

Establishing Semantok Reservoir Operation Rules to Obtain the Highest Crop Intensity in Semantok Irrigation Area

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Abstract: The Indonesian government is improving food security by building water infrastructure, including 61 dams for agricultural irrigation. Semantok Dam, one of these projects, serves *Daerah Irigasi* (D.I.) Semantok (1906 ha). However, long-term inflow data is still lacking and the reservoir operation rules are still under development. This research aims to develop Semantok reservoir operating rules to maximize cropping intensity. Rainfall-runoff simulation was conducted using the F.J. Mock method. Calibration (2017–2019) and verification (2020–2023) resulted in optimal parameters with minimum volume error, which were then applied to full-period F.J. Mock simulations (1999–2023). The resulting simulated inflows was used to calculate irrigation water requirements using the Net Field Requirements (*NFR*) method for two cropping patterns: double cropping of rice-secondary crops and quadruple cropping onion. The reservoir operating rules were optimized for wet, normal, and dry years (probability exceeding 35%, 50%, and 65%). This study examined cropping intensity under various hydrological conditions. Cropping Pattern (CP) I achieved 300%, 281%, and 242%, while CP II achieved 400%, 400%, and 374% in wet, normal, and dry years, respectively. Future research should optimize water allocation at the sub D.I. level to improve irrigation efficiency and agricultural profitability.

Keywords: Cropping Intensity; Irrigation Water Requirements; Optimization; Reservoir; Water Availability

Introduction

Food security is defined as consistent access to sufficient, safe, and nutritious food necessary for a healthy life (Maxwell & Frankenberger, 1992; World Bank Group, 2024; World Food Programme, 2025). It remains a central concern both globally and nationally. In Indonesia, the Food Law No. 7 of 1996 defines food security in terms of availability, safety, equitable distribution, and affordability at the household level. Growing population pressure and the impacts of climate change continue to pose serious challenges to water resources management. In response, the government has prioritized infrastructure development to strengthen food production capacity, focusing especially on dam

construction to secure reliable water resources for agriculture.

As of 2023, 42 of the 61 dams planned under the 2020–2024 Strategic Plan had been completed, leading to higher cropping intensity, expanded irrigation coverage, and increased water-storage capacity (Hartadi & Hidayah, 2024; Kementerian PUPR, 2023). These efforts reflect the government's long-term strategy to strengthen food security through improved water management infrastructure. One of the key projects reflecting this approach is the Semantok Dam in East Java.

Semantok Dam, located in Nganjuk Regency, East Java, was completed in 2019 and began operation in 2022 to provide both flood control and agricultural water

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supply. This dam is designed to reduce Q_{25} flood inflow to the reservoir by $237.18 \text{ m}^3 \text{ s}^{-1}$ and downstream flooding by $137 \text{ m}^3 \text{ s}^{-1}$ (Kementerian PUPR, 2022). In another location, Ghaisani et al. (2024) found that Meninting Dam reduces flood discharge by $91.58 \text{ m}^3 \text{ s}^{-1}$. Beyond its flood mitigation function, the Semantok Dam also supports agricultural activities by supplying irrigation water to 1906 ha of irrigated area. To ensure the function of this dam is optimized, it is necessary to have an appropriate operation rule to manage the water in Semantok Reservoir efficiently. However, the operation rule of Semantok Reservoir is still being refined. Therefore, the preparation of the Semantok reservoir operation rules is important to determine the appropriate water release throughout the season.

Due to the lack of long-term inflow data, rainfall-runoff modelling is used to estimate the inflow into the Semantok Reservoir. Several methods are commonly applied for this purpose, including the NRECA method, the Thornthwaite–Mather method, and the Soil Moisture Accounting (SMA) method. The NRECA method was developed to support rural water resource planning (NRECA, 1980); the Thornthwaite–Mather method is primarily used for evapotranspiration and water balance studies (Thornthwaite & Mather, 1955); and the SMA method simulates watershed hydrology based on soil moisture conditions (Crawford & Linsley, 1966). Among these, the Mock method—developed by Dr. F.J. Mock in Bogor, Indonesia, in 1973—is considered the most appropriate for the Semantok catchment. As an empirical method specifically designed for tropical hydrological conditions (i.e., Indonesia), it incorporates rainfall, evaporation, and catchment characteristics, making it particularly well-suited for application in Indonesian watersheds such as Semantok.

This monthly approach is suitable for long-term analysis (Batas et al., 2023; Chandrasasi et al., 2020; Efendi et al., 2019; Jayanti et al., 2023; Mock, 1973; Setiadi et al., 2022), which is quite effective in providing estimates of discharge flow. For example, the method modelled in the Cimanuk–Boyongbong watershed has good modelling with a correlation coefficient (R) of 0.8 in the calibration process (Permana & Susetyaningsih, 2024). This monthly approach is suitable for long-term analysis and general water resources planning. Furthermore, along with the development of more detailed demands, some studies began to adopt a semi-monthly period in some areas in Indonesia (Adiningrum, 2016; Krisnayanti et al., 2021; Rasyid & Afdhaliah, 2021). For example, the method modelled with semi-monthly period in Bener Reservoir watershed with a correlation coefficient (R) of 0.782 in the calibration process (Pratiwi et al., 2022). In this research, the F.J. Mock method was tried to shorten the period

again, with a one-third monthly period to adjust the irrigation water supply period at *Daerah Irigasi* (D.I.) Semantok. Thus, it can be easier to arrange the reservoir operation rules with the aim of maximizing the crop intensity.

