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Original Research Article

Integrated Hydrological–Empirical Modeling for Lake Water Balance Estimation in a Data-Scarce Volcanic Catchment

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Abstract

Menjer Lake has undergone various human interventions, such as land use change and hydropower consumption, but has no water level monitoring data in its small catchment area of 2.7 km² and steep morphology. Thus, the objective of this study was to integrate a hydrological model with an empirical model to estimate the water balance of a lake in a data-scarce catchment. The results indicate that the runoff model for an ungauged river demonstrates the good performance of the hydrological model using the Soil and Water Assessment Tool (SWAT) based on its similarity to observed rainfall (R^2 = 0.93). However, the lake water balance is very complex because of multiple input and output sources. Moreover, land-use change had no significant impact on runoff, as no anomaly was found in the runoff model results. Under existing conditions, artificial inflow plays a significant role in the water balance input and output of Menjer Lake. The artificial inflow covered 76% of the water input, with an outflow of 12.3%, preventing any deficit phase. Overall, this study underscores the importance of considering manual calibration with rainfall data in data-scarce areas. The good correlation between rainfall-runoff shows that this model is also acceptable.

Keywords: Hydrological model; lake storage; lake water balance; runoff; SWAT Model

1. Introduction

Lakes play a vital role in surface water availability, environmental and ecological services, recreation, and hydroelectric power generation (Amorim et al., 2021; Ganguli et al.,2022). Numerous studies have been conducted on water balance, water quality, sedimentation, climate change, land use change, and human intervention (Guzha et al., 2018; Bai & Zhao., 2023). Compared to rivers, lakes are more susceptible to various environmental changes. Persistent deviations in lake levels beyond typical variations can have severe economic and environmental consequences (Alemu et al., 2020). Catchment areas are sources of lake water input from surface runoff and groundwater, which can affect both water quantity and quality (Purwono et al., 2020; Chevallier et al., 2023). Therefore, to address the above issue, several models have been developed to estimate the water balance of lakes and the hydrological processes in catchment areas (Chevallier et al., 2023; Yang et al., 2024). In recent years, the integration of hydrological models with empirical models has been employed to study the connections between water systems in catchment areas, providing a more comprehensive understanding of the water processes.

Menjer Lake, located in Central Java, Indonesia, was selected for this research because of its role as a multipurpose reservoir, such as for hydroelectric power plants, tourism destinations, and sites for inland aquaculture using floating net cages. The lake receives substantial precipitation input but faces significant human intervention despite its relatively small catchment area. Menjer Lake is a volcanic lake formed by a massive eruption in the Dieng area of Wonosobo, part of the Dieng Volcanic Complex (Bergen, et al., 2000), similar to Lake Merdada (Fadlillah & Widyastuti, 2016; Suhendro et al., 2022). Since 1973, the lake has been used for hydroelectric power generation, tourism, and land-based fish farming using floating net cages. Menjer Lake has become a major vacation destination (Arobi et al., 2025).

Currently, Menjer Lake faces several threats, including land-use change and reduced precipitation. From 2021 to 2023, rapid land-use changes occurred in the catchment area, largely driven by tourism growth. This phenomenon mirrors the trends observed in other catchments in Indonesia (Suprayogi et al., 2022). Over time, vegetation cover has declined, with an increase in arid and urban land areas and a reduction in farmland and mixed forest areas within the Menjer Lake catchment area. Moreover, field surveys have revealed the lake's strategic importance for tourism, with ongoing construction and land leveling for housing and commercial purposes. Land conversion has led to the development of tourist amenities, such as parks, restaurants, and resorts. Furthermore, as runoff is primarily influenced by land use, climate, and soil conditions, these changes also affect the infiltration process and overland flow (Bai & Zhao, 2023), ultimately altering the hydrological inputs to the lake.

This study found that natural surface inflow data from river discharge were limited, primarily because of the steep terrain of the lake morphology and its catchment area. The topography of the lake catchment and shoreline causes inflows to resemble waterfall-like flows. In addition to these natural inflows, the lake has one artificial input from the Serayu River, which has a consistent discharge input. Consequently, relying solely on observed lake levels for validation is insufficient, given the variations in rainfall inputs and distributions. To improve model performance, soil and rainfall data are commonly adjusted based on in situ measurements (Orth et al., 2015) or the Soil Conservation Service Curve Number (SCS-CN) method. Mass surface runoff can contribute to sedimentation in a water body due to erosion, as highlighted by Wang et al. (2018). However, the steep topography of Menjer Lake complicates the monitoring of streamflow and sediment yield from the catchment. Christanto (2022) demonstrated that the Soil and Water Assessment Tool (SWAT) model can effectively simulate rainfall–runoff processes, even in ungauged catchments such as Menjer Lake. Consequently, new methods and techniques have been applied in recent studies to advance research in the field of water exchange (Zhang et al., 2016; Wu et al., 2017; Long, et al., 2023).

Combinations of SWAT models and empirical calculations have been employed to investigate the complex relationships between river flows from catchment areas and lake water balance. For instance, (Fadlillah and Widyastuti (2016), Alemu et al. (2020), and Yang et al. (2024) studied lake water balances using empirical models in other lakes. Wu et al. (2017) developed integrated hydrological and hydrodynamic models for data-scarce areas using both SWAT and three-dimensional models. Numerous studies have focused on pollutant assessment in lakes and rivers (Feng et al., 2019; Dey et al., 2021; Fadlillah & Widyastuti, 2016). However, none of these studies developed integrated runoff models to collect input streamflow data in mountainous catchment areas, which lack monitoring stations for model validation, such as in Menjer's catchment.

