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Real-time Application and Statistical Evaluation of Reservoir Operating Rules Under Inflow Uncertainty in Monte Carlo Simulations

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ABSTRACT Reservoir Operating Rules (ROR) have been well-known in Indonesia as guidelines for reservoir operation that comprise the release rules and rule curves derived from the dependable inflow time series in dry, normal, and wet conditions. However, likely because of the incoherence of the original application concept of ROR, the real performance of ROR in reservoir operation has so far remained unclear. This paper proposes a practical application concept of ROR and evaluates the performance of its implementation for annual storage conservation and periodic demand satisfaction under inflow uncertainty in the integrated system of Segawe Regulating Weir, Wonorejo Multipurpose Dam, and Tiudan Regulating Dam. The release rules for the three hydraulic structures were integrated into a unified "Wonorejo ROR" through optimization of water allocation over 36 ten-day operational periods. The performance of the application of Wonorejo ROR was evaluated based on several operational success and failure events in Monte Carlo simulations, for which 1,000 years of unique and independent synthetic inflow time series were generated from the Thomas–Fiering model. Under the application concept of ROR, the release decisions for the three hydraulic structures were made in real-time solely based on the actual water level of Wonorejo Reservoir and the rule curves of Wonorejo ROR. For comparative purposes, the Monte Carlo simulations were carried out to evaluate two alternatives of Wonorejo ROR, namely ROR-D65 and ROR-D80, which had different dry inflow exceedance probabilities. Based on the specified events in the Monte Carlo simulations, ROR-D65 and ROR-D80 resulted in reliabilities of 76.4% and 81.3% for annual storage conservation, and the lowest reliabilities of 73.9% and 52.4% for periodic demand satisfaction, respectively. In addition, other reservoir operational performances and a comprehensive interpretation of the proposed application concept of ROR are presented in this paper.

KEYWORDS Inflow uncertainty; Monte Carlo simulations; Real-time application of Reservoir Operating Rules; Reservoir operational performance; Thomas-Fiering model.

1 INTRODUCTION

The Indonesian Government's Education and Training Center for Water Resources and Construction—nationally known as Pusat Pendidikan dan Pelatihan SDA dan Konstruksi (2017)—suggested that there are two guidelines for annual reservoir operation, namely the Reservoir Operating Rules (ROR) and the Annual Plan for Reservoir Operation (APRO), which are known in Indonesian respectively as *Pola Operasi Waduk* (POW) and *Rencana Tahunan Operasi Waduk* (RTOW). It was stated that a reservoir operation must comply with the two guidelines, so that the reservoir's storage can be conserved to satisfy the water demands throughout the year. In this context, APRO is the main guideline for reservoir operation that must be updated once a year. Meanwhile, ROR is a long-term guideline that must be updated at least once in five years, and is only used for the derivation of an APRO. Each guideline must be derived by simulating or optimizing the water balance of the reservoir's inflow, storage, and outflow in all operational periods to generate release rules (the reservoir's outflows) and rule curves (changes in the reservoir's storage). The decision-making process in this simulation is commonly referred to as "operating policy," as it must consider the reservoir's characteristics, the water demands, and the water allocation constraints (You and Cai, 2008; Loucks and van Beek, 2017; Men et al., 2019). In further conceptual detail, APRO and ROR can be differentiated as follows (Pusat Pendidikan dan Pelatihan SDA dan Konstruksi, 2017).

a) ROR comprises release rules and rule curves for three conditions, namely lower normal (dry), normal, and upper normal (wet), whereas APRO comprises them only for the upcoming year.
b) The initial water level of each rule curve of ROR must be equal to the final water level, whereas that of the rule curve of APRO is the reservoir's water level estimated for the end of the current year.
c) The dry, normal, and wet inflow time series for ROR are determined respectively with 65%, 50%, and 35% exceedance probabilities, whereas inflow

time series for APRO are predicted according to "informasi ramalan musim (seasonal forecast information)" from the Indonesian Agency for Meteorological, Climatological, and Geophysics.

A clear connection to this study can be made by addressing two issues of the concept of APRO as described by Pusat Pendidikan dan Pelatihan SDA dan Konstruksi (2017). First, the rule curve of APRO was stated to be in between the dry and wet rule curves of ROR, and its final water level must be equal to that of the normal rule curve of ROR. Although such a requirement may appear reasonable, it would effectively reduce the storage capacity in the derivation of APRO in compliance with the rule curves of ROR. This will become a problem if the inflow time series predicted for APRO differ substantially from the dependable inflow time series for ROR. More precisely, due to mass conservation, the rule curve requirement may actually become a constraint that will force the outflows to be either greater than needed or inappropriately less than available in certain periods. This means that if the predicted inflow time series turn out to be accurate, an APRO may instead result in a non-efficient demand satisfaction throughout the year.

Second, the application concept of APRO states that the reservoir's water level must be immediately adjusted if it deviates from the rule curve of APRO (Pusat Pendidikan dan Pelatihan SDA dan Konstruksi, 2017). One problem with this application concept is that it will likely be difficult to implement, since a reservoir's actual inflow is rarely known in real-time. Another problem is that the application of APRO contradicts the purpose of release rules, which is to guide demand satisfaction. This is because, if the actual inflow time series differ from those predicted, applying APRO will lead to an irregular demand satisfaction, as the reservoir operation focuses only on storage conservation.

