International Journal on Advanced Science Engineering Information Technology

Vol.11 (2021) No. 3
ISSN: 2088-5334

Loads of Pollution to Lake Toba and Their Impacts

Lukman[a,*], H. Hidayat[a], Luki Subehi[a], Rahmi Dina[a], Novi Mayasari[a], Irma Melati[a], Yuli Sudriani[a]

[a] *Research Center for Limnology,Indonesian Institute of Sciences (LIPI), Cibinong, 16911, Indonesia*
*Corresponding author: *lukman@limnologi.lipi.go.id*

***Abstract*— Lakes provide various ecosystem services that support biotic habitats and human life. In contrast, many lakes in the world are degraded due to pollutant supply from surrounding areas and human activities in the lake. Lake Toba, which is the largest lake in Indonesia, has indicated a polluted condition. However, the source and load of each pollutant are not yet known. A study has been conducted to determine nutrient and organic load levels entering the lake represented by Total Phosphorus (TP) and Chemical Oxygen Demand (COD), respectively. Observations were carried out in November 2017 at 22 locations, i.e., at 12 inlet rivers debouching to the lake and 10 sites at the lake. The pollutant impact was assessed from water class criteria based on COD, waters trophic status based on TP, and vertical oxygen profile representing cage aquaculture (CA) and non-cage aquaculture (NCA) areas. Based on COD and government regulation number 82/2001, water quality at the lake inlets was class III and IV. In the lake area, water class in NCA was III, while in CA the water class tends to be III and IV. Estimated TP loading from the catchment area was 138 tonnes/yr, while that from cage aquaculture activity was 570.33 tonnes/yr. Pollutants have caused the worsening of water class, increasing water column anoxia in the hypolimnion layer and eutrophication in Lake Toba.**

***Keywords*— Pollutant load; Chemical Oxygen Demand; total phosphorus; Lake Toba.**

Manuscript received 29 Jul. 2020; revised 1 Dec. 2020; accepted 31 Jan. 2021. Date of publication 30 Jun. 2021.

I. INTRODUCTION

Lake is an essential ecosystem with various biotic habitats and contributes to human life, both as a provider of various ecosystem services and a source of economic activities. Numerous ecosystem services include provisioning, supporting, and regulating services [1], [2]. Lake is an indicator of changes in the surrounding area described in its metabolic system, including the ecosystem process in a range of space and time domains [3].

Lakes in the world are currently facing continuous degradation [1], including eutrophication. Eutrophication that has become a global concern is a sign of threat towards lake damage-causing serious water quality decrease, significant economic loss. Eutrophication is an ecosystem response to nutrient loads, especially phosphorus (P) and nitrogen (N), sourced from natural and anthropogenic activity. Oversupply of phosphorus is recognized as a trigger of “cultural eutrophication” [4], [5], [6]. Moreover, lakes' function and ecosystem services can also be altered due to the climate change effect [7].

Lake Toba, the largest lake in Indonesia located in North Sumatra Province (Fig. 1), has shown disturbing conditions, especially marked by eutrophication. The trophic status of Lake Toba ranged from oligotrophic until eutrophic [8], [9], and eutrophication of Lake Toba was characterized by high Total Phosphorus (TP) levels. It is one of the inland waters that has multi-sectoral multi-functional roles and a high rate of utilization. Lake Toba's primary use for a long time is for fishing; a part of the area is a tourist destination, particularly water areas, which have been used for cage aquaculture. The catchment area of the lake has been used for settlement areas and agricultural activities [10].

Human activities in the lake and surrounding area are potential threats to the lake ecosystem. Thus, it is necessary to pay attention to the potential pollutant loads entering the lake waters. Thus, besides paying attention to the phosphorus, another pollutant like organic load must also be seen because organic material accumulation would lead to anoxic conditions on the bottom part of the waters.

In temperate regions, lakes' anoxic condition is related to the onset of stratification [11]. Moreover, hypoxia progresses in temperate lakes during winter stratification and closely related to depth, organic carbon concentration, and chlorophyll concentration [12]. A study on tropical lakes in Indonesia [13] found that the range of area of hypolimnetic depletion rate of the lakes is 0.046 – 5.9 g m^{-2} y^{-1}. Within this rate, the lakes are predicted to face an anoxic condition crisis on nearly all hypolimnetic layers in the future, given that there are no changes in rates of shoaling of oxygen-deficient water and vertical mixing. The condition can be aggravated by anthropogenic activities in the catchment area of the lakes that increase nutrient and organic loads and the impacts of climate change.

Land-use changes in the catchment area and aquaculture activities in Lake Toba are likely to proliferate the anoxic hypolimnion zone. In this paper, pollution load from human activities that potentially influence Lake Toba's environmental conditions would be described. This study aimed to reveal the pollution load to the lake and how they affect lake water quality.

II. Material and Method

Observations were conducted at 12 rivers as inlets and 10 locations of Lake Toba waters (Fig.1) in November 2017. Several supporting parameters, i.e., dissolved oxygen (DO), temperature, conductivity, Total Dissolved Solids (TDS), and pH, were measured at the lake's inlets and waters Horiba Type U-20 Water Quality Checker. Furthermore, in inlets, the flow rate was also measured using the velocity-area method, and the Total Suspended Solids (TSS) were analyzed following gravimetric methods. A Secchi disk apparatus was used to measure water transparency (Secchi depth) in the lake area.

