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Daily Water Balance Analysis of the Sempor Reservoir in Central Java Using the SWAT Model for Operational Reliability Assessment

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ABSTRACT Sempor Reservoir plays a crucial role in supporting irrigation water supply, raw water provision, and flood control in Central Java. Effective reservoir operation requires reliable estimates of inflow and water availability to ensure sustainable water allocation under varying hydrological conditions. This study analyzes the daily water balance of Sempor Reservoir using the Soil and Water Assessment Tool (SWAT) model to simulate inflow and assess operational reliability. Daily rainfall and climate data for 2015–2024 were used, with streamflow observations used for model calibration (2015–2022) and validation (2023–2024). Model performance was evaluated using the Nash–Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2). The SWAT model performed very well, achieving NSE = 0.83 and R^2 = 0.87. These performance statistics indicate that the simulated inflows closely matched the observed discharge and provide confidence in the model's application for water balance analysis. Daily water balance results show that deficit conditions occur mainly during the dry season. Annual inflow and demand were 184.02 million m^3 and 186.45 million m^3, resulting in a deficit of 2.43 million m^3. The reservoir was full for 36 days, sufficient for 311 days, and insufficient for 18 days, indicating approximately 95% reliability. Overall, the results demonstrate that the SWAT model is an effective tool for evaluating daily reservoir water balance and operational performance. The findings provide useful information for reservoir operation, water allocation planning, and sustainable water resources management under changing hydrological conditions. The results also provide valuable information for water managers in optimizing reservoir operation, improving water allocation efficiency, and reducing the impacts of seasonal water shortages.

KEYWORDS Inflow; Outflow; Reservoir; SWAT; Water Balance.

1 INTRODUCTION

Sempor Reservoir is one of the reservoirs located in Central Java Province, specifically in Sempor Subdistrict, Kebumen Regency. The reservoir was constructed in 1958 with the primary purpose of supporting the irrigation system. Since its construction, Sempor Reservoir has become an important infrastructure for Kebumen Regency and surrounding areas, not only in providing irrigation water for agricultural land but also in flood control and supplying raw water. Additionally, the community also utilizes the reservoir for fisheries and tourism.

Sempor Reservoir has a catchment area of approximately 42.31 km^2 with an initial capacity of 52 million m^3, most of which consists of forest and agricultural land. However, over time, challenges in managing the dam have increased. Changes in land use around the catchment area, such as the conversion of forests into agricultural land or residential areas, have caused significant negative impacts. According to research by Hapsari et al. (2021), the catchment area of the Sempor Reservoir has undergone changes in land use from 1984 to 2019. The most significant change occurred in residential land, which increased in area by 857.24 ha or 47.49% of the total land change that occurred in the catchment area of Sempor Reservoir.

Land use conversion from forested and agricultural areas to residential land within the Sempor Reservoir catchment alters watershed hydrological responses by increasing surface runoff and sediment transport. Sediment generated during rainfall events is subsequently deposited in the reservoir, leading to a gradual reduction in effective storage capacity, particularly in erosion-prone areas (Marhendi, 2013). Arini et al. (2019) reported that sedimentation in the Sempor Reservoir reaches 166,173 tons/year, with a sediment thickness rate of 3.72 mm/year, indicating a significant impact on long-term reservoir storage.

Sempor Reservoir also serves as a raw water source for the Tirta Bumi Sentosa Kebumen Regional Water Utility and supplies irrigation water to the Sempor Irrigation Area. Setiawan (2018) projected a substantial increase in domestic water demand, from approximately 242.69 L/day in 2013 to 2,441.64 L/day in 2033. However, the reservoir is reported to meet only 61% of the total irrigation water demand due to reduced storage capacity (Putri and Sapei, 2024). Furthermore, Saputro and Asyifa (2018) identified a minimum annual irrigation water requirement of 1,071.62 L/s, with unmet demand occurring during April, September, and October, highlighting periods of operational vulnerability.

Given the decreasing availability of water in the Sempor Reservoir, it is necessary to optimize reservoir water use. Water balance calculation is a crucial first step in efficient reservoir management. A water balance provides an overview of the equilibrium between inflow and outflow in the reservoir, enabling reservoir managers to regulate water allocation for various needs without compromising long-term water availability. Additionally, water balance analysis is important for addressing climate change impacts, as it supports mitigation and adaptation measures against flood and drought risks (Noerhayati, 2015).

According to Triatmodjo (2008), reservoir inflow is influenced by hydrological conditions of the catchment, including rainfall characteristics, soil properties, topography, and land use patterns within the watershed. Therefore, this study utilizes the Soil and Water Assessment Tool (SWAT), a physically based and semi-distributed hydrological model, to estimate inflow into the Sempor Reservoir. SWAT is capable of simulating daily streamflow and assessing the impacts of land use and water management on watershed hydrology using available secondary data. By utilizing historical and current conditions, the model supports water availability analysis and scenario evaluation related to climate variability and land use change, making it suitable for daily reservoir inflow estimation in this study (Neitsch et al., 2005).

Although previous studies have examined land use change, sedimentation, and water demand in the Sempor Reservoir system, these studies generally focus on individual aspects of water resources management. Consequently, there remains limited understanding of how daily inflow variability affects reservoir storage dynamics and the ability of the reservoir to meet water demands on a day-to-day basis, particularly because reservoir operation and water allocation decisions are implemented on short-term time scales. Therefore, an integrated daily-scale reservoir water balance analysis is required to capture short-term inflow–outflow fluctuations that cannot be adequately represented by monthly or annual analyses. Based on this motivation, the following section describes the methods used to conduct the daily reservoir water balance analysis in this study.

2 METHODS

2.1 Time and Place

The research was conducted from October 2024 to April 2025. It was carried out at the Sempor Reservoir, Kebumen Regency, Central Java. A map of the research location is shown in Figure 1.

