VOL. 16, NO. 12, JUNE 2021 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ASSESSING THE SELF PURIFICATION OF LAKE MANINJAU BASED ON DEPTH STRATIFICATION

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ABSTRACT

This study aims to determine the self-purification of Lake Maninjau based on the depth stratification. Sampling was carried out at the locations where there was lake water use, namely in the middle, domestically, in the hydropower area, in the endemic fisheries and at the aquaculture cages under SNI 6989.57: 2008. The measured parameters were BOD and the environmental parameters of pH, DO, and temperature were used to determine the lake stratification. Lake Maninjau's self-purification was determined by comparing the deoxygenation (K_1) and reaeration (K_2) coefficients. Based on the pH, DO, and temperature profiles, the epilimnion layer was found at 0-22 m depth and the hypolimnion layer started at a depth of 22 m. The BOD concentrations obtained did not meet the Government Regulation quality standards of 21.87-47 mg/L. The deoxygenation coefficient K_1 in the epilimnion layer ranged from 0.04-1.49/day while in the hypolimnion layer it ranged from 0.08-0.54/day. The reaeration coefficient K_2 in the epilimnion layer ranged from 0.04 to 0.57/day while in the hypolimnion layer, it ranged from 0.005 to 0.04/day. Wind speed and depth play a significant role in determining the lake's self-purification capacity. The self-purification of the lake was still held mainly in the epilimnion layer at depths of 0-9 m while in the hypolimnion layer deeper than 22 m, its ability begins to diminish. This indicates that most of the lake waters have a significantly decreased natural self-purification capacity.

Keywords: lake maninjau; deoxygenation; lake stratification; reaeration; self-purification.

1. INTRODUCTION

Lake Maninjau is one of the ancient lakes formed by the devastating eruption of the Sitinjau volcano. The lake is located in Agam regency, West Sumatra at an altitude of 461.5 m asl with a maximum length of 16,460 m and a width of 7,500 m. The total area of Lake Maninjau is 97.375,000 m^2 and it has a beach length of 52.68 km. The average depth is 105 m and a maximum depth of 165 m. The total water volume is 10,226,001,629 m^3 [1]. The lake has an important role in supporting the economy of the surrounding community through tourism, as a water source for hydroelectric power, for fishery and cage cultivation activities, and as a raw water source for drinking water [2]. As a result of the increasing burden of waste entering the lake due to anthropogenic activities, the quality of Lake Maninjau is deteriorating. The input of the organic pollutant load mainly caused by fish cages around the lake produces 13,894.52 kg BOD/day and 20,841.78 kg COD/day [3]. Meanwhile, the levels of TP (0,28-0,59 mg/L) and TN (0,96-2,09 mg/L) are already quite high, indicated hypereutrophic conditions [4].

Lakes have specific aquatic ecosystems capable of controlling the physical, chemical, and biotic processes that are essential for the formation of air quality and water purification [5]. Self-purification and ecological remediation are inseparable from the important multifunctional role of aquatic biota [6]. Biotic processes can control and influence the physical, chemical, and biological processes in the formation of the water quality in aquatic ecosystems. One quantitative measure that has been used to evaluate the purification of surface water from dissolved contaminants is the biological oxygen demand (BOD). This is the amount of oxygen consumed by bacteria in the decomposition process of organic matter [7]. In lakes, wind-induced currents and thermocline structures mainly control the vertical distribution of heat, solutes, and nutrients in the water column [8].

Thermal stratification is very important when determining the mixing patterns in lakes. In a tropical country such as Indonesia, the annual temperature variation is relatively small. As a consequence, the temperature difference between the epilimnion and hypolimnion is slight [9]. The thermal differences in the water column result in incomplete mixing in the aquatic layer forming stratification. Photosynthesis takes place at the lake surface, and the subsequent decomposition of organic material occurs in the deeper layers [9]. The high load of pollutants entering the body of water can change the physical and chemical conditions of the water and reduce the self-purification capacity. The self-purification of the water from dissolved organic contaminants is estimated by the amount of oxygen consumed by the bacteria in organic matter (OM) decomposition. The water purification from OM is based on the development and analysis of the oxygen sag curve, which represents the temporal development of BOD and dissolved oxygen (DO) concentrations [7].

Self-purification is expressed through the ratio of the coefficient of reaeration (K_2) and the coefficient of deoxygenation (K_1) or K_2/K_1 [10]. Self-purification research has been carried out previously in three sampling stations on the east and west sides of Lake Maninjau at a depth of 0, 2, 4, 6 and 10 m in the middle of the lake in rain and dry conditions [11]. The overall purification ratio (K_2/K_1) of Lake Maninjau was in the range of 1.28-5.05 in rainy conditions and 1.11- 7.23 in dry conditions. This shows that the Lake Maninjau epilimnion zone can still assimilate organic pollutants. The input of pollutant

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sources into the lake continuously causes the organic burden of the waters to continue to increase. It creates an increase in the BOD and COD concentrations as the depth increases, whereas the shallow lake waters tend to be mixed due to turbulence [11]. In this study, self-purification in the hypolimnion layer and its relationship to flow velocity and wind speed at the lake surface is not yet known. This study's main objective is to evaluate the natural purification of the biodegradable organic contaminants in Lake Maninjau and its surrounding locations using the purification ratio approach mentioned above. Another goal is to determine if the changes in temperature, pH, and DO profiles correspond to depth. From these two aspects, self-purification was evaluated based on depth stratification and the sources of contaminants coming from around the lake.