Several studies have been conducted to establish the Semantok Reservoir Operation Rule. One of them is research by Firdaus et al. (2020) which optimizes Semantok Reservoir to fulfill the demands of irrigation water and raw water. In this research, F.J. Mock modelling also conducted to obtain Semantok reservoir inflow. Furthermore, Larasati et al. (2021) optimized the allocation of irrigation water from each weir and the water source did not come from Semantok Reservoir. Nevertheless, this research is different because it performs a calibration and verification process on Mock modelling, which has not been conducted in previous studies. Furthermore, this research also adapts the modelling conditions to the actual situation in the field, such as the total area of D.I. Semantok and the onion cropping pattern that reach four times a year. Another factor that encouraged this research was the unoptimized operation rule of the reservoir. Therefore, this research starts with reservoir inflow modelling using the F.J. Mock method, then continues with the development of the Semantok Reservoir operation rule which aims to maximizing crop intensity in D.I. Semantok.

Method

Study Area and Data Collection

Figure 1 shows the study area namely Semantok Watershed, which is located in Nganjuk Regency, East Java, Indonesia. The watershed has an area of 54.04 km^2 and functions as a catchment area with two main rivers, Semantok River and Tritik River. Semantok River has a main river length of 18.19 km, whereas Tritik River has a main river length of 18.64 km (Prasetyo et al., 2024). Semantok watershed has an outlet namely the Semantok Dam, which plays an important role in fulfilling water requirements in the downstream area, especially for D.I. Semantok.

D.I. Semantok has an area of 1906 ha, which is divided into six sub D.I. and each characterized by presence of a weir in the upstream of irrigation network. The six sub D.I. including: sub D.I. Ngomben with an area of 499 ha, Margomulyo with an area of 154 ha, Rejoso with an area of 465 ha, Jati with an area of 227 ha, Janeng with an area of 245 ha, and Jatirejo with an area of 316 ha. D.I. Semantok is a irrigated area with an altitude of 57~82 meters above sea level. This area has a maximum third of the monthly rainfall is 290 mm. It has average temperatures between 23.1 to 26.9 °C with air

humidity of 61% to 91%. The length of irradiation is always above four hours per day, with daily evapotranspiration values ranging from 2.62 to 5.41 mm.

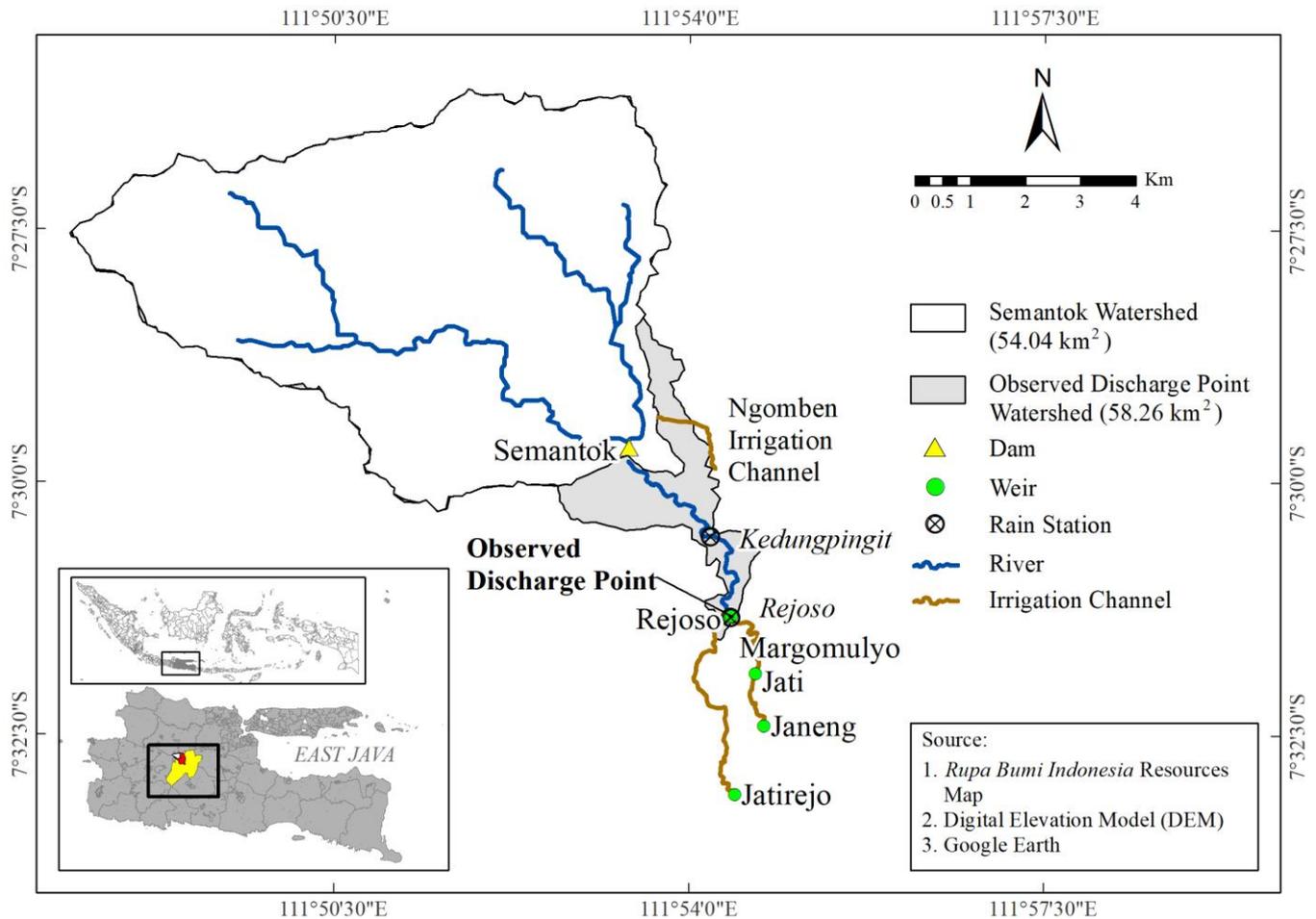


Figure 1. Contains the study location: Semantok Watershed and irrigation area, observation points at the junction of Margomulyo and Rejoso Weirs, and location of rainfall stations.