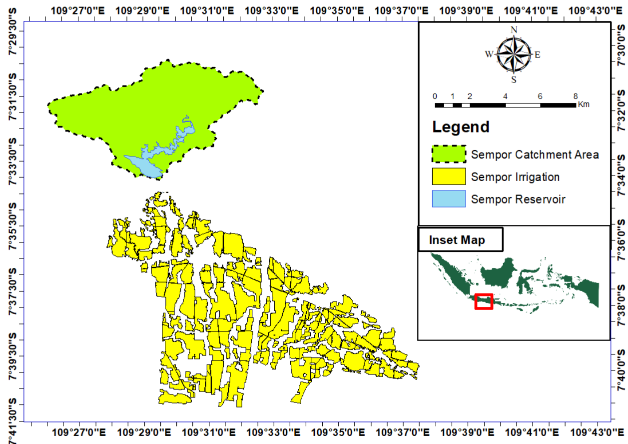

Figure 1. Location of Sempor Reservoir and Its Watershed Boundary in Central Java.

2.2 Tools and Materials

In this study, the tools used included a set of laptops with Microsoft Excel software and the QGIS 10.3 plugin QSWAT+ 2012. Although QGIS 10.3 and QSWAT 2012 are relatively older versions, they were selected because they provide stable performance and reliable integration for SWAT watershed delineation and HRU generation. These versions are also widely used in previous SWAT-based studies and ensure consistent data processing workflows and compatibility of input and output formats, thereby reducing potential errors related to software updates and plugin changes. The materials utilized consisted of climate and rainfall data, which were sourced from the Serayu Opak River Basin Agency and the Progo Bogowonto Luk Ulo Water Resources Management Agency, covering a 10-year period from 2015 to 2024. Additionally, daily discharge data from the Sempor Reservoir outlet were obtained from the Serayu Opak River Basin Agency. Land use maps for the year 2019 were acquired from the Geospatial Information Agency (BIG) through its official online database. Digital Elevation Model (DEM) data were also obtained from BIG, while soil maps for the Sempor Reservoir catchment area were provided by the Serayu Opak River Basin Agency.

2.3 Research Procedure

The research procedure was conducted in several stages, beginning with the collection of secondary data, followed by a literature study, data processing, and report writing. The literature study was conducted to gather supporting theories that would help in the preparation of the research. After data collection, the next stage was data processing. The calculation of reservoir water availability (inflow) was performed using the Soil and Water Assessment Tool (SWAT) model and program. The input data used are rainfall data, climate data, soil type, and land use maps.

In this study, water demand (reservoir outflow) consists of water demand for irrigation, raw water supply, evaporation losses, and seepage representing the downward movement of water from the reservoir into the unsaturated (vadose) zone. The calculation of irrigation water requirements refers to Planning Criteria 01 (Ministry of Public Works, 2022). The next step is to perform a water balance calculation. From the results of this calculation, the reliability of the reservoir in fulfilling its function can be determined.

In analyzing rainfall characteristics required as input for hydrological modeling, several statistical parameters were calculated to describe the variability and distribution of maximum daily rainfall. These statistical analyses are necessary to ensure that the rainfall data used in the model are representative and suitable for subsequent hydrological simulations. First, the standard deviation (S_d) was calculated to measure the variability of maximum daily rainfall relative to its mean value, as expressed in Equation (1).

$$S_d = \sqrt{\frac{\sum \left(X_i - X_{rt}\right)^2}{n-1}} \tag{1}$$

where X_i represents the maximum rainfall in the i year, X_{rt} is the average maximum daily rainfall, and n is the total number of data points. The standard deviation provides an initial indication of rainfall variability, which is further evaluated using additional statistical measures.

The Coefficient of Variation (C_v) is then computed to evaluate the relative variability by comparing the standard deviation with the mean maximum rainfall, and is calculated by Equation (2).

$$C_v = \frac{S_d}{X_{rt}} \tag{2}$$

In addition, the Coefficient of Kurtosis (C_k) helps assess the sharpness of the rainfall distribution, and is calculated by Equation (3).

$$C_k = \frac{n^2 \sum \left(X_t - X_{rt}\right)^2}{\left(n-1\right)\left(n-2\right)\left(n-3\right) {S_d}^4} \tag{3}$$

Similarly, the Coefficient of Skewness (C_s) measures the asymmetry of the rainfall distribution and is given by Equation (4).

$$C_s = \frac{n \sum \left(X_t - X_{rt}\right)^3}{\left(n-1\right)\left(n-2\right) {S_d}^2} \tag{4}$$

These statistical parameters were used to evaluate the suitability of the rainfall data for frequency analysis and design rainfall estimation. For determining design rainfall, the Gumbel method is used with Equation (5) to calculate the design rainfall X_t.

$$X_t = \bar{X} + \frac{S_d}{S_n}\left(Y_t - Y_n\right) c \tag{5}$$

where S_n is the variance reduction factor, and Y_t and Y_n are the return period and average values.

In analyzing rainfall characteristics, several statistical parameters were calculated to describe the variability and distribution of maximum daily rainfall, including standard deviation (S_d), coefficient of variation (C_v), skewness (C_s), and kurtosis (C_k) (Equations (1–4)). These parameters were used to evaluate the consistency and reliability of rainfall data and to support rainfall frequency analysis and design rainfall estimation using the Gumbel method (Equation (5)). It should be noted that this statistical analysis was conducted solely to assess rainfall data characteristics and suitability. The SWAT model itself uses the daily rainfall time series directly as input; therefore, the calculated statistical parameters were not used as direct input parameters in the SWAT simulations.

The simulated daily hydrological components generated by the SWAT model are subsequently used to quantify the reservoir water balance. These components form the basis for calculating daily changes in reservoir storage and evaluating water availability under existing conditions. In this study, the simulated daily discharge generated by the SWAT model represents the reservoir inflow used in the subsequent water balance calculations.

