Analysis of main components of Lake Toba's water quality in different seasons

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ABSTRACT

Lake Toba is one of the largest lakes in North Sumatra Province, Indonesia. Its waters are used for multiple purposes, constituting an important natural and economic resource. Most of the waters of Lake Toba come from the overflow of disposal of agriculture, livestock, fisheries, tourism, households, and other activities. The present study identified water quality based on total nitrogen, total phosphorus, chlorophyll-a and other water quality parameters carried out at 60 sampling sites grouped into 6 observation stations, *i.e.*, control areas (located in the middle and far from direct activities), community floating net cages, company floating net cages, settlement, hospitality, and river mouths. The main water quality components were very dynamic at the monitoring stations in three seasons (rainy, transition, and dry). Total nitrogen concentration tended to be higher in the rainy season than in the transition and dry seasons. However, all stations tended to be classified as mesotrophic or higher in all seasons, with total nitrogen concentrations greater than 12.5 mg L^{-1}. Total phosphorus at the six stations was highly dynamic in all seasons and tended to decrease in the dry season. The concentration of total phosphorus was higher at the settlement and hospitality stations than at the other stations. The total phosphorus of the settlement and hospitality stations reached 0.18 mg L^{-1} and 0.17 mg L^{-1}, respectively, in the rainy season. In general, total phosphorus concentrations in the waters of Lake Toba were above 0.1 mg L^{-1}, which allowed the lake to be classified as above mesotrophic status.

Introduction

Lake Toba is located in North Sumatra Province, and is the largest lake in Southeast Asia. The surface area, water volume, and maximum depth of Lake Toba are 1,124 km^2, 256.2×10^9 m^3, and around 508 m, respectively (Garno *et al*., 2020). Lake Toba is surrounded by seven regencies, *i.e.*, North Tapanuli, Simalungun, Dairi, Humbang Hasundutan, Karo, Samosir, and Toba Samosir. Lake Toba provides many ecological and economic benefits. Ecologically, Lake Toba is a habitat for various endemic and non-endemic freshwater organisms. Anggreini and Supriyadi (2019) documented the presence of several fish species in Lake Toba, including Batak fish (*Tor douronensis* Valenciennes), Mozambique tilapia (*Oreochromis mossambicus* Peters), Nile tilapia (*Oreochromis niloticus* Linnaeus), marble goby (*Oxyeleotris marmorata* Bleeker), cork (*Channa striata* Bloch), goldfish (*Cyprinus carpio* Linnaeus), bilih (*Mystacoleucus padangensis* Bleeker), Java barb (*Barbonymus gonionotus*

Bleeker), and betok fish (*Anabas testudineus* Bloch). Economically, Lake Toba is currently used as a water source for people's daily needs, such as drinking water and clean water. In addition to being a tourist destination, Lake Toba is also an important site for floating net cages for fish farming and marketing.

Currently, Lake Toba is used for community livelihoods (household needs, including drinking water sources) and other industrial activities (tourism, agriculture, fisheries, and livestock). Human activities, such as fishing and fish farming in floating net cages, settlements, agriculture, livestock, and tourism, can be a source of pollution in Lake Toba. Some reports indicate that the current status of Lake Toba waters is getting worse every year (Lukman *et al*., 2021; Barus *et al*., 2022). Since 2009, the lake shifted from oligotrophy to mesotrophy (Barus *et al*., 2022). It would be difficult to avoid this condition because most human activities surrounding Lake Toba originate from and drain into the lake. Consequently, the capacity of the water body is reduced due to the high concentration of agricultural fertilizers dissolved in water, domestic waste discharged into the lake, feed and fecal residues from fish farming on floating net cages, and other excess organic waste. Excessive organic waste from floating net cages stimulates the decomposition process, leading to a decrease in dissolved oxygen and an increase in H_2S, ammonia, nitrogen, and phosphorus compounds (Garno *et al*., 2020).