A. Analysis of Pollutant Loads

The pollutant load was observed at eight inlet rivers and ten lake sites by measuring Chemical Oxygen Demand (COD) and Total Phosphorus (TP) parameters. The COD level was measured following permanganatmetric method of closed reflux spectrophotometric method, and TP was determined by the destructive method and the ascorbic acid method consecutively [14].

B. Impact of Pollutant Loads

Chemical Oxygen Demand (COD) value was used to determine water classes at each location, referring to The Indonesian Government Regulation number 82/2001. The TP load from the catchment was calculated from the instantaneous nutrient input and water flow rate, while the cage aquaculture TP load was calculated based on feed conversion rate and fish production.

Data of lake waters TP concentration is displayed in the form of trophic status distribution picture of waters concerning the Indonesian Minister of Environment regulation number 28/2009. The COD data are presented in a graphical form showing the water class level.

The phosphorus load is represented by TP and calculated [15] on year (yr) period by the equation:

$$J_N = J_E + J_{PR} \text{ (mg/yr.)} \quad (1)$$

J_N = Natural input
J_E = Catchment input
J_{PR} = Precipitation input
Total P input of to the lake

$$J_T = J_N + J_A \text{ (mg/yr.)} \quad (2)$$

J_T = Total input to the lake
J_A = Artificial input
Total loading (L_T) of TP calculated by using the equation:

$$L_T = J_T/A_o \text{ (mg/m}^2\text{/yr.)} \quad (3)$$

A_o = Lake volume

Vertical oxygen profile was observed at six lake sites, representing cage aquaculture (CA) and non-cage aquaculture (NCA) areas, using the Ringko profiler instrument. The vertical profile of DO in the water column will be used to elucidate the cage aquaculture activity on the condition of the lake, especially on the bottom part of water, namely critical and anoxic conditions indicated by DO values of ≤2.0 and 0 mg/L, respectively.

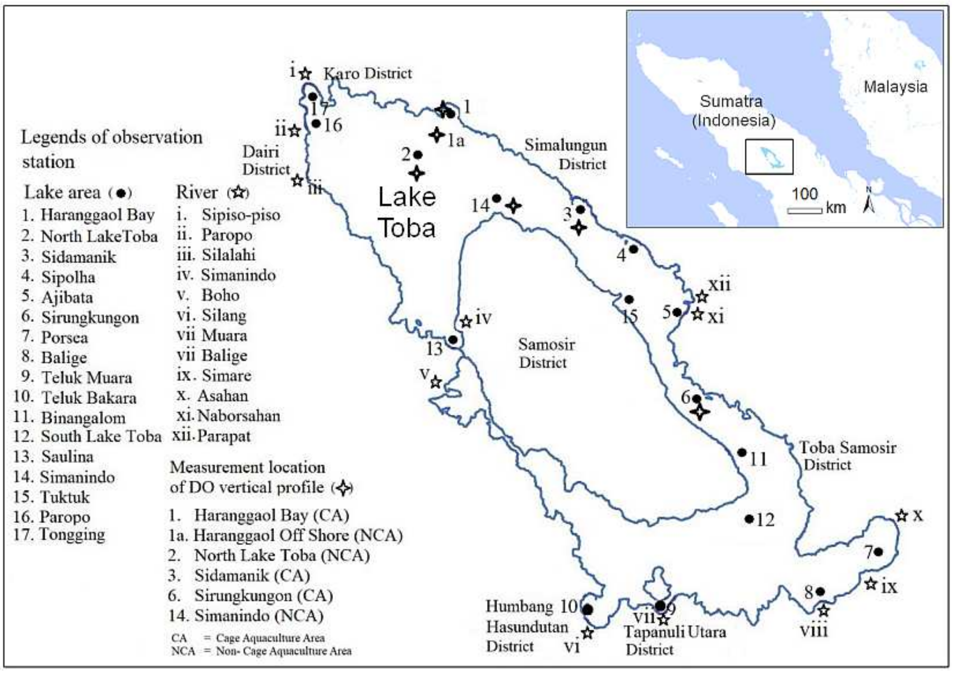

Fig. 1 Lake Toba area and the distribution of sampling locations

III. Results and Discussion

Water quality parameters of rivers, the inlets of Lake Toba, namely temperature was still in natural condition and ranged between 20.6 – 25.9°C. The pH was between 7.5 -8.3, slightly tends to be alkaline. DO was generally still quite high (>6.0 mg/L), and the level of conductivity was between 0.010 - 0.106 mS/cm. The highest TSS level of river sites were found at Sipiso-piso (45 mg/L), but the highest TDS levels were found at River Boho and River Silang that reached 0.067 and 0.063 mg/L, respectively (Fig. 2).

Generally, the catchment area contributes significantly to the aging process of the lake with various input loads. In Lake Toba, the two inlets with relatively high TSS concentrations were Sipiso-piso River and Silang River. Meanwhile, those which have high TDS were Silang River and Boho River. Sipiso-piso River on the north side of the lake has been known as a catchment with intensive use, especially for agriculture. Simultaneously, the Silang River on the southwest side of the lake has been known as an inlet, which is the largest catchment with the most significant water input to the lake. Levels of TSS are a good picture of erosion rates in a catchment, as models show that conditions related to sedimentation rates of waters body are mainly affected by the catchment area [14].