For modelling water balance, the SWAT model is employed, where factors such as precipitation, surface runoff, evapotranspiration, water seeping into the vadose zone, and groundwater flow are considered. The water balance is represented by the following Equation (6).

$$SW_t = SW_0 + \sum\nolimits_{i=1}^{t} R_{day} - Q_{surf} - E_a - W_{seep} - Qgw \tag{6}$$

where SW_t is the final soil water content, and R_{day}, Q_{surf}, E_a, W_{seep}, and Q_{gw} represent daily precipitation, surface runoff, evapotranspiration, seepage of water into the unsaturated (vadose) zone, and groundwater flow, respectively. This equation represents the daily water balance framework used to quantify changes in soil water storage and to support the estimation of inflow and outflow components in the reservoir system.

The stages in SWAT modelling are as follows:

1. Sub-Basins Delineation
   This stage uses DEM and river network data to delineate Sub-Basins based on natural topographic boundaries, dividing the area into Sub-Basins using a default threshold size. The threshold size determines the number of Sub-Basins and river networks.
2. Hydrological Response Unit (HRU) Formation
   HRUs are formed by considering soil type, land slope, and land cover, which are reclassified according to the SWAT database. HRUs are redefined using a 20% threshold by soil type, land slope, and land cover to determine the final HRUs for each Sub-Basin.
3. Daily Discharge Simulation
   Rainfall and climate data are processed in a weather generator and converted into .txt format. These data are then input into SWAT Editor for modeling after Sub-Basins and HRUs are delineated.
4. Model Calibration and Validation
   To assess the reliability of the simulated discharge and water balance results, model performance was evaluated by comparing simulated outputs with observed discharge data using statistical performance indicators. The simulation results are calibrated and validated using the Sequential Uncertainty Fitting Version 2 (SUFI-2) method. Calibration involves the iterative adjustment of hydrological parameters to improve the accuracy of the model's predictions. According to Latifah et al. (2013), the NSE and R^2 values of the daily discharge simulation results must be determined. The coefficients of determination (R^2) and Nash-Sutcliffe (NSE) efficiency were used to analyze the adjustment of the values predicted by the model to the observed data (Neitsch et al., 2005). NSE is calculated using Equation (7).

$$NSE = 1 - \frac{\sum_i (Qm - Qs)^2}{\sum_i (Qm_i - Qs_i)^2} \tag{7}$$

Where NSE is the Nash-Sutcliffe Efficiency, and Qm and Qs represent the observed and simulated discharge values, respectively. Qm_i and Qs_i are the average observed and simulated discharge values. The NSE value indicates the predictive skill of the model, with higher values representing better agreement between simulated and observed data.

To assess the accuracy of the model's simulation patterns, the coefficient of determination (R^2) is used, with values ranging from 0 to 1. The R^2 value is calculated using Equation (8).

$$R^2 = \frac{\left[\sum_i (Qm_i - Qm)(Qs_i - Qs)\right]^2}{\sum_i (Qm_i - Qm)^2 \sum_i (Qs_i - Qs)^2} \tag{8}$$

The combined use of NSE and R^2 provides a comprehensive evaluation of model performance, which is essential for validating the reliability of the simulated inflow used in the reservoir water balance analysis. NSE and R^2 are classified into five categories, as shown in Table 1.

Table 1. Classification of NSE and R2 performance rating (Moriasi et al., 2007)

NSE	R^2	Classification
$0.75 < NSE \leq 1$	$0.75 < R^2 \leq 1$	Very Good
$0.60 < NSE \leq 0.75$	$0.60 < R^2 \leq 0.75$	Good
$0.36 < NSE \leq 0.60$	$0.50 < R^2 \leq 0.60$	Satisfactory
$0 < NSE \leq 0.36$	$0.25 < R^2 \leq 0.50$	Bad
$NSE \leq 0$	$R^2 \leq 0.25$	Inappropriate

The results of these performance indicators are used to determine the reliability of the SWAT model outputs, which serve as the basis for subsequent reservoir water balance analysis.

The SWAT model employs 548 hydrological parameters for calibration, although not all of them are used in the calibration process. The selection of parameters is based on literature studies of commonly used parameters in SWAT modeling. These parameters are calibrated through a trial-and-error process to achieve the best possible results. Once calibration is complete, the next step is validation, which involves running the model over a different time period to verify its consistency and ensure its reliability in predicting outcomes.

According to Firdaus et al. (2014), the validation process is conducted by running the calibrated model with the same parameters but for a different time period. After calibration and validation, the NSE and R^2 values are calculated again for each SWAT model.

For irrigation water requirements, the Net Field Water Requirement (NFR) is calculated by Equation (9).

$$NFR = ET_c + P + WLR + Re \tag{9}$$

where ET_c is the crop evapotranspiration, P is precipitation, WLR is water layer replacement, and Re is effective rainfall.

To determine Diversion Requirements (DR) for irrigation using Equation (10).

$$DR = \frac{NFR \times A}{e \times 8.64} \quad (10)$$

where A is the area in ha, and e is the efficiency of the irrigation system.

The Evapotranspiration Reference (ETo), which accounts for the climatic conditions affecting evaporation, is calculated by Equation (11).

$$ETo = c \cdot (W \cdot Rn + (1 - W) \cdot f(u) \cdot (ea - ed)) \quad (11)$$

where c is a weather adjustment factor, W is the factor affecting solar radiation, Rn is net solar radiation, and $f\ (u)$ is the wind function.

In determining the Water Layer Replacement (WLR), the amount of water required for replenishing the layer of water in the soil is 50 mm/month.

For irrigation land preparation, to calculate the water needed during land preparation is by Equation (12).

$$IR = \frac{M \cdot e^k}{e^k - 1} \quad (12)$$

where IR is the irrigation requirement, M is the water required for soil saturation, and k is a constant.