The various development activities in the Lake Toba area, which are increasing rapidly, require various studies on the relationship between nutrient conditions and water inputs. Water quality analysis, including physical, chemical, and biological parameters, continues to be carried out to determine the current status of the Lake Toba environment. Not only physical and chemical variables are monitored, but biological variables are also assessed to determine water quality. Phytoplankton is one of the aquatic organisms playing a key role as primary producers in the water. Phytoplankton respond to changes in water conditions with changes in abundance, species number, and community structure (Ferreira *et al*., 2011). The abundance of phytoplankton is influenced by several factors, including nutrients, light conditions, temperature, pH, and predation by zooplankton and planktivorous fish (Lau and Lane, 2002; Jiang *et al*., 2014). In turn, these factors are also strongly influenced by the seasonal climate.

Based on the above considerations, the main objective of this work was to assess the current trophic status of Lake Toba in three different climatic seasons, *i.e.*, rainy, transition, and dry seasons. The main sources of pollution affecting the trophic level of Lake Toba were identified by measuring nutrients and phytoplankton biomass (UNEP-ILEP, 1990). Several points are considered as water sources or suppliers relevant for the study, *i.e.*, control areas, settlements, hospitality, community floating net cages, company floating net cages, and the river mouth. Therefore, another important objective of this work was to assess the potential conflicts arising from the use of water resources for multiple purposes.

Materials and Methods

Description of the study area

This research was carried out from 2020 to 2021 in Lake Toba, North Sumatra Province, Indonesia, during the three main seasons defined by the regional weather forecast information by the Meteorology, Climatology and Geophysics Agency (BMKG; available from http://www.bmkg.go.id) (rainy, transition, and dry). Samples were collected in February 2020 (rainy season), March 2021 (transition season), and August 2021 (dry season). A total of 2 L of water was collected at 60 sites representing 6 observation stations, *i.e*., control (sites away from various human activities), settlements, hospitality (hotels and restaurants), community floating net cages, company floating net cages, and river mouths (Supplementary Figure 1; Supplementary Table 1). The identification of the six categories is based on the assessment of activities that mainly affect the water entering Lake Toba. Samples from each station were taken from 3 integrated water layers, *i.e*., 0-1 m, 2-3 m, and 3-6 m (Supplementary Figure 1).

The measurement of water quality

The variables measured in this study included water temperature (°C), Dissolved Oxygen (DO, mg L^{-1}), Total Nitrogen (TN, mg L^{-1}), Total Organic Matter (TOM, mg $KMnO_4$ L^{-1}), Total Phosphorus (TP, mg L^{-1}), chlorophyll-a (APHA, 2005), and brightness and water transparency.

TOM measurement was carried out according to SNI 06-6968.22-2004 (Indonesian National Standard) with the following formula:

$$TOM = \frac{(X-Y)\times 31.6 \times 0.01 \times 1000}{V} \quad (1)$$

where:
TOM: Total Organic Matters (mg L^{-1})
X: titrant volume for water sample (mL)
Y: titrant volume for aquadest (blank solution) (mL)
31.6: 1/5 from molecular weight of $KMNO_4$
0.01: normality of $KMNO_4$
V: sample volume (mL)

Brightness was measured following (Carlson, 1977):

$$TSI\ (SD) = 10\left(6 - \frac{\ln SD}{\ln 2}\right) \quad (2)$$

where:
TSI: Tropic State Index
SD: Secchi Disk depth (m)

TSI and chlorophyll-a concentration were measured following (Carlson, 1977):

$$TSI\ (ChlA) = 10\left(6 - \frac{2.04 - 0.68 \ln ChlA}{\ln 2}\right) \quad (3)$$

where:
ChlA: Chlorophyll-a concentration (mg m^{-3}) (Simon and Helliwell, 1998)

TSI and total phosphorus were measured following (Carlson, 1977):

$$TSI\ (TP) = 10\left(6 - \frac{\ln(\frac{48}{TP})}{\ln 2}\right) \quad (4)$$

where:
TP: Total Phosphorus concentration (mg m^{-3})

Kratzer and Brezonik (1981) developed Carlson's TSI equation for total nitrogen as follows:

$$TSI\ (TN) = 10\left(6 - \frac{\ln(\frac{1.47}{TN})}{\ln 2}\right) \quad (5)$$

where:
TN: Total Nitrogen concentration (mg L^{-1})

Data analysis

Data were analyzed using Pearson correlation, simple linear regression, and dendrogram using Minitab 18 software. Sampling stations were grouped based on the similarity of the water quality using the average values assessed by computing cluster (Canberra distance) and biplot analyses (PCA) using the R 4.1.2 software. The cluster plot and biplot analyses used one representative unit per station for a total of six stations.

