Modeling the influence of floating net aquaculture and nutrient loads from catchment on the trophic status of a tropical volcanic lake

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Abstract. Lake Maninjau in West Sumatra Province of Indonesia is a 10,779 Ha tropical volcanic lake with 12,951 Ha of the catchment area. Having been used as a power plant, tourism, catch fishery, and floating net aquaculture, the lake was said to have become eutrophic since almost two decades ago. Maninjau is one of National Priority Lakes in Indonesia which means that it needs to be revitalized. Many studies mentioned aquaculture and land use change in the catchment as the driver of eutrophication. However, none of these studies could pinpoint which of the two factors give a greater impact on the lake’s eutrophication process. This could lead to an error in determining priorities in revitalization measures. The objective of this study is to assess the influence of aquaculture and catchment load on Lake Maninjau eutrophication by using a combination of catchment and lake model which consists of SWAT model, 2-dimensional multilayers hydrodynamics and water quality model. Results showed that floating net aquaculture generally gives major impact (>97%) on eutrophication not only in the lakeshore area but also in the entire water body. Catchment area gives minor impact and only observed in a relatively shallow area. The results suggest that the important part and higher priority of restoration strategy should be reducing the nutrient load from floating net aquaculture.

Keywords: catchment load, eutrophication, floating net aquaculture, water quality model, Lake Maninjau.

1. Introduction
Lake Maninjau is located in Agam Regency of the West Sumatra Province, Indonesia. Categorized as a medium sized lake, the volcanic lake has a maximum surface area of 10,778.4 Ha and a minimum catchment area of 12,950.7 Ha at 465 masl The catchment area lies in eight villages namely Bayur, Duo Koto, Koto Gadang, Koto Kaciak, Koto Malintang, Maninjau, Batang, and Tanjung Sani. Its current utilizations are tourism, catch fishery, hydroelectric power plant, and floating net aquaculture. Several studies [1] stated that eutrophication has occurred in Maninjau since the early 2000s, which indicated by frequent algal blooms and fish mass death. Being one of Indonesian National Priority Lakes, strategic measures are being developed to restore the lake into its best possible condition.
According to Janssen *et al* [14], nutrient load reduction is an effective restoration measure regardless of the lakes spatial aspects of nutrient loading and hydrology. The next step would be determining whether there is major nutrient source which gives a major impact on the lakes eutrophication. Reducing such nutrient source will likely accelerate restoration progress. In contrast, manipulating minor nutrient source without taking significant measures on the major nutrient source will likely delay restoration progress. Hence, knowing which nutrient source plays a major part in the eutrophication process is vital in developing restoration measures.

Several researches labeled domestic, commercial and agricultural waste from Maninjau watershed as sources of nutrients [11], while other studies mentioned floating net aquaculture as a major factor which exacerbate eutrophication process in Maninjau [10]. However, none of these studies mentions the extent of influence from each factor to the lake’s water quality. This research proposes a method to assess the impact of floating net aquaculture (FNA) and catchment load to Lake Maninjau’s eutrophication.

### 2. Methods

Soil and Water Assessment Tool (SWAT) model were used for determining daily discharge and organic load from the catchment. In order to sufficiently represent the real entire catchment, the difference between computed and real total area of catchment must not exceed 5%. Hence, 85 and 286 sub-catchments of 25 Ha and 1 Ha resolution, respectively, were taken into account. The catchment morphometric data of 8x8 m resolution were obtained from the Indonesian Geospatial Agency [18]. The total area of these 371 sub-catchments were 12,892.32 Ha or 5% less than the real surface area of the entire catchment according to 8x8m resolution DEM. Land use data were analyzed from Landsat 8 OLI Image 2018 using ArcGIS 10.2 combined with the ground check. Kurambik River discharge data were obtained from direct observation in 2018 and were used to calibrate SWAT model. SWAT model results were then used as inputs for 2-dimensional multilayers hydrodynamics and water quality data ([19]). Bathymetry data of Lake Maninjau were obtained from bathymetry mapping in 2001 [20] and 2017 using a multibeam echosounder. Daily lake water level data obtained from the State Electricity Enterprise (PLN) of Maninjau were analyzed to determine its maximum, minimum, and average water level with its time of occurrence. The recorded water level data ranged from 462.6–464.75 masl with an average of 463.2 masl. Calibration of a lake model was conducted using data from six stations during high water level in March 2018. Chlorophyll-a data profile were from RINGKO data logger adjusted to analyzed samples in the laboratory. Lake model validation used data of average (June 2017) and low water level (November 2017) obtained from Technical Service Unit for Lake Sanitation Technology Transfer. FNA locations were identified from ArcGIS 10.2 Basemap, while its loadings were estimated using methods described by Schmittou [21] and aquaculture operational data from Rasidi et al. ([22]). Assumptions used in FNA load calculations are summarized in table 1. Lake water quality data for calibration was sampled from six locations and analyzed in March 2018. Secondary data for validation were obtained from Technical Service Unit for Lake Sanitation Technology Transfer (UPT LATPD).

