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Optimizing Kedungombo Reservoir Operations to Meet Irrigation Water Needs

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ABSTRACT

The Kedungombo Reservoir plays an important role in providing irrigation water for several irrigation areas in Central Java. However, the existing reservoir's operational conditions still face obstacles in meeting water needs, especially during low inflow during the dry season. This condition causes a water deficit that impacts the decline in reservoir operational performance. Therefore, evaluation and optimization of reservoir operations are needed to improve the effectiveness of meeting irrigation water needs. This study aims to analyze the operational performance of the Kedungombo Reservoir under existing conditions and evaluate improvements in reservoir operational performance after optimization using Solver. The analysis of the mainstay discharge was carried out using the Weibull method based on inflow data from 2015–2025 with the mainstay discharge scenarios Q20, Q50, and Q80. Irrigation water needs were calculated based on the cropping pattern and the service area of the Kedungombo Reservoir irrigation area. Reservoir operation simulations were carried out using HEC-ResSim, while reservoir operation optimization was carried out using Solver with the objective function of minimizing the deficit in irrigation water needs. The results of the study indicate that the existing operating conditions have a reliability level of 66.44% at Q20, 54.72% at Q50, and 44.98% at Q80. After optimization, the reliability level increased to 74.86% at Q20, 73.73% at Q50, and 74.00% at Q80. In addition, optimization was also able to reduce the vulnerability value and increase the operational resilience of the reservoir. The results of the study indicate that reservoir operation optimization can increase the effectiveness of Kedungombo Reservoir management in meeting irrigation water needs.

Keywords: kedungombo reservoir, reservoir operation optimization, hec-ressim, solver, water requirements

INTRODUCTION

In recent decades, climate change has had a significant impact on the availability and management of water resources in various regions, including Indonesia. Changes in rainfall patterns, the increasing frequency of extreme weather events, and increasingly long periods of drought have caused uncertainty regarding the continuity of river discharge and reservoir inflow. Common water resource problems in Indonesia are excess water during the rainy season, which can potentially cause flooding, while during the dry season, water shortages and a decline in water quality are common, including reservoir water as the primary water source for various needs [1]. These conditions require a water resource management system capable of effectively regulating water availability and distribution throughout the year.

One of the important infrastructures in water resource management is a reservoir. A reservoir is an artificial water reservoir formed by the construction of a dam [2]. Reservoirs have various functions, including providing raw water, providing a water source for irrigation, controlling flooding, and being used for hydroelectric power generation [3], [4]. In addition, reservoirs function as a means of storing excess water during the rainy season to then be redistributed during the dry season. The existence of reservoirs also changes water flow patterns in a planned manner so that the use of water resources becomes more effective and provides greater benefits for the community and the surrounding environment [5].

The role of reservoirs is becoming increasingly important because the irrigation sector is one of the largest water users in Indonesia's water resources management system. The success of agricultural activities is greatly influenced by the continuity and adequacy of irrigation water supplies, especially in areas dependent on reservoir systems. The existence of reservoirs can make the use of water resources for the community more efficient, so optimal reservoir operation is considered very important [6]. However, inflow instability due to changes in hydrological conditions causes reservoir managers to face challenges in maintaining a balance between water availability and the needs of various water utilization sectors, especially the irrigation sector, which requires a continuous water supply throughout the planting season [7], [8].

Under certain conditions, particularly during the dry season or when inflow is low, irrigation water needs are often not optimally met due to limited reservoir capacity. Lack of water availability can result in crop failure, requiring effective water management and utilization strategies to mitigate the negative impacts [9]. On the other hand, increasing water needs due to the development of the agricultural sector, increasing cultivated land area, and increasing planting intensity cause irrigation water needs to continue to increase over time. The limited availability of water resources, accompanied by increasing needs for their utilization, requires effective and efficient management. Therefore, an analysis of reservoir operations is needed to optimize the utilization of available water resource potential so that it can meet various needs sustainably [10].