The data used includes rainfall data, climatology data, reservoir storage characteristics data, discharge data at observation points, and cropping pattern data. Rainfall data obtained from the Kedungpingit Rain Station (07°30'27" S-111°54'15" E) and Rejoso Rain Station (07°31'19" S-111°54'24" E) in 1999–2023. The rain data obtained in the form of daily rain data and accumulated into one-third monthly data. Inflow simulation was conducted using rainfall data from the Kedungpingit Rain Station spanning 1999–2023, whereas inflow modelling employed regional rainfall data from 2017–2023. Calculation of regional rainfall using the Polygon Thiessen method obtained influence area of Kedungpingit Rain Station is 56.87 km² and Rejoso Rain Station is 1.49 km². For inflow simulation, the Semantok Reservoir is located in the Semantok watershed with an area of 54.04 km² and influenced by the Kedungpingit Rain Station only. Meanwhile inflow modelling using the watershed at observation discharge

point with an area of 58.26 km² and influenced by Kedungpingit and Rejoso Rain Stations (see Figure 1).

Climatological data consists of average temperature, average humidity, wind speed, and length of sunshine. The data were obtained from Sawahan Climatology Station (08°15'54.5" S-111°46'0.55" E) from 2017–2023. The data obtained in form of daily climatological data and averaged into monthly data. Semantok characteristic curves was obtained from Semantok Dam Management Unit. Observed discharge data from 2017–2023 were obtained from the Nganjuk Public Works and Housing Department. The data contains discharge flow from Margomulyo and Rejoso weirs. Cropping Pattern (CP) data were obtained from interview to farmers in D.I. Semantok which was conducted in August of 2024.

Reservoir Inflow Estimation

Reservoir inflow is an important factor to

determine the water availability of a reservoir. The availability of water reservoir is closely related to its reliability. Nevertheless, reservoir inflow data is not always well recorded, either because water level recording devices such as Automatic Water Level Recorder (AWLR) are unavailable, or because the period of recording water level data is relatively short, making it unsuitable for estimating reservoir water availability. Hence, it is necessary to estimate the reservoir inflow through rainfall-runoff modelling. One of the methods in modelling rainfall-runoff is the F.J. Mock method. The F.J. Mock method is a method with a simple tank concept. F.J. Mock concept starts with Precipitation (P) that falls opposite to Actual Evapotranspiration (AET). To obtain the AET value, it requires the Evapotranspiration (ET_0) value. The ET_0 was calculated using Penman-Monteith (Equation 1) with the aid of the *CropWat 8.0* program.

$$ET_0 = \frac{0,408\Delta \cdot (R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0,34 \cdot U_2)} \quad (1)$$

with ET_0 is an evapotranspiration value (mm day^{-1}), Δ is the slope vapor pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$), R_n is net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$), G is the soil heat flux density ($\text{MJ m}^{-2} \text{day}^{-1}$), γ is psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T is average air temperature ($^\circ\text{C}$), e_s is saturated pressure (kPa), e_a is ambient vapour pressure (kPa), U_2 is wind speed at 2 m above ground (m s^{-1}). ET_0 value is a daily evapotranspiration were obtained from monthly averaged climatological data.

The deficit from P and AET is precipitation that reaches the ground surface (ER). ER descends to the subsurface layer and there is Initial Soil Moisture (ISM). If the ER that falls plus the ISM exceeds the Soil Moisture Capacity (SMC), then there will be Direct Runoff (DRO). In the subsurface layer, there is an infiltration process (I) into the groundwater layer. Infiltration coefficient depend on the season. In the wet season is called the Wet Infiltration Coefficient (WIC), while in the dry season is called the Wet Infiltration Coefficient (DIC). Infiltration goes down to the bottom then meets the Initial Groundwater Storage ($IGWS$). The infiltration process also influenced by the groundwater recession constant (K) which determines the speed of water entering the subsoil. The deficit between the Groundwater Storage (GWS) and $IGWS$ is called ΔS . ΔS multiplied by the infiltration that goes down becomes Baseflow (BF). The final output is the total flow, which is the DRO plus BF .

Modelling will provide better results if calibration and verification process is carried out (Jian et al., 2021). In this research, calibration and verification were carried out using discharge data at the observation point, which is between Rejoso and Margomulyo weirs (see Figure 1).

The calibration process aims to obtain the desired Mock parameters: WIC , DIC , SMC , $IGWS$, and K . Mock modelling began in January, assuming ISM equal to SMC , as the study area experiences peak rainfall during this month, resulting in saturated soil conditions. The calibration and verification process is carried out with two scenarios, the first scenario is calibration in 2017–2020 and verification in 2021–2023, while the second scenario is calibration in 2017–2019 and verification in 2020–2023. The calibration and verification process is performed to achieve objective function of maximum correlation coefficient (R) or minimum Volume Error (VE). The R and VE is calculated using Equation 2–3.

$$R = \frac{\sum_{i=1}^n (P_i - \mu_p)(O_i - \mu_o)}{\sqrt{\sum_{i=1}^n (P_i - \mu_p)^2} \sqrt{\sum_{i=1}^n (O_i - \mu_o)^2}} \quad (2)$$

$$VE (\%) = \left(\frac{\sum_{i=1}^n (O_v - P_v)}{\sum_{i=1}^n O_v} \right) \cdot 100 \quad (3)$$

with P_i is the calculated discharge ($\text{m}^3 \text{s}^{-1}$), O_i is the observed discharge ($\text{m}^3 \text{s}^{-1}$), μ_p is the average calculated discharge ($\text{m}^3 \text{s}^{-1}$), μ_o is the average observed discharge ($\text{m}^3 \text{s}^{-1}$), P_v is calculated volume discharge ($\text{m}^3 10\text{day}^{-1}$) O_v is observed volume discharge ($\text{m}^3 10\text{day}^{-1}$), and n is the number of data.