There is categorically no robust explanation for the concept of APRO and ROR as described by Pusat Pendidikan dan Pelatihan SDA dan Konstruksi (2017). This is due to the fact that real inflow time series cannot easily be accurately predicted one year ahead (van Dijk et al., 2013; Montanari and Koutsoyiannis, 2014), nor can they necessarily be assumed as such in 'dry,' 'normal,' or 'wet' conditions (Koutsoyiannis and Montanari, 2007; Vogel et al., 2015). Indeed, simplified conceptualization in hydrology is a common practice in water resources management and engineering, and it may be accepted due to the complexity of hydrological uncertainty (Chow et al., 1988; Haan, 2002). However, based on the two issues discussed above, APRO appears to have been conceptualized as if it assumes certainty in predicted inflow time series, despite acknowledged uncertainty, or as if practical implementation considerations were secondary. Moreover, the application concept of ROR as described by (Pusat Pendidikan dan Pelatihan SDA dan Konstruksi, 2017) raises the question of why an ROR must be derived in the first place. This is because the release rules of ROR would have essentially no practical value, and the rule curves that were stated to guide APRO could simply be generated from historical data of actual storage changes.

This study does not argue that APRO can never be relevant as an annual plan for reservoir operation. If a model exists (or will exist) that can accurately predict inflow time series for an entire future year, APRO could be derived directly from such predictions without complying with ROR rule curves and applied as the annual plan. Otherwise, since ROR comprises release rules and rule curves from three dependable inflow conditions, it may instead be applied practically as anticipatory guidance in real-time storage conditions.

Unlike APRO, the derivation concept of ROR as described by Pusat Pendidikan dan Pelatihan SDA dan Konstruksi (2017) has been widely used in studies on reservoir water allocation in Indonesia, producing various results on reservoir operational performance (Soentoro et al., 2018; Santoso et al., 2021; Waluyadi et al., 2021; Azmeri et al., 2022; Agastya et al., 2023; Bachtiar et al., 2023; Putranto et al., 2023; Fauziyah et al., 2023; Iqbal et al., 2023; Rediasti et al., 2023; Sastrawan et al., 2023; Agastya et al., 2024; Haditama et al., 2024; Mujiburrakhman et al., 2024; Wahyuni et al., 2024; Santosa et al., 2025). However, these performances are based only on specified inflow scenarios, making them still irrelevant to actual inflow uncertainty and confirming that the application concept of ROR remains unclear.

As mentioned earlier, this study proposes a new application concept of ROR as real-time anticipatory guidance in annual reservoir operation. The performance of this application will be evaluated for storage conservation and periodic demand satisfaction under inflow uncertainty using Monte Carlo simulations. Although the current case study involves the integrated system of Segawe Regulating Weir, Wonorejo Multipurpose Dam, and Tiudan Regulating Dam in Tulungagung Regency, the application concept of ROR will be discussed in general terms so that it can be further studied for other reservoir operations.

2 METHODS

2.1 Reservoir Performance Criteria

Reservoir operational performance can be regarded as the result of a stochastic process, since the demand satisfac¬tion in each period de¬pends on those in previous and subsequent periods and is influenced by inflow uncertainty (Chow et al., 1988; Haan, 2002). For this reason, a reservoir performance for every period in one year—j = 1, 2, ..., N—is best evaluated on the base of three criteria first introduced by Hashimoto et al. (1982), namely reliability, resiliency, and vulnerability. Note that these three criteria were originally defined in probabilistic terms of operational success and failure events, but they will be defined here in the relative frequency terms, F(E), which are more straightforward and appropriate for this study.

2.1.1 Reliability

By assuming the release-demand ratio, k_j, as the measure of demand satisfaction, and k_{min} as the minimum allowable release-demand ratio, then a success and a failure in a reservoir operation can be stated when $k_j \geq k_{\text{min}}$ and $k_j < k_{\text{min}}$, respectively. The reliability to which (Hashimoto et al., 1982) referred itself is the frequency for the reservoir operation to succeed in the demand satisfaction in period j, $F(k_j \geq k_{\text{min}})$. Accordingly, since $1 - F(k_j \geq k_{\text{min}})$ is the frequency for the reservoir operation to fail, or $F(k_j < k_{\text{min}})$, $F(k_j \geq k_{\text{min}}) = 1$ implies that the reservoir operation would almost certainly succeed in upcoming year's period j. Hence, it is clear that the higher the reliability, the better the reservoir performance.

2.1.2 Resiliency

Resiliency is a criterion that can describe the reservoir performance to turn a failure in period j into a success in period $j+1$. This criterion is defined as the frequency for the reservoir operation to succeed in the demand satisfaction in period $j+1$ given that a failure occurred in period j, $F(k_{j+1} \geq k_{\text{min}} \mid k_j < k_{\text{min}})$, as in Equation (1).

$$F(k_{j+1} \geq k_{\text{min}} \mid k_j < k_{\text{min}}) = \frac{F(k_j < k_{\text{min}} \cap k_{j+1} \geq k_{\text{min}})}{F(k_j < k_{\text{min}})} \tag{1}$$

$F(k_j < k_{\text{min}} \cap k_{j+1} \geq k_{\text{min}})$ in Equation (1) is the frequency for the reservoir operation to fail in period j and succeed in period $j+1$. In this case, it does not equal $F(k_j < k_{\text{min}})$ multiplied by $F(k_{j+1} \geq k_{\text{min}})$, since $k_j < k_{\text{min}} \cap k_{j+1} \geq k_{\text{min}}$ is actually a unit event caused by the dependency of k_{j+1} on k_j (Hashimoto et al., 1982; Chow et al., 1988; Haan, 2002). This means that if $F(k_{j+1} \geq k_{\text{min}} \mid k_j < k_{\text{min}}) = 0$, then a failure that would occur in the upcoming year's period j would almost certainly be followed by a failure in period $j+1$, even if $F(k_{j+1} \geq k_{\text{min}}) > 0$. However, it can be noted that the resiliency from Equation (1) would be undefined if $F(k_j \geq k_{\text{min}}) = 1$. Furthermore:

a) if $F(k_{j+1} \geq k_{\text{min}}) = 1$, then $F(k_{j+1} \geq k_{\text{min}} \mid k_j < k_{\text{min}}) = 1$;
b) if $F(k_{j+1} \geq k_{\text{min}}) = 0$, then $F(k_{j+1} \geq k_{\text{min}} \mid k_j < k_{\text{min}}) = 0$.