Effective and efficient management of reservoir operations is a crucial aspect in supporting food security and the sustainability of agricultural systems. Inappropriate reservoir operation can lead to an imbalance between inflow, reservoir storage, and water demand, thereby increasing the potential for a deficit in irrigation water distribution [11]. Consequently, operational pattern policies within the water resources system serve to manage water within the system so that water allocation can be carried out according to needs and existing availability conditions [12]. Therefore, reservoir operational patterns are needed that can optimally adjust water release so that irrigation water needs can be met without disrupting the sustainability of reservoir storage.

One of the strategic reservoirs that plays a crucial role in meeting irrigation water needs in Central Java Province is the Kedungombo Reservoir. This multi-purpose reservoir is used for irrigation water supply, flood control, hydroelectric power generation, fisheries, and raw water supply for the community. In its irrigation function, the Kedungombo Reservoir plays a crucial role in supplying water to downstream irrigation areas, thus ensuring optimal operational continuity. However, fluctuating hydrological conditions often cause reservoir operations to face a mismatch between water availability and irrigation water demand. During periods of low discharge, reservoir capacity can decrease to near the minimum operating elevation, thereby reducing the reservoir's ability to optimally meet irrigation water needs.

In addition to being influenced by hydrological factors, the increasing water demand due to the development of the agricultural sector also poses a challenge to the operation of the Kedungombo Reservoir. The expansion of agricultural land and the increasing intensity of planting have led to a greater need for irrigation water from year to year. This situation demands a more adaptive and optimal reservoir operation strategy to ensure effective water distribution in accordance with water availability. Reservoir operations that still use conventional operating patterns without considering optimization have the potential to result in water waste in certain periods and water shortages in others. Therefore, an optimization approach to reservoir operations is needed to determine a water release pattern that can provide the best balance between reservoir capacity and irrigation water needs.

Reservoir operation optimization is a method used to determine the best operating pattern based on the relationship between inflow, storage, release, and water demand. An optimization model is one approach that can be used to develop reservoir operation guidelines by optimally considering various aspects related to the reservoir's utilization objectives. Furthermore, this model also takes into account various constraints that can limit the utilization of water resources so that reservoir management can be carried out more effectively and efficiently [13]. Through optimization, water release can be regulated in such a way that the level of water demand is met more optimally while still maintaining the sustainability of the reservoir's storage capacity.

With the development of water resource modeling technology, reservoir operation simulation and optimization can be performed using various hydrology software. One software widely used in reservoir operation simulation is HEC-ResSim. This model is able to represent the dynamic relationship between inflow, storage, release, and reservoir elevation, so it can be used to evaluate reservoir operation patterns under various hydrological conditions [14]. In addition, optimization using Solver can be used to determine reservoir operation scenarios that provide the most optimal results in minimizing irrigation water deficits.

Various previous studies have shown that optimizing reservoir operations can improve the effectiveness of water resource management. Research on the Way Rarem Reservoir showed that optimization using dynamic programming can increase the level of reservoir operational reliability compared to existing conditions [15]. Other studies on the Gondang Reservoir and Bili-Bili Reservoir also showed that optimizing reservoir operations can reduce the deficit in irrigation water needs and increase the efficiency of water distribution [16]. Evaluation of the success of reservoir operations is generally carried out using reservoir performance indicators, namely reliability, resilience, and vulnerability. Reliability indicators are used to describe the level of success of the reservoir in meeting water needs, resilience indicators show the system's ability to recover after experiencing a failure, while vulnerability indicators describe the severity of failure when a water deficit occurs [17]. These three indicators are important for evaluating the extent to which a reservoir operating system is able to adapt to changing hydrological conditions.

Although numerous studies have been conducted on reservoir operation optimization, studies on Kedungombo Reservoir operation optimization using integrated simulation using HEC-ResSim and optimization using Solver are still relatively limited, particularly in evaluating reservoir performance based on reliability, resilience, and vulnerability indicators. However, Kedungombo Reservoir plays a strategic role in meeting irrigation water needs, requiring more optimal operational management to address future inflow fluctuations and increased water demand.