After getting the best modelling from one of the scenario and objective function, a feasibility test is carried out to determine the quality of the model. The tests carried out are Nash-Sutcliffe (NSE) and Mean Absolute Error (MAE). In this research, the formulation of each test is using Equation 4–5.

$$NSE = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (O_i - \mu_o)^2} \quad (4)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |P_i - O_i| \quad (5)$$

with P_i is the calculated discharge ($\text{m}^3 \text{s}^{-1}$), O_i is the observed discharge ($\text{m}^3 \text{s}^{-1}$), μ_p is the average calculated discharge ($\text{m}^3 \text{s}^{-1}$) μ_o is the average observed discharge ($\text{m}^3 \text{s}^{-1}$), and n is the number of data.

The calibrated parameters were used to estimate inflow in 1999–2023 at Semantok Reservoir using Semantok watershed.

Irrigation Water Requirements

Calculation of irrigation water requirements is needed to determine the water requirements in each crop period. By understanding these requirements, it becomes possible to ensure that the water supply adequately supports the proper growth of agricultural crops. One of the methods used to calculate irrigation water requirements is the Net Field Requirements (NFR) method as in Equation 6.

$$NFR = ET_c + PL + P + WLR - R_e$$

with NFR is irrigation water requirement in fields ($l\ s^{-1}\ ha^{-1}$), ET_c is the consumptive use of crops ($mm\ day^{-1}$), PL is the land preparation ($mm\ day^{-1}$), P is the value of percolation ($mm\ day^{-1}$), WLR is the value of water replacement ($mm\ day^{-1}$) and R_e is effective rainfall ($mm\ day^{-1}$). ET_c is obtained from ET_0 multiplied by the plant coefficient (K_c) presented in Equation 7.

$$ET_c = ET_0 \cdot K_c \tag{7}$$

The calculation of irrigation water requirements is carried out every one-third monthly period. The NFR that has been calculated is the irrigation water requirement in fields, so it is necessary to calculate the

water requirement at the intake (KAI) based on the NFR value multiplied by irrigation area and divided by irrigation efficiency presented in Equation 8.

$$KAI = \frac{NFR \cdot A}{EI} \tag{8}$$

with KAI is water requirement at intake ($m^3\ s^{-1}$), EI is irrigation efficiency (%), and A is irrigation area (ha).

There are two types of CP applied in D.I. Semantok. The first type is double cropping rice-secondary crops, while the second type is quadruple cropping onion. Farmers in sub D.I. Jatirejo applied CP II: quadruple cropping onion, while farmers from the other sub D.I. applied CP I: double cropping rice-secondary crops. All cropping patterns started in first period of November as presented in Figure 2.

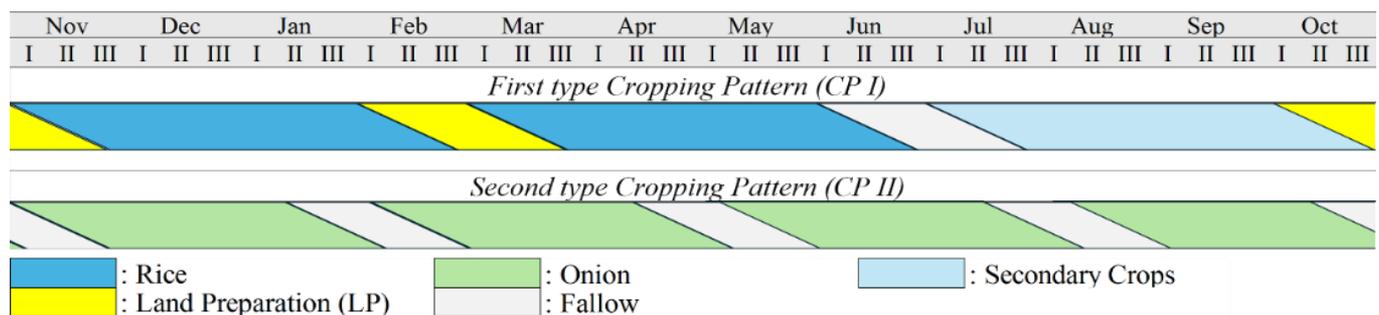


Figure 2. Two types of cropping pattern in Semantok irrigation area: double cropping rice-secondary crops (above) and quadruple cropping onion (below). Land Preparation (LP) is pre-planting activities and fallow is soil resting activities before reuse.

Optimization Model for Reservoir Operation

In establishing a reservoir operation rules, there are three important components that must be considered, namely inflow, outflow, and reservoir storage characteristics. Semantok Reservoir inflow is obtained from F.J. Mock simulation. Besides, it also considers the rain that falls on surface of the reservoir (Kementerian PUPR, 2013). Inflow from catchment area and rain on the reservoir surface will be the water availability in Semantok Reservoir as calculated using Equation 9.

$$V_b = \frac{V_j + (10 \cdot A \cdot R_j)}{10^6} \tag{9}$$

with V_b is the volume of water availability (MCM), V_j is one-third monthly inflow ($m^3\ s^{-1}$), A is the area of reservoir surface (ha), and R_j is average rainfall in one-third monthly ($m^3\ 10day^{-1}$).

Reservoir outflow is related to reservoir water demand. Currently, Semantok Reservoir has a release target only to fulfill irrigation water requirements in D.I. Semantok with an area of 1906 ha. It also considers water loss due to evaporation and river maintenance (duty flow) with a 95% exceedance probability.

Semantok Dam is a rockfill dam with a storage capacity of 22.44 Million Cubic Meter (MCM) with a spillway elevation of 90.14 meter above Mean Sea Level (mMSL). The minimum storage capacity is 4.68 MCM at an elevation of 81.14 mMSL. The relationship between elevation, storage volume, and surface water area is presented in Figure 3.

Semantok dam technical data is required for reservoir operation rules such as Minimum Operation Level (MOL) at elevation +81.14 mMSL, Normal Water Level (NWL) at elevation +90.14 mMSL, and Flood Water Level (FWL) at elevation +91.50 mMSL, as presented in Figure 4.

