Water balance model aided in estimating net groundwater inflow at Lake Maninjau, West Sumatra - Indonesia

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Abstract. Sustained lake functioning requires proper catchment land and water management. To address this, quantitative information and comprehensive understanding of the spatiotemporal dynamics and hydrological budget of the lake ecosystem are required. However, measuring hydrologic components such as groundwater discharge into a freshwater body is difficult, since its direct measurements are costly, time-consuming, and hardly implemented. Therefore, this study was intended to quantify groundwater inflow to the lake through an effective approach using the water balance modeling technique. Herein, groundwater discharge and contribution were calculated as the water balance residual in terms of net groundwater inflow. It can be considered a minimum estimate of groundwater inflow, as there the groundwater outflow maybe exists but not quantifiable. The approach has been applied for Lake Maninjau which is categorized as a deep, regulated, and tecto-volcanic lake located in West Sumatra Province, Indonesia. The result indicates that the groundwater inflow slightly moderately influences the fluxes of new water volume (the region between observed lowest and highest lake water level) at the upper layer of Lake Maninjau. Its contribution was equivalent to at least 20-28% according to the assessment for the years of 2013 and 2014. Annually, the new water volume recharged from the groundwater inflow corresponded to at least 182-281 million m$^3$. Moreover, these findings enhance a previous study stated that the terrain system of Lake Maninjau is dominated by a rare groundwater aquifer.

1. Introduction

Lakes are normally influenced by all hydrological system components which consists of atmospheric water, surface water, and groundwater. Referring the lake as the accounting unit of interest, the tropical lake yields water from: (1) the atmosphere by rainfall directly fall over the surface of the lake; (2) land surface water, by river flows, overland flows and in some artificial settings; and (3) groundwater, by subsurface flows and seepage into the lake. On the other hand, the lake losses water to: (1) the atmosphere, through lake surface evaporation mechanism; (2) lake outflow discharges, through river flows from the lake and water intake points for any water uses and abstractions; and (3) groundwater outflow from the lake. The fluxes of water mass to, and from the lake concerning each of these components result in a change in lake water level and its water storage [1, 2]. In general, it would represent the water budget of the lake. Understanding and quantifying the lake water budget under the attention of the entire hydrological system is fundamental in lake management since the water balance ensures an adequate water supply and affects the nutrients within and from the lake. Additionally, lake water balance information is an essential element of many scientific investigations that are prompted primarily by chemical and biological lake studies [3, 4].
Mathematically, the concept of a lake water balance is relatively simple. However, in practice, measuring each component and quantifying the water balance fluxes of lakes accurately is not easy work. One of the most difficult assessments is measuring and considering the groundwater inflow and its contribution to the lake water balance [5]. Predicting groundwater recharge especially in a deep lake is difficult, since its direct measurements are costly, time-consuming, and difficult to execute. Currently, there are several methods to estimate groundwater discharges into freshwater bodies, such as hydraulic-head surfaces mapping in combination with boreholes water level monitoring and GIS techniques [6] and groundwater tracers using isotope techniques [7, 8]. These two methods have also been widely used, however, they are expensive and demand the existence of specialized types of equipment and infrastructures, and cannot provide very accurate quantification as well [6, 9]. Another approach is to employ numerical watershed (rainfall-runoff) models to simulate the recharge rate of groundwater, as done in recent studies [10, 11].

One of the deep lakes in Indonesia that lacks information on water balance and the hydrogeological processes related to lake-groundwater interaction is Lake Maninjau. This lake was categorized as a tropical, tecto-volcanic, and multipurpose lake. Hydropower generation and floating net aquaculture are two activities that are relatively high in utilizing the primary energy of the lake. Previous studies [12, 13] mentioned that the groundwater contribution to the lake is 89%, which means substantial influence. However, this contribution value seems to be overestimated, since the fluxes of lake water storage were not considered and the estimated lake outflows data input was too high in the calculation. This reason follows the fact that Lake Maninjau often experiences a water deficit for the operation of the hydroelectric power plant, particularly during the dry season [13]. In that case, the water storage should be no problem if groundwater inflow is a dominant contribution. Other environmental problems in this lake are frequent algal bloom and fish kills.

