can ensure the continued provision of benefits to the local community while safeguarding the lake's ecological integrity for future generations.

Materials and Methods

Time and place of research

The research was conducted from March to April 2023 at Anak Laut Lake. Water sampling locations were carried out at 4 different stations in Anak Laut lake (Figure 1.). The sampling was conducted at the research site directly (in situ) and at the Laboratory of the Environmental Health and Disease Control Technical Centre Class I Medan (ex-situ). Water sampling was conducted in four (4) times, following the tidal cycle, namely new month, first quarter, full moon, and last quarter. The sampling was also carried out at high and low tides. There are 14 water quality parameters measured/analyzed in this study (Table 1.).

Data analysis

Water quality data is analyzed specifically and comprehensively with the use of standardized methods. This is done to comply with Government Regulation and is similar to methods used by the Canadian Council of Ministers of the Environment (CCME, 2017) and the Pollution Index method (MoE, 2013).

Result and Discussion

Lake depth and water level

The full moon phase had the highest average depth value, according to the measurements (Table 2.). The high tide that entered the lake was the cause of this. Muhtadi *et al*. (2020) and Leidonald *et al*. (2023), discovered that in coastal lakes, the full moon causes a higher-than-normal tidal wave with extremely high propagation into the lake. Coastal lakes have a wide range of water levels between 2.27 and 2.57 m between the new and full moon phases. In the first and last quarters of the neap tide, the lake's tidal range was 0.17 to 0.27 m. Anak Laut Lake's high tidal elevation (>2 m) suggests that the lake's waters are very dynamic.

According to Short (1991), Anak Laut Lake has meso tidal characteristics, which are similar to those of Lake Siombak (Muhtadi *et al*., 2020). Meso tidal is defined as a tidal range of 2 to 4 m. Compared to other tidal lakes, Anak Laut Lake had a greater tidal range. There was an elevation difference of 0.30 to 1.30 metres between Lagos and Lekki Lagoons in Nigeria (Ahmed, 2014). Lake Nokoue's water level varied from 0.15 m at low tide to 1.25 m at high tide (Zandagba *et al*., 2016). Between 0.52 and 1.02 metres in the dry season and between 0.36 and 0.81 metres in the wet season, Lake Chilika, India, was measured (Mahanty *et al*., 2016). The tidal range of coastal lakes in the Mediterranean (sub-tropical) is only 0.13 to 0.90 m (Umgiesser *et al*., 2014). This demonstrates how the regular impact of coastal tides on Anak Laut Lake, resulting from its close proximity to the Indian Ocean.

Current

The tides have an impact on the currents of Lake Anak Laut. Currents are caused by the inflow and/or outflow of water from the lake as a result of tidal dynamics (Muhtadi *et al*., 2020). As a result, station 1's lake current is higher than other stations' currents (Table 2. and Table 3.). This is because the station is situated in a place that is directly linked to the seawater's entry and outflow into the lake, which is caused by the tides in the Indian Ocean. During the full moon or lunar phase, the current speed reaches its temporary maximum. This is because, under a full moon, high tide raises the water level and increases current compared to neap tide (first quarter and last quarter). Putro and Lee (2020) assert that during full moon tide, the sun and moon align themselves parallel to the earth, maximising their combined gravitational power. This finding is in line with their findings. Due to this, sea levels increase to their maximum point, increasing the speed of current (Rose *et al*., 2022; Turki *et al*., 2023).

Water transparency and turbidity

Spatially, the highest water transparency was found at station 1 (Table 2. and Table 3.).This station's proximity to the open sea and sandy substrate account for its exceptional water

transparency. The lake's seawater enters in a clearer state than the ocean. Station 3 or the area near the mangrove with mud substrate have the lowest water transparency. This station has low water transparency because it is closest to the Gosong River inflow, which causes the water to be severely suspended by silt and sand. This confirms the findings of Muhtadi *et al*. (2020; 2023a), who found that lower sunlight penetration is caused by the influx of silt particles from river flow. Temporally, the highest water transparency values were obtained in the early month phase because there was a large tide in this phase and the measurement time was also when approaching the highest tide. This large tide condition causes maximum mixing and turnover of water with seawater. Muhtadi *et al*. (2020), stated that at high tide the brightness of the waters is higher because at this time the influence of the sea which has high brightness is more influential on the overall condition of the waters.

Particularly during low tide, station 2 or the FLB (Fish Landing Base) area has the maximum turbidity (Tables 2. and 3.). This is due to the fact that station 2 is a ship activity location, and from observations, ship trash, including ship oil, is produced there and ends up in the waterways. The bulk of the people who live near Lake Anak Laut are fishermen, therefore even though the ships are small, there are a lot of them. Ship waste, such as oil and grease, and leftover ship washing water, are two sources of pollution in the port area (Rudiyanto *et al*., 2021). According to the research, there is an oil palm factory nearby, which is the primary reason why the water at station 2 is the murkiest compared to the other stations. As a result, the water turns brown and suspended. High turbidity and low transparency are caused by this industry's enormous discharge ditch, which flows directly into the FLB area, especially during rainy seasons. According to Baird *et al*. (2017), suspended matter has an effect on the clarity and colour of the water. The presence of both dissolved and suspended organic and inorganic elements, such as suspensions from drainage canals that empty into the sea, is what causes turbidity.

Temporally, the high-water level during high tide causes significant stirring, and as the tide recedes, the largest turbidity is found during the full moon (Tables 4. and 5.). According to Van Maren *et al*. (2023) and Turki *et al*. (2023), the creation of seawater circulation patterns and suspended material distribution patterns is significantly influenced by tides that occur in the waters.