2.1.3 Vulnerability

Vulnerability may be defined as a criterion that describes how severe, significant, or worth considering are the failures that would occur in period j. Based on how it was explained by Hashimoto et al. (1982), vulnerability will be defined here by referring to Figure 1. It can be seen that a distribution of release-demand ratios in period j can be made of a number of the k-factor intervals, k_i, where $k_i < k_{\text{min}}$ is classified as a failure ($i \in f$), while $k_i \geq k_{\text{min}}$ is classified as a success ($i \in s$).

Hashimoto et al. (1982) defined the vulnerability of reservoir operation in period j, ν_j, by considering only the failure events. However, if ν_j also assumes the success events, and the deficit of $1 - k_i$ is the measure of deficiency in demand satisfaction, then ν_j can essentially be defined as in Equation (2).

$$\nu_j = \sum_{i \in f} (1 - k_i) \frac{F(k_i)}{F(k_j < k_{\text{min}})} + \sum_{i \in s} (1 - k_i) \frac{F(k_i)}{F(k_j \geq k_{\text{min}})} \tag{2}$$

It can be seen that ν_j in Equation (2) will be undefined if $F(k_j < k_{\text{min}})$ or $F(k_j \geq k_{\text{min}})$ is equal to zero. Hence:

a) if $F(k_j \geq k_{\text{min}}) = 1$, then

$$\nu_j = \sum_{i \in s} (1 - k_i)\, F(k_i);$$

b) if $F(k_j < k_{\text{min}}) = 1$, then

$$\nu_j = \sum_{i \in f} (1 - k_i)\, F(k_i).$$

This equation itself describes that vulnerability must consider both how severe and how likely the deficits are in a period, as two operational periods may ideally have the same reliability but different vulnerabilities. It can also describe that depending on the k-factor distribution, although $F(k_j \geq k_{\text{min}}) = 1$ must result in $\nu_j \leq 1 - k_{\text{min}}$, $F(k_j \geq k_{\text{min}}) < 1$ would not necessarily result in $\nu_j > 1 - k_{\text{min}}$.

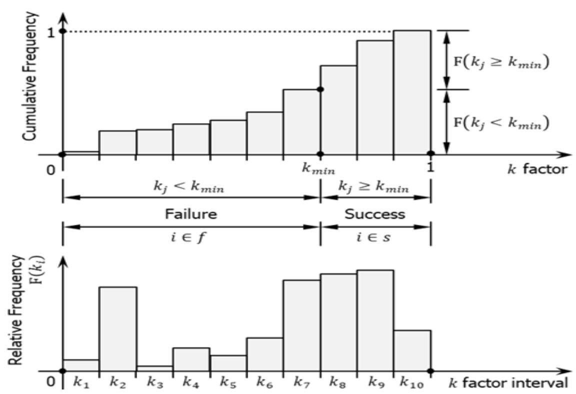

Figure 1. Illustration of a distribution of the release-demand ratios from reservoir operation in period j.

2.2 Monte Carlo Simulations and Thomas-Fiering Model

If sufficient historical data of reservoir operation are not available, the frequencies of events for reservoir performance evaluation can be obtained from Monte Carlo simulations. As shown in Figure 2, Monte Carlo simulations involve simulating reservoir operation repeatedly by continuously introducing uncertainty into the inflow time series (Haan, 2002). Ideally, the uncertainty can be introduced using a probability function. However, inflow data are needed over a long span of years to generate such smooth periodic probability functions. In order to illustrate the three criteria of reservoir performance, Hashimoto et al. (1982) themselves used the inflow time series that were generated from the Thomas–Fiering model as in Equation (3) (Chow, 1964; Haan, 2002).

$$I_{j+1} = \bar{I}_{j+1} + b_{j+1,j}(I_j - \bar{I}_j) + \epsilon_{j+1}\, s_{j+1}\sqrt{1 - r^2_{j+1,j}} \quad (3)$$

Developed by Thomas and Fiering (1962), Equation (3) is an autoregression model in which the inflow in period $j+1$, I_{j+1}, is assumed to be dependent on that in period j, I_j, based on some statistical relationship parameters of I_{j+1} and I_j. Although it seems deterministic, this model can be used to generate synthetic inflow time series for Monte Carlo simulations of a reservoir operation, since ϵ_{j+1} is a standard normal variate that defines the relationship uncertainty between I_{j+1} and I_j. In this case, the statistical relationship parameters can be determined from historical data, where $\bar{I}_j$ and s_j are respectively the mean and the standard deviation of inflows in period j, and $r_{j+1,j}$ is the correlation coefficient between inflows in period $j+1$ and those in period j. Meanwhile, $b_{j+1,j}$ itself is the regression coefficient for inflows in period $j+1$ based on those in period j, which is equal to $\frac{r_{j+1,j}\, s_{j+1}}{s_j}$.