Based on all the above problems, a quantitative assessment of groundwater discharge into the lake using different approaches is necessary. In this study, numerical modeling of lake water balance has been developed to provide a low-cost tool, and aided for reliable estimation of groundwater inflow and contribution to Lake Maninjau’s water budget.

2. Methods

2.1 Site description

The study area concerns the Lake Maninjau system, which consists of the lake water body (102.26 km²) and its catchment area (128.72 km²). It is a caldera lake and has a deep water body (maximum depth of 168 m a.s.l), which originated from tecto-volcanic processes that occurred around 52,000 years ago. As located within the great sumatra fault zone and likely semi-mountainous area, complex terrain of the lake catchment ranges from 462 m to 1705 m a.s.l. Hydrological balance condition is much affected by seasonal rainfall variability, and abundance inflows could be seen clearly during the rainy season (October to April) and becomes less along the dry season (April to October). Administratively, the lake is located in the Agam Regency of the West Sumatra Province (Figure 1). Detailed information about the environmental condition and geological setting of the Lake Maninjau system are described in recent studies [14, 15].
2.2 Lake water balance approach and net groundwater inflow estimation
The hydrological system of Lake Maninjau has been formulated based on catchment-lake interaction that consists of three compartments: the lake, the connected river catchment, and the adjacent groundwater mass. It is quantified in the form of daily lake water balance equation, as follow:

\[
\Delta S = S_{t+1} - S_t = (Q_{riv_{in}} + R + Q_{gw_{in}} - Ev - Q_{lake_{out}} - Ggw_{out})_t
\]

where \(\Delta S\) is the change in lake storage or water volume; \(t\) is the unit time on a daily basis; \(Q_{riv_{in}}\) is cumulative of incoming river flows; \(R\) is the rainfall dropped over the lake; \(Q_{gw_{in}}\) is the total groundwater inflows; \(Ev\) is the evaporation from the surface area of the lake; \(Q_{lake_{out}}\) is the lake outflows, and \(Ggw_{out}\) is the outgoing groundwater. All variables are conditioned into the volumetric dimension (m\(^3\)).

The water balance approach (Equation 1) entails determining the groundwater component from the following equation:

\[
Q_{gw_{in}} - Q_{gw_{out}} = \pm \Delta S + Ev + Q_{lake_{out}} - Q_{riv_{in}} - R
\]

Due to a reason that the outgoing groundwater flow from the lake was not measured directly, so its observed data is not available. Thus, the equation to estimate the groundwater balance (Equation 2) was simplified to:

\[
Q_{gw}\text{residual} = \pm \Delta S + Ev + Q_{lake_{out}} - Q_{riv_{in}} - R
\]

\(Q_{gw}\text{residual}\) is the groundwater residual, is the net value of groundwater inflow to and the groundwater outflow from the lake. Quantitatively, the positive groundwater residual (+\(Q_{gw}\)) can be considered as a possible minimum estimated groundwater inflow to the lake, as there may be groundwater outflow also exists, and vice versa. Accounting for the groundwater discharge in terms of inflow rate and contribution for Lake Maninjau was calculated using (Equation 3) for 1\(^{st}\) January 2013 to 31\(^{st}\) December 2014. Compared with other years, all observed data within this period have a good data quality. Furthermore, the water balance assessment for accounting the net groundwater inflow was
carried out with the temporal resolution on a daily time interval. A brief description of how each element in Equation 3 is quantitatively defined, are described as below:

- **Rainfall (R)**
  The rainfall has not been measured yet in a regular network over the lake catchment, therefore, to solve this problem, the product of reanalysis daily rainfall data of 2013-2014 from the Global Satellite Mapping of Precipitation, GSMaP (https://sharaku.eorc.jaxa.jp/GSMaP_CLM/index.htm) was used as the data input. The GSMaP provides the rainfall product with 11.132 x 11.132 km spatial resolution, accordingly, the rainfall property of the Lake Maninjau is represented by 7 grids of the GSMaP node.