Temperature

At stations 1-4, the range of temperature values fluctuated significantly with high and low tides (Table 2. and Table 3.). Since the weather was variable when the samples were taken, this range of results was obtained. The intensity of sunlight acts extremely effectively on the surface layer, causing the temperature of the surface waters to rise during hot weather. Because it is gloomy and rainy during the sample measurement, the average temperature during the full moon phase is lower. This is from Muhtadi *et al*. (2020; 2023a), who claim that fluctuations in the water's temperature show a relationship between the temperature and outside variables like the weather. Sunshine, either directly or indirectly, has a significant impact on temperature. According to Government Regulation, No. 22 of 2021, the temperature of Lake Anak Laut is within normal bounds and is comparatively good, based on direct field measurements of the water's surface temperature.

Total Suspended Solid (TSS)

Station 2 had the greatest TSS during low tide (Table 2.). The source of this TSS is the polluted waste from nearby operations, particularly the garbage from oil palm farms where station 2's waste channel meets it. Effluent from the palm oil sector is typically heated to a high temperature, with a brownish colour, and contains both suspended and dissolved materials, such as oil residues and colloids. The physical state of the water at station 2 is also apparent due to its murky water condition, which increases in proportion to the amount of suspended solids in the water as a result of pollution waste entering the system. This explains why suspended solids and turbidity have a positive correlation, as reported by Muhtadi *et al*. (2023a). Solid industrial waste will settle in the rivers if it cannot dissolve entirely. The station where the suspended materials are taken out of the ocean at high tide has the highest total suspended solids (TSS). The value obtained from the TSS test is 8.67 to 11.67 $mg.L^{-1}$, which is not significantly different from the research conducted in Lake Siombak by Muhtadi *et al*. (2023a). The mass of water that is moved by rivers or land towards the sea brings inorganic items like sand and mud, which is the reason for the high TSS value. Similarly, there are also many biological solids, including microorganisms, and organic compounds made from industrial waste.

According to measurements, station 1 has the greatest TDS value (Table 2. and Table 3.). This is assumed to be the result of salts and minerals in the seawater entering this station, which raise the total dissolved solids measurements. Many chemical components, including sodium (salt), calcium, magnesium, potassium, nitrate, bicarbonate, carbonate, and sulphate, are present in saltwater, contributing to its high TDS value and high salinity. The highest TDS values were obtained during the new

moon and the lowest during the first half-moon phase. This is due to the difference in tides and ebbs that occur, where during the dead moon tides occur high tides. In contrast to the tides in the first half of the month which produce lower tides. Higher tides will carry more suspension substances. This is by Muhtadi *et al*. (2020), which state that there is a minimum tide during the neap tide (namely in the first and second half of the month, while during full moon tide, there will be maximum tides and ebbs