Besides the Thomas-Fiering model, another widely used model is the Autoregressive Integrated Moving Average (ARIMA). This model is basically more capable of representing complex autoregressive and moving average processes (Box et al., 2016; Shumway and Stoffer, 2017). However, it requires relatively long and stationary data to ensure stable estimation of statistical parameters (Box et al., 2016; Hyndman and Athanasopoulos, 2018). In contrast, the Thomas-Fiering model is a first-order Markov chain developed specifically for simpler streamflow synthesis (Thomas and Fiering, 1962). As the 10-day inflow data used in this study span only 15-20 years (Mujiburrakhman et al., 2024), they are more suitable for the Thomas–Fiering model that performs well with limited data availability (Salas et al., 1980; Clarke, 1994; Koutsoyiannis, 2000). Furthermore, the purpose of this study is only to evaluate the performances of the application of ROR for annual storage conservation and periodic demand satisfactions. Therefore, the Thomas-Fiering model is sufficient to be used in this study, since it was designed to preserve relevant key periodic statistical parameters, namely the mean, variance, and lag-one autocorrelation (Thomas and Fiering, 1962; Salas et al., 1980; Kottegoda and Rosso, 2008). As for the Monte Carlo method, it can

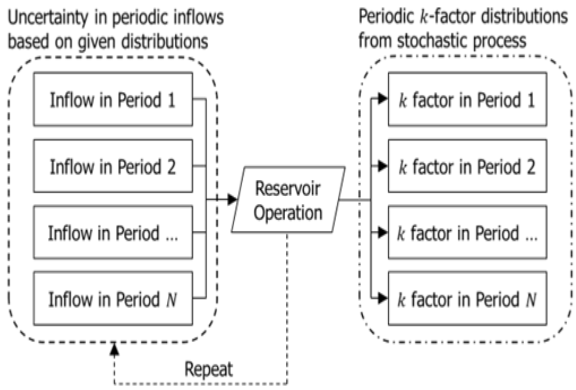

Figure 2. Monte Carlo simulations scheme for a reservoir performance evaluation.

explicitly manage inflow uncertainty in reservoir simulations (Loucks and van Beek, 2017), and has a flexible framework to evaluate and characterize performance variability of ROR under a wide range of inflow realizations (Kindler, 1977; Lai et al., 2022). The main disadvantage of the Monte Carlo method itself is that the simulation must be repeated many times to result in an output distribution that may represent the population (Haan, 2002; Janssen, 2013). However, as long as the input distribution fits the historical data distribution (Aitken et al., 2022; Maia et al., 2024), Monte Carlo simulations can be carried out as many times as needed until the output statistical parameter of interest—such as the mean or a percentile—is no longer changing significantly, or has converged (Faber, 2021).

2.3 The Case Study of Reservoir Operating Rules

Segawe Regulating Weir (7° 59' 46.90" S – 111° 49' 11.63" E), Wonorejo Multipurpose Dam (8° 1' 11.87" S – 111° 48' 18.91" E), and Tiudan Regulating Dam (8° 2' 47.52" S – 111° 50' 28.62" E) are three hydraulic structures in the Ngrowo sub-watershed of the Brantas River basin. These three hydraulic structures are now integrated under the management of *Perusahaan Umum Jasa Tirta I* (Jasa Tirta I Corporation). The complete water allocation scheme of the three hydraulic structures can be seen in a previous study (Mujiburrakhman et al., 2024), and a simplified version of it will be shown in Figure 4. However, it can be generally described as follows.

a) Segawe Regulating Weir must release some or all of its inflow downstream for the Song River's ecosystem maintenance (duty flow) and irrigation of the Blader, Kluwih, and Gelang paddy fields (PF Blader–Kluwih–Gelang), while it may also divert an amount of impounded inflow into Wonorejo Reservoir.

b) Wonorejo Multipurpose Dam must release its storage for usually 10 hr/day to conserve the daily storage of Tiudan Regulating Dam and generate electricity.

c) Tiudan Regulating Dam must release its storage 24 hours nonstop for the Gondang River's duty flow, the Paingan paddy field (PF Paingan) irrigation, and domestic water supply.

In this study, local inflows were assumed only for Segawe Regulating Weir and Wonorejo Multipurpose Dam. The release rules for the three hydraulic structures themselves were integrated into an ROR. As it consists of only the rule curves of Wonorejo Reservoir, this ROR is here called the "Wonorejo ROR." For comparative purposes, two alternatives of Wonorejo ROR were derived, namely ROR-D65 and ROR-D80. The wet and normal inflows for both alternatives of ROR are determined respectively with 35% and 50% exceedance probabilities, while the dry inflows for ROR-D65 and ROR-D80 are determined respectively with 65% and 80% exceedance probabilities. The four dependable inflows were generated for 36 operational periods from the flow-duration curves created using the Weibull equation (Chow et al., 1988; Haan, 2002), and they are shown along with the demands for irrigation and domestic water supply in Figure 3(a). These dependable inflows and water demands were determined from the same data used in a previous study (Mujiburrakhman et al., 2024). Both alternatives of Wonorejo ROR themselves were derived through an optimization that considered priority constraints on water allocation in all periods, for which the model has also been discussed in the previous study. The wet release rules for ROR-D65 and ROR-D80 from the optimization were the same as the water demands throughout the year, while the normal and dry release rules are shown in Figure 3(b). The dry, normal, and wet rule curves of these release rules are shown in Figure 3(c).

2.4 Aplication of Wonorejo ROR

The operation of the three hydraulic structures in Monte Carlo simulations was programmed in Microsoft Excel. There were three terms of release defined for all purposes, namely release rule, release decision, and actual release. They were defined in m^3/s and as functions of daily hour indexes—$t = 1, 2, \ldots, 24$—in period j as follows.

- **Release rule**, $Q_j^{p;c}$, is the release in dry, normal, or wet conditions as in the Wonorejo ROR.
- **Release decision**, $\hat{Q}_t^p$, is the release decided solely based on the actual water level of Wonorejo Reservoir and the rule curves of Wonorejo ROR.
- **Actual release**, Q_t^p, is the release that must satisfy the principle of mass conservation and the water allocation constraints.