- **Lake Evaporation (Ev)**
  This element was calculated using an empirical formula which allows the determination of potential or reference evaporation. Herein the approximation of daily evaporation was calculated using the Thornthwaite Temperature Index Method [16]. Daily air temperature and other climatic variables were collected from the available global data product of the Climate Forecast System Reanalysis (CFSR), made by the National Centers for Environmental Predictions, NCEP (https://globalweather.tamu.edu/).

- **River Inflow Discharge (Qrivin)**
  The long-term observed data obtained from a dense regular hydrological gauging network is not available. Therefore, the element of total incoming river flow to the lake was calculated using a kinematic wave-based distributed rainfall-runoff model [17]. The model received spatial information on the rainfall, hydro-topographic, land-use type, and soil property as the model input with spatial resolution disaggregated to 30 x 30 m. The hydro-topographic data includes flow direction, flow accumulation, corrected river network, and catchment boundary. These data were extracted and delineated from the 30-m SRTM DEM product (https://dwtkns.com/srtm30m/). Besides, infiltration rate, soil depth, river dimension, and other soil properties were obtained through direct measurements and laboratory analysis. Landsat satellite imageries had been interpreted to produce a land-use map, which was validated by ground checking. As further, a calibrated model parameter (NSE = 0.70) was set up in executing the rainfall-runoff model to get a set of long-term estimated daily river inflow hydrographs (2013-2014) from 157 river outlets, which are flowing to the lake.

![Figure 2. Intake water outflows for the hydroelectric power plant (left) and sanitary gate (right) in Lake Maninjau.](image)

- **Lake Outflow Discharges (Qlakeout)**
  Since 1983, the lake has been used to generate hydroelectric power for West Sumatra, produced around 68 MW at maximum load. For this purpose, an artificial weir was
constructed at the natural lake’s outlet (inlet of the Antokan river), which has two sanitary gates over the weir. Therefore, the lake was modeled with two outflow points, namely hydropower intake and sanitary gate (Figure 2). The outgoing flows through the hydropower intake have been measured on daily time intervals by the hydropower office, and this study used those data. The sanitary gate has two gates, called the gate 1 (water flows through the bottom surface of the gate) and gate 2 (water flows over the top of the gate). In normal condition, gate 1 has a fixed opening of about 10 cm from the weir (462 m a.s.l), while gate 2 has about 15 cm opening gate below the existing water level. Both gates have the function of controlling the lake water quality. Empirically, using hydraulic formulas, the outgoing flows from sanitary gates 1 and 2 are estimated following Equations 4 & 5, respectively:

\[ Q = \mu \times L \times a \times \sqrt{2 \times g \times Z} \] \hspace{2cm} (4)
\[ Q = \mu \times L \times H^{3/2} \] \hspace{2cm} (5)

where \( Q \) is the outflow discharge; \( \mu \) is the discharge coefficient; \( L \) is the gate width; \( g \) is the gravity coefficient; \( Z \) is the difference between the water level and the opening gate position; \( H \) is the water level.

- **Lake Water Volume (Water Storage) Change (\( \Delta S \))**

The daily water level in Lake Maninjau was monitored manually by the Maninjau Hydropower Plant Office. To define the lake water volume element, the observed lake water level was collected for the years 2013-2014. Another procedure, the water level-volume and the water level-area of Lake Maninjau water body relationships were derived from a combination between the lake’s bathymetry and catchment topography (Figure 1). The area and volume corresponding to different lake water levels, from the particular layer to the maximum lake water level, are calculated using a GIS Software through this map. Finally, either linear or non-linear empirical relationship between these three variables could be formulated (Figure 3). Moreover, the observed daily water level changes were converted to the lake water volume and its surface area changes utilizing those equations.