Based on these problems, this study was conducted to analyze the operational performance of the Kedungombo Reservoir under existing conditions and evaluate the improvement in reservoir operational performance after optimization using Solver. Reservoir operation simulations were conducted using HEC-ResSim with the mainstay discharge scenarios Q20, Q50, and Q80 to illustrate the condition of water availability at various levels of discharge reliability. Furthermore, the simulation and optimization results were evaluated using reliability, resilience, and vulnerability indicators to determine the effectiveness of the reservoir operation pattern in meeting irrigation water needs. The results of this study are expected to provide recommendations in the operational management of the Kedungombo Reservoir so that irrigation water distribution can be carried out more effectively, efficiently, and sustainably.

RESEARCH METHODS

This research was conducted at the Kedungombo Reservoir in Central Java Province, under the management of the Pemali Juana River Basin Agency (BBWS). Kedungombo Reservoir is a multipurpose reservoir primarily used to meet irrigation water needs. Its operation is affected by annual hydrological conditions, which cause fluctuations in inflow and changes in reservoir capacity. Under low discharge conditions, reservoir capacity can decrease to near the minimum operating elevation, potentially creating a deficit in meeting irrigation water needs. Therefore, this research focused on evaluating and optimizing reservoir operations to improve irrigation water service performance.

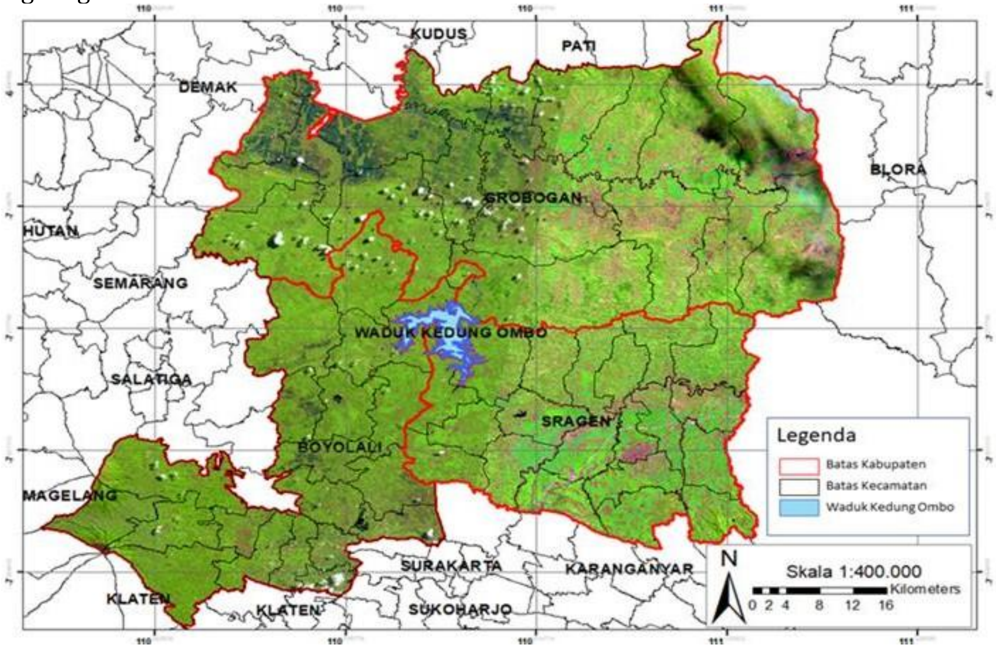

Figure 1. Location of Kedungombo Reservoir

The data used in the study included reservoir technical data, discharge data, climate data, and cropping pattern data for the irrigation service area. Reservoir technical data, including storage capacity, water level elevation, dam dimensions, spillway, and intake, were obtained from the Pemali Juana Watershed Management Agency (BBWS) [18]. edungombo Reservoir inflow data was obtained from the Pemali Juana Watershed Management Agency (BBWS) for the years 2015–2025. In addition, climatological data, including air temperature, relative humidity, solar radiation intensity, and wind speed, were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) through the Central Java Geophysical Station for the period 2015–2025. Cropping pattern data for the Kedungombo Reservoir service area for 2025–2026 was also used to calculate irrigation water requirements.