Accordingly, to enhance the application of integrated models, this study employed the SWAT model for hydrological modeling and an empirical model for water balance in data-scarce areas. Innovative approaches and methods are necessary for generating and monitoring streamflow and sediment in these regions (Long, et al., 2023). To address this need, this study aims to (1) simulate runoff in data-scarce areas, (2) analyze the lake water balance model based on the correlation between rainfall and runoff, and (3) evaluate the Influence of the Hydropower Plant on Lake Storage.

2. Methods

2.1. Study Area

Administratively, Menjer Lake is situated in Wonosobo Regency, Central Java, in Maron Village, Garung District. A naturally occurring lake, Telaga Menjer, was created by volcanic activity that started on Mount Pakuwaja. According to Pratama et al. (2021), Menjer Lake was produced by quaternary volcanic units (Qhvsn) and a volcanic tuff breccia rock unit (Qhvm). According to their assessment, umbrik andosol predominated in over 93% of the Menjer Lake area. Other soil types, including lithosol and lithic andosol, were also present. Menjer Lake experiences considerably high precipitation, with an average annual rainfall of more than 3000 mm. The topography of the Telaga Menjer region is marked by steep terrain, with over 40% of the region categorized as extremely steep (Figure 1). The area is elevated at a height of approximately ±1300 m above sea level. The Serayu River's influx impact s Menjer Lake. The lake water body is approximately 0.58 km² in size, with a 2.27 km² water catchment area and a maximum depth of 36–40 m. This region mostly uses its land for agriculture and mixed woodlands.

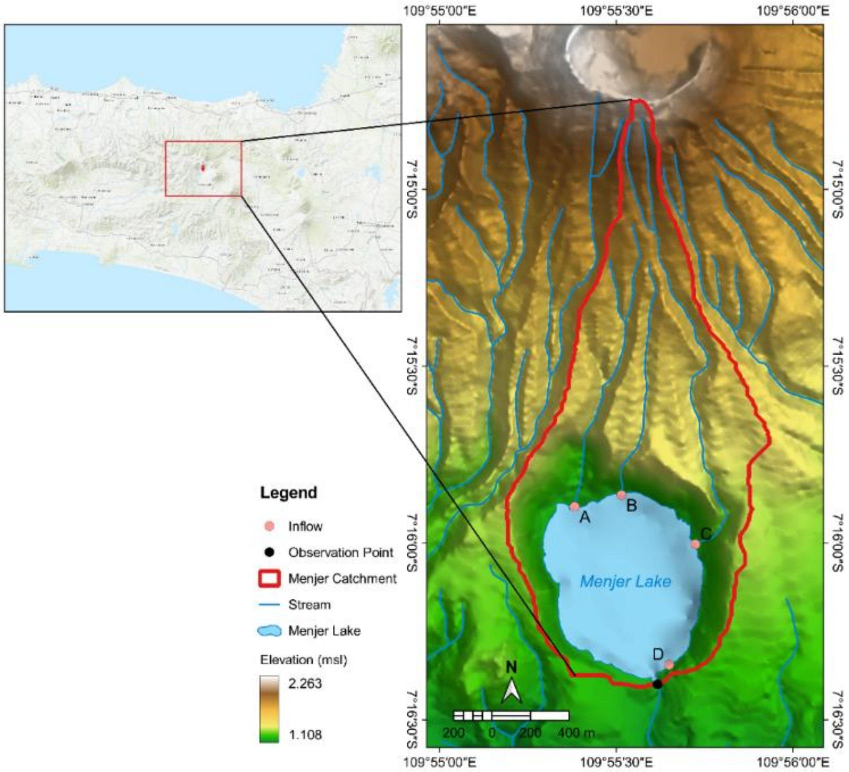

Figure 1. Menjer Lake's catchment area

Lake Menjer was chosen as the study area because of its complexity in terms of land use change and water input. The existing condition of Menjer Lake indicates that it has experienced land use change from 2021 to 2023 due to tourism development (Arobi et al., 2025), primarily around the lake (Figure 2). These changes have had a major impact on soil loss, infiltration processes, and the hydrological cycle, particularly in small catchment areas (Aneseyee et al., 2020). The increase in barren land (2 5) from crop land, shrubland (1 %), and grassland from mixed forest (1%) indicates land clearing before the construction of settlements or ecotourism facilities. Land cover conditions also play an important role in determining surface water flow levels. In this regard, Guzha et al. (2018) indicated that the presence of vegetation on land can reduce surface water flow.

2.2. Data Collection

2.2.1. Precipitation and Temperature

In this study, rainfall data were obtained from observations at the Garung Hydroelectric Power Plant, located near point D (**Figure 1**). The dataset comprised daily rainfall records from January 2021 to September 2023. These rainfall data were used to calculate precipitation directly over the lake surface as input and to model runoff using the SWAT model. The temperature data for evapotranspiration were derived from the National Aeronautics and Space Administration's (NASA) satellite observations.