### Table 1. Assumptions used for FNA load calculation.

| Parameter                  | Value |
|----------------------------|-------|
| FCR                        | 1.61  |
| Production/plot/period (kg)| 1,112 |
| Cultivation period (days)  | 153   |
| **Fish Content**           |       |
| Water (%)                  | 81    |
| N (%)                      | 11.2  |
| P (%)                      | 4.1   |
| Parameter     | Value |
|--------------|-------|
| Food content |       |
| Water (%)    | 5     |
| N (%)        | 5.5   |
| P (%)        | 1.2   |

The scheme of hydrodynamics and water quality model, along with the equation to determine segment size and time step refer to Harsono [19] using an explicit backward scheme with open boundary condition. Segment size and time step were 60 m x 60 m and 0.09 s, respectively. Vertical segmentation of the water body is shown in Table 2.

**Table 2. Vertical segmentation used for lake model.**

| Number of layer | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
|-----------------|----|----|----|----|----|----|----|----|----|----|----|
| Layer thickness (m) | 0.5 | 0.5 | 1  | 3  | 5  | 5  | 5  | 20 | 20 | 50 | 53 |
| Depth (m)      | 0.5 | 1  | 2  | 5  | 10 | 15 | 20 | 40 | 60 | 110| 163|

The influence of aquaculture and catchment on the lake trophic status distribution was computed for each segment using the following equations:

\[
f_{FNA} = \frac{\beta_{FNA}}{\beta_{FNA} + \beta_C} \times 100\%, \quad f_C = \frac{\beta_C}{\beta_{FNA} + \beta_C} \times 100\%
\]

\[
\beta_{FNA} = M - (FNA0 - C1) - (FNA0 - C0)
\]

\[
\beta_C = M - (FNA1 - C0) - (FNA0 - C0)
\]

whereas

\[f_{FNA}, f_C: \text{influence factor of floating net aquaculture (FNA) and catchment (C)}\]

\[\beta_{FNA}, \beta_C: \text{influence of FNA and C on chlorophyll a concentration (mg/m}^3)\]

\[M: \text{chlorophyll a concentration from calibrated and validated model (mg/m}^3)\]

\[(FNA0 - C0): \text{chlorophyll a concentration from simulation of no FNA and catchment loadings (mg/m}^3)\]

\[(FNA0 - C1): \text{chlorophyll a concentration from simulation of no FNA and existing catchment loadings (mg/m}^3)\]

\[(FNA1 - C0): \text{chlorophyll a concentration from simulation of existing FNA and no catchment loadings (mg/m}^3)\]

Trophic classification refers to Regulation of the Minister of Environment and Forestry No. 28 Year 2009 [23]. The average of FNA and catchment influence factor in each layer were computed using the following equations:

\[
f_{FNA} = \frac{\sum f_{FNA} \times A_s}{\sum A_s}, \quad f_C = \frac{\sum f_C \times A_s}{\sum A_s}
\]

whereas

\[f_{FNA}, f_C: \text{average influence factor of floating net aquaculture (FNA) and catchment (C) per layer (\%)}\]

\[A_s: \text{segment area (m}^2)\]
3. Results and Discussion

3.1. Loads from Lake Maninjau catchment

SWAT calculated discharge and organic loads from 85 and 286 sub-catchments of 25 Ha and 1 Ha resolution (figure 1), respectively. For brevity, 25 Ha and 1 Ha resolution catchment shall be mentioned as large and small sub-catchment, respectively. Forest is a relatively major land use in large sub-catchment, except in the northern sub-catchment of the lake which has wide and low slope area for rice fields. Small sub-catchments in the northern area are also dominated by rice fields, while those in the western area are dominated by bushes (figure 2).

![Figure 1](image.png)

**Figure 1.** Location and area of 25 Ha and 1 Ha resolution sub-catchment produced by SWAT.
Figure 2. Land use composition (%) in large (top) and small (bottom) sub-catchment.

During maximum lake water level, large sub-catchments in the northern to eastern part of the catchment are major contributors of runoff and dissolved organic nitrogen (figure 3) since they are larger than other sub-catchments and mainly occupied by rice fields and settlements. Similarly, this pattern is also observed during average and minimum lake water level.