The research phase began with an analysis of Kedungombo Reservoir inflow data for 2015–2025 as the basis for calculating the mainstay discharge, water balance simulations, and reservoir operation simulations. The reliable discharge analysis was conducted using the Weibull method to obtain the reliable discharges Q20, Q50, and Q80. The Weibull equation used is stated as follows:

$$P = \frac{m}{(n+1)} \times 100\%$$

where P is the probability of occurrence, m is the data sequence number, and n is the amount of data. The mainstay discharge is used as the basis for reservoir operation simulations under various hydrological conditions. Irrigation water requirements are calculated using CROPWAT software based on climatological data and cropping patterns in the irrigation service area. Reference evapotranspiration is calculated using the Penman–Monteith method with the following equation:

$$ET_O = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2(es - ea)}{\Delta + \gamma(1 + 0.34u_2)}$$

Water requirement calculations take into account crop water requirements, effective rainfall, irrigation efficiency, cropping patterns, and irrigated area. Next, a water balance analysis is performed using data on inflow, reservoir capacity, evaporation losses, reservoir discharge, and spillway runoff. The water balance equation used is as follows:

$$S_{t+1} = S_t + I_t - R_t - E_t - Sp_t$$

Where S_{t+1} is the next period's storage, S_t is the current period's storage, I_t is the reservoir inflow, R_t is the reservoir discharge, E_t is the evaporation loss, and Sp_t is the spillway overflow. The Annual Reservoir Operation Plan (RTOW) is prepared using HEC-ResSim software based on the mainstay discharges Q20, Q50, and Q80. Simulations are performed by considering inflow data, reservoir storage, irrigation water requirements, and the operating rules of the Kedungombo Reservoir. Furthermore, reservoir operation optimization is performed using Solver to obtain the optimal water release pattern with the aim of minimizing the irrigation water deficit. The optimization objective function is stated as follows:

$$\text{Min Z} = \sum_{i=1}^{N} (D_i - R_i)^2$$

Where D_i is the water demand in period i and R_i is the reservoir release in period i. The decision variable in the optimization is the reservoir water release in each operating period. Optimization is carried out by considering the reservoir storage and reservoir release constraints, namely:

$$S_{min} \leq S_t \leq S_{max}$$

and

$$R_{min} \leq R_t \leq R_{max}$$

The water balance equation is also used as a constraint function in the reservoir operation optimization process. The Kedungombo Reservoir's operational performance is evaluated using reliability, vulnerability, and resilience indicators. Reliability is used to determine the reservoir's success in meeting irrigation water needs and is calculated using the following equation:

$$\text{Reliability} = \frac{n_s}{N} \times 100\%$$

Vulnerability is used to evaluate the severity of water deficit when a reservoir fails to meet irrigation water needs.

$$\text{Vulnerability} = \frac{\sum \text{Deficit}}{\text{Number of failure periods}}$$

Meanwhile, resilience is used to measure the ability of a reservoir system to recover from a failed condition to a successful conditionl.

$$\text{Resilience} = \frac{\text{Number of failed to successful}}{\text{Number of failed periods}}$$

These three indicators are used to evaluate the effectiveness of the simulation results and optimization of Kedungombo Reservoir operations.

RESULT AND DISCUSSION

Reservoir Operation Optimization Model Formulation

Optimization of Kedungombo Reservoir operations was carried out using the Solver method to obtain the optimal reservoir water release pattern to meet irrigation water needs at the mainstay discharge conditions of Q20, Q50, and Q80 [19]. The optimization model was constructed based on the objective function, decision variables, constraint functions, and the reservoir water balance equation. The optimization objective function was used to minimize the deficit in irrigation water needs in each operating period [20]. The decision variables in the model were reservoir water releases (releases) in each semi-monthly period. Meanwhile, the constraint function was used to ensure that reservoir operations remained within the minimum operational storage limits and maximum reservoir storage limits. Based on the analysis results, the minimum operational storage for Kedungombo Reservoir was set at 93.11 MCM, which represents the Minimum Operating Level (MOL). The inflow data used came from the Weibull mainstay discharge for the period 2015–2025 with a semi-monthly operating interval [21].