2.2.2. Lake Inflow

Inflow data were collected from surface runoff and river discharge. As shown in **Figure 1**, four creeks were identified as inputting Menjer Lake: A, B, C, and D. Rivers A, B, and C are characterized by intermittent flow, with discharge occurring only during the rainy season as a result of surface runoff. River D is an artificial input that serves as a hydropower inlet from the Serayu River. The discharge input from this river is consistently 1.944 m^3/s, except from July to August, when it decreases to 1.6053 m^3/s. This reduction occurs during the dry season when the discharge of the Serayu River declines. The discharge data from river D were obtained from the monitoring records of the Garung Hydroelectric Power Plant located at point D (**Figure 1**).

2.2.3. Lake Levels and Outflow for Hydropower

Daily lake level data were obtained from the Garung Hydroelectric Power Plant. Outflow data from January 2021 to December 2023 were obtained from the discharge records of the Garung Hydroelectric Power Plant. Water releases were conducted at a constant flow rate of 1.844 m^3/s. However, the total discharge recorded from July to August decreased to 1.544 m^3/s because of the reduction in lake inflow during these months.

2.3. Data Analysis

2.3.1. Lake Water Balance Calculation

Lake water balance is described as the amount of water stored in a lake during a certain period of time. This can be indicated by the lake volume or lake level. However, lake-level fluctuations are affected by input and output processes (Dessie et al., 2015; Fadlillah & Widyastuti, 2016; Yang *et al.*, 2024). These processes include inputs from precipitation on the lake surface area (P), runoff from the catchment area (R), groundwater inflow (G_{in}), and inflow (I). The outputs are affected by evapotranspiration (E), groundwater output (G_{out}), and outflow (O).

The water balance during a specific time can be described in Eq. 1 as follows

$$_{\Delta}S(P + R + G_{in} + I) + (E + G_{out} + O) \quad (1)$$

The units for all components were converted to m^3/d or $m^3/month$. Groundwater inflow and outflow, known as the groundwater net (G_{net}), have been neglected in several studies because of the difficulty in estimating them (Dessie et al., 2015; Fadlillah & Widyastuti, 2016; Yang *et al.*, 2024). Despite this, groundwater provides a significant amount of input and output based on the leakage. Therefore, this study also calculated groundwater based on lake water fluctuation using a modified equation (Fadlillah & Widyastuti, 2016), as shown in Eq. (2).

$$G_{net} = \Delta H - (P - E \times A) - R \qquad (2)$$

where G_{net} represents groundwater inflow and outflow, presented by seepage and leakage; A is the lake surface area; and ΔH is the lake level fluctuation. In this study, the lake level was measured using the monthly average lake level from January 2021 to December 2023. P represents precipitation on the lake surface (m/month).

2.3.2. Lake Surface Area

The lake surface area (A) was calculated by visually interpreting satellite images (Fadlillah & Widyastuti, 2016). However, a limitation of this method is that satellite images are sometimes obscured by clouds, such as in the case of Lake Menjer, which is located at a high elevation. Therefore, this study only selected images that provided clear visualization with no clouds. In this study, lake surface areas were visually digitized from Sentinel-2 images with the least cloud coverage at different times. The images were taken in April 2021, April 2022, July 2022, and July 2023. To provide additional monthly lake surface area data, this information was combined with lake data to provide a correlation using Pearson's correlation (Yang et al., 2024).

2.3.3. Precipitation

There is one rainfall monitoring station in the Menjer Lake catchment area, located near location point D (Figure 1), which records daily rainfall depth in millimeters. Although there was only one rainfall station, it can represent the entire catchment because it is a small area of 2.27 km², which is assumed to have uniform rainfall variation.
To estimate precipitation (P) on the lake surface area (A), the rainfall data from the monitoring station (P_i) were calculated using the following equation (Eq. 3)

$$P = P_i \times A \qquad (3)$$

Subsequently, the daily rainfall data were aggregated into monthly data (mm/month).

2.3.4. Evapotranspiration on the Lake Surface Area

The potential evaporation (E_p) was computed using the Thornthwaite method (Thornthwaite, 1948; Qomariyah & Masitoh 2025). This formula is suitable for use under conditions of limited data because it is primarily based on the temperature and latitude of the location (Adem et al., 2017; Xiang et al., 2020). Temperature data were obtained from satellite sources because of the limited availability of data from climatological stations. Specifically, temperature data were acquired from NASA satellite imagery owing to ground data limitations. The calculation of potential evapotranspiration was conducted using the Eq. 4,5,6 as follows

$$6\,x\,\left[\frac{(10xt)^a}{I}\right] x \left[\frac{N}{12}\right] x \left[\frac{1}{30}\right] \quad (4)$$

$$(675\,x\,10^{-9})x\,I^3 - (771\,x\,10^{-7})\,x\,I^2 + (179\,x\,10^{-4})\,x\,I + 0{,}492 \quad (5)$$

$$(\tfrac{t}{5})^{1{,}51} \quad (6)$$

where ET_o is the reference evaporation (mm/month), t is the monthly mean temperature (°C), N is the monthly adjustment factor related to the hours of daylight, a is the empirical coefficient based on latitude, and I is the heat index for the year. For the lake surface area, ET_o was multiplied by the lake surface area.