In calculating the Effective Rainfall for paddy ($R_e\ Paddy$) and Secondary Crops ($R_e\ Palawija$), Equation (13) is the formula for effective rainfall for paddy crops.

$$R_e\ Paddy = \frac{0.7R_{80}}{\text{period of observtion}} \quad (13)$$

And Equation (14) for Secondary Crops (*Palawija*).

$$R_e\ Palawija = \frac{0.5R_{80}}{\text{period of observtion}} \quad (14)$$

These formulas are crucial for managing the water resources of Sempor Reservoir and ensuring efficient irrigation for the agricultural regions relying on the reservoir.

3 RESULTS AND DISCUSSION

3.1 General Conditions of the Research Location

The Sempor Reservoir is located at coordinates 7°28'30" S – 7°34'30" S and 109°25'0" E – 109°30'0" E. The reservoir has an initial storage capacity of 52 million m^3 and is part of the Sempor River catchment area, covering approximately 4,231 ha. In this study, rainfall data were represented by three rainfall stations located within the catchment area, namely Sempor, Kedung Wringin, and Sampang stations. Meanwhile, the calculation of irrigation water demand was based on data from Sindut, Adimulyo, and Watubarut stations. The catchment area of the Sempor Reservoir consists of various land use types, as summarized in Table 2. A spatial distribution of land use in the Sempor River Basin is shown in Figure 2.

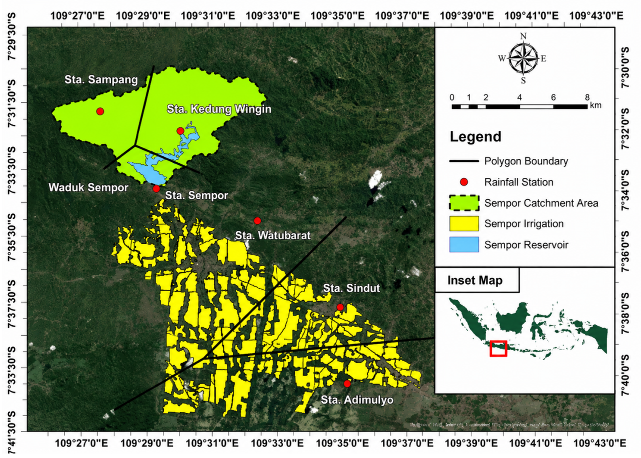

Figure 2. Climatological station at the research site.

Table 2. Land use in the catchment area of the Sempor reservoir

No	Land Use	Area (ha)	Percentage (%)
1	Water	255	6.03
2	Range-brush	153	3.62
3	Forest-evergreen	2,714	64.15
4	Range-grasses	15	0.37
5	Urban	455	10.76
6	Agricultural Land-Generic	309	7.32
7	Rice	327	7.74
Total		4,231	100

Based on the Ministry of Environment and Forestry (2022), slope conditions can be classified into five classes. The Sempor Reservoir catchment area is categorized as a mountainous or highland region, characterized by steep slopes associated with the South Serayu Hills. These hills consist predominantly of old rock formations and sandstone, resulting in steep terrain conditions (Astuti, 2018). The slope classification map of the catchment area is presented in Figure 3.

Based on data from the FAO, the type of soil found in the catchment area of Sempor Reservoir consists of one type, namely Lithosols. To support hydrological analysis in this region, climate and rainfall data were also collected from several stations. The catchment area

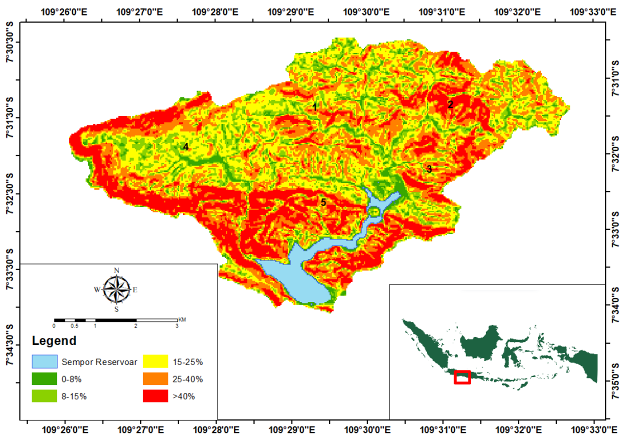

Figure 3. Map of slope classes in the catchment area of Sempor Reservoir.

of Sempor Reservoir has three rainfall stations, namely Sampang, Kedung Wringin, and Sempor, as well as one climatology station. The highest average daily rainfall occurs in December at 13.66 mm, while the lowest occurs in August at 1.08 mm. Additionally, the catchment area of Sempor Reservoir has an average relative humidity of 84.52%, an average temperature of 26.96°C, an average wind speed of 4.8 m/s, and an average solar radiation of 40.64%.

3.2 Application of the SWAT Model

The process of delineating the catchment area of Sempor Reservoir resulted in five sub-basins by setting a specific threshold size. This threshold size plays a role in the formation of river networks, which then determines the number of sub-basins. The smaller the threshold value, the more sub-basins will be formed (Li et al., 2023). A summary of the results of the formation of sub-basins in the catchment area of Sempor Reservoir is shown in Figure 4.

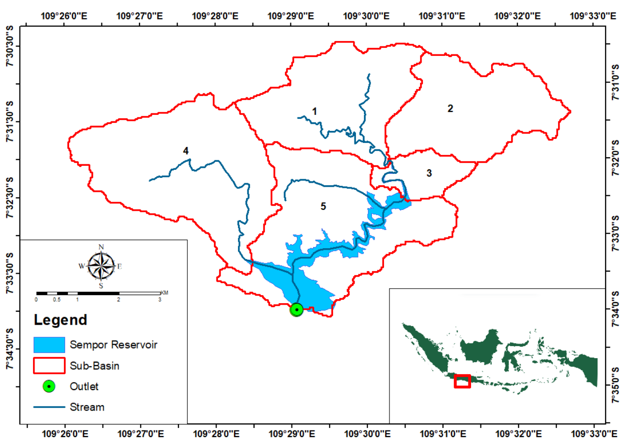

Figure 4. Map of the Sub-Basin in the catchment area of Sempor Reservoir.