Reservoir operating rules are required to manage water releases in order to meet the Target Release (T_R), which defines the planned release volume based on irrigation demand and system capacity. In practice, the Actual Release (A_R) reflects the volume actually discharged from the reservoir, which is influenced by operational constraints or hydrological fluctuations. Therefore, reservoir optimization is conducted under these operating conditions to ensure reliable and efficient water delivery. In reservoir optimization, there are reservoir in wet, normal, and dry year conditions

(Ebrahimian et al., 2020; Lee et al., 2023), which have an exceedance probability of 35%, 50%, and 65% respectively (Kementerian PUPR, 2017). These scenarios

enable the optimization model to manage seasonal water availability.

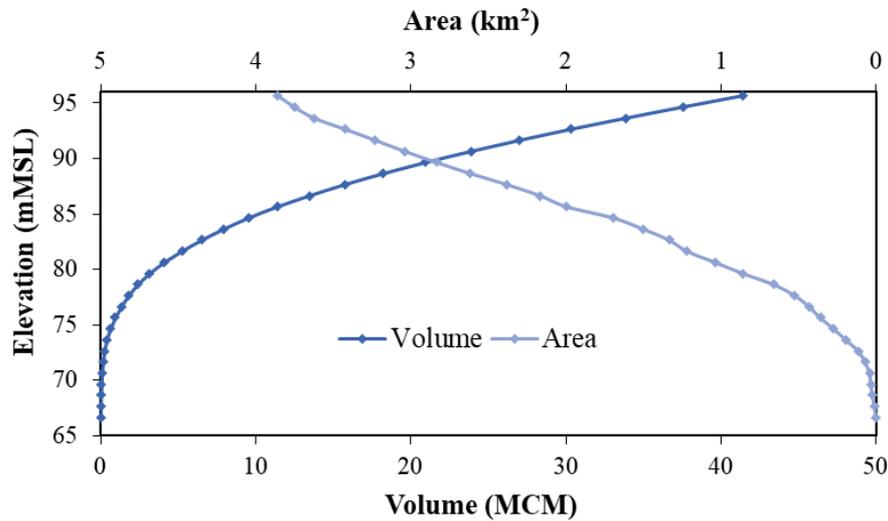


Figure 3. The relationship between elevation in meter above Mean Sea Level (mMSL), storage volume in Million Cubic Meter (MCM), and surface water area of Semantok Reservoir, commonly known as Semantok Characteristic Curve. It is used to determine area and volume of the reservoir at an elevation for developing the operation rules.

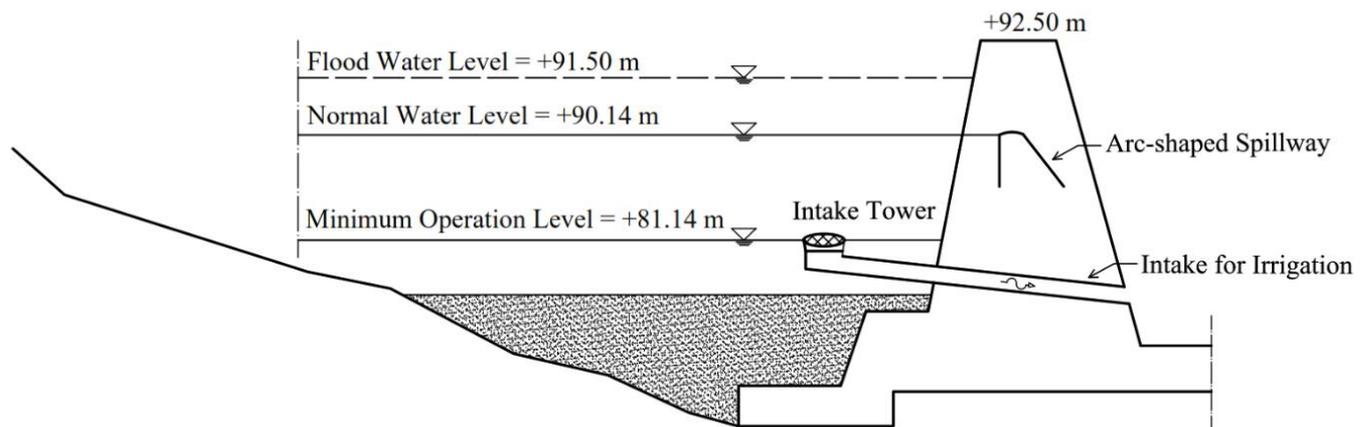


Figure 4. Technical data of Semantok Reservoir, such as Minimum Operation Level (MOL), Normal Water Level (NWL), and Flood Water Level (FWL), serve as constraints in reservoir optimization.

The objective function of this optimization process is to maximize the annual cropping intensity (Z), expressed as a percentage. This metric reflects the extent to which irrigated area is utilized across multiple cropping seasons within a year. The mathematical formulation is calculated using Equation 10.

$$\text{Maximum } Z = \sum_{i=1}^3 \frac{100}{A_x} A_i + \sum_{i=1}^4 \frac{100}{A_y} A_i \quad (10)$$

with Z is annual cropping intensity (%), A is potential irrigated area: $A_x = 1591$ ha (excluding sub D.I. Jatirejo) and $A_y = 316$ ha (sub D.I. Jatirejo), A_i is irrigated area in cropping season i (ha), i is cropping season index.

The decision variable in this model is the irrigated area (A_i) that can be supplied with irrigation water, based on water availability in each cropping season i , with $i = 1, 2, 3$, and 4.

The optimization process was subject to several constraints to ensure feasibility and alignment with established standards. First, the allocated area for each cropping pattern (A_i) was limited to not exceed the maximum available area (A) for each cropping season. Second, a minimum irrigation efficiency factor (k) of 0.7 was applied to ensure adequate water supply for crop growth, consistent with the design criteria of the Kementerian PUPR (2013). Third, the actual reservoir release (A_R) was constrained to remain at or below the

target release (T_R) for each defined time step (e.g., one-third monthly).