2.4.1 Release rule

From Figure 3, the release rules for the PF Blader–Kluwih–Gelang irrigation, $Q_j^{IK;c}$, the PF Paingan irrigation, $Q_j^{IP;c}$, and domestic water supply, $Q_j^{DS;c}$, under condition c, were equal to the water demands multiplied by the corresponding k-factors:
$Q_j^{IK;c} = D_j^{IK}\, k_j^{I;c}$, $Q_j^{IP;c} = D_j^{IP}\, k_j^{I;c}$, $Q_j^{DS;c} = D_j^{DS}\, k_j^{DS;c}$.

The release rule for electricity generation itself included the turbine flow rate, $Q_j^{W;c}$, and the operational hours of Wonorejo Power Plant. Both $Q_j^{W;c}$ and the operational hours were determined in the same manner as explained by (Mujiburrakhman et al., 2024), from which $Q_j^{W;c}$ according to ROR-D65 and ROR-D80 varied from 9.9 to 12.0 m^3/s and 7.3 to 11.9 m^3/s, respectively, for 10 to 14 hr/day.

2.4.2 Release decision

In the Monte Carlo simulations, it was assumed that the operational date would change at 5 a.m., and Wonorejo Power Plant would stop operating at 10 p.m. The release decisions for all purposes—$p = IK, W, IP, DS$—were determined only at 5 a.m. and 5 p.m., where:

a) if $t = 5$ or $t = 17$, then $\hat{Q}_t^p = \hat{Q}(Z_t^W)$;

b) if $t \neq 5$ and $t \neq 17$, then $\hat{Q}_t^p = \hat{Q}_{t-1}^p$.

To determine the release decision as a function of the actual water level of Wonorejo Reservoir, $\hat{Q}(Z_t^W)$, it can first be seen in Figure 3(c) that each rule curve may or may not intersect with another rule curve within certain periods, where:

a) there is no overlap among the three rule curves, $Z_t^{\text{dry}} < Z_t^{\text{normal}} < Z_t^{\text{wet}}$;

b) there is overlap between the dry and normal rule curves, $Z_t^{\text{dry}} = Z_t^{\text{normal}} < Z_t^{\text{wet}}$;

c) there is overlap between the normal and wet rule curves, $Z_t^{\text{dry}} < Z_t^{\text{normal}} = Z_t^{\text{wet}}$.

Based on these three rule curve comparisons, the positions of the actual water level of Wonorejo Reservoir were categorized as in Table 1, and then $\hat{Q}(Z_t^W)$ for each purpose was determined as in Table 2. In general, it can be seen that when the reservoir's actual water level was exactly above a rule curve (dry, normal, or wet), the release decision would be determined as the release rule corresponding to that rule curve. This is the application concept of ROR as some real-time anticipations in reservoir operation, which does not consider the actual inflow.

2.4.3 Actual release

The integrated water allocation was assumed as in Figure 4, where the principle of mass conservation for the three hydraulic structures was that the change in stor-

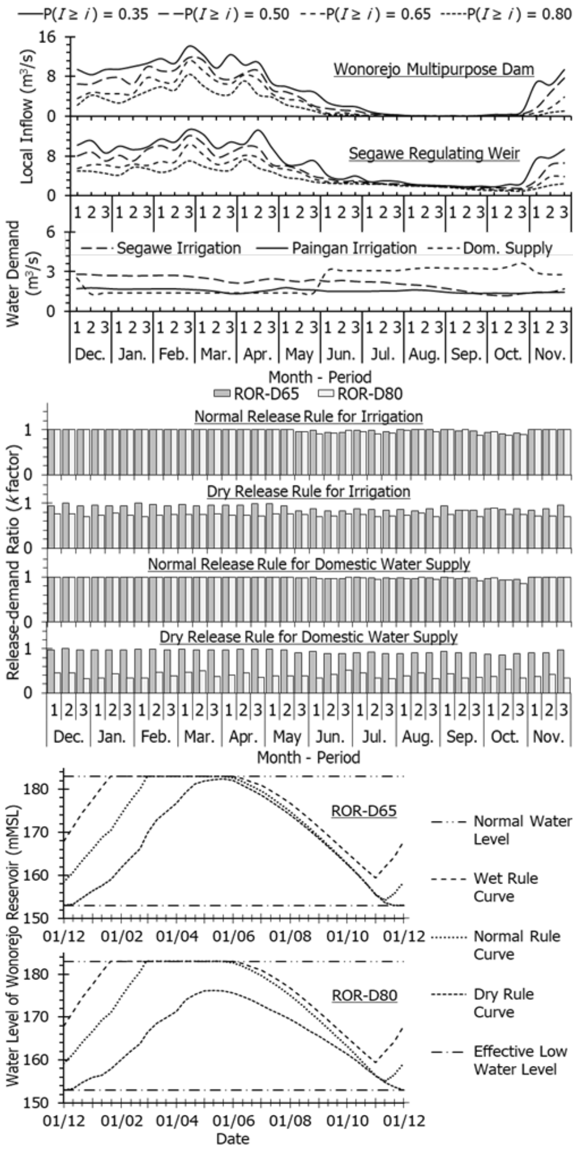

Figure 3. (a) Dependable inflows of Segawe Regulating Weir and Wonorejo Multipurpose Dam along with the demands for irrigation and domestic water supply; (b) Dry and normal release rules of Wonorejo ROR; (c) Dry normal, and wet rule curves of Wonorejo ROR.