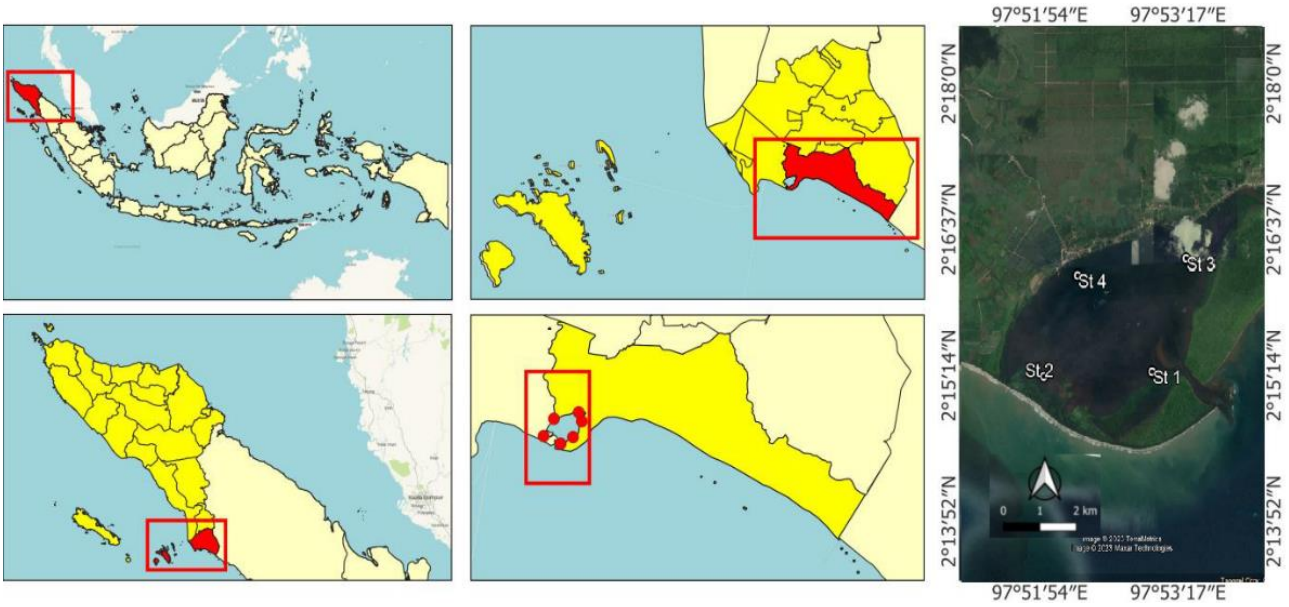

Figure 1. Research location map

Table 1. Water Quality Parameter Measurement Tools

Parameters	Tools	Unit	Description	Methods
Water transparency/ WT	Secci disch	M	In-situ	light refraction in the water column
Turbidity	Turbidity meter	NTU	In-situ	Optical properties due to light dispersion
Temperature	DO meter/ Lutron DO-5510	^{0}C	In-situ	heat sensor on the probe
Total Suspended Solid/TSS	TSS meter	mg. L^{-1}	In-situ	suspended material sensor on the probe
Total Dissolved Solid/ TDS	TDS meter	mg. L^{-1}	In-situ	dissolved material sensor on the probe
Depth	Scale board	M	In-situ	length of rope inserted into the lake
Water level	Nautide app	M	In-situ	tide measurement application
Current	Langrarian	m.s^{-1}	In-situ	release a floating object or drifter into the sea, then measure the distance and time
Salinity	Refractometer (Atago 2493)		In-situ	light refraction in Refractometer
pH	pH meter (Atago DPH-2)	-	In-situ	pH sensor on the probe
Dissolved oxygen/ DO	DO meter/ Lutron DO-5510	^{0}C	In-situ	Oxygen dissolved sensor on the probe
Biological Oxygen Demand/ BOD	Incubation and winkler	mg.L^{-1}	Ex situ	comparison of DO 0 and DO of incubation for 5 days
Chemical Oxygen Demand/ COD	Reflux method	mg.L^{-1}	Ex situ	Amount (ml) of potassium permanganate used to oxidize organic materials
Nitrate/ NO_3	Spectrophotometer (UV-Vis Shimadzu 1240)	mg.L^{-1}	Ex situ	brucine acid method: Reaction of brucine with nitrate will form a yellow compound
Phosphate/ PO_4	Spectrophotometer (UV-Vis Shimadzu 1240)	mg.L^{-1}	Ex situ	ascorbic acid method: formation of a molybdenum blue complex measured at a wavelength of 880 nm
Total Coliform/ TC	MPN (*Most Probable Number*)	MPN. 100mL^{-1}	Ex situ	consists of 3 stages: presumptive test, complementary test, and Gram stain

DO and BOD

The DO concentration in Anak Laut lake at low tide of 5.7 to 6.3 mg L^{-1} and 4.7 to 7.4 mg. L^{-1} at high tide (Table 2. and Table 3.). DO concentration shows lower values at low tide and increases when the water is at high tide. The DO is high during the full moon because, during the full moon, the waters are clearer so the intensity of sunlight is higher. Apart from that, the presence of current causes oxygen to be distributed and diffusion occurs so that oxygen becomes higher (Muhtadi *et al*., 2023a).This condition allows aquatic plants such as seagrass at station 1 to carry out photosynthesis well. The concentration of DO in waters is influenced by water turbulence, temperature, and photosynthetic activity (Sinaga *et al*., 2016; Leidonald *et al*., 2019). Based on DO measurements from the surface to almost the bottom of the water, it is known that the DO concentration is higher at the surface. This condition occurs because the presence of oxygen from the atmosphere is closer to the water's surface. A similar thing also happened in the research of Sinaga *et al*., (2016) and Leidonald *et al*. (2019), which states that the concentration of dissolved oxygen at the surface is higher than at the bottom of the waters.

Anak Laut Lake's DO content is 5.7–6.3 mg L^{-1} at low tide and 4.7–7.4 mg.L^{-1} at high tide (Table 2. and Table 3.). At low tide, the DO concentration is lower, while at high tide, the concentration is higher. Because the waters are clearer and the sun's intensity is stronger under a full moon, the DO is higher. In addition, oxygen diffuses and becomes greater due to the existence of current (Muhtadi *et al*., 2023a). This state facilitates the efficient photosynthesis of water plants, as the seagrass at station 1. Temperature, photosynthetic activity, and water turbulence all affect the concentration of DO in water (Sinaga *et al*., 2016; Leidonald *et al*., 2019). The DO content is known to be higher at the surface based on observations taken from the water's surface to nearly its bottom. Because atmospheric oxygen is more prevalent at the water's surface, this situation arises. A similar finding was made by Sinaga *et al*., (2016) and Leidonald *et al*. (2019), whose research indicates that the concentration of dissolved oxygen in the water is higher at the surface than it is at the bottom.

The presence of organic matter from industrial waste is assumed to be the cause of station 2's highest BOD value. This station furthermore contains residual feed from floating net cages (FNC) used for tilapia and grouper. Station 1 has a low BOD value because it is the furthest away from activities that generate organic matter that pollutes the environment and needs to be broken down by microorganisms. The more organic stuff there is in the water, the higher the BOD number. In contrast, as the water's organic matter content drops, the BOD value will rise (Muhtadi *et al*., 2023a). All observation station's BOD test findings show a direct correlation between the pollution level and test results. The state of contaminated waterways is also high when the BOD value is high. One indicator of waste contamination in a body of water, particularly organic pollution, is BOD (Muhtadi *et al*., 2023a). Tables 4 and 5 demonstrate that BOD values increased over time throughout the last quarter period. Lower tides were the cause of this, and organic materials from the station's waste palm oil intake also entered the lake at the same time.