Table 1. Formulation of Optimization Model for Kedungombo Reservoir Operation

Description	Model Settings
Objective Function	Minimizing the Irrigation Water Deficit
Constraint Function	a. Storage: 93.11 MCM ≤ S_i ≤ maximum reservoir capacity
	b. Release: 0 ≤ U_i ≤ irrigation water demand
State Transformation	$S_{t+1} = S_t + I_t - R_t - E_t - Sp_t$
Target Demand	Irrigation water demand for the Kedungombo Reservoir service area
Inflow	Weibull dependable discharge Q20, Q50, and Q80 for the period 2015–2025
Water Loss	Reservoir evaporation
Operating Interval	Semi-monthly
Optimization Method	Microsoft Excel Solver

The optimization model is used to obtain the optimal reservoir water release pattern so that irrigation water needs can be met with a minimum level of water shortage at each mainstay discharge condition [21].

Existing Reservoir Operational Performance

The operational performance analysis of existing reservoirs was conducted using HEC-ResSim simulations based on the mainstay discharges of Q20, Q50, and Q80. Reservoir performance evaluation was conducted using reliability, vulnerability, and resilience indicators to determine the reservoir's ability to meet irrigation water needs. Simulation results show that the reservoir's operational reliability level decreases as the mainstay discharge decreases. In Q20, the reservoir reliability level was 66.44%, then decreased to 54.72% in Q50 and 44.98% in Q80. This decrease indicates that as the reservoir inflow decreases, the reservoir's ability to meet irrigation water needs also decreases. The vulnerability value indicates the total water shortage during the reservoir's operational period. In Q20, the vulnerability value was 678.42 MCM, then increased to 915.25 MCM in Q50 and 1112.19 MCM in Q80. This condition indicates that the water deficit increases at low mainstay discharges. Meanwhile, the operational resilience values of existing reservoirs are relatively low, at 0.08 in Q20, 0.06 in Q50, and 0.05 in Q80. These values indicate that the reservoir requires a relatively long time to return to normal conditions after experiencing a failure to meet water needs.

Table 2. Analysis of Existing Reservoir Operational Performance

Scenario	Reliability (%)	Vulnerability (MCM)	Resilience
Q20	66.44	678.42	0.08
Q50	54.72	915.25	0.06
Q80	44.98	1112.19	0.05

Reservoir Operation Performance Optimization

The analysis of reservoir operational performance resulting from optimization was conducted using Solver based on the mainstay discharges Q20, Q50, and Q80. Evaluation was conducted using reliability, vulnerability, and resilience indicators to assess improvements in reservoir operational performance following optimization. The optimization results showed that reservoir operational reliability increased across all mainstay discharge scenarios. The reliability value in the Q20 condition was 74.86%, while in the Q50 and Q80 conditions, it was 73.73% and 74.00%, respectively. These conditions indicate that reservoir operational optimization is able to increase the reservoir's ability to meet irrigation water needs compared to existing operations [22]. The vulnerability value resulting from optimization also decreased compared to existing conditions. In the Q20 condition, the vulnerability value was 508.17 MCM, then 531.11 MCM in Q50 and 525.67 MCM in Q80. The decrease in vulnerability value indicates that optimization is able to reduce the total water shortage during the reservoir's operational period. Meanwhile, the resilience value resulting from optimization indicates a better reservoir recovery capability compared to existing conditions. Based on the results of the periodic analysis, the resilience value for the Q20 condition was 0.33, while for the Q50 and Q80 conditions it was 0.25 and 0.25, respectively. These values indicate that the optimized operation returned to normal conditions more quickly after experiencing a water deficit.