2.3.5. Lake Inflow Using the SWAT Model for Unmonitored Streamflow

The basic concept of the SWAT model is also based on the Soil Conservation Service Curve Number (SCS-CN) model. In this study, the SWAT application automatically calibrated the model

(Arnold et al., 2012) and required input data that met the parameters specified by the SWAT model. All data needs and sources used in this research are listed in **Table 1.** In this study, discharge modeling was performed to analyze the variations in discharge within the Menjer Lake catchment area for 2021, 2022, and 2023. Notably, this time frame witnessed substantial changes in the land-use patterns within the Menjer Lake catchment area. These land-use alterations are anticipated to influence the hydrological response, resulting in discharge fluctuations.

Topographic data as contour lines from the Indonesian Topographic Map (Geospatial Information Agency/BIG) at a scale of 1:25,000 were converted to a raster in a digital elevation model (DEM) using the topo-to-raster method. Land use data were obtained from the manual interpretation of Sentinel-2 imagery for the period of 2021–2023. Weather data, including rainfall, temperature, humidity, wind speed, and solar radiation, were processed so that they could be read by the SWAT model. The soil map was based on the landforms obtained from the Indonesian Center for Agricultural Land Resources Research and Development and included soil sampling to identify soil texture. Not all soil properties were measured; thus, some parameters were approximated using the pedotransfer functions (Abbaspour et al., 2019). Soil property data from SoilGrids were used to complement the soil data. All spatial data, including the DEM, land use map, and soil map, were overlaid to generate hydrologic response units with discharge as the output.

Tabel 1. Input data for soil and water assessment tool hydrological model

Parameters	Data form	Data sources
Topography	Raster	Indonesian Topographic Map (Geospatial Information Agency of Indonesia)
Land use data	Raster	Sentinel-2
Rainfall data	Tabular	Observation data from Indonesia Power
Temperature	Tabular	Agrometeorological ECMWF Reanalysis v5 (ERA5)
Humidity	Tabular	
Wind velocity	Tabular	
Solar Radiation	Tabular	
Soil Characteristic	Raster and Tabular	Center for Agricultural Land Resources Research and Development (ICALRD), soil samples, soilgrids.org

2.3.6. Limitations of the Model

This research was limited by the lack of a water level monitoring station due to the steep terrain morphology. Therefore, it is not feasible to install lake-level recorders for these rivers. In this model, validation was performed using the rainfall-runoff correlation, as there were no monitoring stations providing water level data in the Menjer catchment.

3. Result and Discussion

3.1. Lake Level and Lake Surface Area

Pearson's correlation results between the lake area (obtained from satellite data) and lake level showed a good correlation, with $r = 0.99$ and $R^2 = 0.98$. This indicates that the lake surface area increased as the lake level rose. After determining the correlation between the lake level and lake surface area, the monthly lake surface area was simulated using the correlation equation $y = 732.07x - 261060$. A comparison of the observed monthly average lake level from 2021 to 2023 with the simulated lake surface area is shown in **Figure 2**. The results of Pearson's correlation between the monthly lake surface area model and the average monthly lake level in **Figure 2** also indicate a good match, with an r-value of 1, showing that the lake surface area model can be used effectively.

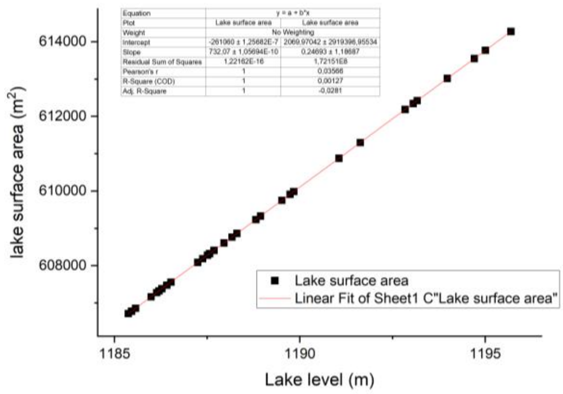

Figure 2. Correlation of monthly lake level versus surface area from the correlation results (b)

As shown in **Figure 3**, the monthly lake level in Telaga Menjer from 2021 to 2023 exhibited a fluctuating trend. This phenomenon is generally caused by several factors, such as rainfall input, groundwater input, and human intervention (Abbott & Anderson 2009). Naturally, lake levels are usually higher during the rainy season. However, in contrast, Menjer Lake shows that the highest lake level occurs in May–August (dry season) every year, whereas the lowest lake level occurs between September and April (rainy season). This condition indicates a phenomenon that is heavily influenced by hydropower plant regulation of water use. For example, the outflow for the hydropower plant during the dry season is less than that during the rainy season, which ultimately causes the lake level in Telaga Menjer to be higher. Given these conditions, the regulation of the hydroelectric power plant has a significant influence on lake level fluctuations in Telaga Menjer.