Degree of Acidity (pH)

Concentration of pH in Anak Laut Lake obtained during the study is still within the normal range and is good for the waters. This is following Government Regulation No. 22 of 2021 that the ideal pH value for water is 7 to 8.5 (Table 2. and Table 3.). Water conditions that are very alkaline or very acidic will endanger the survival of organisms because it will interfere with metabolic processes and respiration. The lowest pH value at station 2 is thought to be due to inputs of pollutants and industrial waste that are acidic will cause a decrease in pH. Leidonald *et al*. (2019), state that organic particles, namely sources of input of organic matter from land that tend to settle in waters, reduce the pH of the water. The low pH value is caused by the process of decomposing organic matter in waste by anaerobic bacteria that produce organic acids.

Nitrate and phosphate

Spatially, nitrate and phosphate were found to be highest at stations 2 and 4 (Table 2. and Table 3.). The high nitrate values at stations 2 and 4 are due to the presence of community and tourism activities that produce domestic and industrial waste into the waters. Station 4, apart from being a tourist area, is also the station closest to residential areas. Nitrate, which is the final oxidation product of ammonium and ammonia from domestic waste, will cause the amount of nitrate to be higher. The phosphate content measured at station 3 is higher than the other stations because in this location there is weathered mangrove litter. These phosphate nutrients come from the decomposition or weathering of mangrove plants. The natural source of phosphate in waters is the decomposition of organic matter and weathering processes (Pérez-Ruzafa *et al*., 2019). Sources of nitrogen and phosphate can also come from "disposal" waste from palm oil plantations with intensive fertilization. Temporally, during high tide, nitrate and phosphate were found to be highest during the last quarter, each with a value of 5.4 mg.

L^{-1} and 0.6 mg. L^{-1} (Table 4. and Table 5.). At low tide, the highest concentration of nitrate is in the new moon phase, namely 4.95 mg.L^{-1} and phosphate in the full moon phase, namely 0.04 mg.L^{-1} (Table 4. and Table 5.).

Salinity

Based on the salinity values obtained, the highest value is found at station 1 followed by stations 2, 4, and 3 (Table 2. and Table 3.). These results show that the more towards the land or river the salinity value will decrease since the salinity value is influenced by the occurrence of high and low tides in the waters. The closer to the sea the salt content will be higher. Muhtadi *et al*. (2020), stated that the area that is strongly influenced by the tidal cycle is the area closest to the sea. This means that the further away from the sea area the salinity will also decrease. The low salinity value at station 3 is due to the area most mixed by fresh water from the river. If station 1 is in the saline or salty category, then station 3 is in the brackish category. The low salinity value is due to mixing with fresh water carried by the river flow. In addition, 2 salinity measurements at this station during rainy weather. This rainwater can reduce salinity because it causes dilution of salt levels in the waters. The high and low values of salinity are influenced by rainfall (precipitation) (Muhtadi *et al*., 2020; 2023a). Temporally, it shows that the salinity value is higher in the new moon and full month compared to the first quarter and last quarter (Table 4 and Table 5). This is caused by the high tidal force entering the lake in the new moon and full moon.

Total coliform

The highest range of total coliform values was at station 4 (Table 2. dan Table 3.). This was due to the presence of livestock, namely warm-blooded mammals such as buffaloes and goats. These livestock produce faeces around the lake. The next highest coliform value was at station 3. This station is an area closer to the river where there is a disposal booth. This is one of the sources of biological pollutants. Coliform bacteria that may be present in water contaminated with human or animal faeces. The low coliform value at station 1 is not only because the station is farthest from land but also because of its high salinity value. The low value of coliform bacteria in coastal areas around the sea is due to the small amount of waste that enters the waters through existing rivers or coliform cannot survive for long due to high salinity (>30 ppt). It was also explained that coliform in high-salinity water can only survive a few hours (Glory and Takarina, 2020).

The most consistent aspects of the water quality in the waters of Anak Laut Lake during high and low tide are temperature, DO, and pH. Tropical regions typically see rather steady temperatures with little variation. According to Odum & Barret (2005), brackish waters have a pH that is generally constant, ranging from 7 to 8.5. However, the DO concentration in the 5–6 range is very steady. This suggests that there is a buffer provided by the coastal lake waters. According to Muhtadi *et al*. (2023a), stable water quality parameters in tropical lake waters include temperature, DO, and pH. Other tropical coastal lakes have stable amounts of pH, DO, and temperature (Barik *et al*., 2017; Sajinkumar *et al*., 2017; Ratnayake *et al*., 2018). In contrast, temperature, DO, and PH concentrations in sub-tropical lakes are more erratic (Elshemy *et al*., 2016; Jamila *et al*., 2016; Bhattrai *et al*., 2017; Raposo *et al*., 2018). In the meantime, there are significant temporal and regional variations in other water quality metrics. Muhtadi *et al.* (2023a), also discovered that Siombak Lake's water quality varies significantly in terms of TDS, TSS, salinity, organic matter, and nutrients.

Table 2. Spatial water quality conditions at high tide in Anak Laut Lake

Water Quality Parameters	Station			
	Station 1	Station 2	Station 3	Station 4
WT (m)	4.8	1.6	0.8	1.6
Turbidity (NTU)	0.97	6.44	3.64	2.87
Temperature (°C)	30.3	30.1	30.3	30.5
TSS (mg.L^{-1})	8	9.5	8	8.25
TDS (mg.L^{-1})	9,809	9,550	4,071	9,262
Depth (m)	6.1	3.9	1.7	3.0
Current (m.s^{-1})	0.13	0.09	0.09	0.08
DO (mg.L^{-1})	5.8	5.3	5.6	5.5
pH	8.2	8.1	8.0	8.1
BOD (mg.L^{-1})	4.7	6.2	5.9	4.9
NO_3 (mg.L^{-1})	1.0	3.9	2.5	3.2
PO_4 (mg.L^{-1})	0.05	0.09	0.39	0.19
Salinity (ppt)	32.3	30.2	27.8	29.2
TC (MPN.100mL^{-1})	31	158	259	432