2. METHODOLOGY

2.1 Sampling and Parameters Analysis

The study was conducted from February to May 2018, sampling 3 times every 2 weeks. The sampling location and depth were determined based on the Indonesian National Standard referring to the surface water sampling method[12], which can be seen in Figure-1. Based on this standard, 5 locations were established by considering lake utilisation and the nearest pollutant source, namely dense settlements, endemic fisheries, aquaculture cages and hydropower, in addition to the centre of the lake. The description of each sampling location is presented in Table-1. Sampling was carried out on a boat using a vertical water sampler. For the central area of the lake with a depth of 160 m, 4 sampling locations were taken while at a lake depth below 30 m, 3 sampling points. The analysed water parameters were BOD_5, temperature, DO and pH, while the measured environmental parameters were wind speed, water discharge and flow velocity. The BOD_5 analysis refers to the Standard Methods for the Examination of Water and Wastewater [13]. The measurement of the lake water quality parameters was then compared with the quality standards of Government Regulation No. 82 of 2001 concerning the Management of Water Quality and Water Pollution Control under class 2 quality standards [14].

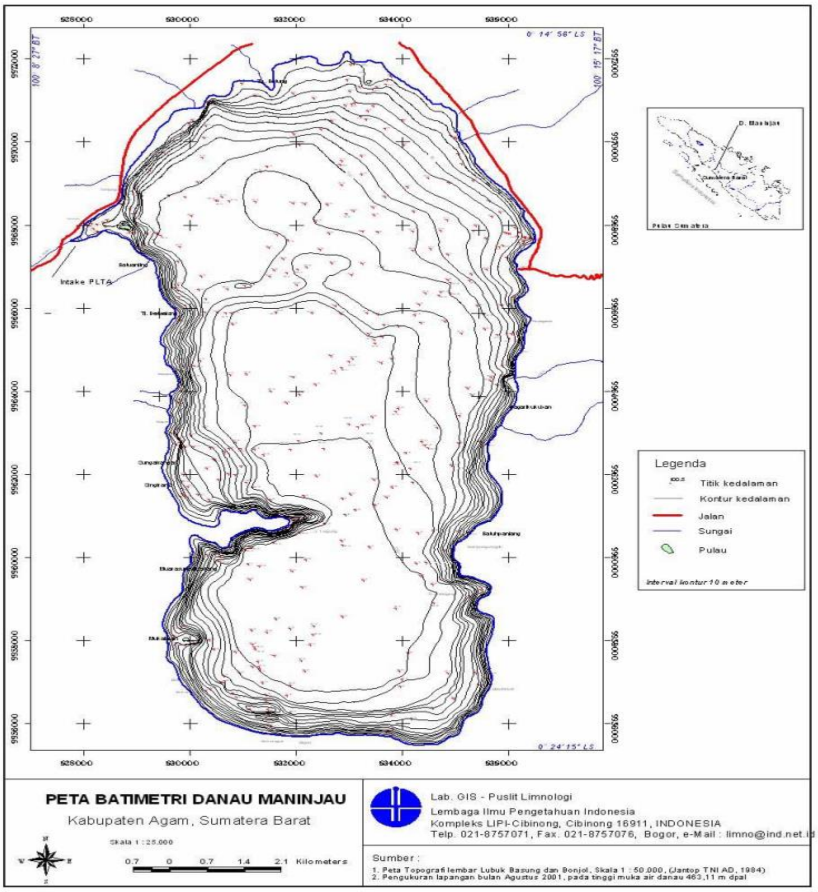

Figure-1. Map of location.

2.2 Self-Purification Calculation

Lake Maninjau's self-purification can be determined through the purification ratio, K_2/K_1, where K_1 is the deoxygenation rate constant and K_2 is the reaeration rate. The deoxygenation rate coefficient (K_1) was calculated using the slope method through the first-order reaction equation from the result of 5 days BOD_5 measurements and the temperature at each sampling

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location [15]. The K_1 value according to the temperature of each sample is calculated through equation 1.

$$K_{1(T)} = K_{1(20C)} \times 1{,}047^{(T-20C)} \quad \text{.........................(1)}$$

The reaeration coefficient (K_2) is calculated using the Thomann and Fitzpatrick equations [16]. The coefficient value of the reaeration rate (K_2) is determined by the data on the depth of the sampling at each sampling point (H), the lake flow velocity (Uo), and the wind speed above the lake surface (Uw) which is then subsidised to equation 2.

$$K_2 = 3{,}93\,\frac{\sqrt{U_0}}{H^{3/2}} + \frac{0{,}728U_w^{0,5} - 0{,}317U_w + 0{,}037U_w^2}{H} \quad \text{.................(2)}$$

Purification ratios are determined by comparing the values of K_2 and K_1 (K_2/K_1) [10]. The purification ratio value is higher than one. This means that the water can purify itself naturally from the pollutant load that enters the lake. However, if the value of the purification ratio is smaller than 1, then this means that the water is not able to purify itself naturally from the pollutant load that enters the lake.

