Modeling approach to determine priority sub-catchment for volcanic lake restoration

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Abstract. Catchment restoration is one of important aspects taken into account when planning lake restoration. The initial step to this is identifying the location and characteristics of the problem areas for further analysis in deciding suitable restoration measures. The objective of this study is to identify and characterize priority sub-catchment to be managed in order to promote Lake Maninjau restoration by using calibrated and validated 2-dimensional multilayers hydrodynamics and water quality model. Results showed that small sub-catchments which are significantly occupied by settlements in the verge of the lake should be prioritized since they provide higher immediate nutrient which lead to eutrophication near the lakeshore area. While large sub-catchments may not cause immediate eutrophication in the lakeshore area, they must also be managed wisely to increase water quality in the much wider part of the lake.

1. Introduction
In 2014, Regent of Agam issued a regulation on Management of the Sustainability of Lake Maninjau Region [1]. The regulation, Agam Regency Regulation No. 5/2014, gives general direction on planning, utilizing, restoring, maintaining, disaster mitigating, monitoring and controlling activities in all catchment and Lake Maninjau water body. It also emphasized that management of the lake’s region must ensure sustainability of natural resources and public welfare, socially, economically, and ecologically. Since the lake was declared as one of the national priority lakes, restoration measures in both catchment and water body were designed. According to the Regency Regulation, reforestation, replantation, ecofriendly technology utilization, are among important measures to restore catchment and lake condition.

Previous studies showed various impacts of catchment characteristics and utilizations on the accumulating reservoir and/or lake. Social-ecological change in the catchment resulted in significant ecosystem reorganization at Lake Changdang in the Lower Yangtze River Basin [2]. Concentrations of several water quality parameters in reservoirs surrounded by forest were lower than that of reservoirs surrounded by diverse land use type [3]. Higher turbidity in a reservoir surrounded by diverse land use consists of urban area and forest, than in a reservoir surrounded by agricultural area [4]. Our previous research result showed that the extent of catchment loads influence on Lake Maninjau eutrophication was rather insignificant compared to that of more than 22,000 intensive floating net aquaculture (FNA) distributed near the entire lakeshore [5]. However, the model showed that eutrophication would still take place in relatively vast area consists of littoral zone due to
catchment nutrient loads alone. This suggests that there is a number of sub-catchments that needs to be restored in order to accelerate the lake restoration program. While the model showed that significant eutrophication due to catchment loads alone would likely occur majorly in eastern to southern part of the lake, detailed information on which sub-catchment contributes more on eutrophication is still needed. Subsequently, characteristics of problem catchment, such as land use and typical nutrient loads, can be useful for deciding suitable restoration measures. Such information may be valuable for deciding priority on catchment management in order to restore the lake. Our research aims to obtain the information.

2. Methods
Lake Maninjau of Agam Regency in West Sumatra is a medium sized volcanic lake which also supplies a 68 MW hydroelectric power plant. According to the State Electricity Enterprise (PLN) of Maninjau, the lake’s water elevation range is 462.6–464.75 m asl with an average of 463.2 m asl. We used a multilayers two dimensional hydrodynamics and water quality model [6] that was calibrated and validated [5] to assess the impact of nutrient loads from the total catchment without any FNA on the lake’s trophic status, namely in chlorophyll-a [7]. For brevity, the multilayers two-dimensional hydrodynamics and water quality model hereafter referred to as the lake model. Discharge and organic loads from the catchment, as inputs to the lake model, were calculated using Soil and Water Assessment Tool (SWAT). SWAT automatic delineation with 25 Ha resolution was used to define sub-catchments for SWAT model domain. In order to obtain maximum representation of the total catchment, we also used 1 Ha resolution to ensure that the small sub-catchments located very near to the edge of the lake were represented in the model. Hydrology part of SWAT model was calibrated with direct observation on one sub-catchment [8]. SWAT model used morphometric data of 8x8 m resolution from the Indonesian Geospatial Agency and land use data analyzed from Landsat 8 OLI Image 2018 using ArcGIS 10.2 combined with the ground check.

The kinetic scheme of the multilayers two-dimensional hydrodynamics and water quality model were numerically solved 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 1.

Table 1. 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 lake model then used to calculate the impact of nutrient loads from 25 Ha and 1 Ha resolution sub-catchment on the lake trophic status distribution separately. The influence of small catchment (1 Ha resolution) and large catchment (25 Ha resolutions) was measured using the following equations:

\[
 f_{C1H} = \frac{\beta_{C1H}}{\beta_{C1H} + \beta_{C25H}} \times 100\%, \quad f_{C25H} = \frac{\beta_{C25H}}{\beta_{C1H} + \beta_{C25H}} \times 100\%\]  

whereas

\[
 \beta_{C1H} = M - (FNA1 - C0) - (FNA0 - C25H1 - C1H0) - (FNA0 - C0) \\
 \beta_{C25H} = M - (FNA1 - C0) - (FNA0 - C25H0 - C1H1) - (FNA0 - C0)
\]