Results

Water brightness showed significant differences between sampling stations in each season (Table 1; Supplementary Figure 2). In the rainy season, the sampling sites with the highest brightness value were located in the control zones and company floating net cages (5.31 m and 5.62 m, respectively). The higher the brightness value in water. the higher the penetrating light and the lower the organic matter or dissolved particles. The lowest brightness values in each season were found in the hospitality sites, with an average value between 2.08 and 2.92 m (Table 1; Supplementary Figure 2). Excluding the hospitality sites, these values were still within the standard limits set by Minister of Environment Decree No. 51/2004, which states that the brightness level of the waters should be >3 m. In the hospitality sites, water brightness values were in agreement with TOM values, which tended to be stable at a high level in the dry season (see below).

The water temperature was higher in the transition season. The highest temperature, 27.32°C, was found in community floating net cages (Supplementary Figure 3).

The lowest DO was measured at the control station in the transition season (Supplementary Figure 4). Low DO values of <5 mg L^{-1} were found in each season at the control, hospitality, and settlement stations. The highest DO value of >5 mg L^{-1} in each season was consistently found in the company's floating net cage station (Supplementary Figure 4).

The highest level of total nitrogen decreased from the rainy season to the dry season (Supplementary Figure 5). The control station had the highest total nitrogen value, reaching 24.2 mg L^{-1} in the rainy season, while the settlement station had the greatest total nitrogen value of 18.0 mg L^{-1} in the dry season.

High variability of total phosphorus concentrations was observed in several stations of Lake Toba (Table 1; Supplementary Figure 6). The highest values in the rainy, transition, and dry season were measured in the settlement (0.18 mg L^{-1}), control (0.17 mg L^{-1}), and hospitality stations (0.16 mg L^{-1}), respectively (Table 1; Supplementary Figure 6).

In the rainy season, TOM concentration had relatively similar values at each season and station, ranging from 130.4 to 133.9 mg $KMnO_4$ L^{-1} (Supplementary Figure 7). Each station showed a decrease in the TOM concentrations in the dry season. The lowest and the highest TOM values were measured in the control station (87.7 mg $KMnO_4$ L^{-1}) and in the settlement station (125.8 mg $KMnO_4$ L^{-1}) (Supplementary Figure 7).

Chlorophyll-a concentration showed higher variability between stations in the transition season (Table 1; Supplementary Figure 8). In this season, the smallest and largest concentrations were measured in the control station and the community floating net cages, respectively.

The first two dimensions of PCA described the 79.7%

Table 1. The range and average value of the Secchi Disk depth (m), total phosphorus (mg L^{-1}) and chlorophyll-a (μg L^{-1}) in each station during rainy, transition, and dry seasons.