Table-1. Description of the sampling stations in Maninjau lake.

Sampling Location	Position	Description
Aquaculture cage	S: 00º13’13,3’’	Dense aquaculture cage
	E: 100º10’08,8’’	
Domestic	S: 00º18’59,9’’	Densely-populated settlement
	E: 100º09’53,3”	
Endemic	S: 00º15’33,2’’	Endemic fisheries
	E: 100º10’50,5’’	
Centre of the lake	S: 00º22’17’’	The deepest part of the lake
	E: 100º11’22,3’’	
Hydropower	S: 00º17’24,1’’	Hydropower intake, conservation area, sandy bottom substrate and tourist area.
	E: 100º08’58,8’’	

3. RESULTS AND DISCUSSIONS

3.1 Lake Stratification

The determination of self-purification is based on lake stratification. Lake stratification is reviewed based on the temperature, pH, and DO profiles in relation to depth. The stratification profile was observed in the middle of the lake as well as in other sites.

3.1.1 Temperature profile

The temperature profile of Lake Maninjau can be seen in Figures 2a and 2 b. Lake Maninjau’s temperatures in various depths range from 28.03 to 31.47ºC. The range in temperatures recorded at different depths does not differ significantly, by 3ºC. In the middle of the lake (Figure 2a.), the temperature at 0-22 m depth decreased by ± 1.5ºC while for deeper than 22 m, the temperature only changed ± 0.5ºC. It tends to be stable until the bottom. It shows that the epilimnion layer in the middle of the lake is at a depth of 0-22 m and that the hypolimnion layer started at a depth of 22 m. The difference in temperature between the two layers is only around ± 2 ºC.

In Monoun Lake, which has a maximum depth of 96 m, the higher thermal variation is 26.70°C at the surface down to 20.4°C at 8 m (Kling, 1988). Surface temperature and thermal stratification vary according to the air temperature. The temperature difference between the surface layer with the bottom ranging from 0.5-3.3°C was also shown in the crater lake of Uganda with a 30 m depth [17]. The temperature of tropical lake waters found in several lakes in Africa ranges from 18.6 to 32.5°C. This is closely related to the surrounding air temperature [18]. The number of lakes found in the tropics at higher latitudes, often with little annual variation in solar radiation and other factors such as seasonal winds, rainfall and humidity, play a dominant role in determining the passage of time and the rate of heat change and associated thermal stratification[19].

At the domestic sampling location, 0-15 m indicates a temperature change of around 1^{0}C. In contrast, at a depth greater than 15 m, there is only a little difference ± 0.05^{0}C. Nevertheless, a trend can be seen in that the epilimnion layer is 0-15 m deep and the hypolimnion layer is >15 m deep. The aquaculture site has a depth of 19 m and the temperature change at 0-9 m is around 0.6^{0}C, while the temperature change at a depth of 9-19 m is ± 0.46^{0}C. The temperature profile at the aquaculture location is similar to that of the domestic site to a depth of 15 m. However, no stable temperature values were seen in the deeper parts such as at the aquaculture cage at depths >19 m. The boundary between the epilimnion and hypolimnion layer at this location is not clear. Meanwhile, the temperature at the hydropower plants with a shallow depth of 2.5 m shows that the

VOL. 16, NO. 12, JUNE 2021 ISSN 1819-6608
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difference is small ± 0.5°C. There were not many different, endemic fishing sites with a depth of 5 m, the temperature difference is ± 1^0C.These two locations demonstrate the tendency that temperature stratification with depth is unclear. Apart from in the middle of the lake, only the domestic site shows a reasonably clear temperature stratification between the epilimnion and hypolimnion layer. Meanwhile, the other locations with a depth of fewer than 20 m indicate that there is no clear stratification between the two layers.

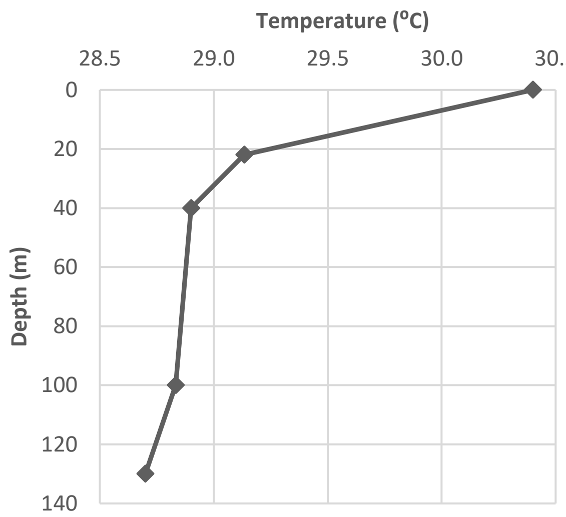

Figure-2a. The temperature profile in the middle of the lake.

