Water balance of Maninjau watershed with SWAT hydrological model

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Abstract. Lake Maninjau was one of the international tourist destinations before the 2000s. Aside from being used as a source of 66 MW hydroelectric power built in 1972, currently, this caldera lake is also used for aquaculture. Lake Maninjau ecosystem, which consists of water bodies and watersheds, has an area of 23,729.3 Ha. The surface area of Lake Maninjau at +461.5 m asl is 9,737.5 Ha. Calculation of water balance in the Lake Maninjau watershed becomes a necessity because of its multi-functional status. Maninjau watershed water balance is estimated using SWAT (Soil and Water Assessment Tools) model. Rainfall data from Climate Hazard Group Infrared Precipitation with Station (CHIRPS) was reanalyzed and compared with local rainfall data. The simulation conducted for 1981 - 2019 on the sub-watershed scale produced NSE and $R^2$ values of 0.61 and 0.7, respectively. The simulation was scaled up for the entire catchment of Lake Maninjau. Simulation results showed that an average annual rainfall of 2,483.9 mm/year produced a surface flow, interflow, base flow, and recharge to aquifer of 7.8 mm/year, 1397.4 mm/year, 273.4 mm/year and 14.7 mm/year, respectively.

Keywords: model, water balance, SWAT, hydrology

1. Introduction
Lakes are formed in various ways which depend on geographical position, geology and biological processes that develop in the area. Some are formed due to catastrophic processes such as earthquakes, volcanic eruptions, landslides, even meteor collisions. Others are formed due to gradual natural processes such as glacial activity, changes in river dynamics, wind, and dissolution processes. In addition, lakes can also be resulted from human activities, such as reservoirs.

Lake Maninjau, a 9,737.5 Ha lake at 461.5 m asl located in Tanjung Raya sub-district of Agam Regency, is classified as volcanic lake. It is estimated that this caldera lake began to form around 60,000 years ago when the ancient Maninjau volcano erupted and spewed 220-250 km$^3$ of volcanic materials which spread to 75 km from the center of the eruption. Its formation process is divided into 3 phases [1] namely the volcanic caldera collapsed due to large eruptions, the caldera will describe the morphology of
the ring fracture and become the center of subsequent sediment deposition then sub-aerial sediment, landslides, and debris fans accumulate inside the floor and edge of the caldera, which is the beginning for the formation of lake formation, this process is filling in the caldera and filling lake sediments formed when volcanism reactivates and erupts, resulting in higher levels of sedimentation.

Lake Maninjau has an important role for the surrounding community. It is now utilized for tourism activities, hydroelectric power plant, fishing activities, and aquaculture using the floating fish net. Anthropogenic activities around the lake can reduce the quality of the lake’s water environment, for example: disposal of domestic waste, hospital, restaurants, agricultural waste and fish feces resulting from floating fish net [2]. Previous study [3] showed that there has been a decrease in outflow discharge data between 1930 - 1941 and 1967 – 1974, especially in the second period. This means that water was unavailable during these periods.

Calculation of water balance gives an overview of the availability of water in the watershed. It can provide the information needed for determining allowed maximum water usage. In a simple calculation, the water balance is the change between inputs and outputs over a period of time either in the form of a reservoir, consumed or released [4]. Important factors for calculating water balance are the availability of rainfall data, air temperature, solar radiation, humidity, land cover and soil type, and rock condition in the study area.

SWAT (Soil Water Assessment Tool) is a spatial and temporal model that can simulate water, sediment, nutrients, and displacement of dissolved materials in the catchment area on a daily or sub-daily scale. SWAT can be integrated directly with GIS through ArcSWAT as a tool for ArcGIS, QSWAT for QGIS (Quantum GIS) and MWSWAT for MapWindos. SWAT was used to simulate Lake Tana’s water balance in Ethiopia [5], analyze hydrology condition of the Dodokan watershed [6], impact of Best Management Practice (BMP’s) on loading and hydrology response in Jatigede Catchment Area [7], and predicting sediment loading to Lake Sumpur, West Sumatra [8]. The calculation was then used to analyze whether the water discharge can be accommodated. It also provided an overview of the lake function as flood control. The purpose of this study is to predict and analyze the water balance of Maninjau Watershed to provide a description of the amount of water that can be flowed into Lake Maninjau by using SWAT hydrological modeling.