The Hydrological Response Unit (HRU) was formed using land cover, soil type, and slope maps (Table 3).

Table 3. Results of land use reclassification based on SWAT codes

SWAT Code	Land Use
AGRL	Agricultural Land-Generic
FRSE	Forest-evergreen
RICE	Rice
RNGB	Range-brush
RNGE	Range-grasses
URBN	Urban
WATR	Water

The HRU formation process initially used default settings and produced 325 HRUs without filtering. This made the model complex and required a long calculation time. To simplify this, a threshold by percentage method of 20% was used for land cover, soil type, and slope (Utomo et al., 2020).

The SWAT model was applied to simulate discharge using rainfall and climate data from three stations. The simulation was conducted for the years 2018–2022 with a 3-year warm-up period (NYSKIP) from 2015 to 2017 to achieve more stable results (Palao et al., 2013). The stages consist of 3 years of warm-up, 5 years of calibration, and 2 years of validation. The simulation results before the calibration are shown in Figure 5.

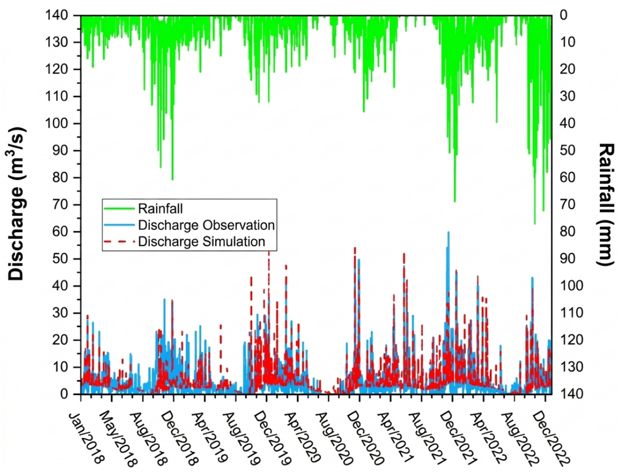

Figure 5. Comparison of simulated discharge (before calibration process) with observed discharge.

The simulation results produced an NSE value of 0.45 (Satisfactory) and an R^2 value of 0.65 (Good), indicating that the model performance is quite good but not yet optimal. The calibration process aims to adjust the parameters that affect the SWAT model, thereby minimizing the difference between the SWAT model discharge and the observed discharge in the field (Saputri et al., 2023). Calibration and validation processes were carried out using SWAT-CUP software with the SUFI-2 (Sequential Uncertainty Fitting Version 2) method.

In SUFI-2, uncertainty in the model input parameters is accounted for by using a uniform distribution. Parameter values are selected randomly within a specified range, allowing for the exploration of different possible scenarios and their effects on the model's outcomes (Sao et al., 2020). Model output uncertainty is measured by calculating the range of simulation results, known as 95% Probability Prediction Uncertainty (95%PPU). The 95%PPU is calculated by taking the 2.5% and 97.5% values from the cumulative distribution of model outputs generated through the Latin Hypercube Sampling (LHS) method (Abbaspour et al., 2007). LHS selects parameter combinations randomly but evenly, ensuring that all possibilities are tested in the simulation (Tapas et al., 2025).

In SUFI-2, the *p-factor* measures how much of the actual data the model can predict accurately, while the *r-factor* indicates the uncertainty in the simulation results by reflecting the width of the 95%PPU range. A higher *p-factor* shows better prediction accuracy, and a larger *r-factor* indicates greater uncertainty in the model's predictions. A good model has a *p-factor* > 0.75 and an *r-factor* < 1.5 (Abbaspour et al., 2015).

Model calibration begins with sensitivity analysis to identify the parameters most influential on model performance. Global Sensitivity Analysis measures the impact of changes in input parameters on simulation results, with *t-stat* and *p-value* as indicators. Sensitive parameters are indicated by high *t-stat* and low *p-value*, indicating a significant influence on model results (Abbaspour et al., 2007). After the first simulation with 50 iterations, the sensitivity ranking of parameters is determined based on *t-stat* and *p-value* values, as shown in Figure 6 and Figure 7.

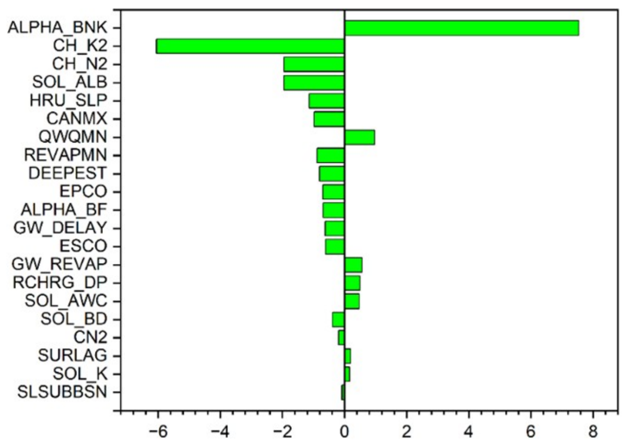

Figure 6. Graph of *t-stat* values.