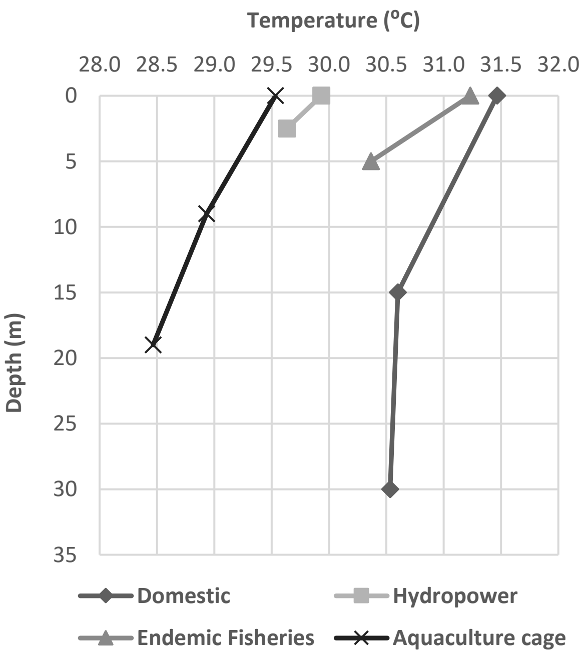

Figure-2b. The temperature profile in the domestic, hydropower, endemic fisheries and aquaculture cage areas.

The meteorological conditions control the stratification and currents in lakes. Both the waves and currents are driven by wind [9]. Wind speed can be as important as or even more important than the air temperature for influencing lake stratification and water temperature [20]. They reported that larger surface area lakes have higher wind mixing due to the increased surface momentum. Although Lake Maninjau is a large lake with wind speeds recorded during the study at 0.77-1.33 m/s, at certain times, it can increase up to 10.4 m s^{-1}[21]. This affects lake mixing. If the surface temperature falls far enough, epilimnion and hypolimnion can be mixed and the entire lake is homogenised to one layer [9]. Boehrer revealed that in the equator's vicinity, where the annual temperature variation is relatively small, as a consequence, the temperature difference between the epilimnion and hypolimnion is also small.

3.1.2 DO profile

The DO profile in the centre of the lake, which is the deepest part, can be seen in Figure-3a. The DO concentrations in the surface layer of the lake ranged from 8.80 to 9.90 mg/L. The DO value has exceeded the DO saturation limit by 13%-36%. The high level of dissolved oxygen was recorded at all locations. This may be due to the high photosynthesis level of the phytoplankton community which results in higher dissolved oxygen values [22]. However, this value decreases dramatically when the lake depth is around 22 m, which reaches 1.60 mg/L. This decrease indicates a high rate of oxygen used to decompose the organic compounds in the water column. The oxygen reduction in the middle of the lake is inversely proportional to the BOD_5 concentration in a range of 40.70 mg/L-67.56 mg/L with the increase in depth. The O_2 profiles and consumption rates in the water column and the sediment of the hypolimnion are functions primarily related to nutrient concentration, lake morphometry and allochthonous organic input [23].

A depth that is deeper than 22 m indicates an anoxic state with DO 0.01 mg/L. When viewed according to the temperature and DO profiles, both temperature and oxygen reduction have the same tendency to start at a depth of 20 m. This confirms that at the beginning at a depth of 20 m, there is a hypolimnion layer. This has been revealed by previous studies [24] in that DO was recorded in Lake Maninjau at 5-12 mg/L which then decreased dramatically at a depth of 25 m, indicating anoxic conditions. Meanwhile, the previous study by Henny and Nomosatryo [25] shows anoxic conditions fluctuating at a depth of 10-20 m. There is a tendency for the hypolimnion layer to increase and raise the epilimnion layer.

The DO profiles at the domestic, hydropower, endemic fisheries and aquaculture cage locations can be seen in Figure-3.b. The highest surface DO concentration was at the domestic site at 9.9 mg/L. The DO decreases sharply at 15 m in depth, i.e. 1.9 mg/L, and the decrease continues to occur. The lake experienced anoxic conditions at the bottom at a depth of 30 m with a DO of 0.8 mg/L. The contribution of organic compounds at the domestic location is quite high at 42.48 mg BOD/L at the

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surface, reaching 63.31 mg BOD/L at the bottom. In the aquaculture cage at 0-9 m depth, the DO decreases sharply from 8.8 mg/L to 2.1 mg/L and then reduces to 1.7 mg/L at the bottom at 19 m. This is in line with the BOD value at the surface of this point which was 50.82 mg/L. The increase continues to a depth of 19 m, where 71.11 mg/L is the highest BOD at the bottom of the lake.

Meanwhile, the oxygen stratification in the hydropower and endemic fisheries locations was at depths of 2.5 m and 5 m respectively, although a decrease in DO did not make the condition anoxic. The surface DO in the hydropower ranged from 9.2 mg/L to 4.1 mg/L and in the endemic fisheries site, it was from 9.8 mg/L to 2.9 mg/L at the bottom of the lake. Likewise, the increase in the BOD concentration from the surface to the bottom is 57.5-69.56 mg/L in hydropower and 60.44-55.64 mg/L in endemic fisheries respectively, showing no significant changes. In lake ecosystems, the biodegradable portion of the dissolved organic carbon average of the biodegradable DOC (BDOC) is about 14% of the total pool [26]. However, Sepp stated that the high concentration of oxidisable organic matter in anthropogenic effluent is a significant threat to the oxygen regime of surface waters. The deeper the lake, the higher the oxygen utilisation rate. The oxygen levels in the deepwater layers will continue to decrease along with the utilisation of oxygen by organic decomposing microorganisms and the oxidation of reduced metabolites such as Fe^{2+}, H_2S, and NH_4 [27]. In shallow lakes, turbulent diffusion occurs due to wind action, which leads to mixing conditions that can enhance oxygen transport and increase the DO concentration.