Table 3. Analysis of Reservoir Operation Performance Resulting from Optimization

Scenario	Reliability (%)	Vulnerability (MCM)	Resilience
Q20	74.86	508.17	0.33
Q50	73.73	531.11	0.23
Q80	74.00	525.67	0.25

Comparison of Existing Operational Performance and Optimized Operational Performance

A comparison of reservoir operational performance was conducted to determine the effect of optimization on the ability of the Kedungombo Reservoir to meet irrigation water needs under the mainstay discharge conditions of Q20, Q50, and Q80. The evaluation was conducted using reliability, vulnerability, and resilience indicators. The analysis results showed that the optimized reservoir operation was able to improve operational performance compared to existing conditions in all mainstay discharge scenarios. The level of reservoir operational reliability increased quite significantly after optimization. Under Q20 conditions, reliability increased from 66.44% to 74.86%. Meanwhile, under Q50 conditions it increased from 54.72% to 73.73%, and under Q80 conditions it increased from 44.98% to 74.00% [8]. In addition to increasing reliability, reservoir operational optimization was also able to reduce vulnerability values. Under Q20 conditions, vulnerability values decreased from 678.42 MCM to 508.17 MCM. In the Q50 condition, the vulnerability decreased from 915.25 MCM to 531.11 MCM, while in the Q80 condition, it decreased from 1112.19 MCM to 525.67 MCM. This decrease indicates that the optimization of reservoir operations is able to reduce the total water shortage during the operating period [17]. The resilience value resulting from the optimization also shows an increase compared to the existing condition. In the Q20 condition, the resilience increased from 0.08 to 0.33. Meanwhile, in the Q50 condition, it increased from 0.06 to 0.25, and in the Q80 condition, it increased from 0.05 to 0.25. This indicates that the optimized operation has a better recovery ability after experiencing a water deficit condition [22].

Table 4. Comparison of Existing and Optimized Reservoir Operational Performance

Scenario	Condition	Reliability (%)	Vulnerability (MCM)	Resilience
Q20	Existing	66.44	678.42	0.08
Q50	Existing	54.72	915.25	0.06
Q80	Existing	44.98	112.19	0.05
Q20	Optimization	74.86	508.17	0.33
Q50	Optimization	73.73	531.11	0.23
Q80	Optimization	74.00	525.67	0.25

CONCLUSION

Based on the analysis of Kedungombo Reservoir operations using HEC-ResSim simulations and Solver optimization at the mainstay discharges of Q20, Q50, and Q80, it was found that the existing reservoir's operating conditions are still suboptimal in meeting irrigation water needs. This is indicated by the reservoir's operational reliability, which tends to decrease at low mainstay discharges, reaching 66.44% in Q20, 54.72% in Q50, and 44.98% in Q80. Furthermore, the existing reservoir's operational vulnerability remains quite significant, with total water shortages of 678.42 MCM in Q20, 915.25 MCM in Q50, and 1,112.19 MCM in Q80, respectively. The existing reservoir's operational resilience is also relatively low, indicating that the reservoir requires a longer time to return to normal conditions after experiencing a failure to meet water needs.

The results of reservoir operational optimization using Solver show improved reservoir operational performance across all mainstay discharge scenarios. The reliability level increased to 74.86% in Q20, 73.73% in Q50, and 74.00% in Q80. Furthermore, the vulnerability value decreased to 508.17 MCM in Q20, 531.11 MCM in Q50, and 525.67 MCM in Q80. The reservoir resilience value also increased compared to the existing condition by 0.33 in Q20 and 0.25 in Q50 and Q80. These results indicate that reservoir operation optimization can improve the reservoir's ability to meet irrigation water needs while reducing the total water deficit during the operational period.

In general, Kedungombo Reservoir operation optimization can produce a more effective reservoir operation pattern than the existing condition, particularly in increasing irrigation water supply during low to medium mains discharge conditions. Therefore, reservoir operation optimization can be used as an alternative management strategy for Kedungombo Reservoir operations to support sustainable irrigation water supply.

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