Based on the sensitivity analysis results presented in Figure 6 and Figure 7, the parameters that most influence the model results are ALPHA_BNK (baseflow alpha factor for bank storage), CH_K2 (effective hydraulic conductivity of the main channel), CH_N2 (Manning's

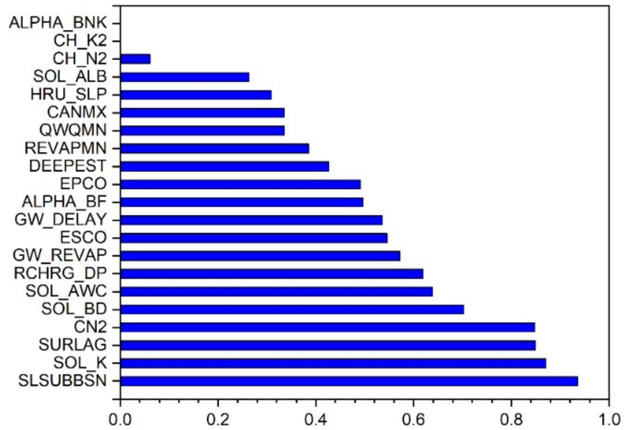

Figure 7. Graph of *p-value* values.

roughness coefficient for the main channel), SOL_ALB (soil albedo), and HRU_SLP (average slope of the Hydrological Response Unit). These parameters represent key hydrological processes that control runoff generation, soil water movement, and channel flow routing in the study area. SLSUBBSN and SURLAG strongly influence the timing and response of surface runoff, while SOL_K and SOL_AWC affect soil permeability and soil water retention capacity. ALPHA_BNK regulates the rate of water release from the riverbank to the main stream, influencing baseflow contribution. CH_K2 indicates the hydraulic conductivity of the channel bed, whereas CH_N2 represents channel roughness that affects flow velocity. In addition, parameters such as SOL_ALB and HRU_SLP also influence hydrological responses related to soil energy balance and surface runoff characteristics. Therefore, these parameters were prioritized during the calibration process.

Table 4. Most sensitive SWAT parameters identified

No	Parameter	Hydrological Process
1	APLHA_BNK	Baseflow
2	CH_K2	Channel routing
3	CH_N2	Flow resistance
4	SOL_ALB	Evapotranspiration
5	HRU_SLP	Runoff
6	SURLAG	Runoff timing
7	SOL_AWC	Soil moisture

The SWAT model calibration process was carried out in four iterations to improve the accuracy of discharge simulations. As a result, the R^2 value increased from 0.862 (very good) in the third iteration to 0.864 (very good) in the fourth iteration, while the NSE value rose from 0.78 (very good) to 0.79 (very good). This improvement indicates that the gradual parameter adjustments successfully improved the model's performance and produced more accurate and stable discharge simulations (Abbaspour et al., 2007). The complete list of calibrated SWAT parameters is provided in the Appendix. The main text highlights the most sensitive parameters identified from the sensitivity analysis, as these parameters were prioritized during calibration.

The results of discharge simulations using the SWAT model after the calibration process, compared with observation data from Serayu Opak River Basin Agency for the period January 2015 – December 2022, are shown in Figure 8.

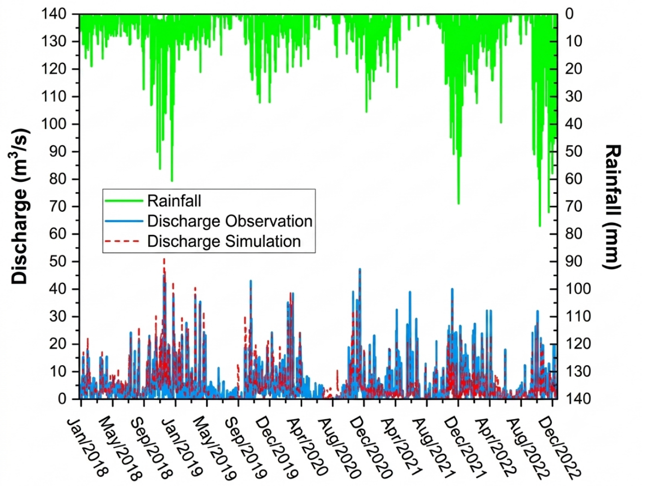

Figure 8. Comparison of simulated discharge (after calibration process) with observed discharge.

The model performance obtained in this study ($NSE = 0.83$ and $R^2 = 0.87$) indicates very good agreement between simulated and observed discharge. According to the performance criteria proposed by Moriasi et al. (2007), NSE values greater than 0.75 represent very good model performance for daily streamflow simulation. Comparable SWAT-based studies in tropical reservoir catchments in Indonesia, such as the Mrica Reservoir, reported NSE values of 0.73 and R^2 values of 0.74 during validation (Hidayat et al., 2016). Therefore, the calibration and validation results obtained for the Sempor Reservoir are comparable to, and even higher than, those reported in other tropical reservoir studies, confirming the reliability of the SWAT model under tropical climate conditions. The discharge simulation results after validation are compared with the Serayu Opak River Basin Agency observation data and are shown in Figure 9.

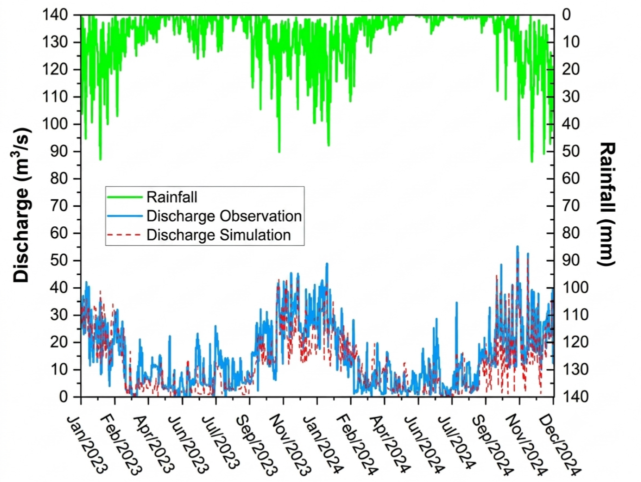

Figure 9. Comparison of simulated discharge (after validation process) with observed discharge.

Distribution suitability tests were performed using the chi-square test and the Smirnov-Kolmogorov test. The calculated chi-square value of 7.0 is smaller than the critical value of 7.815, thus meeting the requirement. In the Smirnov-Kolmogorov test, the *Dmax* value of 0.23 is also smaller than the critical value of 0.409, indicating that the data distribution is appropriate. Based on the results of both tests, the log Pearson type III distribution method is deemed suitable for use. The simulation results show that the flow fluctuations follow the reliable rainfall pattern, including peak and low flow periods, thus providing an overview of the long-term river flow conditions. This flow will be used as the main input in water balance calculations, which form the basis for analyzing the availability and distribution of water resources in the catchment area of Sempor Reservoir. The reliable flow graph is shown in Figure 10.