age over a given hour must be equal to inflow minus outflow in the same given hour:

$$\frac{dS}{dt} = I(t) - O(t)$$

(Chow et al., 1988). Especially for Segawe Regulating Weir, which is incapable of storing its inflow, the mass conservation was assumed to be $\frac{dS}{dt} = 0$. Thus, in Figure 4,

$$I_t^S = Q_t^{SD} + Q_t^{IK} + I_t^{CT}.$$

On the real field, the downstream releases for the Song River's duty flow and the PF Blader–Kluwih–Gelang irrigation—$Q_t^{SD} + Q_t^{IK}$—can technically be controlled by the river gates. Meanwhile, the connector tunnel inflow, I_t^{CT}, can only flow freely over an ogee-crested weir at the tunnel's inlet. Therefore, the local inflow of Segawe Regulating Weir, I_t^S, was allocated as in Equations (4) to (6), where D_t^{SD} is the demand for the Song River's duty flow: 0.4 m^3/s.

$$Q_t^{SD} = \min\left(D_t^{SD},\, I_t^S\right) \tag{4}$$

$$Q_t^{IK} = \min\left(\hat{Q}_t^{IK},\, I_t^S - Q_t^{SD}\right) \tag{5}$$

$$I_t^{CT} = I_t^S - Q_t^{SD} - Q_t^{IK} \tag{6}$$

The mass conservation for Wonorejo Multipurpose Dam was assumed as in Equation (7). In this equation, the final storage, S_t^{Wf}, and the spillover, F_t^W, were determined by considering the initial storage, S_t^{Wi}, and the maximum storage capacity, $S_{\max}^W$, as in Equations (8) and (9).

$$\frac{dS}{dt} = \frac{S_t^{Wf} - S_t^{Wi}}{dt} = I_t^W + I_t^{CT} - E_t^W - Q_t^W - F_t^W \tag{7}$$

$$S_t^{Wf} = \min\left[S_{\max}^W,\, S_t^{Wi} + \left(I_t^W + I_t^{CT} - E_t^W - Q_t^W\right)dt\right] \tag{8}$$

$$F_t^W = \frac{\max\left[0,\, S_t^{Wi} + \left(I_t^W + I_t^{CT} - E_t^W - Q_t^W\right)dt - S_{\max}^W\right]}{dt} \tag{9}$$

In Equation (7) to (9), the actual release for the operation of Wonorejo Power Plant, Q_t^W, was always equal to the release decision from Table 2. The evaporation in Wonorejo Reservoir itself, E_t^W, was determined as a function of the evaporation height and the reservoir's water surface area. By referring to Singer et al. (2021), the hourly height distribution for one day of the reservoir's evaporation was assumed as in Table 3. Meanwhile, the daily evaporation rates and the reservoir's characteristic curves can be seen in a previous study (Mujiburrakhman et al., 2024).

Similar to that for Wonorejo Multipurpose Dam, the mass conservation for Tiudan Regulating Dam was assumed as in Equation (10). However, the actual releases for the PF Paingan irrigation, Q_t^{IP}, and domestic water supply, Q_t^{DS}, were not always equal to the corresponding release decisions. This is because the regulating dam's release capacity actually depends on the inflow, $Q_t^W + F_t^W$, which can cause a water surplus or a storage deficit.

$$\frac{dS}{dt} = \frac{S_t^{Tf} - S_t^{Ti}}{dt} = Q_t^W + F_t^W - Q_t^{GD} - Q_t^{IP} - Q_t^{DS} \tag{10}$$

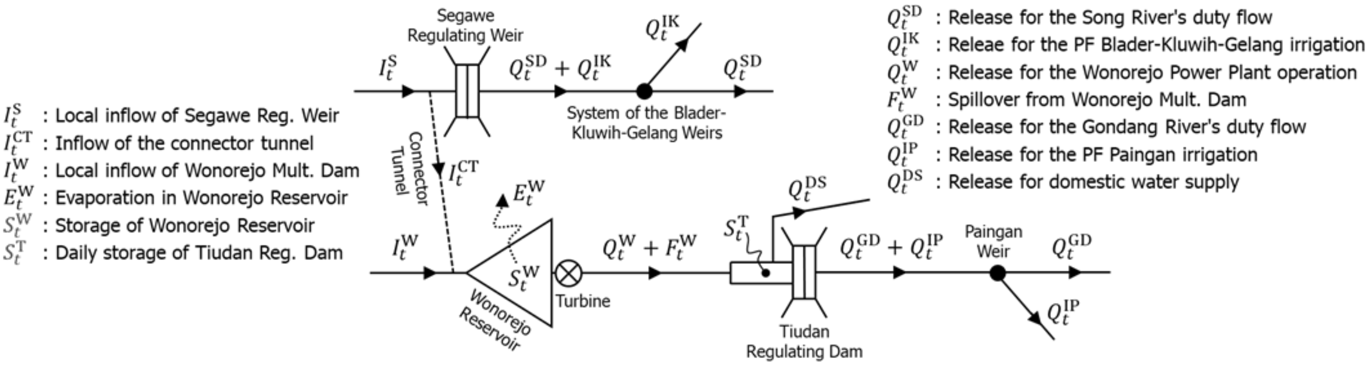

Figure 4. Water allocation scheme assumed for the integrated system of Segawe Regulating Weir, Wonorejo Multipurpose Dam, and Tiudan Regulating Dam in Monte Carlo simulations.