Sampling sites	Rainy						Transition						Dry					
	Secchi disk depth (m)		Total phosphorus (mg L^{-1})		Chlorophyll-a (µg L^{-1})		Secchi disk depth (m)		Total phosphorus (mg L^{-1})		Chlorophyll-a (µg L^{-1})		Secchi disk depth (m)		Total phosphorus (mg L^{-1})		Chlorophyll-a (µg L^{-1})	
	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average
Control	4.00-6.500	5.31	0.08-0.27	0.14	0.00-4.47	2.55	0.30-5.50	3.20	0.04-0.96	0.17	1.66-5.23	3.09	2.00-5.50	3.81	0.06-0.13	0.08	1.64-4.82	3.38
Settlements	0.33-6.00	4.10	0.12-0.42	0.18	1.33-4.42	2.70	1.00-4.50	2.93	0.04-0.30	0.09	2.23-16.65	5.87	0.50-5.00	3.42	0.06-0.38	0.13	0.86-5.81	3.60
Hospitality	0.200-4.00	2.12	0.09-0.28	0.17	1.44-3.84	3.07	0.50-3.50	2.08	0.04-0.14	0.08	2.41-12.20	6.01	1.00-4.50	2.92	0.06-0.41	0.16	2.88-5.84	4.19
Community floating net cages	0.60-5.50	3.48	0.07-0.27	0.11	1.59-6.45	4.20	2.50-5.00	3.57	0.04-0.06	0.05	2.46-22.24	7.92	1.50-6.50	3.15	0.05-0.12	0.07	2.06-4.66	3.47
Company floating net cages	4.50-6.30	5.62	0.08-0.14	0.11	3.40-6.15	4.68	3.40-5.00	3.95	0.04-0.07	0.06	2.36-4.32	3.31	3.00-5.00	3.95	0.06-0.16	0.10	2.65-4.09	3.66
River mouths	0.50-6.50	3.83	0.07-0.27	0.14	1.44-7.00	3.43	1.00-5.50	3.26	0.04-0.14	0.07	1.44-16.65	4.82	0.50-5.50	3.04	0.05-0.18	0.09	1.61-7.21	3.77

(PCA1, 47.6%; PCA2, 32.1%) of the total variance (Supplementary Figure 9). The biplot analysis showed a negative association between TOM and brightness, DO, temperature and, partly, total nitrogen. Also, TOM was positively associated with chlorophyll-a and TP. Hospitality sites showed a higher influence of TOM, TP and, partly, chlorophyll-a. Community floating net cages and river mouths were mostly associated to total nitrogen and temperature. Company floating net cages and control stations were affected by DO and brightness. The settlement station was associated to TP and, partly, TOM.

The observation stations were grouped into two clusters (Supplementary Figure 10), including the control and the company floating net cages stations, and the hospitality, settlement, and river mouths stations, along with, at a higher distance, the community floating net cages. The stations with the highest similarity in water quality characteristics were the settlement and river mouths.

Discussion

The characteristics of the waters of Lake Toba were very dynamic from time to time, changing from one station to another. The variability can be caused by the high waves that even reach 2.5 m in each season, which stirs the water body and affects the movement of the water.

Generally, the highest brightness values were found at the company's floating net cages during the rainy season, while the lowest brightness values were found at the hospitality stations during the transition season (Table 1; Supplementary Figure 2). The high brightness level in the company floating net cages might be due to the proper selection of the sites, which are characterized by high depths, and to the large amount of organic and inorganic compounds that are transported by water currents to other stations. In contrast, the low level of brightness at the river mouth was presumably due to the carrying of particles into the water flow (runoff) resulting from anthropogenic activities, such as agriculture, animal husbandry, households, and others, from land to the lake.

The highest temperature was observed at the community floating net cages sites during the transition season, while the lowest temperature was observed at the settlement sites during the transition season (Supplementary Figure 3). The water temperature of the six stations remained within the acceptable levels according to the Regulation of the Minister of Health (Permenkes), Republic of Indonesia, No. 32/2017 concerning the environmental health quality standards and water health requirements for the needs of sanitary hygiene, swimming pool, solus per aqua (health through water), and public baths. The low temperature in a water body is a consequence of the lack of sunlight penetration (Parker, 2012). Solar radiation, air temperature, weather, and climate are several factors that affect water temperature distribution (Boyd, 2015). The low temperature detected at the settlement, reaching 24.73°C in dry seasons, could be affected by the high turbidity caused by organic and inorganic particles (Supplementary Figure 3). In the dry season, the inflow of water from settlement, hospitality, agriculture and all water sources into the lake directly affects its turbidity. During the dry season, there will be an increase in dissolved particles in the water, which will inhibit water productivity and increase the turbidity level. In addition, an increase in organic and inorganic particles in the water can limit the penetration of sunlight and cause uneven photosynthetic processes in the water, especially in deep areas. This result was in line with the TOM concentrations, which were stable at a high level in the settlement (Supplementary Figure 7). Low temperatures can constrain the metabolism of aquatic biota. Activity in some fish populations decreases at temperatures <20°C (Parker, 2012), and the ideal temperature for the *Tilapia* group is between 26.1 and 32.2°C or between 26 and 30°C (De *et al*., 2016).