The application of the measured and estimated daily values of the water balance elements in Equation 3 gained the only one unknown element, it is the net groundwater inflow to the lake. GIS Software, Fortran Compiler, and GNU Plot are three main tools, which have been used for data processing, making algorithms, and visualization of the model outputs. The source code of the water balance approach for net groundwater inflow estimation is part (sub model) of the Eco-Hydro Version 3.0 Model development by the Authors.
3. Results and Discussion

The area-weighted (averaged area) rainfall and evapotranspiration from the lake catchment and lake water body (herein called as the evaporation instead of evapotranspiration) as well as the river inflow fluctuation from 157 river outlet points and its cumulative value for 2013-2014 are illustrated in Figure 4. In general, the incoming water to the catchment through rainfall is higher than that to the lake, while the water losses through evapotranspiration in the catchment are also higher than that from the lake. The reanalysis GSMaP rainfall product produced relatively high rainfall depth especially in the period of the rainy season (October to April), the rainfall depth could reach more than 100 mm per day. However, the rate of daily evapotranspiration from both the catchment and lake is relatively low, which is less than 5 mm per day. The evapotranspiration depth during the dry season is higher than that in the rainy season. It is due to higher air temperature during the dry season as well as, the existence of medium to high-intensity winds compared with the condition in the rainy season.

![Image](https://example.com/image.png)

**Figure 4.** Lake Maninjau water balance data for 2013-2014, including (a) area-weighted daily rainfall and evapotranspiration for the catchment area and over the lake water body; and (b) continuously-estimated surface water inflow from 157 rivers and their cumulative inflow.

All the estimated hydrographs which represent the incoming flow to the lake from 157 rivers, for both years, follow a similar pattern with the rainfall. The high flows correspond with the high rainfall. According to the field investigation, the thin soil profile and the significant slope gradients mostly exist over the southern and western catchment area. Hence, it does not assist the development of the interflow part of the hydrological response in those areas. Figure 4 shows that maximum cumulative stream inflow from 157 rivers could reach 70-90 m/sec, while for each river only up to 1-10 m/sec. Besides, Figure 5 displays an example view of spatial information of the river discharge for each river segment located in the Northern and Eastern catchment area of Lake Maninjau. The river flows less water during the dry season, such as in July. In this study area, many rivers are becoming intermittent when there is no rain for several days.
Figure 5. Example display of spatial information of the monthly estimated river flows in the Northern and Eastern Catchment Area of Lake Maninjau during the peaks of the dry season (July) and the rainy season (December) in 2013.

Lake water level fluctuation in relation to daily rainfall and lake outflow values are shown in Figure 6. The highest daily water level changes are generally taking place in the dry season and the beginning of the rainy season. During the dry season, many other hydropower plants in Sumatra can not be operated properly due to the limited supply of energy primer with the source from river flows [13]. Thus, the Maninjau Hydroelectric Power Plant has an increment in hydropower generation demand. On the other hand, to increase the storage capacity of the lake before reaching the peak of the rainy season, the Maninjau Hydropower Plant takes an operation to increase the lake water use at the beginning of the rainy season.
Figure 6. Fluctuations of the daily observed lake water level (top figure) and their changes (middle figure), in comparison with the fluctuations of rainfall input and lake outflows through the hydropower intake and sanitary gate (middle and bottom figures), for the period of 2013-2014.
Figure 7. Estimated daily net groundwater inflow in relation to daily rainfall (top) and total river inflow to the lake (bottom), from 2013 to 2014.