Table 3. Spatial water quality conditions at low tide in Anak Laut Lake

Water Quality Parameters	Station			
	Station 1	Station 2	Station 3	Station 4
WT (m)	3.3	1.0	0.6	1.2
Turbidity (NTU)	2.2	8.8	6.9	4.1
Temperature (ºC)	30.9	31.2	30.5	30.7
TSS (mg.L^{-1})	7.8	9.8	9.5	7.5
TDS (mg.L^{-1})	8,168	8,370	3,443	8,441
Depth (m)	4	3	1	2
Current (m.s^{-1})	0.09	0.07	0.04	0.05
DO (mg.L^{-1})	5.6	5.2	5.4	5.3
pH	8.0	7.8	8.0	8.0
BOD (mg.L^{-1})	5.5	8.1	6.1	5.8
NO_3 (mg.L^{-1})	1.5	5.2	2.4	3.0
PO_4 (mg.L^{-1})	0.03	0.05	0.02	0.03
Salinity (ppt)	30.4	29.0	26.5	28.3
TC (MPN.100mL^{-1})	23	245	415	446

Table 4. Temporal water quality conditions at high tide in Anak Laut Lake

Water Quality Parameters	Tide Phase			
	New Moon	First Quarter	Full Moon	Last Quarter
WT (m)	2.6	1.9	2.1	2.3
Turbidity (NTU)	3.92	3.77	4.31	1.92
Temperature (ºC)	31.3	30.6	29.8	29.5
TSS (mg.L^{-1})	10.75	8.50	6.25	8.25
TDS (mg.L^{-1})	8,589.00	7,616.00	8,108.50	8,377.50
Depth (m)	3.9	3.5	3.1	3.9
Current (m.s^{-1})	0.12	0.07	0.16	0.15
DO (mg.L^{-1})	5.5	5.5	5.5	5.6
pH	8.3	8.0	8.1	8.0
BOD (mg.L^{-1})	9.4	3.9	4.0	4.5
NO_3 (mg.L^{-1})	3.3	0.9	1.2	5.4
PO_4 (mg.L^{-1})	0.1	0.1	0.0	0.6
Salinity (ppt)	31	29	30	29
TC (MPN.100mL^{-1})	70	14	777	18

Overall, the study's findings indicate that, with the exception of the nitrate and phosphate parameters in every measurement, Lake Anak Laut's waters remain within normal bounds. Nonetheless, according to government rule number 22 of 2021, the metrics for turbidity, BOD, and total coliform on a number of measurements have met the quality norms. Generally speaking, though, the water quality is still appropriate for supporting aquatic biota. This is also evident from the abundance of aquatic life that is present in the lake. Anak Laut Lake is home to at least 165 species and genera of aquatic biota, according to Muhtadi *et al*. (2023b). Nine species of mangroves, two species of seagrass, fifty-five species of fish, three species of prawns, ten species of crab, thirteen species of clams, twelve gastropods, three sea cucumbers, two sand dollars, two horseshoe crabs and one sea urchin make up these aquatic animals.

Lake pollution status

Based on the calculation of the CCME method and the pollution index, the water quality status of Anak Laut Lake was found to be marginal to poor. Marginal conditions indicate that water quality is often threatened and disturbed, and conditions often deviate from natural and desired levels. Poor conditions mean that water quality is almost always threatened and impaired, conditions usually deviate

from natural and desirable levels (CCME, 2017). Based on the calculation, nitrate and phosphate are parameters that exceed the quality standard value at all observation stations. The high values of nitrate and phosphate at each station are due to pollutant waste from community, industrial, and ship activities, especially stations 2-4 which are closer to land. The high levels of nitrate and phosphate in the waters are thought to be contributions of nutrients from anthropogenic discharges from various human activities such as households, settlements, and livestock that enter the waters (Perez-Ruzafa *et al*., 2019). This is also the cause of station 2 with the lowest water quality score and station 1 which is close to the sea or further from the source of polluting waste having the highest water quality score.

Spatially, station 1 is "better" than the other stations (Figure 2.). This is due to station 1 being closer to the sea where station 1 directly experiences "washing" or dilution by seawater. Station 2, which is located in the form of a bay and is a "channel" for discharges from oil palm plantations, allows organic wastes to be "trapped at station 2. This is as shown by Muhtadi *et al*. (2023a), where at the inlet/outlet stations of coastal lakes the water conditions are "better" than other stations. Based on calculations with CCME and PI methods temporally, it is known that the lowest score is obtained during the dead moon phase (first quarter and last quarter). The high pollution during the dead moon is due to low tidal conditions so that organic matter trapped in the lake is decomposed. Indeed, tidal water with high discharge from the ocean is a good "wash" for coastal lake waters (Muhtadi *et al*., 2023a).

Based on the scores, the methods with the highest to lowest order of sensitivity are the CCME and PI methods. The CCME method is considered the most appropriate method for analyzing water quality with a higher level of effectiveness and sensitivity. Uddin *et al*. (2021), who conducted a study on the use of the CCME method and other methods including the PI method to determine the status of water quality stated that the CCME method most sensitively responds to water quality dynamics at each monitoring location with few and many parameters, with or without biological parameters. Based on observations and results of parameter analyses, the method for calculating water quality status that is closest to the actual conditions at the research site is the CCME method. The CCME method is more complex because it takes into account the magnitude of the measured and tested values of each parameter that exceeds the quality standards and the difference in results that exceed the quality standards contained in CCME (2017), in contrast to the PI method with simpler calculations using average and maximum values. In addition, the use of the type and number of parameters in the CCME method is also quite flexible and depends on the local conditions of the waters.