A load of dissolved organic material in aquatic ecosystems is a combination of various organic compounds originating from the catchment area (allochthonous material) and the results of the primary production and decomposition process in the waters (autochthonous). During the fluvial flow, organic matter movements undergo a microbiologically continuous process and contribute to the ecological and biochemical condition [18]. The COD reflects the level of organic pollution in the waters and is associated with domestic pollutants, mainly from the catchment area.

The Indonesian Government Regulation number 82/2001 refers to the water quality standards class (water class) in Indonesia, and one of the considered water quality parameters is COD. Water quality standards are set on water sources related to the quality level for human utilization. The lake's inlets' water quality was water class III and IV, with the COD level ranging from 28.2 to 70.4 mg/L (Fig. 3). Referring to COD data, some of the inlet rivers entering Lake Toba have indicated a bad water quality condition (water class III). Even River Silang, Sipiso-piso, Parapat, and Naborsahan were classified into class IV, indicated a high domestic activity on the watershed.

High community activity has been seen in Lake Toba's surrounding area, both in the catchment and water areas. Besides the dense and widespread human settlements in the catchment area, there were also agricultural and plantation activities. The Parapat City, where the Naborsahan river dan Parapat river flow, is the leading tourist destination of Lake Toba. The city has a dense population and a high economic activity. This is supposed to contribute to the anthropogenic load on the rivers. Factors of climate, geomorphology, land use and vegetation structure in the watershed contribute to water quality in inland waters. Mainly, land use and land cover contribute dominantly to the supply of dissolved organic matter and influence the organic material quality through biochemical and degradation processes [19].

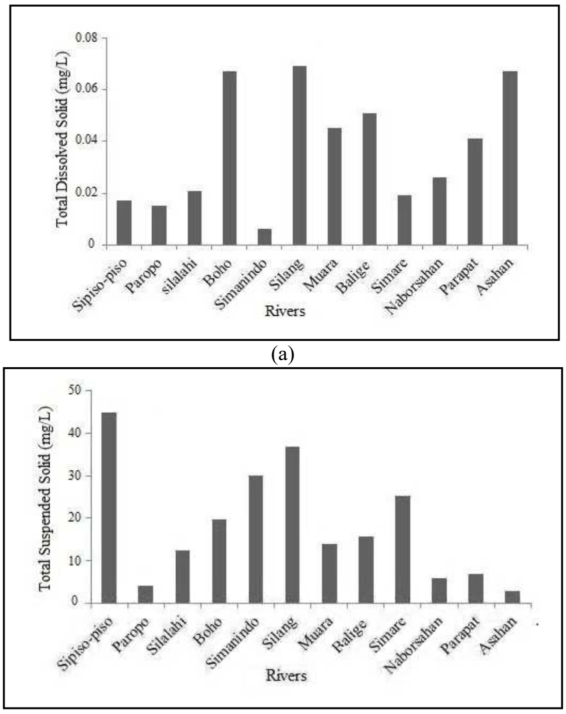

Fig. 2 The level of (a) TDS and (b) TSS in Lake Toba inlets

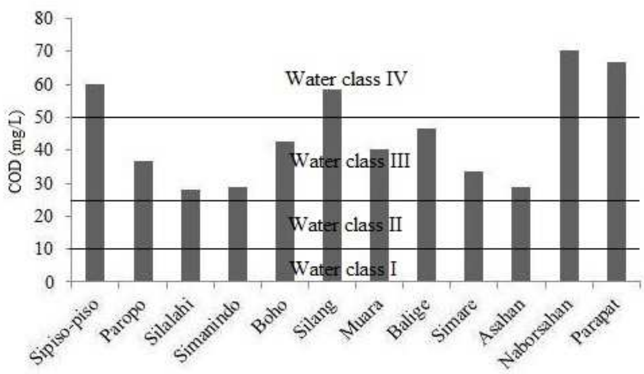

Fig. 3 Water classes at Lake Toba inlets based on COD values

Note: the water class criteria were based on COD (in mg/L) (Indonesian Gover. Reg. number 82/2001). Water class (mg/L) I: $\leq$10; II: $\leq$25; III: $\leq$50; IV: >50

Observed TP at inlets showed that the TP supply was quite high, especially in the Parapat and Naborsahan rivers. Based on an instantaneous TP loading, the Parapat River was the highest (0.203 mg/L), whereas referring to yearly loading estimation, the Silang River was the highest (32.4 tonnes) (Table 1).

Land-use changes have a high impact on water quality. In this case, forest degradation and agriculture were highly correlated with water quality chemical and physical parameters. In Malaysia, forest degradation, urban development, and agricultural activities were the primary sources of water quality deterioration, indicated by the impact of urban land use (87%), agricultural land use (82%), forest land use (77%), and other land use (44%) [20].

TP's watershed contribution to the lake was estimated to reach about 138,500 kg/year, while those flowing out via the River Asahan as the lake's outlet reached 131,373 kg/yr. The Silang River has been the highest TP contributor (32.4

tonnes/yr.), while the highest TP concentration has been found in the River Parapat (0.203 mg/L) (Table 1). Based on the input and output data, with no other activities, the estimated TP accumulation in Lake Toba was 7.124 kg/yr or about 7.1 tonnes/yr.