The net groundwater inflow (positive groundwater residual) indicates that incoming water from the groundwater reaches a value higher than the total river inflow (Figure 7). Moreover, the estimated groundwater inflow is highly-responsive to heavy rainfall events, which may increase its inflow rate more than river discharge. In that condition, it is likely dominated by shallow groundwater flow when the soils reach saturation. As mentioned above, the component of groundwater inflow in this study may include three components, they are subsurface flows that directly go into the lake, quick groundwater flows, and deep groundwater flows. The annual water volume (above figure) and flow rate (bottom figure) of each water balance element in Lake Maninjau for the years of 2013 to 2014 are presented in Figure 8. In summary, the mean annual water volume of each component (in a million m³): 269.27 (rainfall over the lake); 451.86 (total river inflow); 231.94 (total net groundwater inflow); 161.78 (losses water due to evaporation); and 472.32 (total lake outflow discharge). The mean annual rainfall dropped over the catchment area is about 3700 mm/year. The climatic and geomorphological condition of the lake reveals that total river inflow is estimated to have the highest flow rate (14.3 m³/sec), which is relatively similar to the lake outflow through the hydropower intake (14.0 m³/sec). In addition, flow rates of the net groundwater inflow and the lake outflow from the sanitary gate are 7.4 m³/sec and 0.97 m³/sec, respectively. Moreover, the dynamic flux of each component is predicted to be capable of producing the total water volume of the lake of 10.26 billion m³ per year that is slightly varied.
Figure 8. In summary, quantitative values of Lake Maninjau’s water balance element, as an example of output display (Graphical User Interface, GUI) of the Eco-Hydro Model version 3.0.

The net groundwater input was likely higher during the heavy rains in the rainy season but maintained a relatively stable flux along the dry season. To simplify in making quantification of the net groundwater inflow contribution to the lake water volume, herein the lake water mass is divided into two regions, namely new and old waters. The new water volume is defined as the total water volume resulted from summing up the water mass inside the region between the lowest (462.6 m a.s.l) and highest (463.6 m a.s.l) water level as observed from 2013 to 2014 (see Figure 6, top). On the other hand, the old water volume is assumed as the total amount of water mass below the observed lowest water level. Accordingly, as a contribution to the total lake water volume (new water and old water), averaged groundwater inflows were equivalent to at least 2.5% and 1.6% for 2013 and 2014, respectively. Moreover, the result indicates that the groundwater inflow slightly moderately influences the fluxes of new water volume at the upper layer of Lake Maninjau. Annually, the new water volume recharged from the groundwater inflow corresponds to at least 182-281 million m$^3$. It represents the
contribution of equivalent to at least 20-28% according to the assessment for 2013 and 2014 (Figure 9). In general, the net groundwater inflow contribution to the total lake water volume flux for the case of Maninjau is relatively minor. This finding is in accordance with a previous study [15] that pointed out the volcanic terrains around Lake Maninjau were dominated by rare groundwater aquifers, capable of keeping groundwater in a small volume.

![Figure 9. Annual contribution (2013-2014) of the water mass from the rainfall over the lake, cumulative river inflow, and the net groundwater inflow to the total lake water volume (top) and the new water volume at the upper layer of Lake Maninjau (bottom).](image)

4. Conclusion
The hydrological balance for Lake Maninjau has shown that groundwater inflow slightly moderately influenced the fluxes of new water volume (the region between recorded lowest and highest lake water level) at the upper layer of Lake Maninjau, representing at least 20-28% according to the water balance assessment in 2013 and 2014. Annually, the new water volume, which is recharged from the groundwater inflow corresponds to at least 182-281 million m$^3$. Its annual contribution to the total lake water volume (old water + new water) is estimated to be equal 1.6-2.5%. These findings correct the overestimated result (groundwater contributes 89%) of a previous study [12] that the calculation did not consider the fluxes of lake water storage. The flux of groundwater inflow to the lake was often affected by the rainfall event and the regulated water level condition due to the hydropower plant and the existing sanitary gate operation rules. The lake outflows during the dry season and the beginning of the rainy season have shown relatively higher due to an increase in hydropower generation demand and its operating rules to increase the storage capacity of the lake before reaching the peak of the rainy season, respectively. Thus, the lake water level will be declined during those periods and affects the incoming groundwater. Moreover, the estimated groundwater inflow is highly responsive to the heavy rainfall events that makes its inflow rate to be higher than river discharge. In that condition, it is likely dominated by shallow groundwater flow paths when the soils reach saturation.
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