The highest DO concentrations were measured in the company's floating net cages during the dry season, while the smallest DO concentrations were measured at the control stations in the transition season (Supplementary Figure 4). Similar to the brightness level, the high oxygen levels in the company floating net cages are thought to be due to the proper selection of the sampling sites, taking into account the depth and underwater currents so that the oxygen level tends to be higher than the other stations. Further, high DO levels could be affected by the high brightness level, leading to a high light penetration and photosynthesis activity by phytoplankton. In addition, the intensity of sunlight during the dry season is high, which promotes the photosynthetic process of plankton in the waters around the company's floating net cages and increases the DO concentration (Garno *et al*., 2020). Conversely, the low DO concentrations might be caused by the high turbidity level because of dissolved organic matter or suspended particles which directly and indirectly affect the level of brightness and DO. The DO concentrations in Lake Toba are still within the tolerance range for aquatic biota according to the standard quality of >5 mg L^{-1} set by the Indonesian government on the Decree of the State Minister of Environment No.51/2004.

The average total nitrogen in Lake Toba waters ranged from 12.5 to 26.9 mg L^{-1} (Supplementary Figure 5). According to the Decree of the State Minister of Environment No.42, the threshold concentration of ammonia (NH_3-N) in water is 5 mg L^{-1}. Meanwhile, Governor's Decree No. 45/2002 set that the maximum nitrite (NO_2-N) level in water is 3 mg L^{-1}. Further, according to the Governor's Decree No. 45/2002, the quality standard for water's nitrate (NO_3-N) level is not more than 30 mg L^{-1}. Davidson *et al*., (2015) reported that the high levels of nitrogen contamination in open water areas used by the community can have adverse effects on human health when consumed as drinking water. Wurtsbaugh *et al*., (2019) described that the high nitrogen level in water is able to contribute to the harmful algae blooms threatening the inhabiting organisms. Total nitrogen is one of the test parameters determining the trophic status of lake waters (UNEP-ILEP, 1990). In the present study, the total nitrogen concentrations indicated a trophic status between eutrophy and hypertrophy with values >1.9 mg L^{-1} and a mean value of total nitrogen of >12.5 mg L^{-1} in all stations (KLH, 2009; OECD, 1982; MAB, 1989; UNEP-ILEC, 2001).

In Lake Toba, TP concentrations were relatively high, with an average range of 0.048-0.177 mg L^{-1} in all observation stations (Table 1; Supplementary Figure 6). The high concentration of TP in the settlement during the rainy season was presumably due to the large amount of household waste containing detergents, agricultural activities using fertilizers, household activities residues, and fish or livestock feed leftovers leaching into water bodies. These factors are phosphorus sources promoting fertility in waters. These findings are in line with the study performed by Handayani *et al*., (2011), who reported that the highest phosphate concentration was found in the settlements in Lake Batur, Bangli Regency, Bali Province. According to Carlson (1977), lakes with mean TP concentrations greater than 0.1 mg L^{-1} are classified as eutrophic. Meanwhile, other reports stated that lakes with TP concentrations >0.1 mg L^{-1} are categorized as hypertrophic (KLH, 2009; OECD, 1982; MAB, 1989; UNEP-ILEC, 2001). Therefore, based on the range of TP of 0.005-0.02 mg L^{-1}, the trophic status of Lake Toba was between eutrophy and hypereutrophy. The settlement and hospitality stations had hypertrophic fertility levels in the rainy and dry seasons. In the transition season, hypertrophic fertility was found in the control stations. According to Government Regulation No.82/2001 on management of water quality and control over water pollution, TP concentrations in Lake Toba remained within the acceptable level for public consumption, the maximum acceptable concentration of 0.2 mg L^{-1}.