Both spatially and temporally, the quality status of Anak Laut Lake shows that water conditions at high tide are "better" than at low tide (Figure 2.). This is because, at high tide, the water discharge into the lake is 'fresh' and clean water brought in from the sea, and at low tide is water that has been brought in from surrounding waters such as oil palm plantations. The difference in conditions is caused by the tidal water dynamics factor (water flow/discharge) which is

Table 5. Temporal water quality conditions at low tide in Anak Laut Lake

Water Quality Parameters	Tide Phase			
	New Moon	First Quarter	Full Moon	Last Quarter
WT (m)	1.5	1.4	1.4	1.7
Turbidity (NTU)	5.28	5.91	7.22	3.67
Temperature (ºC)	30.4	31.9	30.3	30.7
TSS ($mg.L^{-1}$)	10.25	8.25	7.75	8.25
TDS ($mg.L^{-1}$)	7,592.00	6,427.25	6,981.75	7,421.25
Depth (m)	2.1	2.9	2.3	2.8
Current ($m.s^{-1}$)	0.06	0.03	0.08	0.07
DO ($mg.L^{-1}$)	5.4	5.3	5.5	5.3
pH	8.2	7.8	7.9	7.9
BOD ($mg.L^{-1}$)	11.4	4.8	4.3	5.0
NO_3 ($mg.L^{-1}$)	4.95	2.38	1.30	3.38
PO_4 ($mg.L^{-1}$)	0.03	0.03	0.04	0.03
Salinity (ppt)	29.8	27.4	29.5	27.5
TC ($MPN.100mL^{-1}$)	27	19	1.065	18

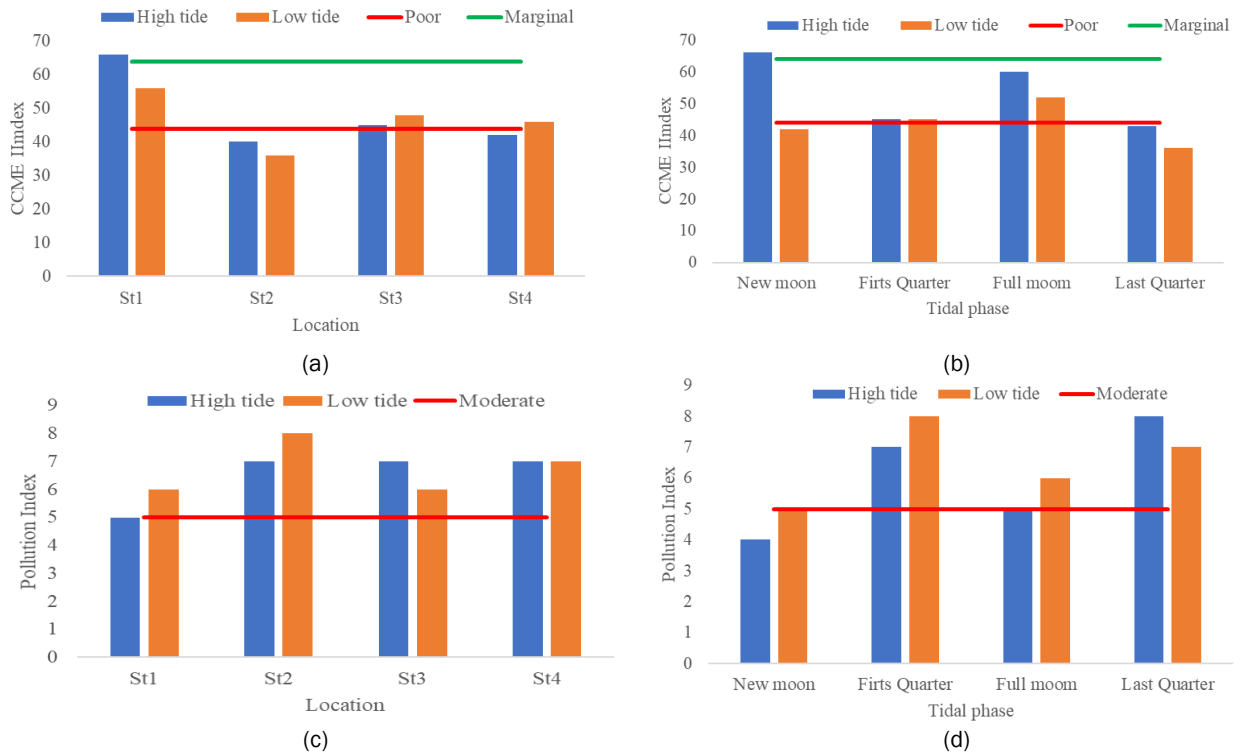

Figure 2. Calculation results of pollution status in Anak Laut Lake: a) CCME method at high tide, b) CCME method at low tide, c) PI method at high tide, and d) PI method at low tide.

one of the factors determining the condition of the waters in Lake Anak laut (Leidonald *et al*., 2023). This is the same as that obtained by Muhtadi *et al*. (2023a), that high tide conditions are better than low tide. The water quality condition in Anak Laut Lake is similar to Siombak Lake in the less to poorly polluted category. Meanwhile, the pollution status in other coastal lakes is moderate to well polluted in Akkulam-Veli coastal lake (Sheela *et al*., 2012) and Lake Nokoue (Zandagba *et al*., 2016). Greek lakes in Italy also show good condition (Christia *et al*., 2014).

