Changes in water quality and trophic status associated with cage aquaculture in Lake Maninjau, Indonesia

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Abstract. The cage aquaculture unquestionably has been degrading lake water quality by increasing nutrients and organic carbon in lake water and sediments. The question is to what extent this condition affects other key indicators such as the temporal changes in trophic status and the thickness of anoxic hypolimnion layer where the anoxic water column is moving upward pushing up the oxic epilimnion layer. The condition in Lake Maninjau could be worse since the lake is steadily producing sulfide which can cause not only oxygen depletion in the water column but also the phosphate release from the sediments. The study is based on the long term monitoring data from on going research for about 8 years observation. The results indeed show the anoxic water column is moving upward increasing the thickness of anoxic hypolimnion layer and decreasing epilimnion layer from 30 m to 10 m depth. The trophic status of the lake also has changed from mesotrophic to eutrophic decreasing the water transparency to even a critical level < 1m. The months of July to September with prolonged hot season could be the critical time for trophic condition for the lake. The results suggest that determination of these conditions further could help identify and predict the critical time for possibility of fish kill.

1. Introduction
Cage aquaculture has been a major pressure to Lake Maninjau contributing major nutrients especially phosphorus (P) and organic carbon loading [1,2]. The main source of nutrient inputs in Lake Maninjau has known from the cage aquaculture counted around 400 ton/year. Ninety five percents of nutrient waste load as nitrogen and phosphorus that enter the lake were from cage aquaculture [3]. Increase P and organic carbon inputs has degraded water quality and reduced oxygen level in the water column [2,4].

The eutrophication problem and indication of toxic cyanobacteria (Microcystis) blooming also has been reported by previous study [2,5,6,7]. The fact that the lake is a tectono-volcanic containing fair amount of sulfur, the organic carbon inputs has increased hydrogen sulfide production in the hypolimnion subsequently could trigger the phosphorus release from sediment [4,8]. These findings indicate that the source of phosphorus not only from the external but also from the internal suggesting that P is not subject to limiting factor for the algal growth. Excessive algal biomass also contributes to more nutrient and organic carbon inputs to the lake. Furthermore combined aerobic and anaerobic microbial degradation and sulfate reduction bacteria (SRB) activity could cause the oxygen depletion in lake water column.

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The eutrophication and degrading water quality related to the oxygen depletion has also adversely affected the fish. Frequent fish kill incident due to degrading lake water quality has been reported each year [3].

The cage aquaculture unquestionably has impacted on lake water quality by enriching the lake with nutrients and organic carbon in the water column and by accumulating them in the sediment [2,7,9]. To what extend the excess of nutrients and carbon sources in the lake could affect the temporal changes of the trophic status and the thickness of anoxic hypolimnion layer where the anoxic water column is moving upward pushing up the epilimnion layer. As mostly on the deep tropical lakes, the stratification is permanent and the hypolimnion is permanently anoxic. The hypolimnetic hypoxia is common however if the magnitude of hypolimnetic hypoxia increases and the anoxic water column close to the water surface, with increasing the surface lake mixing by strong wind could initiate the upwelling that turns over the anoxic water column to the surface causing the entirely lake anoxic. Massive fish kill reported were mostly driven by this phenomena [3,10].

Although many studies have been done on the impact of cage culture on lake water quality in Lake Maninjau, trophic status even phytoplankton community but the studies were merely based on the short-term research [1,2,5,6]. We have reported the same type of study on nutrients dynamics from the long-term observation until 2011 however we did not discuss on the temporal changes on trophic status [2]. The study objectives are to evaluate the changes in water quality related to oxic-anoxic layer of water column and eutrophication and to observe and evaluate temporal changes of trophic status and secchi depth and to determine the key indicators for critical lake condition to develop possible early warning system. This study is based on the long-term monitoring data from on going research for about 8 years observation from 2005 to 2013.