2. Materials and Methods
Lake Maninjau is geographically located at 0° 12' 26.63" - 0° 25' 02.80" South latitude and 100° 07' 43.74" - 100° 16' 22.48” East longitude. At 461.5 m asl, the surface area of this caldera lake is 9,737.5 Ha with a catchment area of 14,800 Ha [1]. Administratively it is located in Tanjung Raya Sub-District, Agam District, West Sumatra Province. The geology of Lake Maninjau according to the geological map of Padang sheet, Sumatra is composed of pumice tuff and andesite and andesite from the Maninjau caldera, all of these rocks were from Pleistocene or 1.8 million years ago [9].

Based on rainfall data of 1984 – 2000, which was obtained from Maninjau Power Plant Station, the monthly rainfall pattern were relatively evenly distributed throughout the year with an average monthly rainfall of 299 mm [3]. The highest and the lowest rainfall were observed in November and June, respectively.
2.1. Data collection

This research uses ArcGIS 10.3 software with ArcSWAT 2012 as a spatial data processing tool and model simulation, Google Earth Pro for testing accuracy of land cover data, Microsoft Excel 2016 for processing statistical data and GPS (Global Positioning System) in taking ground check points. Following are the types and sources of data used in this study. Rainfall and river discharge data for validation were obtained from the observation station owned by RC for Limnology on the Kurambik River. Figure 2 shows rainfall and water level gauging sites in River Kurambik and table 1 shows data requirement for the SWAT hydrology model.

**Figure 1.** Location of study area (left) and 3D visualization of Maninjau Watershed.

**Figure 2.** Water level and Rain gauge site in River Kurambik.

**Table 1.** Summary of data requirements.
2.2. SWAT model for water balance simulation

The watershed hydrological simulation model uses the SWAT (Soil and Water Assessment Tools) model, which is a semi-distributed model and can be run continuously or discretely by event based simulation. The SWAT model is used to predict the flow, sediment, and nutrients of a watershed and can be used for management by developing watershed management scenarios.

SWAT was first developed in the early 1990s by the United States Department of Agriculture (USDA) [10]. It was then improved to predict the impact of land management practices on water, sediment, agricultural and chemical yields on a watershed scale with various spatial and temporal aspects. The calculation of the hydrological cycle is based on the water balance equation as follows [11].

\[
SW_i = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})
\]

Where \(SW_i\) is the final water content on day \(i\) (mm\(\text{H}_2\text{O}\)), \(SW_0\) represents the initial soil water content on day \(i\), \(R_{day}\) is the amount of rainfall on day \(i\), \(Q_{surf}\) is the amount of surface flow on day \(i\), \(E_a\) describes the amount of evapotranspiration on day \(i\), \(W_{seep}\) represents the amount of water entering the unsaturated zone of the soil profile on day \(i\), and \(Q_{gw}\) is the total flow of groundwater on day \(i\). Runoff is a calculation using SCS Curve Number Procedure.

Characteristics of Maninjau Watershed, as input for the hydrology model, uses digital elevation model (DEM) from DEMNAS (http://tides.big.go.id/DEMNAS/). The use of high-resolution DEM data was expected to improve the simulation results, especially on flow discharges, because Maninjau watersheds tend to have narrow slope types and short streams. Several studies have shown that DEM resolution is the most sensitive input of SWAT models for flow discharge simulations [12].

Soil type data were obtained from a review scale map (Puslitanak, 1:250,000). An analysis of soil samples to obtain soil characteristics was also carried out. Land use was obtained from the Landsat 8 OLI classification in 2018.

Model simulations were carried out in two different time scales, for the Kurambik Sub-Catchment as an experimental basin using data from river and rain monitoring stations, the data used are; rain and discharge data with 15-minute recording. Discharge data was the result of the conversion of water level observations with Automatic Water LevelRecorder (AWLR) using Hobo U-20, while rainfall was observed with a tipping bucket sensor with a resolution of 0.2 mm equipped with a data recorder.

To calculate the water balance of all watersheds, simulations are carried out with the Climate Hazard Group InfraRed Precipitation with Station (CHIRPS) data input. CHIRPs are rainfall data developed by the United States Geology Survey (USGS), Earth Resources Observation and Science (EROS). CHIRPS...
data combines satellite imagery with a resolution of 0.05° with an in-situ station to make an analysis of rainfall time series available from 1981 to 2019 through CHIRPS Daily Improve data at latitude 50° LU to 50° LS [13]. Tuo et al.[14] suggested that an accurate representation of the temporal and spatial variability of precipitation is very important to achieve an accurate hydrological model.