Conclusion

Water quality fluctuates greatly following the tidal cycle. The concentration of organic matter (BOD) and nutrients (NO_3 and PO_4) as well as Total Coliform showed higher in the last quarter phase where the water entering the lake was very low. The water quality status of Anak Laut Lake is categorized as marginal-poor based on CCME (score 42-66) and moderate based on PI (score 5-8). In general, water quality conditions are "better" at high tide (new month and full moon) than at low tide (first quarter and last quarter). In actuality, Anak Laut Lake's pollution status is applicable throughout the dry season; therefore, more research is required to ascertain the pollution status during the wet season. Government intervention is required for oil palm plantations to plug the channel and reroute the Singkil River in order to prevent pollution of this lake.

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References

Ahmed, A.S.M. 2014. Hydrodynamic Modeling of Lagos and Lekki Lagoons. *Int. J. Adv. Biol. Biomed. Res.,* 4(4): 416–427.

Baird, R.B., Eaton, A.D. & Rice, E.W. 2017. Standard Methods for The Examination of Water and Wastewater. Washington, D.C.: American Public Health Association.

Barik, S.K., Muduli, P.R., Mohanty, B., Behera, A.T., Mallick, S., Das, A., Samal, R.N., Rastogi, G. & Pattnaik, A.K. 2017. Spatio-temporal variability and the impact of Phailin on water quality of Chilika lagoon. *Cont. Shelf Res.,* 136: 39–56. http://doi.org/10.1016/j.csr.2017.01.019

Bhattrai B.D., Kwak S., Choi K. & Heo W. 2017. Long-term changes of Physicochemical Water Quality

in Lake Youngrang, Korea. *Korean J. Ecol. Environ.,* 50(1): 169-185. https://doi.org/10.11614/KSL .2017.50.1.169

[CCME] Canadian Council of Ministers of the Environment. 2017. Canadian Water Quality Guidelines for the Protection of Aquatic Life: CCME Water Quality Index, User's Manual—2017 Update. In Canadian Environmental Quality Guidelines, 1999; Canadian Council of Ministers of the Environment: Winnipeg, MB, Canada, 2017. Available online: https://ccme.ca/en/res/wqimanualen.pdf (accessed on 10 June 2023)

Christia, C., Giordani, G. & Papastergiadou E. 2014. Assessment of ecological quality of coastal lagoons with a combination of phytobenthic and water quality indices. *Mar. Pollut. Bull*., 86(1–2): 411–423. https://doi.org/10.1016/j.marpolbul.2014.06.038

Dianto, A., Afandi, A.Y., Zahid, A., Rahmadya, A., Sunaryani, A., Rohaningsih, D., Verawati, D., Daruati, D., Ali, F., Rustini, H.A., Wibowo, H., Ridwansyah, I., Subehi, L., Anwar, M., Novianti, R., Oktaviani, T.S. & Sudriani, Y. 2020. Identification of Indonesian Lakes in Indonesia. Limnology Research Centre LIPI, Cibinong. (Indonesian version)

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: 1-13. https://doi.org/10.1007/s12665-016-6136-x

[GR] Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management

Glory, E. & Takarina, N.D. 2020.Preliminary Detection of Coliform Bacteria and Zink (Zn) Pollution in Blanakan River Estuary, Subang, West Java. *IOP Conf. Ser. Earth Environ. Sci*., 550(1): p.012031. https://doi.org/10.1088/ 1755-1315/550/1/012031

Jamila, H., Mouldi, B. & Moncef, G. 2016. Assessment of the Water Quality of Bizerte Lagoon of Tunisia by Use of Statistical Analyses. *Hydrol. Current Res.,* 7(2): 237. https://doi.org /10.4172/2157-7587.1000237

Kjerfve, B. 1994. Coastal lagoon processes. *Eleseiver Oceanogr. Ser*., 60: 1-8. https://doi.org/10.1016/S0422-9894(08)70006-0

Leidonald, R., Muhtadi, A., Lesmana, I., Harahap, Z.A. & Rahmadya, A. 2019. Profiles of temperature, salinity, dissolved oxygen, and pH in Tidal Lakes. *IOP Conf. Ser. Earth Environ. Sci*., 260(1): p.012075. https://doi.org/10.1088/1755-1315/260/1/012075

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.

Mahanty, M.M., Mohanty, P.K., Pattnaik, A.K., Panda, U.S., Pradhan, S. & Samal, R.N. 2016. Hydrodynamics, temperature/salinity variability and retention time in the Chilika lagoon during dry and wet period: measurement and modelling. *Cont. Shelf Res.,* 125: 28-43. https://doi.org/ 10.1016/j.csr.2016.06.017

[MoE] Ministry of Environmental. 2003. Guidelines for Determining Water Quality Status. Indonesia: State Minister of Environment

Muhtadi, A., Yunasfi,R.L., Sandy, S.D., Junaidy, A. & Daulay, A.T. 2016. Limnological status of Lake Siombak, Medan, North Sumatra. *Oseanologi dan Limnologi Di Indonesia,* 1(1): 39-55.