Figure 3. Nutrient loads from large (top) and small (bottom) sub-catchments during maximum lake water level.
3.2. Floating net aquaculture load
Tanjung Sani, the southernmost village surrounding Maninjau, has the longest shoreline with the highest number of FNA (figure 4). Using assumptions given in Table 1, dissolved organic nitrogen and phosphorus daily load from each plot are 0.49 kg and 0.08 kg, respectively. Incorporating FNA load with segment size 60 x 60 m produced a distribution of organic load density ranging from 0–35.44 kg/segment/day. According to aquaculture density per segment, the highest and the lowest average number of FNA per segment is found in Duo Koto and Koto Gadang, respectively.

3.3. Calibration and validation
Calibration using chlorophyll-a data in six locations observed in March 2018 produced an overall error value of less than 5% (figure 5). Validations of the model using data from Technical Service Unit for Lake Sanitation Technology Transfer in June for average water level and November for low water level have a strong correlation with 4.6% and 1.4% error, respectively (figure 6). Hence, the model can be considered as reliable.
Figure 5. Comparison of calculated and observed concentration of chlorophyll-a profile of six stations in March 2018.

Figure 6. Validation results using data during average (left) and low (right) water elevation.

According to the model’s calculation, chlorophyll-a distribution in the surface layer is highly influenced by advection. Diffusion plays more role than advection in distributing chlorophyll-a in the deeper area. The highest concentration of chlorophyll-a can be found in areas near the lakeshore. This happens mainly due to the low current in lakeshore areas which receive organic loads from FNA and the catchment area. Such tendency can be observed in the upper five layers or down to 10 m deep. Since higher and wider concentrations of chlorophyll-a are observed in high water level (figure 7), simulations were set during the high water level.
Figure 7. Chlorophyll a distribution in three layers of high, average, and low water level.
3.4. Assessment of FNA and Catchment Load Impact

![Diagram showing chlorophyll a distribution](image)

Figure 8. Chlorophyll a distribution resulted from three scenarios.
Simulations for the assessment using scenario where neither loading from FNA nor the catchment (FNA0-C0) gives the background status of Lake Maninjau which is oligotrophic, since the chlorophyll-a concentration in the entire surface and depth were relatively similar ≤ 2 mg/m³. Hence revitalization may be targeted to oligotrophic status. Without any FNA in the lake (scenario FNA0-C1), the impact of existing load from the catchment is clearly seen from eutrophication near the lakeshore, especially in eastern to southern area. However, the impact is less substantial compared to that of floating net aquaculture. Without any loadings from the catchment, current FNA practice (scenario FNA1-C0) can result in eutrophication to a higher extent not only near the lakeshore but also in the entire area of the water body (figure 8).

Figure 9 shows the spatial distribution of influence factors of FNA (\( f_{FNA} \)) and catchment (\( f_C \)) on the lakes trophic status denoted by chlorophyll-a concentration. Despite higher chlorophyll-a concentration near the lakeshore, influence factors of FNA in the middle part of the lake surface to 2 m deep are greater than that in the lakeshore, excluding the northern lakeshore which are not eutrophic (figure 9). This suggests that FNA gives major and global impact to the lakes water quality. Within depth range of 2–10 m, FNA influence factors are greater than 99% in all area. FNA influence factors in 10–20 m deep are fragmented and tend to be higher in the lakeshore area. Catchment influence factors, on the other hand, are greater near the lakeshore although the values are still much lower than FNA influence factor.

Figure 10 shows the average of FNA and catchment influence factor of each layer. The average of FNA influence factors are increasing from 97.63% in the first layer (0-0.5 m deep), to 100% in the fifth layer (5-10 m deep) and 0% in layers deeper than 20 m. The average of catchment influence factors are decreasing from 2.37% in the first layer to 0.01% in the fourth layer (2-5 m deep) and 0% in layers deeper than 5 m. The results emphasize that FNA gives higher and wider impact on eutrophication in Lake Maninjau. Therefore restoration measures must include relatively drastic measures to reduce floating net aquaculture load to the lake.
Figure 9. Factor of FNA and catchment influence on chlorophyll-a concentration.
4. Conclusion

Our study showed that floating net aquaculture and catchment load indeed responsible for the eutrophic process in Lake Maninjau. However, the major factor influencing Lake Maninjau’s trophic status, particularly of chlorophyll-a concentration, is floating net aquaculture. FNA affects more than 97% of eutrophication on the surface, not only in lakeshore but also on the entire surface and down to 20 m deep. Hence, the important part and higher priority of restoration strategy should be reducing the nutrient load from floating net aquaculture.

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