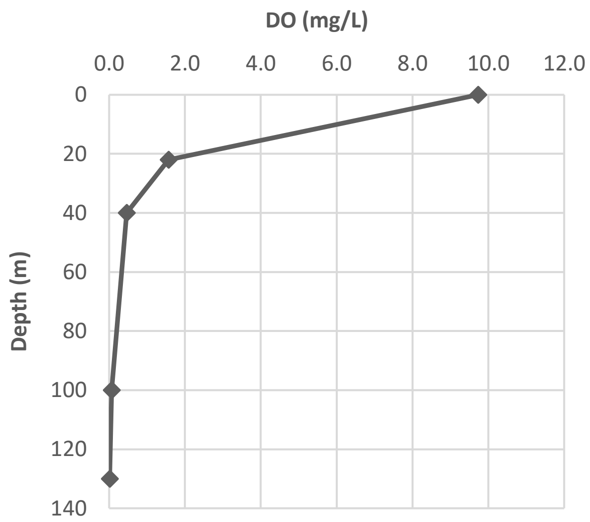

Figure-3a. DO profile in the middle of the lake.

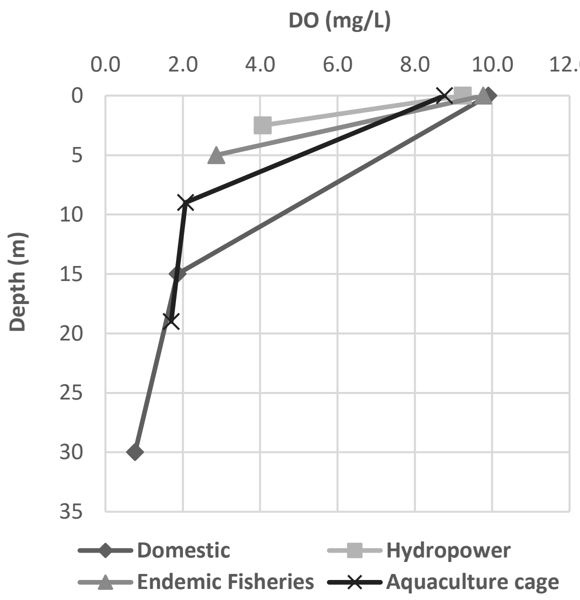

Figure-3b. DO profile in the domestic, hydropower, endemic fisheries and aquaculture cage areas.

3.1.3. pH profile

The pH values at each sampling location at various depths can be seen in Figures 4a and 4b. The pH value of Lake Maninjau in all sampling locations is alkaline, ranging from 7.64 to 9.40. The pH decreases with an increase in depth. The pH profile is slightly different from the temperature and DO patterns, especially in the middle of the lake (Figure-4a). The pH decreases gradually from 9.0 on the surface to 8.4 and 8.0 at a depth of 20 m and 40 m. At above 40 m depths, the pH tends to be constant at around 8 at 100 m in depth, before dropping to 7.66 at the bottom of the lake. The pH difference between the surface and the bottom of the lake is more than 2. The high pH at the surface is not only influenced by photosynthesis. It is also due to the higher temperature at the surface compared to the bottom. The increased pH in the water column is interpreted as a reflection of the photosynthetically-increased pH in the lake water [28]. The elevated pHs are presumably the result of intense photosynthesis [29], where the high phytoplankton production causes a high pH in the lake water [28].

The pH profile at the domestic, hydropower, endemic fisheries and aquaculture cage areas can be seen in Figure 4b. The depth of these areas is between 2.5-30 m. At the domestic location, the stratification of weak pH tends to follow the temperature profile where the changes are not too sharp compared to the DO profile. The highest pH values are on the surface of the aquaculture cage and endemic fisheries locations, at 9.2 and 9.4. This might be due to the increased photosynthetic activity and the decomposition of allochthonous matter in the lake, increasing the nutrient concentration at higher temperatures [30]. The nitrogen components of nitrite and ammonia are often found at the fish culture sites due to the fish excreta. Nitrates that are formed through nitrite oxidation under aerobic conditions are a trigger element of

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eutrophication which can encourage an increase in pH. The domestic and agricultural waste inputs are also responsible for the higher pH values in the water. The ideal pH for most fish is in the range of 6.5–8.5. The extreme values can damage the gill surfaces, leading to death [31].

At the aquaculture cage and domestic locations with 19 and 30 m depth respectively, at the bottom, the pH generally reaches 7.6. This is not much different from that of the middle of the lake. In the shallower parts of the lake, such as <5 m in the endemic fisheries and hydropower locations, the pH difference between the surface and bottom of the lake is only 0.5 with a pH value of 8.5-9. It is estimated that starting at a depth of 19 m, photosynthetic activity has been reduced. At this depth, the DO shows anoxic conditions of 1.9 mg/L with temperatures ranging from 28.5^0 - 30^{0}C. Like the temperature profile, the pH profile at the location at a depth of <5 m did not show a significant difference. In a lake with a maximum depth of less than 15 to 30 m, complete mixing is usually frequent [32]. The lake wind speed, which can increase at any time up to 10.4 m.s^{-1}, can stir the lake up, especially in the shallows. As a result, the pH and temperature values on the surface and bottom of the lake are not different. The pH reached very high values during the wind-induced mixing of the shallow lake while the pH decreased in a calm mesocosm [33]. pH usually increases in natural environments due to the uptake of inorganic carbon by the primary producers as a result of their photosynthetic activity [34]. Increased pH values suggest an increased withdrawal of CO_2 due to higher photosynthetic activity [33].