The water quality conditions could be a reflection of the land-use profile in the catchment area, namely: i) upstream region with extensive vegetation coverage condition showing the best water quality; ii) in the middle region with extensive land use for agriculture characterized by high concentrations of nitrogen and phosphorus, and 3) the lower region with high settlement and urbanization indicated by high total and fecal coliform and ammonia nitrogen [21].

The water quality of Lake Toba waters was defined by temperature ranging between 24.5 to 28.6, reflecting a natural condition. The pH tends to be alkaline (7.9 – 8.8). Conductivity was reasonably similar, around 0.11 mS/cm, and turbidity with a maximum of 7.7 NTU was low. The range of Secchi transparency depth was 3.7 – 7.1 m, the shallowest in Simanindo and the deepest in South Lake Toba waters. Based on the Secchi depth and referring to the Indonesian Ministry of Environment Regulation number 28/2009, Lake Toba waters trophic status is mesotrophic to eutrophic condition (Fig. 4).

The health of aquatic ecosystems will reflect the catchment area's health that flows into the lake waters. Therefore, the lake condition is strongly influenced by internal conditions (aquatic ecosystem) and external factors (catchment area). Nutrient phosphorus is considered a key factor affecting lake water quality and determines the lake's primary productivity [16], [22].

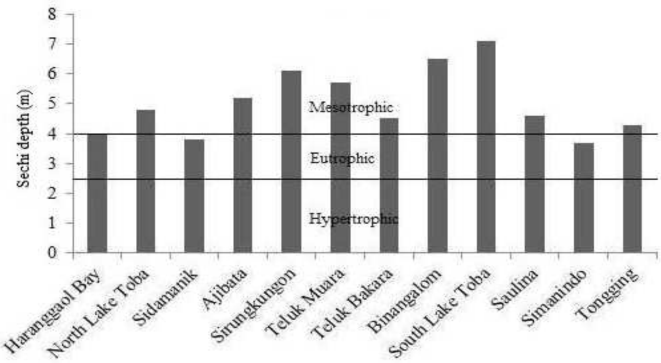

Fig. 4 Secchi depth and trophic status condition of Lake Toba waters

The impact of cage aquaculture activities on lake water quality was assessed from the COD level as a base of water quality standard of water class determination (Indonesian Govern. Reg. number 82/2001) and vertical profile of dissolved oxygen. Based on measured data, the water class in cage aquaculture (CA) and non-cage aquaculture (NCA) areas were almost the same, but there was a tendency that in the CA, the water class was III and IV while in the NCA was III (Fig. 5).

TABLE I
INSTANTANEOUS LOAD OF TP FROM RIVERS AS INLET AND OUTLET OF LAKE TOBA

Station	Name of Rivers	Instantaneous Flow rate (m^3/sec.)[1)]	Instantaneous TP Loading (mg/L)	TP Loading (estimation) (ton/yr.)
Inlets				
1	Sipiso-piso	2.79	0.142	12.494
2	Paropo	1.41	0.083	3.691
3	Silalahi	0.81	0.129	3.295
4	Simanindo	0.93	0.116	3.402
5	Boho	3.77	0.112	13.316
6	Silang[2)]	10.61	0.097	32.444
7	Muara	0.71	0.041	0.918
8	Balige	1.42	0.095	4.254
9	Simare	3.4	0.103	11.044
11	Naborsahan	2.51	0.110	8.707
12	Parapat	0.67	0.203	4.289
	Others	49.57[4)]	0.026[3)]	40.644
	Total	78.60[6)]		138.498
Outlet				
10	Asahan	100[5)]	0.053	131.373

Source of data: 1) Observed (Nov. 2017); 2) Oct. 2009 [24]; 3) The lowest value (Oct. 2009) [24]; 4) Est.: residual catchment flow rate = total flow rate - measured flow rate [19]; 5) River Zona Board of Sumatra II, 2008. (Hydrological Report; *Unpublished*); 6)

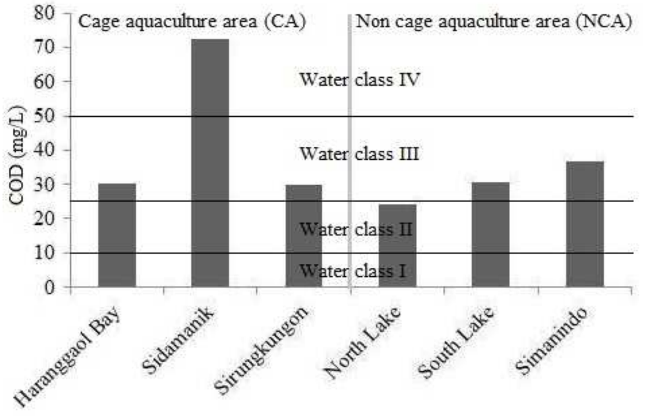

Fig. 5 Water class of cage aquaculture and non-aquaculture areas base on COD (Refers to Indonesian Govern. Reg. Number 82/2001)

Based on the COD level, Lake Toba waters have classified as water class III, even in the CA area, classified as water class IV. This condition is the impact of organic load both from the aquaculture activities and catchment area. The presence of organic matter impacts the availability of oxygen in the water column, particularly in the hypolimnion area.