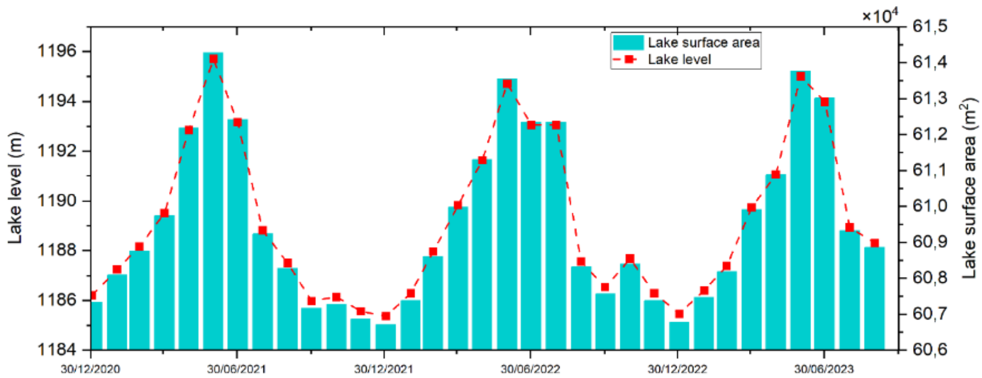

Figure 3. Fluctuation of the monthly lake level of the Menjer Lake collected from 2021 to 2023 and the surface area derived from correlation

3.2. Precipitation and Evapotranspiration on the Surface of the Lake

Precipitation (P) and evapotranspiration (E_p) over the lake surface were calculated using precipitation and evaporation data, along with the lake surface area. The volumes of P and E_p are shown in **Figure 4**. The monthly P–E_p graph shows that the average precipitation fluctuated significantly between the dry and rainy seasons. From January 2021 to July 2023, the highest, lowest, and average monthly precipitation values were 685, 0, and 287 mm, respectively. Compared with other tropical regions, the annual average precipitation of 3411 mm/year is higher than that of the Lake Tana catchment area in Ethiopia (Alemu et al., 2020; Hermawan et al., 2024). In contrast, evaporation remained relatively constant (Yang et al., 2024) and was similarly low to that observed in lakes within the Dieng Highlands (Fadlillah & Widyastuti, 2016). **Figure 4** also indicates that during the dry season, from May to July, evapotranspiration significantly exceeded precipitation.

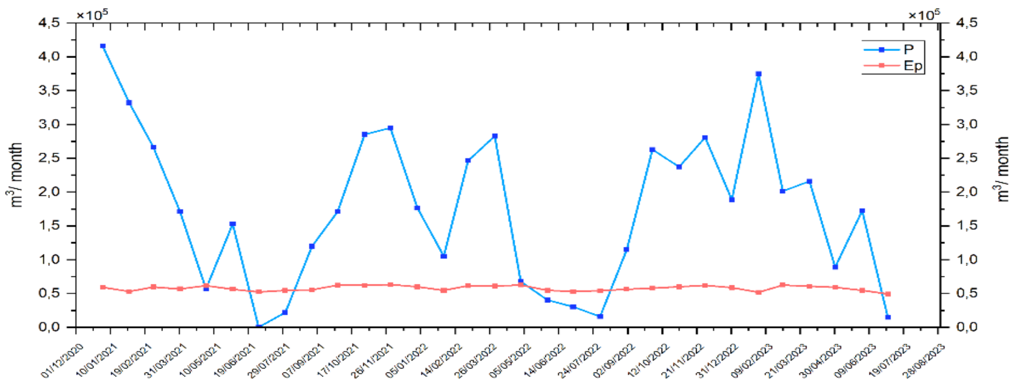

Figure 4. Monthly precipitation and evapotranspiration in the lake surface area

The E_P value and lake body area of Menjer Lake varied monthly, influenced by seasonal conditions. **Figure 4** illustrates the monthly fluctuations in the E_P volume of Lake Menjer. The E_P value tended to be low during dry months, such as July and August, whereas it was higher during rainy months, such as November and December. This study involved monthly evapotranspiration calculations for both the rainy and dry seasons. Typically, the rate of evapotranspiration in tropical regions is lower than that in arid areas because the air conditions are often close to saturation (Cascone et al. 2019). The monthly variations in E_P were influenced not only by temperature but also by local soil, climate, and vegetation conditions.

3.3. Lake Inflow from Unmonitored Stream Flow

Three rivers enter Menjer Lake in the form of a small river and waterfall. Because of the steep slopes along rivers A, B, and C, it was not feasible to install automatic water-level recorders. Consequently, runoff modeling was performed using the SWAT Model. A limitation of this study is that the flow simulation results were not validated using the observed flow data. To ensure the accuracy of the results, several parameters, such as rainfall and soil texture, were based on the observational data. According to Christanto et al. (2020), using ground measurement data allows for better performance than using rainfall data obtained from satellites. To further ensure the accuracy of the flow simulation results, the model was calibrated using the regionalization technique (Swain & Patra, 2017; Meng et al., 2020) and by analyzing the rainfall–runoff correlation. The regionalization technique for SWAT model calibration involved adjusting the parameters within the regional watershed, such as the Serayu watershed.

The results of the monthly runoff simulation for the Menjer Lake catchment area using SWAT are shown in **Figure 5**. Overall, river C had the largest flow discharge, whereas river B had the smallest flow discharge. The graphs show that the flow discharge was dependent on rainfall. In this model, groundwater was not included; however, groundwater inflow and outflow were calculated using Equation 2. The rivers flowing into Menjer Lake were categorized as ephemeral and of order 1. The steep topography of the Menjer Lake catchment area causes rainfall to quickly convert to surface runoff. Consequently, the Menjer Lake catchment has a rapid hydrological response, typically within an hour.