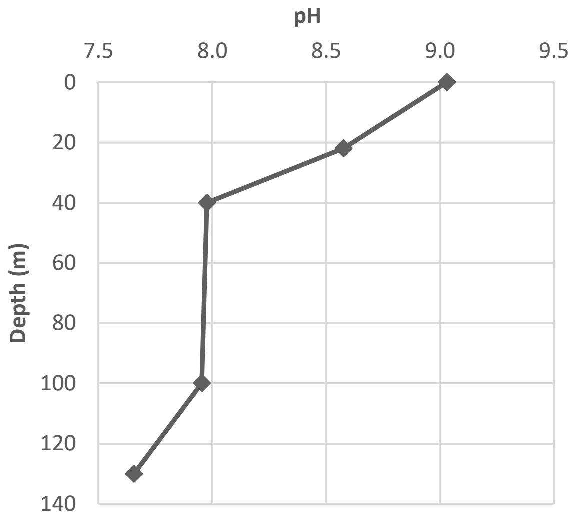

Figure-4a. pH profile in the middle of the lake.

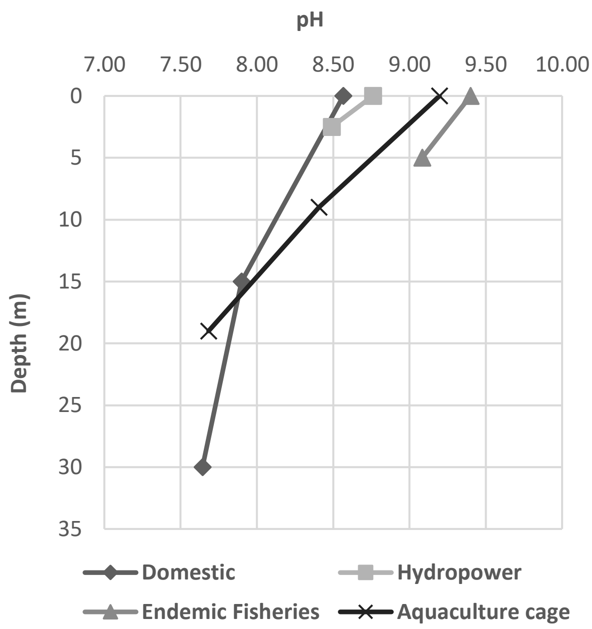

Figure-4b. pH profile in the domestic, hydropower, endemic fisheries and aquaculture cage areas.

3.2. Lake Self-Purification

The ability of Lake Maninjau to self-purify is determined by the value of the purification ratio calculated by comparing the value of the reaeration coefficient (K_2) and the deoxygenation coefficient (K_1). This purification ratio value can determine whether Lake Maninjau is still able to purify itself naturally from the pollutant load that enters it or not. The K_1, K_2, and K_2/K_1 values for the middle of the lake, domestic area, hydropower area, endemic fishery area and aquaculture cages can be seen in Table-2.

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Table-2. Deoxygenation, reaeration coefficient, and self-purification ratios.

Location/depth	Deoxygenation Coefficient (K_1)	Reaeration Coefficient (K_2)	Self Purification Ratio (K_2/K_1)
Middle of the lake			
0	0.54	-	-
22	0.54	0.04	0.07
40	0.28	0.02	0.07
100	0.10	0.01	0.10
130	0.08	0.00	0.00
Domestic			
0	0.99	-	-
15	0.15	0.06	0.40
30	0.13	0.03	0.23
Hydropower			
0	1.49	-	-
2.5	0.07	0.57	8.14
Endemic fisheries			
0	0.82	-	-
5	0.04	0.21	5.25
Aquaculture cage			
0	0.19	-	-
9	0.08	0.10	1.25
19	0.14	0.04	0.28

3.2.1 Deoxygenation rate

The K_1 value was calculated using the slope method through the least square processing with equation 1. The K_1 values from all of the sampling location points ranged from 0.04 to 0.99/day. The K_1 of each sampling point decreases with the increase lake depth. The epilimnion layer has a K_1 value ranging from 0.19-1.49/day. The oxygen concentration in the epilimnion at all locations has exceeded the DO saturation, indicating photosynthesis on the surface of the entirety of the lake site. The highest K_1 value is in hydropower, which is 1.49/day. At this location, it is estimated that there is a water turbine that can mix the waters there, so the rate of deoxygenation is faster. The K_1 values that are also quite high are in the domestic and endemic fisheries locations, which are 0.99/day and 0.82/day respectively. At these locations, the recorded temperature and DO were the highest in all areas and these parameters also play a role in the increasing deoxygenation. In the middle of the lake, the K_1 value has started to decrease compared to other regions, which is 0.54/day. It shows that the level of organic and nutrient pollution has spread to this area and resulted in a high rate of deoxygenation. Meanwhile, in the aquaculture cage area, the K_1 value obtained was the lowest at 0.19/day. Even though this location is a fish culture area, compared to other sites the temperature in this region is smaller so the deoxygenation rate is lower. It proves that the deoxygenation rate is influenced by temperature, turbulence, microbiological activity, and nutrients [35].