The input of organic material is often not be considered in relation to the observation of lake waters condition. Meanwhile, as is known, organic material could have an impact on oxygen availability [25], especially in the hypolimnion zone, and the catchment area also contributes to the hypolimnion condition [26]. Thus, organic materials, which are indicators of domestic pollution, are important to be considered. Due to fish production and used feed with a food conversion ratio (FCR) 1.23, the activity related to cage aquaculture activity in Lake Toba would contribute to organic material loading of about 14.26 tons and the TP loading of about 570 tons/year to the lake waters (Table 2).

TABLE II
PREDICTION OF PHOSPHORUS LOADING FROM AQUACULTURE ACTIVITY IN CAGE SYSTEM

Production of fish (tonnes)[1)]	62,023.3
Estimated feed used (tonnes)[a)]	76,288.66
P content on feed (tonnes)[b]	915.46
P retention by fish (tonnes)[c)]	345.13
P release from faeces (tonnes)[e)]	192.25
load of dissolved phosphorus in the form of metabolite residues (tonnes)[f)]	378.09
Total P release to the waters (tonnes)	570.33

Source:1) Marine and Fisheries Board of North Province Sumatra, 2016 (Aquaculture Statistic Report, 2015; unpublished). 2)Reference [29] a) FCR Nile tilapia = 1.23 ; b) 1.2% of feed; c) 37.7% from P content of feed; d) 21.0% from P content; e) 41.3% from P content of feed

From computation of P loading to the lake (Equation 1, 2, and 3):

With J_{PR} = 2,047 ton/yr. [27]
J_E = 138.498 ton/yr. (Table 1)
J_A = 570.33 ton/yr. (Table 2)

$$\text{then: } J_T = 138.498 + 2.047 + 570.33 = 710.875 \text{ ton/yr.} = 710.875 \times 10^9 \text{ mg/yr.}$$

$$\text{with } A_0 = 1.124 \times 10^6 \text{ m}^2 \text{ [28]}$$

$$\text{So that } L_T = \frac{710.875 \times 10^9 \text{ mg/year}}{1.124 \times 10^6 \text{ m}^2} = 632.45 \text{ mg/m}^2\text{/yr.}$$

Therefore, the estimated TP load to the lake is 632.5 mg/m^2/yr. The amount of released TP from the cage aquaculture activity is four times higher than the TP supply carried through the inlet of the lake. The TP loading from cage aquaculture activity is high. Cage aquaculture activity in Lake Toba has been very prominent and has exceeded the carrying capacity if it refers to oligotrophic status waters condition [9], [30].

For a comparison, cage aquaculture of *O. mykiss* in cascade reservoirs of the Yellow River in China released about 77 tonnes of TP at fish production of 13,800 tonnes [31]. This can be considered a minor nutrient enrichment from cage aquaculture due to a relatively small production scale, high water exchange rate related to high water flow, and management measures in the upstream Yellow River. Meanwhile, the potential loss of phosphor from cage aquaculture activity in Lake Maninjau, Indonesia, was 387 tons at fish production of 36,217 tons in 2011 namely released through the feces 130 tons and wasted as dissolved 257 tons [32].

TP's total input to lake waters from the catchment area and cage aquaculture amounted to 632.45 tons/year (0.63 g/m^2/year). The TP input into Lake Toba has exceeded the allowed limit and passed the lake's carrying capacity. For lakes with 200-meter-average depth (Avg. Lake Toba depth = 228 m [28], the allowed TP input is about 0.6 g/m^2/yr [15]. Based on TP concentration and referring to the Indonesian Minister of Environment regulation number 28/2009, Lake Toba water's trophic status was mesotrophic to eutrophic conditions. Two locations that still show mesotrophic conditions were Porsea (Sta. 7) and Saulina (Sta 13) (Fig. 6).

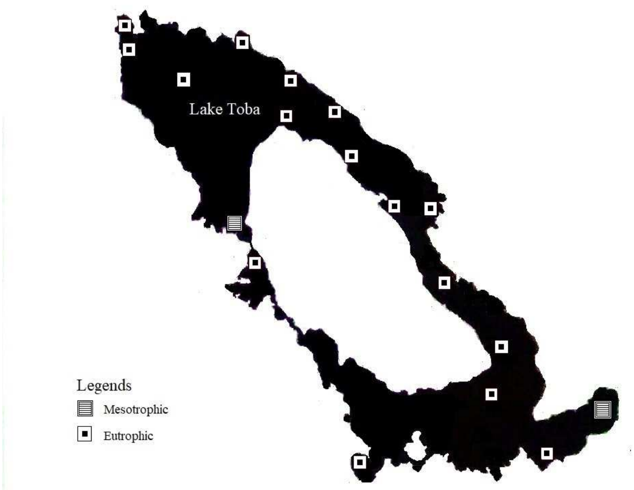

Fig. 6 Lake Toba trophic status based on this study

Overloading TP into Lake Toba can be observed from Lake Toba's trophic status that generally in mesotrophic to eutrophic conditions. This is in line with a study reported that Lake Toba's trophic status based on TP content was between oligotrophic to hypereutrophic [24]. In relation to lake management and restoration planning, information on phosphor loading from external and internal waters is important. Therefore, information related to phosphorus balance is needed for estimating phosphorus load to waters. Increasing the supply of phosphor has a severe long-term influence on freshwater ecosystems, and significant efforts are needed to reduce this supply. Mitigation of eutrophication in an aquatic ecosystem requires a well understanding of factors that controlling phosphor transport from both the catchment area and internal process such as resuspension from sediment [33].