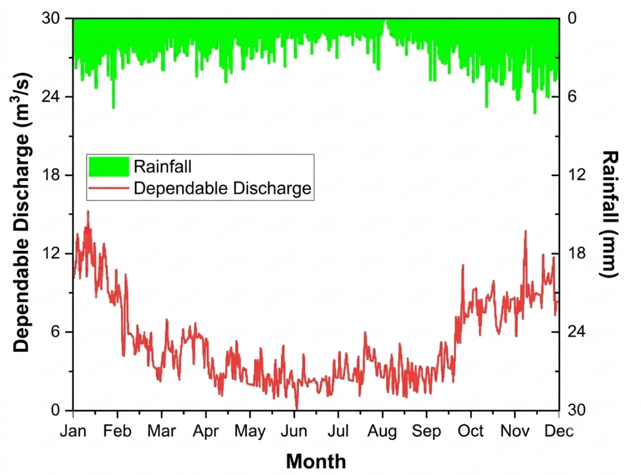

Figure 10. Dependable Discharge of Sempor Reservoir.

3.3 Reservoir Water Availability

Discharge simulations using reliable rainfall data were conducted to reflect long-term hydrological conditions and were used for more accurate water resource management planning. The data used remained the same as in the previous simulation, namely daily rainfall data from 2015 to 2024 from three stations in the catchment area of Sempor Reservoir.

The selection of the Log Pearson Type III distribution ensures that the derived dependable discharge represents long-term hydrological conditions in the Sempor

Reservoir catchment. This dependable discharge is a critical input for reservoir water balance calculations and operational planning, as it is used to evaluate water availability under conservative flow conditions. By linking reliable discharge estimates with daily reservoir inflow–outflow analysis, the reservoir operator can assess storage adequacy, identify potential deficit periods, and support more effective decisions related to irrigation release scheduling and raw water supply management.

3.4 Irrigation Water Requirements

The calculation of irrigation water requirements in Sempor Irrigation area uses reliable rainfall data from three stations, namely Watubarut, Sindut, and Adimulyo. The calculation of reliable rainfall uses the Log Pearson Type III distribution. The highest value was recorded in January period I (8.00 mm/day), and the lowest in June period I (0.78 mm/day). As a result, the highest effective rainfall for rice is 5.60 mm/day and for other crops is 2.13 mm/day.

The cropping pattern system in Sempor Irrigation area follows the Paddy-Paddy-Secondary Crops scheme with three land area categories, each covering 2,040 ha (Category 1), 2,488 ha (Category 2), and 1,950 ha (Category 3). Based on research conducted by Latifah (2017), in general, the average efficiency of primary irrigation channels reached 89.18%, and secondary irrigation channels reached 84.37%, so that the overall efficiency of irrigation channels in the Sempor Irrigation System reached 75.24%. However, in the study, the efficiency value of the channels still refers to Ministry of Public Works (2022), which is 65%.

The calculation of clean water requirements in rice fields (NFR) and water intake requirements or Diversion Requirements (DR) was conducted by considering crop coefficients, evapotranspiration, effective rainfall, and irrigation efficiency. The highest water requirement was recorded in February of Period III (3.31 L/day/ha), while the lowest was in January of Period I (0.63 L/day/ha). The highest DR value was recorded in February of Period III at 10,098.6 L/day, while the lowest was in January of Period I at 671 L/day.

3.5 Water Requirements of Regional Water Utility

This study uses daily discharge data from Serayu Opak River Agency over the past ten years to calculate the raw water requirements of Tirta Bumi Sentosa Kebumen Regional Water Utility, which draws water from the Sempor Reservoir. This approach was chosen because it better represents actual flow conditions compared to theoretical methods that require many assumptions. In the Regional Water Utility water intake system, there are three main inlets with different maximum capacities: Inlet I at 0.07 m^3/s, Inlet II at 0.01 m^3/s, and Inlet III at 0.02 m^3/s, with a total daily volume ranging from 8,153 to 8,333 m^3.

3.6 Water Balance

Water balance calculations were performed to determine the equilibrium between inflow and outflow at the Sempor Reservoir, using a daily approach to reflect more accurate flow fluctuations (Chow et al., 1988). The simulation results show that there are periods when inflow is smaller than outflow, especially during the dry season or when water demand increases, as shown in Figure 11.

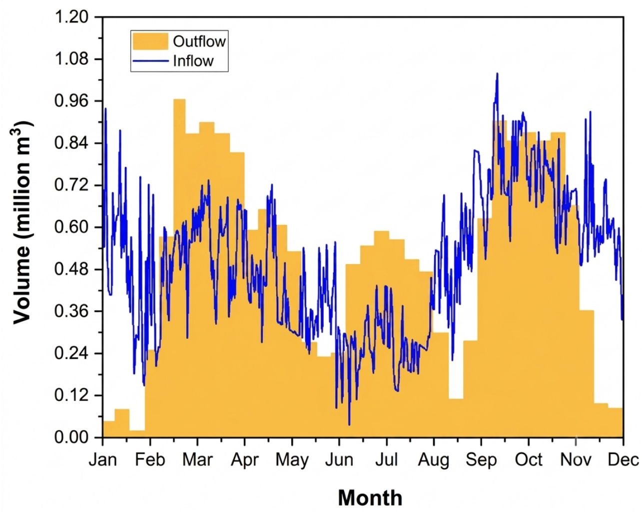

Figure 11. Daily water balance of Sempor Reservoir showing periods of surplus and deficit conditions.