where

\[
 f_{C1H}, f_{C25H} : \text{influence factor of small and large catchment} \\
 \beta_{C1H}, \beta_{C25H} : \text{influence of small and large catchment on chlorophyll a concentration (mg/m}^3) \\
 M : \text{chlorophyll a concentration from calibrated and validated model (mg/m}^3) \\
 (FNA1 - C0) : \text{chlorophyll a concentration from simulation of existing FNA and no catchment loadings (mg/m}^3)\]
(FNA0 − C0) : chlorophyll a concentration from simulation of no FNA and catchment loadings (mg/m³)
(FNA0 − C25H1 − C1H0): chlorophyll a concentration from simulation of no FNA and no loadings from small catchment; existing loadings from large catchment (mg/m³)
(FNA0 − C25H0 − C1H1): chlorophyll a concentration from simulation of no FNA and no loadings from large catchment; existing loadings from small catchment (mg/m³)

3. Results and Discussion
Surface morphology of Lake Maninjau and its catchment resembles a caldera. The whole system encompasses an area of 23,729.1 Ha; 10,778.4 Ha of lake surface area at 465 m asl and 12,950.7 Ha of catchment area. While the lake was surrounded by steep slope areas that were mostly forest (43.7%) and bushes (25.5%), significant areas with lower slope were used for dry fields (19.1%) and rice fields (9.4%). Settlement area (2%) can be found in nearly every side of the lake. As the eastern and southern part of the catchment has relatively narrow low slope area, the settlements in this part are located very close to the edge of the lake (Figure 1).

Figure 1. Spatial distribution of slope in the catchment and bed of Lake Maninjau (left) and Slope histogram of the catchment (right).

Figure 2. Layout of 25 Ha (left) and 1 Ha resolution (right) sub-catchment ([5]).
SWAT automatic delineation generated 85 large sub-catchments and 286 small sub-catchments (Figure 2), respectively. The total area of 371 sub-catchments amount to 98.15% of the actual catchment area and were considered as sufficient. Most large sub-catchments in the western side were relatively dominated by bushes, while those in the other sides were mostly forest area. Small sub-catchments in the western and southern side of the lake were mostly bushes. However, small sub-catchments in the eastern side of the lake have major area of settlements. SWAT simulation results showed that large sub-catchments mostly have higher discharge and organic loads than the small catchments. On the contrary, most small sub-catchments loads have higher inorganic nitrogen loads, which are readily used for phytoplankton growth, than the large sub-catchments. Land use and nutrient loads from all catchments in this research refer to our previous research [5].

Simulations showed that combined with low circulation near the eastern and southern lakeshore, low discharge but relatively high inorganic loads from small catchments give noticeably higher impact on the lakes trophic status. This suggests that the inorganic loads in these areas were immediately used for phytoplankton growth before it has the chance of being transported to another area. While higher discharge and organic loads from large sub-catchments load seemed to have relatively uniform effect in all part of the lake within the same depth, they produce higher chlorophyll-a in areas other than lakeshore down to 10 m deep (Figure 3). This suggests that large sub-catchments organic loads were transported to wider areas by water current while undergo transformation to provide nutrients for phytoplankton growth.

Figure 4 shows the spatial distribution of influence factors of large ($f_{C25\%}$) and small ($f_{C1\%}$) sub-catchments, on the lakes trophic status denoted by chlorophyll-a concentration. The influence factors of large sub-catchments can be observed in the entire part of the lake from the surface to 5 m deep. In the 5th layer (5-10 m deep), the influence factor of the large sub-catchments was fragmented and completely unobservable in the 6th layer (10-15 m). In addition, $f_{C25\%}$ values tend to decrease towards the lakeshore. The result agrees with the previous suggestion that large sub-catchments nutrient loads help promote phytoplankton growth in wider areas, since they tend to be dispersed to the entire water body. Small sub-catchments influence factors, on the other hand, were only observed near the lakeshore and completely depleted in the 5th layer (5-10 m). Small sub-catchments influence factor coverage was less than 20% and was limited to lakeshore area. This also support previous suggestion that their nutrient loads, while can readily be used for phytoplankton growth, tend to be very slowly transported by the low current in the lakeshore. Hence, they were accumulated and also depleted via the phytoplankton growth process in these areas.
Despite having smaller influence factor coverage, small sub-catchments especially in the eastern and southern side contribute more to the lake’s eutrophication. Hence, these sub-catchments should be prioritized to be managed. As these sub-catchments are mostly used for settlements (often located on the verge of the lake), aside from dry field and bushes, strategic and suitable measure must be implemented here. On the other hand, since large sub-catchments determine the trophic status of wider area of the lake, these sub-catchments must also be managed wisely.
4. Conclusion

Our study showed that lake model can be used to assess sub-catchments impacts on the lake’s trophic status and thus identify priority sub-catchments to promote lake’s restoration. In the case of Lake Maninjau, small sub-catchments which are significantly occupied by settlements in the verge of the lake should be prioritized since they provide higher immediate nutrient which lead to eutrophication near the lakeshore area. While large sub-catchments may not cause immediate eutrophication in the lakeshore area, they must also be managed wisely to increase water quality in the much wider part of the lake.

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