The presence of cage aquaculture appears to have an impact on dissolved oxygen in the water column vertically. The waters depth that still has suitable oxygen for animal life ($\geq$ 2 mg/L) in CA was much shallower (maximum 65 m) than in NCA (maximum 103 m). The anoxic water column in CA has been found maximum at 70 m depth, while in NCA was until on 417 m depth (Fig. 7).

Various factors play a role in oxygen distribution in stratified lakes, such as the hydrodynamic conditions, the oxygen supply from the photosynthetic activity, and oxygen utilization for metabolic activity and chemical oxidation. Anthropogenic activity plays a role in increasing the nutrient supply and the impact on the rising of phytoplankton growth in the aquatic ecosystem. The further decomposition of the associated organic matter has increased the lake hypolimnetic hypoxia layer [34].

The existence of cage aquaculture activity has significantly increased the anoxic column's thickness in the hypolimnion layer. Cage aquaculture has supplied organic material that causes metabolic activity in the water column much higher than in the NCA. In Lake Toba, to produce 62,023 tons of fish in the cage system, 76289 tons of feed is required (Table 2). This shows that organic load from cage aquaculture activities can roughly reach 14,266 tons/year.

Oxygen utilization on the water column in the CA area was more intensive than in NCA. In a study conducted by [28] in NCA of Lake Toba, the minimum level of dissolved oxygen (<2 mg/L) was started at 200 m depth of water column. Accumulation of organic matter and other substances at the bottom of the waters causes oxygen depletion in the region. The remineralization of organic matter, either directly through respiration or indirectly through metabolite oxidation, would consume available oxygen [35].

The hypolimnion's oxygen consumption is the impact of organic matter mineralization that is settling from the productive zone, diffusion of oxygen to the sediment, and reducing compounds diffusing from the sediment. Thus, the amount of organic material that sinks would determine the area of oxygen consumption in the lake's deeper layers [36]. In Lake Toba, which is typically stratified [13], oxygen exchange from the epilimnion layer to the hypolimnion layer will be obstructed by the metalimnion layer that likely makes the anoxic condition to be persistent. On the other hand, community activities in the catchment area and cage aquaculture in the continuously growing waters will significantly increase the supply of allochthonous material. This condition may increase the anoxic water column width. The threat of climate change that is widely studied in temperate lakes, which results in a decrease in DO concentrations and expands the stratification period [37] is another factor that led to the worsening of Lake Toba waters conditions.

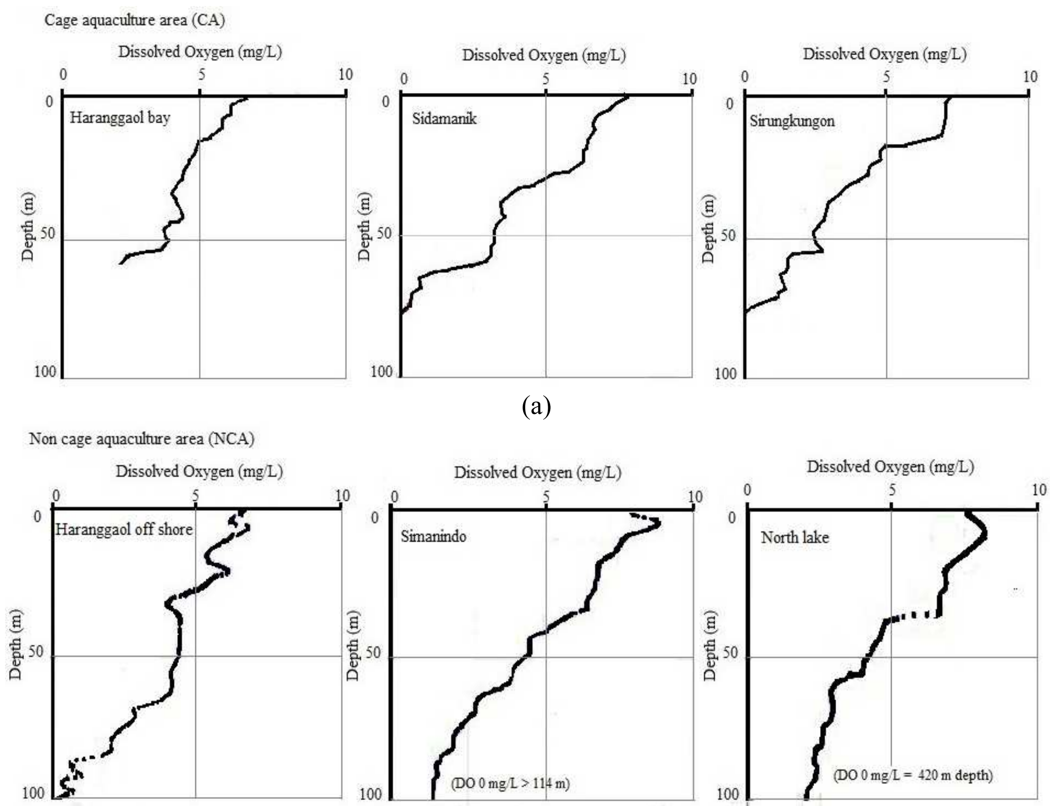

Fig. 7 Critical DO ($\leq$ 2 mg/L) and the start of anoxic conditions ($\approx$ 0 mg/L) in (a) cage aquaculture area (CA) and (b) non cage aquaculture area (NCA).