In the hypolimnion layer, the K_1 recorded was around 0.04-0.54/day. The DO supply to the hypolimnion is decreased due to the simultaneous consumption of oxygen due to respiration and microbial degradation [36]. In these layers, large amounts of decomposing biomass may lead to high oxygen depletion rates (ODRs), potentially causing hypoxic or even anoxic conditions in the hypolimnia [37]. Therefore the DO in the epilimnion layer is higher than in the hypolimnion layer, which is 8.80-9.90 mg/L and 0.01-1.60 mg/L respectively, indicating that the rate of oxygen utilisation for decomposition is higher at depth. The K_1 values ranging from 0.3-0.6/day are included in the category of wastewater requiring treatment [38]. From the K_1 value obtained, Lake Maninjau in all layers belongs to this category. Compared to the deoxygenation rate during the dry period of the previous study of 0.038-0.967/day [11], the results obtained in this study are slightly higher. Different environmental conditions in the sampling period may contribute to the deoxygenation rate. The physical, chemical and biological features of lakes have an important role in the decomposition of organic matter.

The characteristics of the environmental conditions, such as the photosynthetic rate, the permanent stagnation of water below the chemocline, the oxygen deficit, and the accumulation of sulphides in deep water need to be considered [39]. The total sulphide concentrations in Lake Maninjau have reached more than 400 µg/L and they have been higher in the water column in recent years. This can be one of the causes of the oxic-anoxic fluctuations in the lake [25]. Lake Maninjau waters also have a relatively high level of organic pollutants (BOD) but these are not accompanied by sufficient DO concentrations. Consequently, the decomposition rate is slower, as indicated by the low K_1 value.

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3.2.2 Reaeration rate

In addition to the deoxygenation coefficient, the ability of self-purification is also determined by the reaeration coefficient. The reaeration coefficient is calculated based on depth, water velocity, and wind speed using equation 2 [40]. The average lake flow velocity values obtained ranged from 0.1 to 0.3 m/s. The average wind speed values obtained were between 0.77 - 1.33 m/s. The magnitude of the ratio of flow velocity and air velocity can affect the K_2 value obtained. The K_2 values generally range between 0.00-0.57/day. The K_2 for the epilimnion layer ranged from 0.04 to 0.57/day while in the hypolimnion layer, it ranged from 0.005 to 0.04/day. The K_2 value thus decreases with an increase in lake depth. The reaeration rate is regulated by internal turbulence, which in lakes is driven primarily by wind speed (Gelda & Effler, 2002). Shallow water bodies tend to have higher reaeration coefficients due to the ease of mixing in the depth profile and more considerable surface turbulence [35]. The importance of the depth of the lake on the K_2 value can be seen more clearly in the middle part of the lake, where the K_2 at 22 m depth of 0.04/day is higher than that of 130 m depth at 0.005/day, despite the similar flow velocity (0.3 m/s) and wind speed (0.77 m/s).

The highest K_2 value is found at the hydropower site with a 2.5 m depth, i.e., 0.57/day, while the smallest one is found in the middle of the lake with a 130 m depth, i.e., 0.005/day. The reaeration rate of this study is lower than that of previous studies at 0.161-0.691/day [11]. Besides depth, the K_2 is also influenced by wind speed and flow velocity. At the hydropower site, there is a higher flow velocity of 0.15 m/s compared to the flow velocity value in the middle of the lake, of 0.3 m/s. The hydropower plant's wind speed is also higher than the wind speed in the middle of the lake, which is 1.07 m/s at the hydropower plant and 0.77 in the middle. The higher flow rate and wind speed in the water increases the absorption of oxygen from the atmosphere into the stream. Lake Maninjau has a large surface. Lakes with a large surface area have higher wind mixing due to the increased surface momentum [20]. Lake size has been demonstrated to influence the relative contribution of wind and convective mixing to gas transfer, and both contribute to turbulence in the upper water column [41]. Although the solubility of oxygen decreases as the temperature increases, the reaeration rate has been shown to increase with temperature [42]. When the temperature in the lake rises, the oxygen rebalances with the atmosphere. The oxygen demand in tropical lakes continues because of the high water temperatures even during the mixing period, and this compensates for the surface oxygen concentrations [36].

Even though most of the K_2 values obtained at each sampling location compared to the K_2 value of the Minister of Environment Regulation are very small, the K_2 values obtained at the hydropower site are proportional to the K_2 for large rivers with an average speed of 0.46-0.69/day. In comparison, the K_2 value at the endemic locations and cages is equivalent to a small pond (0.10-0.23/day). Nevertheless, the K_2 value shows that the rate of the increase in oxygen into the lake waters is low because, according to Government Regulations, the K_2 value for large lake waters is around 0.23-0.35/day. The small K_2 value indicates that the lake water's oxygen uptake rate from the atmosphere is relatively slow. The time required to recover with a lower reaeration rates is longer than a lake with a larger reaeration rate [42].