2. Materials and Methods
2.1. Sampling Location
Lake Maninjau has surface area of 9737.5 Ha and maximum depth of 165m. The lake is located at 461.50 m above sea level in the Western area of Sumatra, Indonesia. The Lake Maninjau has several inlets of small streams and hot springs from the mountains. The lake has one outlet divided into a small surface outlet and the outflow from the hydropower turbine. Sampling station is located at S 0°22’33.0”, E 100°11’35.1” which is a master station of the deepest area of the lake (Figure 1).

There were about 18630 units of floating net cage in all around the lake in 2013 reported in Lake Maninjau [1]. Water sampling was conducted at least 1 to 3 times each year during the day time. Deep profile water samples were collected by using 2 L Van Dorn water sampler. Water samples were transferred to HDPE bottles. All samples were acidified or preserved except the samples for sulfide analyses. Water samples for sulfide analyses were drawn by a syringe via Tygon tubing to maintain the reduced condition.

2.2. Physicochemical analyses
Physico-chemical characteristics such as temperature and pH was measured by using Water Quality Checker Horiba U-10, while dissolved oxygen (DO) measurement was done by using YSI 6000. Water transparency as secchi depth was measured by using a secchi disc. Water samples for total sulfide concentration were analyzed directly insitu by adding sulfide reagents to the water samples then measured by using HACH DR 2010 Spectrophotometer. Total Nitrogen (TN) and Phosphorus compound (TP) were analyzed by a colorimetric method using Spectrofotometer Shimadzu UV 2100 according to APPHA AWWA [11]. Prior to analyses, water samples for Chlorophyll-a measurement were added with saturated MgCO$_3$ then filtered by using Whatmann GF/F filter paper. The filtrates then were extracted using 90% aceton, subsequently measured at different wavelength using Spectrofotometer Shimadzu UV 2100 [11].
2.3. Data Analyses
Trophic state index (TSI) of each lake was calculated based on chlorophyll-a, TP and secchi depth. The average of TSI scores is used to classify the trophic status of the lakes using the following equations from Carlson and Simpson [12].

\[
\begin{align*}
\text{TSI(Chl)} &= 9.81 \ln \text{[chlorophyll-a (µg/L)]} + 30.6 \quad (1) \\
\text{TSI(P)} &= 14.42 \ln \text{[TP (µg/L)]} + 4.15 \quad (2) \\
\text{TSI(SD)} &= 60 - 14.41 \ln \text{[secchi depth (m)]} \quad (3) \\
\text{TSI(Ave)} &= \frac{\text{TSI(Chl)} + \text{TSI(P)} + \text{TSI(SD)}}{3} \quad (4)
\end{align*}
\]

Optional TSI for total nitrogen was calculated using the following equation from Kratzer and Brezonik [13].

\[
\text{TSI(N)} = 54.45 + \ln \text{[TN (mg/L)]} + 4.15 \quad (5)
\]

The trend of temporal changes of trophic status and secchi depth data are presented in simple radar chart. Simple correlation analysis is conducted using statistical analyses by SYSTAT.

3. Results and Discussion
3.1. Temperature and pH
Annual temperature and pH deep profiles of Lake Maninjau show slight change annually (Figure 2). Our previous study has shown the thermocline shifting slightly in 2009 and 2011 to the upper water column [2], but in 2013 it shifted back to lower water column at 10 – 20 m depth. The fluctuation of the annual temperatures are mostly influenced by climate variability. The lake water temperatures are usually warmer in the hot season than those in the rainy season. As most of the deep lakes in tropical area, Lake Maninjau also experiences thermal stratification especially in the deepest area and the bottom water temperature is constantly colder (26.5 – 27 °C) than the temperature of the surface water.
(28 – 30 °C). Similar pattern for annual pH profiles are observed where the chemocline layers also moved upward to the upper water column in 2011. Although the annual chemocline layer seems to fluctuate slightly the layer still falls within the range at 10 – 20 m depth. The chemocline pattern also likely is influenced by the climate variability. In the contrary to the temperature values, pH values of surface water gradually increase (9 – 11) and the bottom water pH values decrease (7-6) from 2005 to the recent years. High values of pH in the surface water indicate high rate of photosynthesis suggesting that the lake experiences eutrophication. Very high pH value of surface water was observed in 2008, 2009 and 2011. The water color was dark green indicating lake eutrophication. Green scum indicating the presence of toxic cyanobacteria (Microcystis) was also spotted in several areas. The same observation has been reported in previous studies [5, 6, 7]. Prolonged hot season stimulates the photosynthesis process which subsequently increases the water pH [14]. Lower pH values in the bottom water are usually resulted from the microbial degradation of complex organic carbon to simple organic carbon such us fatty acids and CO₂ [15]. Previous study by Lukman et al [1] and Henny [8] observed the increase in COD concentrations in the water column and volatile suspended solids in the sediments in Lake Maninjau by cage aquaculture activity.