Table 1. Positional categories of the actual water level of Wonorejo Reservoir to the rule curves of Wonorejo ROR

Rules curves comparison	Actual water level of Wonorejo Reservoir to the rule curves of Wonorejo ROR				
	Position A	Position B	Position C	Position D	Position E
$Z_t^{dry} < Z_t^{normal} < Z_t^{wet}$	$Z_t^W \geq Z_t^{wet}$	$Z_t^{normal} \leq Z_t^W < Z_t^{wet}$	$Z_t^{dry} \leq Z_t^W < Z_t^{normal}$	$142\,\text{mMSL} \leq Z_t^W < Z_t^{dry}$	$Z_t^W < 142\,\text{mMSL}$
$Z_t^{dry} = Z_t^{normal} < Z_t^{wet}$	$Z_t^W \geq Z_t^{wet}$	$Z_t^{normal} < Z_t^W < Z_t^{wet}$	$Z_t^W = Z_t^{normal}$	$142\,\text{mMSL} \leq Z_t^W < Z_t^{normal}$	$Z_t^W < 142\,\text{mMSL}$
$Z_t^{dry} < Z_t^{normal} = Z_t^{wet}$	$Z_t^W > Z_t^{wet}$	$Z_t^W = Z_t^{wet}$	$Z_t^{dry} \leq Z_t^W < Z_t^{wet}$	$142\,\text{mMSL} \leq Z_t^W < Z_t^{dry}$	$Z_t^W < 142\,\text{mMSL}$

The first step to allocate the daily storage of Tiudan Regulating Dam was to determine the release capacities for the Gondang River's duty flow and the PF Paingan irrigation, $\tilde{Q}_t^{GD}+\tilde{Q}_t^{IP}$, and for domestic water supply, $\tilde{Q}_t^{DS}$. This was done by considering the regulating dam's initial water level, Z_t^{Ti}, as in Equation (11) and (12).

$$\tilde{Q}_t^{GD}+\tilde{Q}_t^{IP} = \begin{cases} D_t^{GD}+\hat{Q}_t^{IP} & \text{if } Z_t^{Ti} \geq 95.7\,\text{mMSL} \\ 0 & \text{if otherwise} \end{cases} \tag{11}$$

$$\tilde{Q}_t^{DS} = \begin{cases} \min\left(\hat{Q}_t^{DS},\, Q^{DS}\left(Z_t^{Ti}\right)\right) & \text{if } Z_t^{Ti} \geq 98.7\,\text{mMSL} \\ 0 & \text{if otherwise} \end{cases} \tag{12}$$

Equation (11) and (12) describe that the regulating dam would not release its storage downstream and for domestic water supply, respectively, when Z_t^{Ti} falls below 95.7 and 98.7 mMSL.

In Equation (11), $\tilde{Q}_t^{GD}$ is always equal to $D_t^{GD} = 1.5\ \text{m}^3/\text{s}$. Meanwhile, $Q^{DS}(Z_t^{Ti})$ in Equation (12) represents the release capacity for domestic water supply according to the regulating dam's water level, as shown in Table 4.

It can be noted that when the water level is at or above 100.20 mMSL, the regulating dam's storage is assumed to flow freely over the river gates downstream.

$$S_t^{Tf} = \min\left[S_{\max}^T,\, S_t^{Ti} + \left(Q_t^W + F_t^W - \tilde{Q}_t^{GD} - \tilde{Q}_t^{IP} - \tilde{Q}_t^{DS}\right) dt\right] \tag{13}$$

$$A_t^T = \frac{\max\left[0,\, S_t^{Ti} + \left(Q_t^W + F_t^W - \tilde{Q}_t^{GD} - \tilde{Q}_t^{IP} - \tilde{Q}_t^{DS}\right) dt - S_{\max}^T\right]}{dt} \tag{14}$$

$$Q_t^{DS} = \begin{cases} \min\left(Q_{\max}^{DS},\, \tilde{Q}_t^{DS} + A_t^T\right), & \text{if } F_t^W > 0 \\ \tilde{Q}_t^{DS} & \text{if } F_t^W = 0 \end{cases} \tag{15}$$

$$Q_t^{IP} = \min\left[D_t^{IP},\, \tilde{Q}_t^{IP} + A_t^T - \left(Q_t^{DS} - \tilde{Q}_t^{DS}\right)\right] \tag{16}$$

$$Q_t^{GD} = \tilde{Q}_t^{GD} + A_t^T - \left(Q_t^{DS} - \tilde{Q}_t^{DS}\right) - \left(Q_t^{IP} - \tilde{Q}_t^{IP}\right) \tag{17}$$

Equation (13) to (17) generally describe that when there would be a water surplus, $A_t^T > 0$, at which $S_t^{Tf} = S_{\max}^T$, A_t^T would have first been allocated for Q_t^{DS} until $Q_t^{DS} = Q_{\max}^{DS}$ if $F_t^W > 0$. Meanwhile, if $F_t^W = 0$, then A_t^T would have been all allocated for $Q_t^{IP} + Q_t^{GD}$, since it was assumed to be the river gate overflow. The allocation of $A_t^T - (Q_t^{DS} - \tilde{Q}_t^{DS})$, or only A_t^T, would first be done for Q_t^{IP} until $Q_t^{IP} = D_t^{IP}$. Therefore, when $\tilde{Q}_t^{GD} + \tilde{Q}_t^{IP}$ and $\tilde{Q}_t^{DS}$ from Equations (11) and (12) were not equal to 0, then $Q_t^{DS} \leq Q_{\max}^{DS}$, $Q_t^{IP} \leq D_t^{IP}$, and $Q_t^{GD} \geq D_t^{GD}$, where $Q_{\max}^{DS} = 5\ \text{m}^3/\text{s}$. The regulating dam's storage curve itself can be seen in Figure 5.