Result and Discussion

Result

Estimated Reservoir Inflow

Two scenarios of callibration and verification previously described were carried out to achieve two objective functions: maximizing the correlation coefficient and minimizing volume error. In addition, statistical and feasibility tests were conducted, with the results shown in Table 1. The best parameter values were obtained from the scenario using calibration from 2017–2019 and verification from 2020–2023, based on the objective of minimizing VE percentage. Table 2 summarizes the F.J. Mock model parameters resulting from this calibration and verification process.

From Figure 5 it can be seen that the calculated discharge does not consistently match the observed

values. During the calibration period (2017–2019), $R = 0.753$ indicates a strong correlation (Pearson, 1895) and $VE = 21\%$ remains within an acceptable threshold (Ouédraogo et al., 2018), making the calibration performance acceptable. During the verification period (2020–2023), the correlation drops to $R = 0.524$ and the volume error rises to 49%, exceeding the commonly accepted threshold of 25% (Ouédraogo et al., 2018). This indicates weaker model performance and classifies the verification as unsatisfactory. Despite these limitations, the results obtained represent the best performance among the tested scenarios and objective functions. This study aligns with Putri et al. (2025), who made a similar decision. After obtaining the parameters in the calibration and verification process, a Mock simulation process was carried out to obtain the one-third monthly inflow of Semantok Reservoir. Furthermore, inflow was simulated under wet, normal and dry year conditions (See Figure 6).

Table 1. Statistical and feasibility test results for two scenarios and two objective functions. The statistical test results are correlation coefficient (R) and Volume Error (VE) while the feasibility test are Nash–Sutcliffe (NSE) and Mean Absolute Error (MAE).

Scenario		Calibration 2017–2019, Verification 2020–2023	Calibration 2017–2020, Verification 2021–2023
<i>Objective Function: VE (%) min</i>			
Calibration	R	0.75	0.71
	VE (%)	21.49	30.09
	NSE	0.47	0.22
	MAE	0.14	0.32
Verification	R	0.52	0.55
	VE (%)	49.49	60.13
	NSE	-1.16	-2.14
	MAE	0.70	1.01
<i>Objective Function: R max</i>			
Calibration	R	0.79	0.75
	VE (%)	58.40	57.21
	NSE	-2.03	-1.56
	MAE	0.74	0.99
Verification	R	0.66	0.60
	VE (%)	67.89	66.73
	NSE	-6.58	-4.42
	MAE	1.51	1.34

Table 2. The parameters of the mock calibration process with a scenario of calibration in 2017–2019 and verification in 2020–2023 with objective function is minimum Volume Error (VE).

Parameter	Unit	Symbol	Min Value	Result Value	Max Value
Wet Infiltration Coefficient	-	<i>WIC</i>	0.6	0.70	0.7
Dry Infiltration Coefficient	-	<i>DIC</i>	0.7	0.80	0.8
Initial Soil Moisture	mm	<i>ISM</i>	-	400	-
Soil Moisture Capacity	mm	<i>SMC</i>	100	400	400
Initial Groundwater Storage	mm	<i>IGWS</i>	100	100	1000
Groundwater Recession Constant	-	<i>K</i>	0.9	0.99	0.99

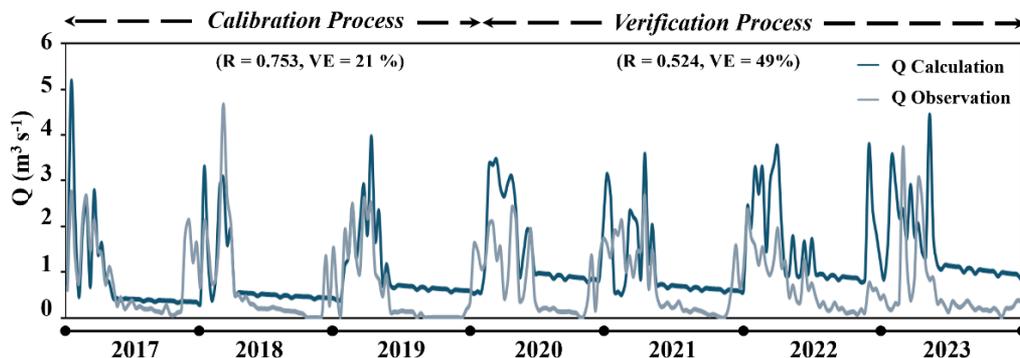


Figure 5. Comparison between observed discharge and calculated discharge with the best scenario: calibration in 2017–2019 and verification in 2020–2023 with minimum Volume Error (VE).

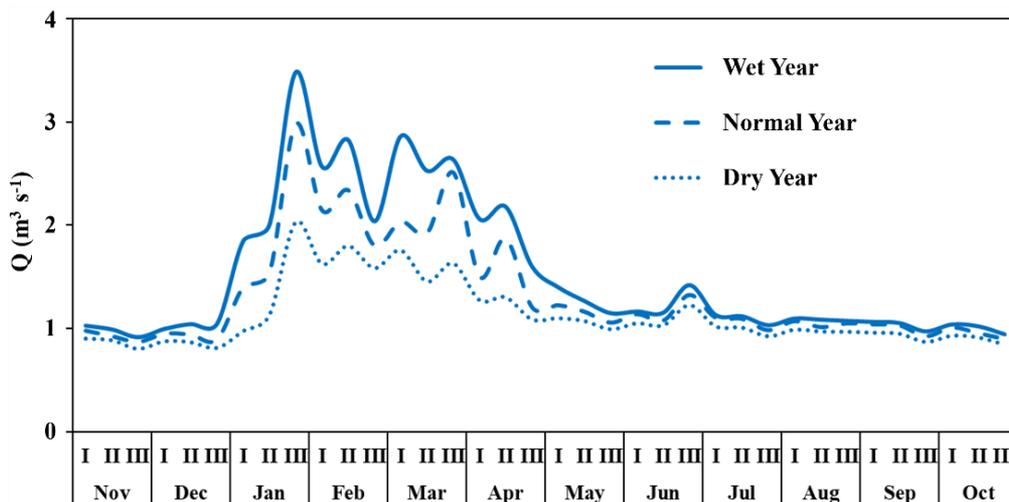


Figure 6. Flow Pattern of Semantok Reservoir with three conditions: wet (35% exceedance probability), normal (50% exceedance probability), and dry (65% exceedance probability).