3.2.3 Self-purification ratio

The K_1 and K_2 values obtained in this study vary according to depth and differ at each sampling location, so the purification ratio also varies. Lake Maninjau's purification ratio values range between 0.06 - 8.14. The ratio of purification of lakes in the epilimnion layer is 0.07-8.14 while in the hypolimnion layer that starts at a depth of 22 m, it is 0.00-0.28. This shows that the closer the sample is to the surface, the higher the value of the lake's purification ratio and vice versa, as the further the sample is away from the surface, the smaller the value. In the middle of the lake at the bottom at 130 m, the purification ratio is almost zero. On the surface of the lake, the high intensity of the incoming solar radiation and the ambient temperature causes an increase in the DO saturation concentration. The result is an increase in DO concentration in the epilimnion section. When organic matter settles to the bottom of the lake, DO is consumed, and hypolimnion which becomes anoxic. The high amount of reduced substances stored in the hypolimnion must be oxidised before the oxygen can be replenished[36]. Therefore, as the lake increases in depth, the rate of incoming oxygen will decrease and the oxygen needed by the microorganisms to decompose the organic compounds increases, thus the value of the lake's purification ratio decreases.

Among the sampling locations, the highest value for the purification ratio was found in the hydropower location, i.e., 8.14 followed by the endemic fisheries site, i.e., 5.25. The relatively low depth and small organic content at this location resulted in a low K_1. The high oxygen uptake rate can compensate for the oxygen deficits characterised by high K_2 values, so this location has a high purification ratio. The lowest lake purification ratio value is found in the middle of the lake at a depth of 130 m, which is equal to 0.00 because there is no more oxygen at the bottom. Meanwhile, in the domestic and aquaculture cage areas which have depths below 30 m, a purification ratio of 0.23 and 0.28 was obtained. The self-purification in the middle of the lake and the domestic location is relatively smaller when compared to the other sites. The areas with higher depths and lower wind speed have lower self-purification abilities, whereas those with lower depths and higher wind speed have a higher capacity.

This indicates the effect of mixing at a lower lake depth according to the value of the purification ratio. The purification ratio of Maninjau lake obtained in this study at a depth of 22 m ranged from 0.07-1.25, which is much lower than that of previous studies of 1,107-7,230 conducted in the epilimnion layer at a depth of 10 m [11]. This value indicates a decrease in the self-purification ability of Lake Maninjau where in this study overall, Lake

Maninjau can perform a natural self-purification process in the epilimnion layer at a depth of 0-9 m. In contrast, for the depths deeper than 9 m, the lake cannot fulfil the natural self-purification process. This indicates that most of the lake waters have a significantly decreased natural self-purification capacity. This is following the last trophic status of Lake Maninjau, which classified it as a hypereutrophic lake [4]. Changes in the physicochemical parameters of ecosystems have a substantial impact on the species that live within them [22]. Very eutrophic lakes (Lake of Zurich until 1970) have a completely anaerobic part near the bottom [43]. Eutrophication due to an excessive P input is interpreted as stimulating phytoplankton growth in the surface layer and the subsequent O_2 depletion in deep waters, resulting in anoxic conditions [44]. Deteriorating water quality is a disturbance that is expected to be less effective at maintaining high diversity because the former allows for competitive exceptions and the latter directly eliminates many species [45].

Wind speed and depth play a significant role in determining self-purification capacity but with the presence of organic pollutants and nutrients, the function is reduced. Lake Maninjau is classified as heavily polluted where the incoming pollutant load, especially biodegradable organic compounds, has exceeded the lake's assimilation ability. The self-purification of the lake is still mainly in the epilimnion layer at a depth of 0-9 m while in the deeper layers, its ability begins to diminish. For further self-lake purification calculations, it is necessary to consider all aspects involved in deoxygenation and reaeration including photosynthesis-respiration, atmospheric reaeration, biochemical oxygen consumption, and microbial oxygen transport in sediment.

4. CONCLUSIONS

The water quality of Lake Maninjau based on the BOD parameters does not meet the PP 82 the Year 2001 quality standard 2. Based on the pH, DO, and temperature profiles in the middle of the lake, the epilimnion layer was found at 0-22 m depth and the hypolimnion layer started at a depth of 22 m. Locations with depths greater than 30 m have temperature, DO, and pH stratifications, while at shallow depths, this is unclear. The purification ratio of Lake Maninjau in the epilimnion layer is about 0.07-8.14 while in the hypolimnion layer, it is 0.00-0.28. Wind speed and depth play a significant role in determining the ability of the lake to self-purify, but with the presence of organic pollutants and nutrients, the capacity is reduced. Lake Maninjau is classified as heavily polluted as the incoming pollutant load, especially biodegradable organic compounds, has exceeded the lake's assimilation ability. Most of the lake waters have a significantly decreased natural self-purification capacity.

ACKNOWLEDGMENT

This work was supported by the Directorate General of Research and Development Strengthening of the Ministry of Research and Higher Education of the Republic of Indonesia through the scheme of Excellent Basic Research of Higher Education (PDUPT) No.051/SP2H/LT/DRPM/2019, fiscal year 2019. Thanks also go to the Faculty of Engineering Universitas Andalas for their financial support of this publication (Grant number 021/UN.16.09.D/PL/2020).

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