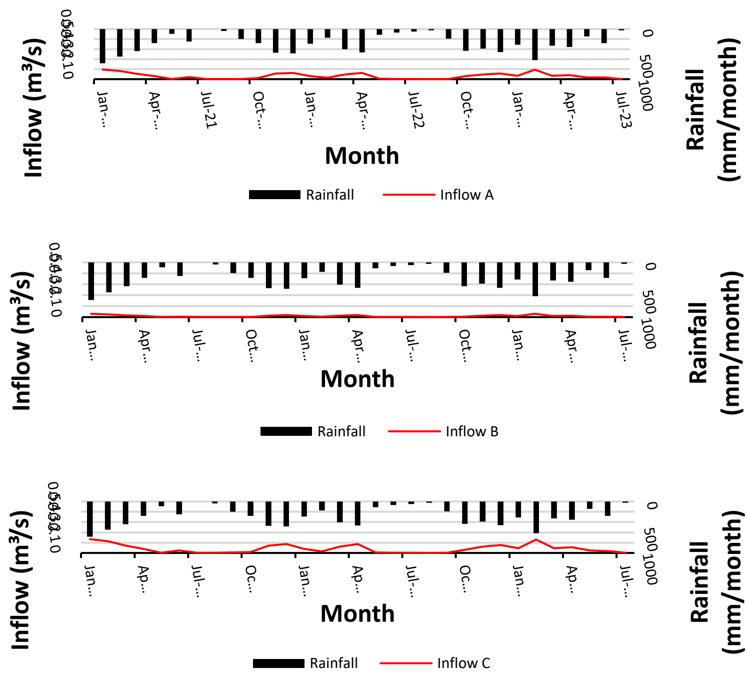

Figure 5. Simulated discharge inflow in rivers A, B, and C and observed rainfall (*P*) from January 1, 2021, to July 31, 2023

3.4. Rainfall- Runoff Validation in Data-Scarce Areas

Although land use changes affect the flow coefficient and the curve number values, there was no significant impact on the runoff model results, such as a sudden peak flood or sudden increase in runoff volume (Shrestha et al., 2021). Moreover, despite the noticeable land use changes from 2021 to 2023, the correlation between land use and runoff at Menjer Lake, as shown in **Figures 6**, indicates that the flow coefficient has no anomaly and has a good correlation (R^2 = 0.93). This also indicates that the SWAT model performed well without water level calibration (Abbaspour et al., 2019; Christanto et al., 2020).

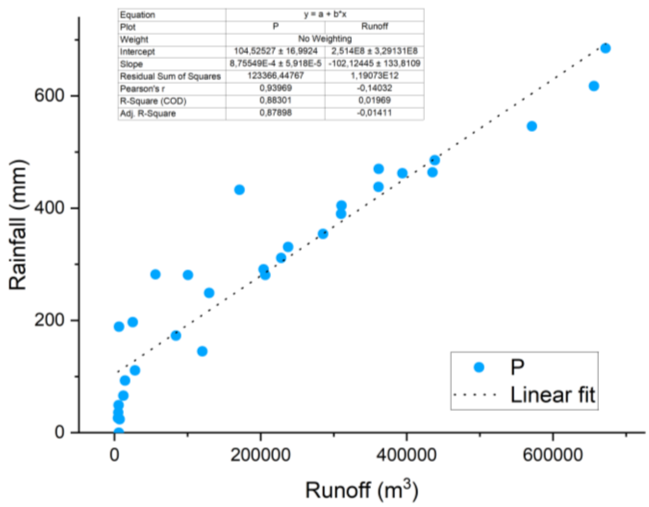

Figure 6. Rainfall–runoff correlation

This stability can be attributed to the small size of the catchment area, which limits the impact of these changes on runoff and groundwater patterns. Overall, the hydrological dynamics of Menjer Lake remained stable, with inflow, outflow, and groundwater patterns exhibiting the expected seasonal variations.

3.5. Runoff and River Outflow and Inflow

The variations in inflow, outflow, and runoff, as shown in **Figure 7a**, indicate that the inflow from the artificial river (I) was dominant. Menjer Lake receives an average yearly river inflow of 5.83×10^7 m³ and an average yearly runoff of 2.4×10^6 m³. The river inflow (I) remains stable because it is used to maintain water input for hydropower consumption. The outflow showed low variation because the same amount of water was consistently extracted for hydropower use. The runoff, covering a 2.7 km² catchment area, is represented by three major rivers. The rainfall–runoff graph for the entire Menjer catchment area displayed a consistent pattern, indicating a correlation between rainfall and surface runoff (**Figure 7b**). As shown in Figure **7b**, the effect of direct changes was not significant (Dessie et al., 2015; Guzha et al., 2018). The estimated river inflow from 2021 to 2023 showed that Menjer Lake received a maximum monthly runoff of 6.72×10^5 m³/month, a minimum of 4.72×10^3 m³/month, and an average runoff of 2×10^5 m³/month.