Note: i) Based on Rinko profiler measurement; ii) Haranggaol bay is a shallow waters; iii) Measurements at Simanindo did not reach maximum depth, because the weather condition was bad (DO was 1.8 mg/L at 114 m water depth) universal soil loss equation and GIS techniques," *Water (Switzerland)*, 2020, doi: 10.3390/w12010135.

IV. Conclusion

Pollution loads into Lake Toba waters originate from activities in the catchment and the waters themselves, including organic matter and phosphorus components. The impact caused by the pollution load is eutrophication that leads the water class worse and reduces the oxic column in the hypolimnion. Cage aquaculture activities need special attention because besides supplying relatively high TP, which stimulates eutrophication, they are also supplying high organic waste in feces and uneaten food, which will cause high COD and anoxic conditions at the bottom part of the lake.

Acknowledgment

This paper is a part of the Study of Lake Toba Environmental Carrying Capacity that received funding from Perum Jasa Tirta I- Malang. This research was also partially funded by LIPI-Research Center for Limnology.

References

[1] J. P. Jenny *et al.*, "Scientists' Warning to Humanity: Rapid degradation of the world's large lakes," *Journal of Great Lakes Research*. 2020, doi: 10.1016/j.jglr.2020.05.006.

[2] C. Mammides, "A global assessment of the human pressure on the world's lakes," *Glob. Environ. Chang.*, 2020.

[3] D. C. Richardson, C. C. Carey, D. A. Bruesewitz, and K. C. Weathers, "Intra- and inter-annual variability in metabolism in an oligotrophic lake," *Aquat. Sci.*, 2017, doi: 10.1007/s00027-016-0499-7.

[4] S. R. Carpenter, E. G. Booth, and C. J. Kucharik, "Extreme precipitation and phosphorus loads from two agricultural watersheds," *Limnol. Oceanogr.*, 2018, doi: 10.1002/lno.10767.

[5] G. Muri *et al.*, "Factors that contributed to recent eutrophication of two Slovenian mountain lakes," *J. Paleolimnol.*, 2018.

[6] H. Du *et al.*, "Evaluation of eutrophication in freshwater lakes: A new non-equilibrium statistical approach," *Ecol. Indic.*, 2019, doi: 10.1016/j.ecolind.2019.03.032.

[7] K. Havens and E. Jeppesen, "Ecological responses of lakes to climate change," *Water (Switzerland)*. 2018, doi: 10.3390/w10070917.

[8] Lukman, M. S. Syawal, and M. Maghfiroh, "Sumatran major lakes: limnological overviews," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 535, no. 1, p. 012064, Aug. 2020, doi: 10.1088/1755-1315/535/1/012064.

[9] H. A. Rustini, E. Harsono, and I. Ridwansyah, "Potential area for floating net fishery in Lake Toba," in *IOP Conference Series: Earth and Environmental Science*, Feb. 2018, vol. 118, no. 1, p. 012032.

[10] A. H. Harianja, A. E. Suoth, E. Nazir, G. S. Saragih, R. Fauzi, and M. Y. Hidayat, "Impact of land use and socio-economic changes in water catchment area on total suspended solid (TSS) in Lake Toba," in *IOP Conference Series: Earth and Environmental Science*, Dec. 2019, vol. 407, p. 012005, doi: 10.1088/1755-1315/407/1/012005.

[11] B. A. Biddanda *et al.*, "Chronicles of hypoxia: Time-series buoy observations reveal annually recurring seasonal basin-wide hypoxia in Muskegon Lake – A Great Lakes estuary," *J. Great Lakes Res.*, 2018.

[12] L. L. Yuan and J. R. Jones, "Modeling hypolimnetic dissolved oxygen depletion using monitoring data," *Can. J. Fish. Aquat. Sci.*, 2020, doi: 10.1139/cjfas-2019-0294.

[13] T. Fukushima, B. Matsushita, L. Subehi, F. Setiawan, and H. Wibowo, "Will hypolimnetic waters become anoxic in all deep tropical lakes?," *Sci. Rep.*, 2017, doi: 10.1038/srep45320.

[14] R. B. Baird, A. D. Eaton, and E. W. Rice, *Standard Methods for the Examination of Water and Wastewater, American Public Health Association*. 2017.

[15] P. J. Dillon and F. H. Rigler, "A Simple Method for Predicting the Capacity of a Lake for Development Based on Lake Trophic Status," *J. Fish. Res. Board Canada*, 1975, doi: 10.1139/f75-178.

[16] S. A. Akrasi, "The assessment of suspended sediment inputs to Volta Lake," *Lakes Reserv. Res. Manag.*, 2005.

[17] P. Chuenchum, M. Xu, and W. Tang, "Estimation of soil erosion and sediment yield in the lancang-mekong river using the modified revised universal soil loss equation and GIS techniques," *Water (Switzerland)*, 2020, doi: 10.3390/w12010135.

[18] T. Lambert and M. E. Perga, "Non-conservative patterns of dissolved organic matter degradation when and where lake water mixes," *Aquat. Sci.*, 2019, doi: 10.1007/s00027-019-0662-z.