![Temperature and pH profiles](image)

**Figure 2.** Deep profiles of temperature and pH

### 3.2. Dissolved oxygen (DO) and total sulfide

Sedimentation of feces and fish pellets from the cage aquaculture and algae drives DO depletion in the hypolimnion lakes by stimulating bacterial respiration and sulfide production from sulfate reducing bacteria (SRB) activity. DO and sulfide deep profiles show that the thickness of anoxic hypolimnion increases pushing up the oxic epilimnion (Figure 3). The results suggest that the anoxic water column is moving close to the surface water. The fluctuation is at the range of 10 - < 20 m. The anoxic line fell at depth of 30 m in 2005 and then moved upwards to at depth of 20 m in 2007 and even moved upward further to 8 m depth in 2011 and bounced back to at depth of 15-18 m in 2013. When we compare to annual sulfide profiles the same trends observed and the sulfide concentrations varied with the highest sulfide total concentrations of > 400 µg/L in 2009, however sulfide level is getting higher in the water column at depth of 20 m observed in the recent years. What the results suggest that fluctuation of oxic-anoxic layer is not only caused by sulfide diffusion or production itself but rather more due to organic carbon degradation by aerobic/faculative bacteria which consume up all the oxygen presence in that layer. Fermentative bacteria subsequently also degrade the excess organic
Trends of total nitrogen (TN), total phosphorus (TP), chlorophyll-a and water transparency

3.3. Trends of total nitrogen (TN), total phosphorus (TP), chlorophyll-a and water transparency

Trends of total nitrogen (TN), total phosphorus (TP), chlorophyll-a and water transparency for most area of the lake has been reported by our previous study [2]. More recent study has been reported on these parameters in the cage aquaculture area [1]. This study only shows the trends at the lake surface water of the deepest area. The results certainly show more elevated concentration of TN, TP and chlorophyll-a in the area near the fish cages when compared to those in the middle and the deepest area where the fish cages are more distance.

This study aims to show that even the water quality in the area far distance from the fish cages has been affected by the cage aquaculture activity. Due to lake stratification the observation in the deepest area can show more distinct changes in lake water quality. Annual TN concentrations increase significantly from 2008 and so does the chlorophyll-a (Figure 5). The annual TP concentrations also increase gradually while the water transparency as secchi depth is in decrease trend. The results are in agreement with other study where the growing number of fish cage units every year indicates more nutrient inputs to the lake [1,3]. The water quality condition really depends on the climate variability during sampling time. More rainfall can dilute the pollutants and wash out the algae and lack of sunlight also limits the algal growth resulting in less photosynthesis process.

carbon producing more fatty acids and CO² which are subsequently utilized by other group bacteria such as denitrifiers, sulfate reduction bacteria (SRB), iron reducers and methanogenic bacteria. Excess organic carbon would trigger more microbial activity in the lake that can lead to oxygen deficit and elevated sulfide concentrations in lake. When the concentration of organic carbon exceeds the concentration of oxygen required, the oxygen depletion will occur [14,15]. DO and sulfide concentrations are in agreement indicating that when sulfide is presence DO is zero and vice versa. The annual changes of thermocline (temperature gradient), chemocline (pH gradient) and oxycline (oxygen gradient) are about the same pattern. These also suggest that most of mineralization and transformation of organics, nutrients and certain elements by microbial and chemical process both aerobically and anaerobically in Lake Maninjau occurs at this depth layer of 10 - < 20 m especially in the borderline of oxic –anoxic layer.