Maninjau watershed water balance calculation is needed as input for 2D multi-layer hydrodynamic and water quality model developed by RC for Limnology. The combination of these models will be used as the basis for lake management according to the lakes carrying capacity. Figure 3 shows a water balance diagram in the Maninjau watershed.

Figure 3. Water balance in Maninjau Watershed.

The SWAT hydrological model was calibrated and validated based on the results of field measurements on River Kurambik. The performance of SWAT hydrology model in simulating streamflow was evaluated using Nash-Sutcliffe efficiency [15] and the coefficient of determination [16]. The NSE statistical model is widely used to show the performance of a model because it can provide more accurate information about the value given. Moriasi et al. [14] divided the statistical value criteria for NSE as: 0.75 <NSE <1.00 (very good), 0.65 <NSE <0.75 (good), 0.5 <NSE <0.65 (satisfying) and NSE ≤ 0.50 (unsatisfactory). The formula used for the coefficient of determination and NSE is shown below:

\[
R^2 = \left( 1 - \frac{\sum_{i=1}^{n} (Q_i^o - Q_i^s)^2}{\sum_{i=1}^{n} (Q_i^o - \bar{Q}_o)^2} \right)
\]

Where \( Q_0 \) is Observation discharge (m³/s), \( Q_0^o \) is Mean observation discharge (m³/s) and \( Q_s \) is simulation discharge (m³/s).

\[
NSE = 1 - \frac{\sum_{i=1}^{n} (Q_i^o - Q_i^s)^2}{\sum_{i=1}^{n} (Q_i^o - \bar{Q}_o)^2}
\]

Where \( Q_0^o \) : Observation discharge (m³/s⁻¹), \( Q_s^o \) in Simulation discharge (m³ s⁻¹), and \( Q_0 \) is Mean observation discharge (m³ s⁻¹).

3. Results and Discussion

3.1. Model setup

SWAT hydrological model divided the watershed into smaller sub-watersheds (figure 4) using Automatic Watershed delineation (AWD) which is the initial stage of the four modeling stages. The second stage was
defining Hydrology Response Units (HRUs) by overlaying slope, land use, and soil maps. The delineation result shows that the area of the Kurambik Sub-watershed is 270.52 Ha while the area of the Maninjau watershed is 14,057 Ha.

![Kurambik Sub-catchment](image1)

![Maninjau Watershed](image2)

Figure 4. AWD and HRU definition in Kurambik Sub-Catchment and Maninjau Watershed.

The SWAT hydrological modeling was conducted in two phases; small scale and large scale. The first phase used minute rainfall with the Green and Ampt Infiltration method to produce a 15-minute time step discharge of Kurambik Sub-catchment (270.5 ha). Its calibration and validation were conducted using rainfall-discharge data on March 2018 - July 2019. The second phase, the up-scaled model for the entire watershed (14,057 ha), used calibrated and validated parameters from the first phase combined with daily rainfall data from CHIRPS.

Soil types in Maninjau are divided into two classes, namely Dystrandeps and Dystropepts. Both soil classes are derived from lava and intermediate tuff. The results of physical soil analysis show that soil in Maninjau is dominated by silt (47% - 62%), sand (19% - 36%) and clay (17% - 18%). Both types of soil are included in the order of Inceptisols which are classified as young soils and are usually very fertile.

Land use from the classification of Landsat 8 OLI in 2018 (table 2) was used in both simulations. Forest was the dominant land use in Kurambik Sub-catchment and Maninjau Watershed. The plantation was found to be the second most dominant land use in both scales. The types of plantations found in Maninjau watershed are oil palm, chocolate, coffee, and various fruits. Common agriculture developed by
the local people were paddy, vegetable, cassava, chili, and tomato. The type of settlement that is commonly found in Maninjau Watershed is a traditional house of the Minang people, a house made of wood with a yard large enough to be planted with fruit trees. The characteristics of each land use class are very important in determining the curve number values in the SWAT modeling [17].