Target Release of Reservoir

Target release in Semantok Reservoir is the total irrigation water requirements in D.I. Semantok with two types cropping pattern (See Figure 7). In addition to target release, the other outflows from Semantok

Reservoir are evaporation from reservoir surface and duty flow for river maintenance. For river maintenance, the value of $0.07 \text{ m}^3 \text{ s}^{-1}$ is obtained based on results of 95% exceedance probability that occurred in December of the third period.

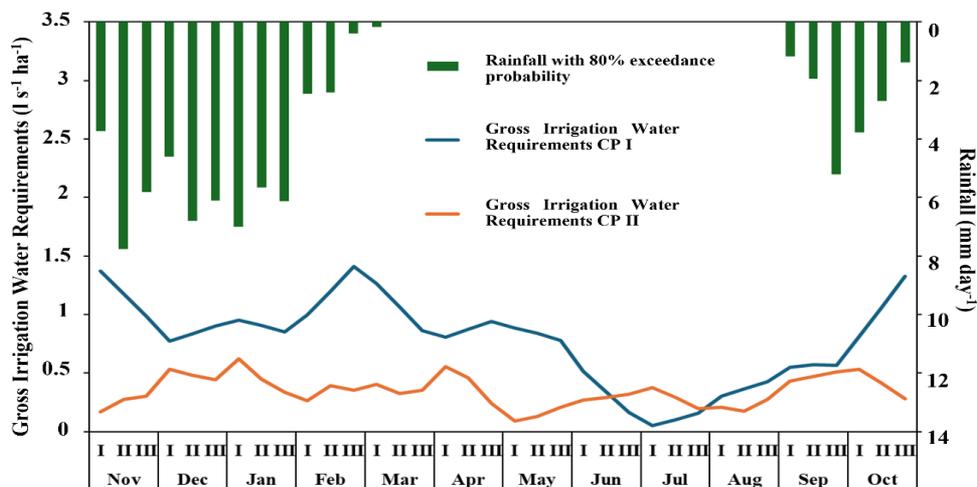


Figure 7. Irrigation water requirements with Cropping Pattern (CP) I: double cropping rice – secondary crops and CP II: Quadruple cropping onion.

Optimization of Reservoir Operation

Table 3 shows that the three conditions of wet, normal, and dry years as well as CP I and II. The results indicate that the cropping intensity in the Semantok Reservoir area varies significantly across hydrological conditions. In wet years, the cropping intensity is fully achieved, reaching 300% for CP I and 400% for CP II

within the D.I. Semantok. During normal years, CP I does not attain completed fulfillment, while CP II attained 400%. In dry years, neither CP I nor CP II fulfills the targeted cropping intensity because of limited water availability. However, all conditions had irrigation reliability of 100% or perfect success rate.

Table 3. Semantok Reservoir optimization results to maximize irrigated area, cropping intensity, and reliability. The first cropping pattern has three cropping seasons while the second cropping pattern has four cropping seasons.

Year Condition	Cropping Season	First Type Cropping Pattern			Second Type Cropping Pattern			Reliability (%)
		Irrigated Area (ha)	Cropping Intensity (%)	Total	Irrigated Area (ha)	Cropping Intensity (%)	Total	
Wet	I	1591	100	300	316	100	400	100
	II	1591	100		316	100		100
	III	1591	100		316	100		100
	IV				316	100		100
Normal	I	1591	100	281	316	100	400	100
	II	1591	100		316	100		100
	III	1284	81		316	100		100
	IV				316	100		100
Dry	I	1388	87	242	312	99	374	100
	II	1398	88		302	95		100
	III	1067	67		283	90		100
	IV				283	90		100

In addition the reservoir release, the optimization process is also very concerned about the reservoir water level. The water level must be considered so that it does not reach the MOL or even the dead storage level.

The dry year condition shows that the water level is still above the MOL so that the reservoir can still operate well in the dry season even though the reservoir inflow tends to be small.

Figure 8 shows the Semantok Reservoir water level after the optimization process in wet, normal and dry