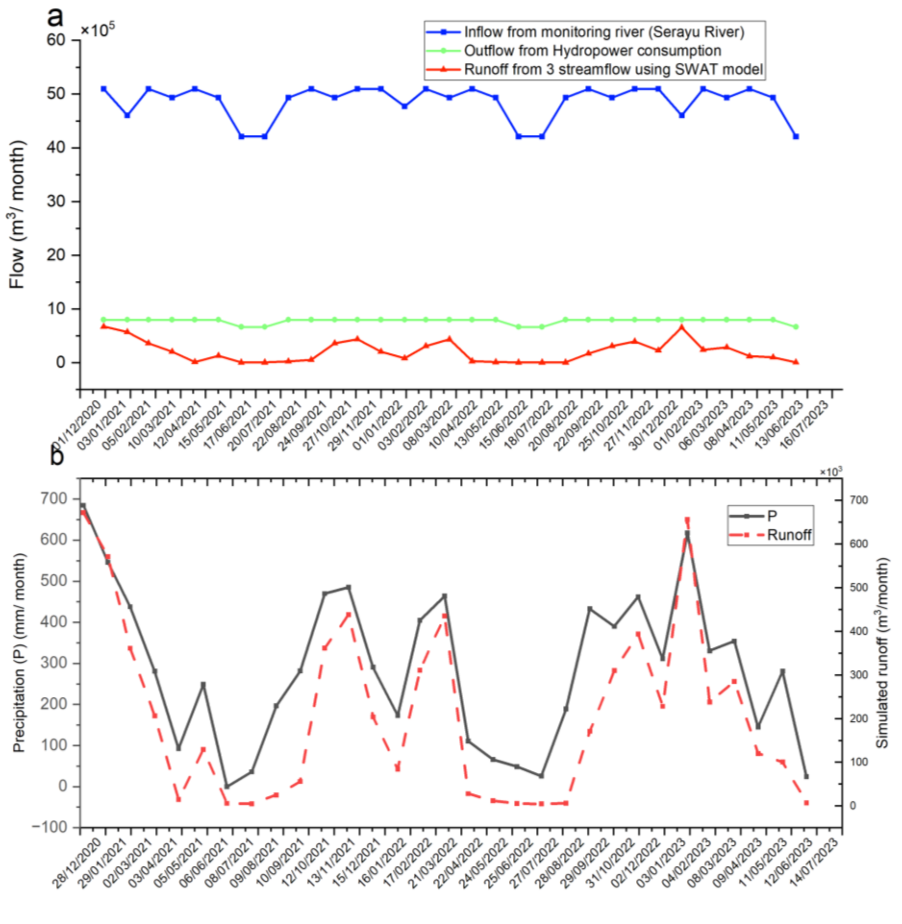

Figure 7. Monthly flow variations from inflow, outflow, and runoff (a); precipitation and runoff variation in the Menjer Lake catchment area (b)

3.6. Groundwater Inflow and Out flow

Groundwater inflow (G_{in}) and outflow (G_{out}) are significantly affected by precipitation and runoff, respectively. Consequently, the estimated G_{in} and G_{out} displayed a pattern similar to that of runoff, indicating a strong relationship between these components. When groundwater decreases, runoff into Menjer Lake also decreases. In small catchments, groundwater inflow is highly dependent on rainfall, and both runoff and groundwater entering the lake through seepage are influenced by precipitation. In the evaluation of the monthly variation in groundwater discharge shown in Figure 8, the groundwater discharge evidently showed significant seasonal variation. During the dry season, with zero precipitation and runoff input, the baseflow from the catchment becomes the primary input to the lake. Thus, *the* G_{out} ranged from 1.82×10^3 to 4.52×10^4 m^3/month, indicating leakage from the lake. Conversely, in the rainy season, the groundwater inflow into the lake can reach up to 10×10^6 m^3. The average yearly groundwater input was 3.7×10^7 m^3, with the maximum, average, and minimum monthly groundwater inputs being 1×10^7, 3.18×10^5, and 9.31×10^3 m^3, respectively.

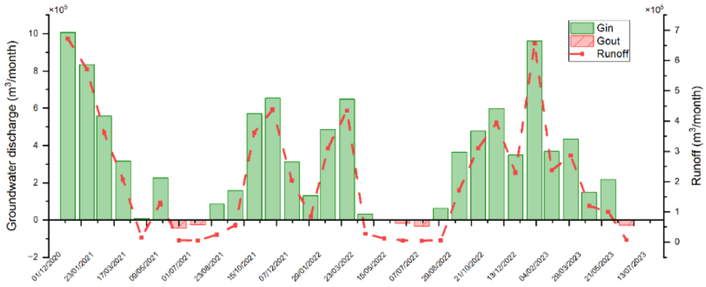

Figure 8. Monthly groundwater discharge volume input (G_{in}) and output (G_{out}) data. Runoff and groundwater discharge exhibited similar patterns.

3.7. Lake Water Balance

The water balance of Lake Menjer is illustrated in **Figure 9a**. The figure indicates that inputs from runoff, groundwater, and precipitation decreased during the dry season (May–August) and increased during the rainy season. Consequently, higher precipitation (*P*) leads to increased runoff (*R*) and groundwater inflow (Alemu et al. 2020). In contrast, evaporation, an output, began to increase during the dry season. The contribution of each component shows that the main input is from artificial river (*I*), whereas the main output is from outflow (*O*). Storage is not included in this graph because it is a product of water balance. **Figure 9b** shows that approximately 76% of the water balance input is influenced by the artificial river, 2.73% by precipitation, and 3.25% by runoff. For the outputs, evapotranspiration on the lake surface accounted for only 0.9%, groundwater inflow and outflow accounted for 4.98%, and outflow accounted for 12.3%.