| Land use   | Kurambik | Maninjau |
|------------|----------|----------|
|            | Area (Ha) | %  | Area (Ha) | %  |
| Forest     | 113.4    | 41.9 | 6375      | 45.3 |
| Agriculture| 25.22    | 9.3  | 2322      | 16.1 |
| Plantation | 101.96   | 37.7 | 3347.5    | 23.8 |
| Settlement | 0.2      | 0.1  | 283.5     | 2    |
| Bush       | 29.97    | 11.1 | 1679.2    | 11.9 |
| Open area  | 0        | 0.0  | 50.7      | 0.4  |
| Total      | 270.75   | 100.0| 14,057.90 | 100  |

### 3.2. Calibration and validation

Calibration is a process to optimize the values of hydrological parameters in the simulation process so as to produce a simulation that can approach the observational data that represents the real events in the field. Calibration was carried out on parameters that are sensitive to river flow discharges and were focused on 12 parameters (table 3) related to discharge, infiltration, interflow, and recession base parameters, namely the parameter group; ground (\_gw), routing (\_rte) and management (\_mgt).

Model validation was carried out in the 2018 simulation using the 2018 land use map. This simulation uses the same parameter values as the parameter values used in the calibration process. The validation results of the model in the Kurambik sub-watershed was good [18] with \( R^2 \) and NSE value of 0.75 and 0.71, respectively (figure 5). Validation results for the second phase were satisfactory with \( R^2 \) and NSE values of 0.64 and 0.62, respectively (figure 6).
Figure 5. Comparison between observed and simulated 15 minutes time step simulation in Kurambik river gauge on validation process.

Figure 6. Comparison between observed and simulated daily simulation in Kurambik river gauge on validation process of the second phase.

Table 3. Final parameter value on model calibration for discharge.

| No | Parameter     | Description                                    | Calibration Range | Calibrated value |
|----|---------------|-----------------------------------------------|-------------------|------------------|
| 1  | CN2           | Initial SCS curve number                      | 0 - 100           | X0,8; x0,8       |
| 2  | Alpha BF      | Alfa base flow (days)                         | 0 - 1             | 0,5              |
| 3  | GW-Delay      | Groundwater delay (days)                      | 0 - 500           | 10               |
| 4  | GW_REVAP      | Groundwater revap. coefficient                | 0,02 – 0,2        | 0,2              |
| 5  | RCHRG_DP      | Deep aquifer percolation fraction             | 0-1               | 0.15:0.25,0      |
| 6  | ESCO          | Soil evaporation compensation factor          | 0-1               | 0,9              |
| 7  | EPCO          | Plant water uptake compensation factor        | 0-1               | 0,84             |
| 8  | CH_N2         | Manning’s n value for main channel            | 0 – 0,3           | 0,03; 0,02       |
| 9  | CH_K2         | Effective hydraulic conductivity in main channel alluvium | 0 - 300     | 15 ; 215         |
| 10 | CH_N1         | Manning’s n value for tributary channel       | 0 – 0,3           | 0,02; 0,05       |
### 3.3. Water balance of Maninjau Watershed

The SWAT simulation model used precipitation input of 2,489.8 mm/year. The entire Maninjau watershed only produces an average direct surface flow of 39.63 mm/year or equivalent to 557.1 m³/year. Annual interflow and baseflow according to the simulation was 1,374.4 mm and 262.25 mm. This proportion is consistent with site observation where most of the rivers in Maninjau watershed are intermittent or non-flowing flows throughout the year. In some rivers, the low flow is also caused by the flow of river water in the middle stream area for irrigated paddy fields, so that the river water runs out when it reaches downstream. For this reason, it is necessary to recalculate the water requirements for irrigated paddy fields, domestic and environmental water which must always flow into lake waters, because rivers that always flow into the lake become habitat for species of lake fish that must enter to river waters.

![Water balance on Maninjau Watershed](image)

**Figure 7.** Water balance on Maninjau Watershed.

### 4. Conclusion

SWAT hydrological model can be used to estimate the water balance in Maninjau watershed. The model validation with monitoring data produced good results, while the validation of the up-scaled model using CHIRPs as rainfall input produced a satisfying result. The results of the water balance analysis are dominated by intermediate flow while the least is surface flow; this is in accordance with the conditions in the field where the river flow is dominated by intermittent rivers. It is necessary to recalculate the water requirements for irrigated rice fields, domestic and environmental water which must always flow into lake waters.
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