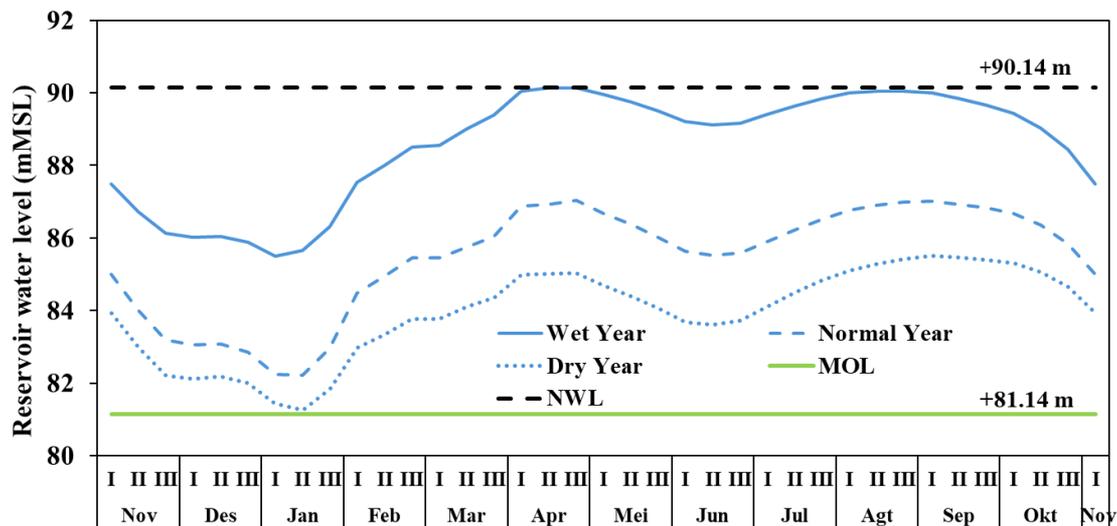


Figure 8. Water level of Semantok Reservoir under the three consecutive conditions (from above): wet (35%), normal (50%), and dry (65%) year conditions. Water level is not less than Minimum Operation Level (MOL) and not more than Normal Water Level (NWL) throughout the season.

Discussion

The evaluation of hydrological model performance reveals a decline in accuracy, highlighting a critical

aspect in assessing model effectiveness. The model performance during the verification period is considered unsatisfactory, as indicated by a decline in the R value to

0.524 and an increase the VE value to 49%. In hydrological modelling, a VE exceeding 25% is generally classified as unsatisfactory (Ouédraogo et al., 2018). The reduced performance of the Mock model attributed to the shortening of the simulation period. In the Kali Madiun sub-watershed, a monthly model by Uwais (2020) achieved R and VE values of 0.91 and 0% during verification, indicating no cumulative difference between observed and simulated discharge. Conversely, a semi-monthly model applied in the Bedog watershed by Adiningrum (2016) showed a higher VE of 14.13%, suggesting increased error with shorter time steps. Further comparison in the Cisadane watershed by Rasyid & Afdhaliah (2021) confirmed that monthly model outperformed compared to semi-monthly, with R and NSE values of 0.76 and 0.70, respectively.

Hydrological modelling was initially performed using a monthly time step for long-term water balance analysis. The model transitioned from a monthly to a daily time step to improve responsiveness to short-term hydrological variability. There are several approaches for modelling daily river discharge. One commonly used method is the Soil Moisture Accounting (SMA) model. Adya Ariska et al. (2020) conducted in the Rokan Hulu sub-watershed, the SMA method successfully simulated water movement with a high accuracy. The best performance was achieved using a calibration (2008–2014) and a verification (2015–2018), resulting volume error 0% during calibration and 10.1% during verification.

More advanced techniques involve deep learning. Zhou & Zhang (2023) applied an ensemble model combining linear and nonlinear methods, one of them is Ensemble Support Vector Regression with Bayesian Optimization (Ensem SVR-BO) yielding an NSE of 0.976 and RMSE of 0.04 in a Karst spring system. Meanwhile, Vu et al. (2023) used a Long Short-Term Memory (LSTM) model to forecast discharge in the Loire River over 1, 3, and 6 month horizons, achieving R values of 0.91, 0.83, and 0.78, with corresponding RMSE of 4.07%, 5.63%, and 6.65%, respectively. These studies suggest that daily forecasting models outperform compared to the Mock model.

The irrigated area expanded following the construction of the Semantok Reservoir, increasing from 1529 ha (Kementerian PUPR, 2023) to 1906 ha in a wet year. During wet years, both CP I and II reached their maximum intensities of 300% and 400%, respectively. In normal years, CP I reached only 281%, while CP II maintained. In dry years, intensities dropped to 242% for CP I and 374% for CP II, reflecting reduced irrigation water availability. CP I consists of five sub D.I. excluding sub D.I. Jatirejo, while CP II consists solely of sub D.I. Jatirejo. These variations highlight the need for efficient

and equitable water allocation strategies to improve cropping intensity, particularly under normal and dry conditions. This condition is similar to the findings of Sodikin et al. (2025), who identified an irrigation water deficit and recommended modernizing irrigation systems to enhance water allocation efficiency.

This highlights the importance of effective reservoir management to ensuring equitable and efficient irrigation water distribution, especially under varying hydrological conditions. In addition, Figure 8 shows that the water level in wet, normal, and dry years is between the Control Water Level (CWL) in accordance with the "Reservoir Operation Module: Water Allocation" by the Kementerian PU (2017), which requires levels to stay between the FWL and MOL. This indicates that the Semantok Reservoir is effectively serving its functions in flood control and irrigation. Supporting this, Rediasti et al. (2023) found that optimized reservoir operations at Meninting Reservoir ensured 100% reliability in meeting irrigation and domestic water demands across all inflow conditions. In a similar case, Anggraheni et al. (2017) highlighted that optimizing operation rules at Wonogiri Reservoir improved water use efficiency and maximizing irrigation *k* factor to a value of 1. These findings affirm the importance of well-managed reservoir operation patterns for sustainable and multifunctional water resource management.

Conclusion

This study successfully optimized reservoir operating rules, ensuring 100% irrigation reliability across wet, normal, and dry years. Before the construction of the Semantok Dam, the potential irrigated area was 1529 ha. After the dam was built, this area expanded to 1906 ha during wet years. It then decreased to 1600 ha and 1134 ha in normal and dry years for CP III respectively, without compromising overall water supply. These quantitative results demonstrate the potential of the optimized rules to enhance agricultural water resilience under diverse climatic scenarios. The current study used the Mock method with a one-third monthly period, which may not fully capture flow dynamics. Future work can address this limitation by incorporating daily rainfall-runoff modelling. Furthermore, optimizing water distribution at the sub D.I. level to achieve more precise and practical allocation patterns is also recommended.

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Author Contributions

Conceptualization, R.R.A.S., E.P.A.P., I.; Methodology, Formal analysis, R.R.A.S., E.P.A.P.; Data curation, Visualization, Writing-original draft preparation, R.R.A.S.; Validation, Writing-review and editing, E.P.A.P., I. All authors have read and agreed to published versions of the manuscript.\

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