The daily water balance analysis indicates that Sempor Reservoir experiences deficit conditions during certain periods, particularly in the dry season when inflow is lower than water demand. The simulation results show that out of 365 days, the reservoir was at full storage for 36 days, sufficient for 311 days, and insufficient for 18 days, corresponding to a reliability level of approximately 95%. On an annual basis, the total inflow was 184.02 million m^3, while total water demand reached 186.45 million m^3, resulting in a deficit of 2.43 million m^3. These deficit periods imply an increased risk to irrigation water supply and raw water availability, especially during prolonged dry conditions. The fluctuation in reservoir water level elevation further reflects the strong influence of seasonal rainfall variability on reservoir operation, highlighting the need for adaptive water allocation and reservoir operation strategies to maintain reliable water availability.

The identified deficit periods have direct implications for irrigation management and planting schedules in the Sempor Irrigation Area. During dry-season conditions when inflow is lower than demand, water availability constraints may require adjustments to planting schedules, such as delaying planting dates or reducing the planted area to prevent crop water stress. From an operational perspective, several adaptive alternatives can be considered, including temporary reduction of irrigation releases, prioritization of essential water uses, and improved coordination among water users. Integrating daily water balance results into operational planning enables reservoir managers to anticipate shortage periods and implement flexible operation strategies to maintain water supply reliability.

3.7 Elevation of Reservoir Operation Patterns

The water level elevation graph during the simulation period is shown in Figure 12. Operational elevation data include Flood Elevation 73.7 m, Spillway Elevation 72 m, Minimum Elevation 45 m, and Dead Storage Elevation 43 m.

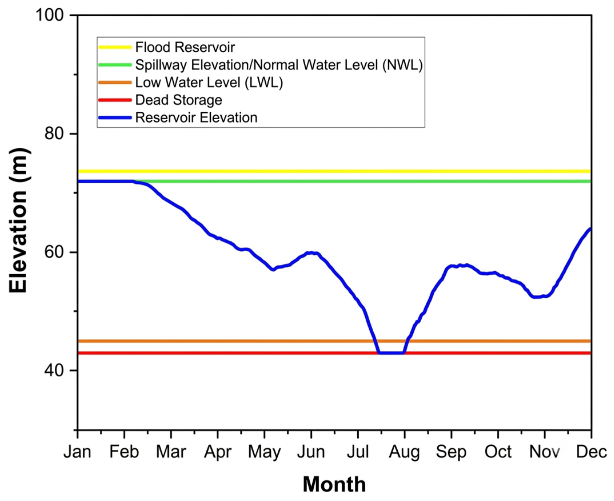

Figure 12. Elevation of dam operation patterns.

From January to early March, the reservoir water level reached the spillway elevation, indicating spill-out conditions during the peak of the rainy season. From March to June, the water level gradually declined due to decreasing inflow at the end of the rainy season, accompanied by increasing irrigation water demand.

During July to early August, the reservoir water level dropped to the dead storage elevation (approximately 43 m), indicating that the reservoir entered a dead storage condition. Under this condition, water release for irrigation and raw water supply becomes highly limited, and reservoir operation is effectively constrained. The reservoir water level began to recover after early August as rainfall increased with the onset of the rainy season.

The occurrence of dead storage conditions during the dry season indicates that the reservoir water level temporarily reached the minimum operational threshold due to low inflow and sustained water demand. This condition represents a recurrent operational situation that typically occurs during prolonged dry-season periods in the Sempor Reservoir system. From an operational perspective, the presence of dead storage emphasizes the importance of adaptive reservoir management, including stricter regulation of water releases, prioritization of essential water uses, and improved drought preparedness measures.

4 CONCLUSION

This study demonstrates that integrating daily-scale water balance analysis with SWAT-based inflow simulation provides a practical basis for reservoir operation decision-making under hydrological variability. The results indicate that the Sempor Reservoir is able to meet an annual water demand of 186.45 million m^3 with an operational reliability of approximately 95%, reflecting generally adequate water availability under existing conditions. However, the occurrence of short-term deficit periods totaling 18 days, particularly during the dry season when inflow is lower than demand, highlights operational vulnerabilities that cannot be captured by annual indicators alone. From an operational and policy perspective, these findings suggest that reservoir management should explicitly account for short-term inflow–outflow fluctuations in addition to annual water balance assessments. The identification of deficit days provides a quantitative basis for implementing adaptive operation strategies, such as adjusting irrigation release schedules, prioritizing essential water uses, and strengthening drought preparedness during low-flow periods. Therefore, the daily water balance approach offers a valuable tool for improving operational reliability and supporting sustainable water resources management in the Sempor Reservoir system.

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APPENDIX

Table S1. SWAT Calibration Parameters

Parameters	Value Range		Input Value
	Minimum	Maximum	
R_CN2,mgt	80.00	85.00	80.12
V_ALPHA_BF,gw	0.60	0.80	0.64
V_GW_DELAY,gw	340.00	360.00	352.41
V_GWOMN,gw	4,500.00	4,700.00	4,560.18
V_GW_REVAP,gw	0.02	0.10.	0.08
V_REVAPMN,gw	225.00	245.00	227.53
V_RCHRG_DP,gw	0.30	0.50	0.36
V_DEEPST,gw	7,000.00	8,000.00	7,850.23
R_HRU_SLP,hru	0.10	0.20	0.12
V_ESCO,hru	0.10	0.30	0.15
V_EPCO,bsn	0.50	0.80	0.65
R_SLSUBBSN,hru	100.00	115.00	111.07
V_CANMX,hru	25.00	35.00	26.14
R_SOL_AWC,sol	0.20	0.50	0.27
R_SOL_K,sol	20.00	26.00	24.81
R_SOL_BD,sol	2.00	2.20	2.05
V_SOL_ALB,sol	0.10	0.20	0.19
V_CH_N2,rte	0.10	0.20	0.15
V_CH_K2,rte	55.00	70.00	55.89
V_ALPHA_BNK,rte	0.40	0.60	0.46
V_SURLAG,bsn	4.00	6.00	5.90

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