Similar case with pH, DO values of surface water increased up to 9 - 11 mg/L in 2008 – 2011 indicating the lake eutrophication. Photosynthetic process during daytime will consume CO₃ and produce O₂ in the water subsequently increase pH and DO in the water [14]. Both pH >9 and DO >9 mg/L could be used as indicators for lake critical condition.
Chlorophyll-a has strong correlation with TP and secchi depth \((r > 0.85)\) but less with TN \((r = 0.68)\). The results indicate that phosphorus is key indicator causing lake eutrophication and the lower water transparency is majorly caused by high chlorophyll-a and not by elevated suspended solids concentration. TN is abundant in lake water and it is usually phosphorus is limiting factor to algal growth. But this is not the case in Lake Maninjau. TP concentrations are > 50 μg/L in 2008 to 2013 exceeded the value of eutrophic condition \([12]\). High P concentration in the lake could also be due to P release from the sediment by sulfide \([4]\).

### 3.4. Trophic status

Although eutrophication is closely related to chlorophyll-a concentrations, to determine the trophic status of lake using trophic status index (TSI) TP concentrations and secchi depth (SD) are also important. These three parameters are the key indicators to determine the trophic status. When the TSI scores of the three indicators are varied, the average TSI scores of TSI-chlorophyll-a, TP and secchi depth is usually used to determine the trophic status. TN is not considered as a strong indicator for eutrophication and not included in calculating TSI average score but sometimes it can be considered when N is considered a limiting factor or when other parameters do not agree each other such as condition when the lake also has problem with invasive macrophyte coverage \([13]\). TSI scores of 40 – 50 classify the mesotrophic condition, 50 – 70 classify the eutrophic condition and above 70 classify the hypereutrophic condition \([12]\).

**Figure 5.** Trends of TN, TP, chlorophyll-a concentrations and water transparency as secchi depth

Based on the TSI scores for each indicator (chlorophyll-a, TP and SD) the trophic status of the lake could range from oligotrophic to hypereutrophic in which does not reflect the real condition. In this case the best predictor is using the average TSI scores of those three parameters. The trophic status of Lake Maninjau changes from mesotrophic in period of 2005-2007 to eutrophic in period of 2008 to 2013 based on the average TSI scores (Figure 6).

The temporal changes of trophic status of lake from 2005 to 2007 did not show any trend but from 2008 TSI scores for all three indicators and the average of three indicators show variability in which the months of July to September even up to December indicate the critical trophic condition (Figure 6). July 2011 was the record high for TSI score indicates highly eutrophic condition even to hypereutrophic level. The surface water pH and DO concentrations reflect the lake condition that year. Temporal changes of trophic status would likely be affected more by the climate variability such as monthly rainfall trend in a year. In the hot season the lake would likely experience more eutrophic condition than that in the rainy season. Rainfall will not dilute the pollutants and wash out the algae but also limit the algal growth due to less sunlight available.
Based on the TSI cores for each variable it shows that TSI(P)>TSI(chl)=TSI(SD). The results suggest that the zooplankton could probably feed more phytoplankton but still enough to cause the water turbid. The water turbid in Lake Maninjau is mostly caused by high chlorophyll-a concentration.

3.5. Implication of indicators

This study also tries to indicate what the implication of indicators that can be used to determine the critical time of lake condition to help predicting when the incident of fish kill would likely to happen. The water quality of lake Maninjau is clearly degrading with the eutrophication problem and the anoxic water column layer is moving upward getting close to the surface. Accumulation of the nutrients and organic waste continuously triggers more microbial activity in the hypolimnion producing more sulfide and other toxic gas leading to oxygen depletion in the upper layer of hypolimnion. Both internal and external loading of phosphorus has prolonged Lake Maninjau in condition of eutrophic state. In long hot weather the algal bloom sometimes accompanied by the toxic algae of Microcystis which is also toxic to fish. Population of blue green algae counted more than 40 up to 60% in almost all areas especially near the fish cages [6]. Prolonged to poor water quality such as exposed to lower oxygen could effect ecosystem structure in lake [16]