The average concentration of TOM at the six observation stations ranged from 87.7 to 162.7 mg KMnO4 L^{-1} (Supplementary Figure 7). The concentration of TOM in the Lake Toba waters was very high. The TOM levels were above the findings reported by Lukman *et al.*, (2013), who observed that the highest TOM content in Lake Maninjau was 25 mg KMnO4 L^{-1}. The high TOM in the settlement and hospitality stations might have resulted from river mouth activities around the lake. Organic waste that can pollute the lake comes from the floating net cages and various activities in the surrounding area. Haryadi (2003) also reported that organic wastes entering public waters come from food, excreta, detergents, cleaning agents, oils and fats, suspended materials, residual insecticides, pesticides, and other synthetic materials. Organic wastes, consisting of carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and other elements and minerals entering public waters come from various human activities, including household-scale industry, settlement, livestock, agriculture, and fisheries (Porpraset, 1989). In general, the TOM concentration of Lake Toba exceeded the quality standards set by the Decree of the Minister of State for Population and Environment No. 2/1988 which states that the TOM threshold is 80 mg $KMnO_4$ L^{-1}. Organic wastes are used by heterotrophic microorganisms as energy and carbon sources for their growth resulting in a lack of oxygen in water. The abundance of nutrients triggers the acceleration of the eutrophication process in the reservoir waters. For example, nitrogen and phosphorus in the Cirata reservoir (Indonesia) come predominantly from domestic waste, accounting for 2,111 tons of nitrogen waste per year and 276.6 tons of phosphorus waste per year, while the fishery activity of floating net cages contributes by 6,612 tons of nitrogen waste per year and 1,041 tons phosphorus waste per year (Brahmana and Ahmad, 1997; Garno *et al*., 2002). Likewise, for the Saguling reservoir, the highest annual discharge of nitrogen and phosphorus waste come from household or residential waste (Garno *et al*., 2002).

Trophic and nutrient status greatly influence macro- and microorganisms structure and functionality in water ecosystems. Ions, minerals, inorganic-organic materials, and toxic pollutants originating from point and non-point sources (Davis and Cornwell (1991) strongly affect the survival, diversity, and abundance of macro- and microorganisms. Nutrient levels control the concentrations of chlorophyll-a (a proxy for phytoplankton biomass). In turn, chlorophyll-a content influences light absorption and water transparency. The highest concentration of chlorophyll-a was detected at the community floating net cages during the transition season, and the lowest concentration was at the control stations during the rainy season (Table 1; Supplementary Figure 8). Therefore, the community floating net cages at that time had the highest concentration of phytoplankton. High phytoplankton concentrations can increase the DO concentration in lakes (Hikmawati *et al*., 2014). Generally, the chlorophyll-a concentrations in Lake Toba were between 2-6 μg L^{-1}, which can be included in the eutrophic range (Hakanson & Bryhn, 2008; KLH, 2009; OECD, 1982; MAB, 1989; UNEP-ILEC, 2001).

The increase in TOM concentrations in Lake Toba was associated with a decrease in the brightness and DO (Supplementary Figure 9). In addition, the increase in TOM in the water was accompanied by an increase in chlorophyll-a and TP concentrations (Supplementary Figure 9). The settlement and river mouths had the highest similarity in water quality characteristics (Supplementary Figure 10). This result might be due to waste from the other settlements and surrounding areas affecting the water quality from the river mouth. Pollutants decrease the water quality of Lake Toba, while enhancing water column anoxia in the hypolimnion layer and eutrophication as observed in November 2017 (Lukman *et al*., 2021). The physical, chemical, and biological properties of Lake Toba's water quality are heavily influenced by the numerous pollution sources.