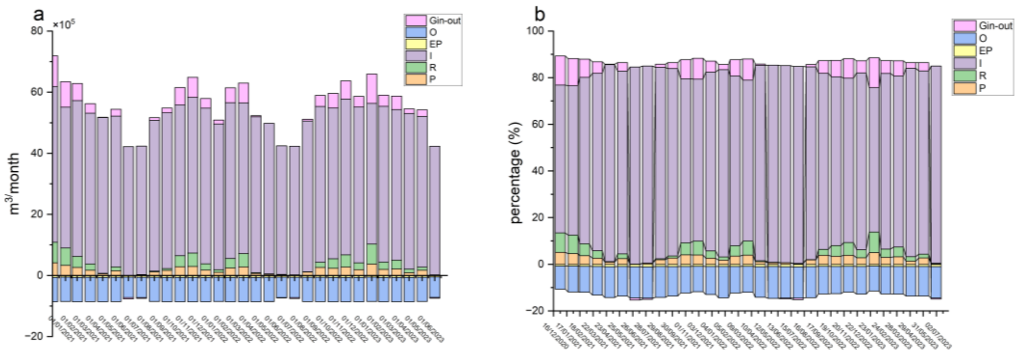

Figure 9. Volume of monthly water balance (a), Percentage of water balance for input and output variables (b)

3.8. Influence of the Hydropower Plant on Lake Storage

Changes in lake storage essentially indicate the condition of the catchment (Bakken et al., 2013). Under real conditions, the storage value of the lake was greatly influenced by the input from artificial rivers (**Figure 10a**). Compared with the storage estimate without hydropower intervention, the storage value was significantly lower and could experience a deficit during the dry months. As shown in **Figure**

10b, in the absence of hydropower, the water balance model for Menjer Lake shows that precipitation, runoff, evapotranspiration, and groundwater inflow and outflow contribute 23%, 27.42%, 7.61%, and 41.97%, respectively. This highlights the crucial role of rainfall as a primary input. Without artificial regulation, the Menjer Lake could face storage deficits, particularly during periods of low rainfall. The changes in Menjer Lake are primarily driven by artificial inputs from hydropower operations, which significantly alter the natural water balance. An anomaly was observed between the calculated storage and lake level. This discrepancy can also be attributed to the impact of hydropower operations on the water balance. During the dry season, the calculated water balance indicates low storage, whereas the lake level indicates a high volume (Zhang et al., 2016). The lake depends significantly on rainfall and runoff for its natural inflows, and without hydropower intervention, it would likely experience storage deficits during dry seasons. Understanding this relationship is crucial for accurately assessing the lake's hydrological behavior, and understanding these dynamics is crucial for effective water resource management and planning in the region.

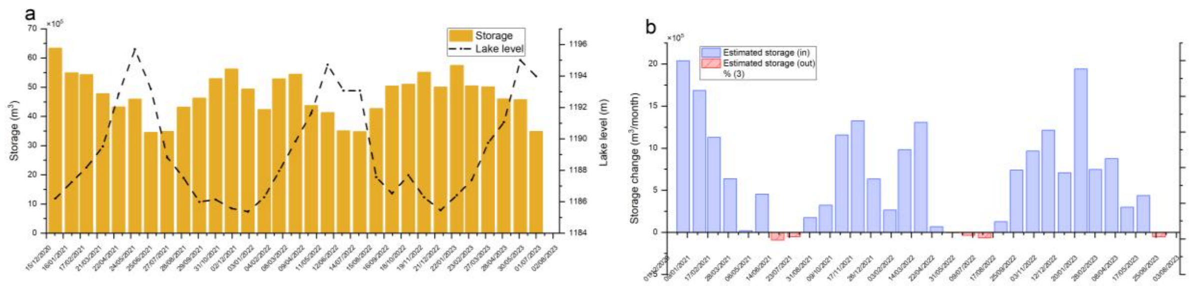

Figure 10. Existing storage volume (a); storage estimation without hydropower intervention. In this model, the artificial river (inflow D) and outflow were neglected (b)

4. Conclusions

This study successfully simulated runoff in a data-scarce area for water balance input calculations and analyzed the lake water balance under existing conditions and a scenario without hydropower intervention. It was also identified that Menjer Lake experienced land use changes between 2021 and 2023. However, the findings indicate that these changes had a minimal impact on runoff, with no anomalies. The runoff model demonstrated good performance, with a strong correlation between rainfall and runoff data even without gauging stations for calibration and validation. The runoff simulations provided valuable insights into the natural water balance components, revealing that, under the existing conditions, artificial inflows from rivers are the primary input for the lake's water balance. This study also highlights the significant impact of hydropower operations on the storage dynamics of Menjer Lake. Under natural conditions, precipitation is considered the main input, whereas groundwater inflow, outflow, and runoff play crucial roles in maintaining lake storage.

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CRedit Author Statement

Lintang Nur Fadlillah: Data Curation, Data Analysis, Conceptualization, Writing the Original Draft, Review Editing. **Afifudin**: Data Analysis and Writing the Original Draft. **Firdaus Rachman Saputra**: Visualization, Software, and Writing the Original Draft. **Sri Utami**: Data Curation and Writing the Original Draft. **Kim Dong Hyeon**: Review and Writing the Original Draft

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