The number of fish cage unit increase by double from 2005 to 2008. Poor water quality observed in 2008 to a low level leading to the incident of massive fish kill in February 2009. The incident of fish kill occurs more frequent every year and it happens 2 to 3 times a year [3]. Both eutrophication and oxygen depletion are the conditions that have lead to fish kill incident. Massive fish kill incident usually is also driven by strong wind that causes lake mixing and turn over the anoxic water column layer to the surface, but in a small case, fish kill usually occurs prior to highly eutrophic condition in the previous months. During cloudy or rainy condition with less sunlight during the day time the photosynthesis rate is lower and the respiration rate is higher at night subsequently the lake would likely experience the oxygen depletion and sulfide will diffuse up to the surface with faster rate taking up all the oxygen available and lead to fish kill incident.

It seems all understand what the cause of fish kill incident however no one knows when to take precautions prior to the incident. With climate variability sometimes the prediction can be obscure. However there is an indicator that can be used to develop early warning system. Online monitoring system also has been initiated by other study [17], however with the lake and weather conditions this system is still not working properly. Our evaluation of temporal changes of water transparency as secchi depth in 8 years clearly indicates that during hot season such as in July-September the lake water was more turbid than those in the early hot season such as in May (Figure 7). Monthly variability in secchi depth values also reflects on the condition during sampling. It is highlighted that there is strong correlation between chlorophyll-a concentration and secchi depth suggesting that the secchi depth could be used as the key indicator for early warning system of lake critical condition.
There were no fish kill incident reported in 2005 – 2008 when the lake water condition improved with secchi depth above 5 m. When the secchi depth decreased to < 3m in August till December 2008 in the following month of February 2009 the massive fish kill incident occurred.

![Figure 7. Temporal changes of water transparency as secchi depth](image)

The eutrophication was also observed first in 2008-2009 with the worst condition observed was in 2011. The lake water turned to dark green containing high chlorophyll-a concentration with obvious presence of filamentous blue green algae of *Microcystis* and with very low secchi depth reaching only 0.8 m. Fish kill incident has occurred almost every year since 2009. The incident was the biggest in 2009 and moderate in 2010-2012 and small in 2013 [3]. The pattern of fish kill incident seems to correlate with the prior conditions of lake water quality and the secchi depth. The water condition with secchi depth of <3m could likely still lead to fish kill incident. However this would need further study on monthly changes of trophic status and secchi depth and the fluctuation of oxic-anoxic layer depth. More thoroughly study on biogeochemical process in this oxic-anoxic layer could be needed to understand better the natural phenomenon in lake Maninjau.

4. Conclusions
The unsustainable cage aquaculture practice in Lake Maninjau unquestionably has been pressuring the lake by increasing the thickness of anoxic hypolimnion thereby moving upward the anoxic water column to the upper column and pushing up the epilimnion further up. The results suggest that although lake hypolimnion continuously generates sulfides, the anoxic layer moving upwards to the upper water column might also as results of other microbial process although it needs further investigation. Steadily increase in phosphorus concentrations in lake water suggests that phosphorus is not a limiting factor for algal growth. The lake trophic condition has changed from mesotrophic to eutrophic after 2008 up to recent years. The secchi depth at below 3 m and pH>9 and DO> 9 mg/L during daytime could be used as early warning system for lake critical condition. The months of July to September with prolonged hot season could be the critical time for trophic condition for the lake. The results suggest that determination of these conditions further could help identify and predict the critical time for possibility of fish kill. However monthly temporal changes in trophic status and water transparency needs further observation to know when the peak of algal blooming and the lowest transparency and what duration of prolonged eutrophic condition coupled with weather condition would likely to cause the fish kill incident and subsequently early warning system for the lake can be developed.
Acknowledgement
The research has been funded by the Indonesian Government. Author would like to acknowledge Triyanto and Tri Suryono as the coordinator project of Lake Maninjau Research in 2005 to 2010 and the lab staffs of Research Lab of Limnology-LIPI who helped with the samples analyses, and Sutrisno, the staff of Lake Maninjau Research Station, who assisted with the field sampling.

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