[19] S. Singh, P. Dash, S. Silwal, G. Feng, A. Adeli, and R. J. Moorhead, "Influence of land use and land cover on the spatial variability of dissolved organic matter in multiple aquatic environments," *Environ. Sci. Pollut. Res.*, 2017, doi: 10.1007/s11356-017-8917-5.

[20] M. Camara, N. R. Jamil, and A. F. Bin Abdullah, "Impact of land uses on water quality in Malaysia: a review," *Ecological Processes*. 2019, doi: 10.1186/s13717-019-0164-x.

[21] A. J. Rodríguez-Romero, A. E. Rico-Sánchez, E. Mendoza-Martínez, A. Gómez-Ruiz, J. E. Sedeño-Díaz, and E. López-López, "Impact of changes of land use on water quality, from tropical forest to anthropogenic occupation: A multivariate approach," *Water (Switzerland)*, 2018, doi: 10.3390/w10111518.

[22] N. Kuczyńska-Kippen and T. Joniak, "Chlorophyll a and physical-chemical features of small water bodies as indicators of land use in the Wielkopolska region (western Poland)," *Limnetica*, 2010.

[23] M. Søndergaard, T. L. Lauridsen, L. S. Johansson, and E. Jeppesen, "Nitrogen or phosphorus limitation in lakes and its impact on phytoplankton biomass and submerged macrophyte cover," *Hydrobiologia*, 2017, doi: 10.1007/s10750-017-3110-x.

[24] S. Nomosatryo and Lukman, "Nitrogen (N) and phosphorus (P) nutrients availability in Lake Toba Norh Sumatra Indonesia," *Limnotek*, vol. 18, no. 2, pp. 127–137, 2011.

[25] T. Steinsberger, R. Schwefel, A. Wüest, and B. Müller, "Hypolimnetic oxygen depletion rates in deep lakes: Effects of trophic state and organic matter accumulation," *Limnol. Oceanogr.*, 2020, doi: 10.1002/lno.11578.

[26] R. Marcé, E. Moreno-Ostos, P. López, and J. Armengol, "The role of allochthonous inputs of dissolved organic carbon on the hypolimnetic oxygen content of reservoirs," *Ecosystems*, 2008.

[27] Lukman, "Evaluasi keseimbangan fosfor di Danau Toba (Evaluation of phosphor balance in Lake Toba)," in *Prosiding Seminar Nasional Limnologi VI tahun 2012*, 2012, pp. 423–431.

[28] Lukman and I. Ridwansyah, "Kajian morfometri dan beberapa parameter stratifikasi perairan Danau Toba (Study of morphometry and several parameters of Lake Toba stratiphication)," *Limnotek*, vol. 17, no. 2, pp. 158–170, 2010.

[29] Z. I. Azwar, N. Suhenda, and O. Praseno, "Manajemen pakan pada usaha budi daya ikan dalam karamba jaring apung (Fish Feeding Management in Cage Aquaculture)," in *Pengembangan Budi Daya Perikanan di Perairan Waduk*, A. Sudradjat, S. E. Wardoyo, Z. I. Azwar, H. Supriyadi, and B. Priono, Eds. Pusat Riset Perikanan Budidaya. BRKP. DKP, 2004, pp. 37–44.

[30] A. Sunaryani, E. Harsono, H. A. Rustini, and S. Nomosatryo, "Spatial distribution and assessment of nutrient pollution in Lake Toba using 2D-multi layers hydrodynamic model and DPSIR framework," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 118, p. 012031, Feb. 2018.

[31] S. Miao *et al.*, "Long-term and longitudinal nutrient stoichiometry changes in oligotrophic cascade reservoirs with trout cage aquaculture," *Sci. Rep.*, 2020, doi: 10.1038/s41598-020-68866-7.

[32] Lukman, I. Srtyobudiandi, I. Muchsin, and S. Hariyadi, "Impact of Cage Aquaculture on Water Quality Condition in Lake Maninjau, West Sumatera Indonesia," *Int. J. Sci. Basic Appl. Res.*, vol. 23, no. 1, pp. 120–137, 2015.

[33] P. Leinweber *et al.*, "Handling the phosphorus paradox in agriculture and natural ecosystems: Scarcity, necessity, and burden of P," *Ambio*, 2018, doi: 10.1007/s13280-017-0968-9.

[34] J. P. Jenny *et al.*, "Urban point sources of nutrients were the leading cause for the historical spread of hypoxia across European lakes," *Proc. Natl. Acad. Sci. U. S. A.*, 2016, doi: 10.1073/pnas.1605480113.

[35] J. Rhodes, H. Hetzenauer, M. A. Frassl, K. O. Rothhaupt, and K. Rinke, "Long-term development of hypolimnetic oxygen depletion rates in the large Lake Constance," *Ambio*, 2017.

[36] B. Müller, T. Steinsberger, R. Schwefel, R. Gächter, M. Sturm, and A. Wüest, "Oxygen consumption in seasonally stratified lakes decreases only below a marginal phosphorus threshold," *Sci. Rep.*, 2019.

[37] S. Missaghi, M. Hondzo, and W. Herb, "Prediction of lake water temperature, dissolved oxygen, and fish habitat under changing climate," *Clim. Change*, 2017, doi: 10.1007/s10584-017-1916-1.