Muhtadi, A., Harahap, Z.A. & Leidonald, R. 2017. Morphometry dynamical of Siombak Lake, Medan Indonesia. *Omni – Akuatika,* 13(2): 48-56. http://doi.org/10.20884/1.oa.2017.13.2.174

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

Muhtadi, A., Yulianda, F., Boer, M., Krisanti, M., Riani, E., Leidonald, R., Hasani, Q. & Cordova, M.R. 2023a. 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., Leidonald, R., Yolanda, O., Harahap, R., Matondang, N.P., Putri, K., Simamora, L.F.M. & Sitompul, G. 2023b. Short communication: the biodiversity of aquatic organisms in Anak Laut Lake, Aceh Singkil District, Indonesia. *Biodiversitas*, 24(9): 4837-4844. https://doi.org/10.13057/biodiv/d240925

Odum, E.P. & Barrett, G.W. 2005. Fundamentals of Ecology (5th ed.). Brooks/Cole Publishing Co, USA

Pérez-Ruzafa, A., Campillo, S., Fernández-Palacios, J.M., García-Lacunza, A., García-Oliva, M., Ibañez, H., Navarro-Martínez, P.C., Pérez-Marcos, M., Pérez-Ruzafa, I.M., Quispe-Becerra, J.I., Sala-Mirete, A., Sánchez, O. & Marcos C. 2019. Long-term dynamic in nutrients, chlorophyll a, and water quality parameters in a coastal lagoon during a process of eutrophication for decades, a sudden break and a relatively rapid recovery. *Front. Mar. Sci.,* 6: 26. https://doi.org/10.3389/fmars.2019.00 026

Putro, A.H.S. & Lee J.L. 2020. Analysis of Longshore Drift Patterns on the Littoral System of Nusa Dua Beach in Bali, Indonesia. *J. Mar. Sci. Eng.,* 8(10): 749. https://doi.org/10.3390/jmse8100749

Raposo, D., Clemente, I., Figueiredo, M., Vilar, A., Lorini, M.L., Frontalini, F., Martins, V., Belart, P., Fontana, L., Habib, R. & Laut, L. 2018. Benthic foraminiferal and organic matter compounds as proxies of environmental quality in a tropical coastal lagoon: The Itaipu lagoon (Brazil). *Mar. Pollut. Bull.*, 129(1): 114–125. https://doi.org/10.1016/j.marpolbul.2018.02.018

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(6): 1191–1199. https://doi.org/10.1007/s11852-018-0628-7

Rose, L., Rohith, B. & Bhaskaran, P.K. 2022. Amplification of regional tides in response to sea level. *Ocean Eng.,* 266: 112691. https://doi.org/10.1016/j.oceaneng.2022.112691

Rudiyanto, G.F., Kurnianto, F.A., Pangastuti, E.I. & Nurdin, E.A. 2021. Sea Water Quality Analysis at Muncar Fishing Port, Banyuwangi Regency, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.,* 975(1): 012007. https://doi.org/10.1088/1755-1315/975/1/012007

Sajinkumar, K.S., Revathy, A. & Rani, V.R., 2017. Hydrogeochemistry and spatio-temporal changes of a tropical coastal wetland system: Veli-Akkulam Lake, Thiruvananthapuram, India. *Appl. Water Sci*., 7: 1521–1534. https://doi.org/10.1007/s13201-015-0333-8

Sheela, A.M., Letha, J., Joseph, S., Chacko, M., Sanal, K.S.P. & Thomas, J. 2012. Water quality assessment of a tropical coastal lake system using multivariate cluster, principal component and factor analysis. *Lakes Reserv. Res. Manag.,* 17(2): 143–159. https://doi.org/10.1111/j.1440-1770.2012.00506.x

Short, A.D. 1991. Macro-Meso Tidal Beach Morphodynamics: An Overview. *J. Coast. Res*., 7(2): 417–436.

Sinaga, E.R., Muhtadi, A. & Bakti, D. 2016. Profile of Temperature, Dissolved Oxygen, and pH Vertically for 24 Hours in Kelapa Gading Lake, Asahan Regency, North Sumatra. *Omni-Aquatics,* 12(2): 114-124. https://doi.org/10.20884/1.oa.2016.12.2.107

Tagliapietra, D., Sigovini, M. & Ghirardini, A.V. 2009. A review of terms and definitions to categorise estuaries, lagoons and associated environments. *Mar. Freshwater Res.,* 60(6): 497-509. https://doi.org/10.1071/MF08088

Turki, E.I., Deloffre, J., Gilbert, R., Mendoza, E.T., Salameh, E., Abcha, N., Lecoq, N. & Laignel, B. 2023. Effects of tidal wave modulation on coastal flooding along a tide-river context: Case of the seine estuary. *Ann. Mar. Sci.,* 7(1): 051-060. https://doi.org/10.17352/ams.000039

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 modelling. *J. Geophys. Res. Oceans,* 119(4): 2212-2226. https://doi.org/10.1002/2013JC009512

Uddin, M.G., Nash, S. & Olbert, A.I. 2021. A review of water quality index models and their use for assessing surface water quality. *Ecol. Indic.*, 122: 107218. https://doi.org/10.1016/j.ecolind.2020.107218

Van Maren, D.S., Beemster, J.G.W., Wang, Z.B., Khan, Z.H., Schrijvershof, R.A. & Hoitink, A.J.F. 2023. Tidal amplification and river capture in response to land reclamation in the Ganges-Brahmaputra delta. *Catena*, 220: 106651. https://doi.org/10.1016/j.catena.2022.106651

Zandagba, J., Moussa, M., Obada E. & Afouda A. 2016. Hydrodynamic modeling of Nokoué Lake in Benin. *Hydrol.*, 3(4): p.44. https://doi.org/10.3390/hydrology30400