The water quality of Lake Toba is altered by the water quality of river water, domestic public waters, agriculture, industry, livestock, floating net cage farming activities, and other activities around and in the lake. A previous study reported some parties interested in the exploitation of Lake Toba area resources with the potential to cause pollution, including tourism actors, floating net cages actors, local communities, farmers, pig breeders, local government, lake transport companies, industrial forests, mineral water companies, and non-governmental organizations. These numerous interests have the potential to raise conflicts in the multiple uses of water resources, principally between tourism and other parties (Tanjung and Hutagaol 2019). Three were the dominant activities affecting the Lake Toba area, *i.e.* tourism, floating net cages, and non-governmental organizations, with the potential for serious conflicts (Tanjung and Hutagaol 2019).

Domestic waste has been reported as the main source of water quality degradation in Lake Toba. In addition, floating net cages in the aquaculture sector in Lake Toba are one of the main sources of pollution (Tanjung and Hutagaol 2019). The Governor of North Sumatra has issued two decrees, No.188.44/213/KPTS/2017, which set the water quality of Lake Toba as oligotrophic and the maximum carrying capacity of the company's floating net cage at 10,000 tons/year. Tanjung *et al*. (2022) proposed that the carrying capacity for floating net cages should be revised from 10,000 tons per year to 67,000 tons per year in relation to the community's economy. In the tourism sector, Tanjung and Hutagaol (2019) reported the potential conflicts in the Lake Toba region related to the international ecotourism development, such as resort, restaurant, and hotels, which includes the floating net cage company actors with tourism actors; floating net cage industry actors with the government; community floating net cage with company floating net cage; local community with the government; and among communities. Tanjung and Hutagaol (2019) recommended that these conflicts could be addressed by involving all stakeholders in policy making, revising the regulation of the Governor, strengthening the floating net cage owner group, and developing eco-edu-tourism. Co-management is needed between the government and the other parties that use Lake Toba's water to ensure its sustainability.

Water quality analysis during three seasons (dry, transition, and rainy) provides information on variations in water quality that can affect all activities and the carrying capacity of the lake. Specific sites had lower dissolved oxygen levels compared to other locations (Supplementary Figure 4). High levels of dissolved substances in the environment can cause low oxygen levels. Hospitality and settlement with the highest nitrogen and phosphorous levels were associated with low oxygen and high organic matter, impairing the overall physical, chemical, and biological quality of the water. Comprehensive wastewater management is urgently needed in the future, especially for all sources potentially contaminating Lake Toba water.

Conclusions

According to the observations carried out in six station groups, including control (far from human activities), settlement, hospitality, community floating net cages, community floating net cages, and river mouths, the main water quality variables in Lake Toba showed a strong difference in the rainy, transition, and dry seasons. The waters of Lake Toba during these seasons tend to be classified above mesotrophy. Management of Lake Toba ecosystems should be carried out regularly to monitor environmental quality and functionality, which are essential elements to support and maintain ecosystem services.

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Online supplementary material:

Supplementary Table 1. Coordinates of sampling sites in six stations in the Lake Toba.

Supplementary Table 2. Determination of trophic status of the Lake Toba according to water quality parameters.

Supplementary Figure 1. Sixty sampling sites representing six stations in Lake Toba.

Supplementary Figure 2. Water brightness at six Lake Toba observation stations in each climatic season.

Supplementary Figure 3. Water temperature at six Lake Toba observation stations in each climatic season.

Supplementary Figure 4. Dissolved oxygen at six Lake Toba observation stations in each climatic season.

Supplementary Figure 5. Total nitrogen at six Lake Toba observation stations in each climatic season.

Supplementary Figure 6. Total phosphorus concentrations at six Lake Toba observation stations in each climatic season.

Supplementary Figure 7. Total organic matter (TOM) at six Lake Toba observation stations in each climatic season.

Supplementary Figure 8. Chlorophyll-a concentrations at six Lake Toba observation stations in each climatic season.

Supplementary Figure 9. Principal component analysis of water quality variables recorded at the six observation stations.

Supplementary Figure 10. Cluster dendogram of six observation stations according to water quality variables using Canberra distance.