Table 2. Release decisions for irrigation, domestic water supply, and electricity generation in accordance with the actual water level of Wonorejo Reservoir and the rule curves of Wonorejo ROR

Position of the actual water level of Wonorejo Reservoir	Release decision as a function of the actual water level of Wonorejo Reservoir			
	PF Blader-Kluwih-Gelang irrigation	Wonorejo Power Plant operation	PF Paingan irrigation	Domestic water supply
Position A	$\hat{Q}\left(Z_t^W\right) = Q_j^{IK;wet}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{W;wet}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{IP;wet}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{DS;wet}$
Position B	$\hat{Q}\left(Z_t^W\right) = Q_j^{IK;normal}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{W;normal}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{IP;normal}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{DS;normal}$
Position C	$\hat{Q}\left(Z_t^W\right) = Q_j^{IK;dry}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{W;dry}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{IP;dry}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{DS;dry}$
Position D	$\hat{Q}\left(Z_t^W\right) = Q_j^{IK;dry}$	$\hat{Q}\left(Z_t^W\right) = 0.8Q_j^{W;dry}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{IP;dry}$	$\hat{Q}\left(Z_t^W\right) = Q_j^{DS;dry}$
Position E	$\hat{Q}\left(Z_t^W\right) = Q_j^{IK;dry}$	$\hat{Q}\left(Z_t^W\right) = 0$	$\hat{Q}\left(Z_t^W\right) = 0$	$\hat{Q}\left(Z_t^W\right) = 0$

Table 3. Hourly height distribution assumed for one day of evaporation in Wonorejo Reservoir

Hour step	Eva. height percentage	Hour step	Eva. height percentage	Hour step	Eva. height percentage
6–7	1.7%	10–11	12.2%	14–15	10.3%
7–8	4.9%	11–12	13.1%	15–16	7.8%
8–9	7.8%	12–13	13.1%	16–17	4.9%
9–10	10.3%	13–14	12.2%	17–18	1.7%

Table 4. Release capacities assumed for domestic water supply according to the water level intervals of Tiudan Regulating Dam

WL interval (mMSL)	Release capacity (m^3/s)	WL interval (mMSL)	Release capacity (m^3/s)
99.20–100.20	>3.65	98.90–98.95	1.16
99.15–99.20	3.65	98.85–98.90	0.80
99.10–99.15	3.00	98.80–98.85	0.50
99.05–99.10	2.48	98.75–98.80	0.26
99.00–99.05	2.00	98.70–98.75	0.08
98.95–99.00	1.56	<98.70	0.00

2.5 Generation of Synthetic Inflows

The Thomas-Fiering model as in Equation (3) was used to generate 1,000 years of 10-day inflow time series for the Monte Carlo simulations. The statistical relationship parameters were determined from the same data used in the determination of the dependable inflows (Figure 3); except, $\bar{I}_j$ and s_j assumed only non-outlier inflows. The high and low thresholds for the outlier inflows were determined using the Water Resources Council method (Chow et al., 1988). Because the catchments of Segawe Regulating Weir and Wonorejo Multipurpose Dam are located side by side, the synthetic local inflows for the two hydraulic structures were generated with the same $\epsilon_{j+1;j}$. This means that there were only 36,000 standard normal variates which were obtained using the Random Number Generation tool in Microsoft Excel. To ensure that the inflow time series in every simulation were unique and independent, I_j in the generation of $I_{j+1} = I_1$ for a simulation was defined as $I_N = I_{36}$ from the same simulation. This means that the synthetic inflow time series in simulation 1, 2, ..., 1,000 did not really occur consecutively.

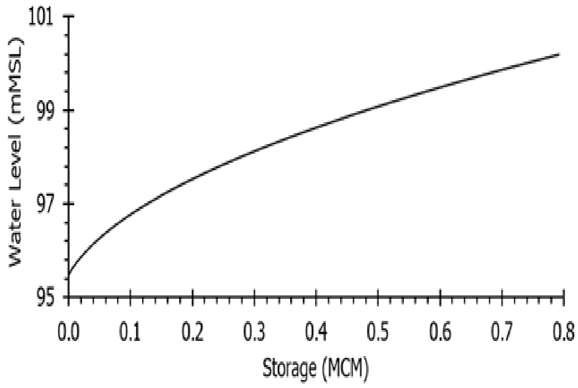

Figure 5. Storage curve of Tiudan Regulating Dam.

2.6 Performance Evaluation of Wonorejo ROR

2.6.1 Demand satisfaction

The actual release-demand ratio in period j, k_j^p, for irrigation and domestic water supply were defined as in Equations (18) and (19).

$$k_j^p = \frac{0.0036}{0.0864\, d_j D_j^p} \sum_{t \in j} Q_t^p, \qquad p = \text{IK, IP} \tag{18}$$

$$k_j^{DS} = \frac{0.0036}{0.0864\, d_j D_j^{DS}} \sum_{t \in j} \min\left(D_t^{DS},\, Q_t^{DS}\right) \tag{19}$$

In Equation (18) and (19), $0.0864\, d_j D_j^p$ and d_j are respectively the total demand (million cubic meters/MCM) and the number of days in period j. The k factors from these equations were the ones considered in the determination of the reliability, resiliency, and vulnerability of reservoir operation as in Equation (1) and (2) and Figure 1. The k-factor distribution itself was made of 40 intervals, where k_{min} for irrigation and domestic water supply were determined to be 0.70 and 0.85, respectively.

2.6.2 Electrical energy

The hydropower of Wonorejo Power Plant, P_t (MW), was determined using Equation (20), where ρ, g, K, l, and D are respectively water density, gravitational acceleration, coefficient of minor head loss, the penstock's length, and its inner diameter.

$$P_t = Q_t^w \rho g \left[H_t - \left(f_t \frac{l}{D} + K \right) \frac{v_t^2}{2g} \right] \eta_t \cdot 10^{-6} \qquad (20)$$

In Equation (20), H_t is the average gross head from the initial and final conditions in hour t. Meanwhile, f_t, v_t, and η_t are respectively the Darcy friction factor, the flow velocity, and the hydropower efficiency, which were functions of Q_t^W (European Small Hydropower Association, 2004; Munson et al., 2012). For practicality, f_t was approximated using the Vatankhah (2014) equation, and η_t was determined according to a typical efficiency curve for the Francis turbine (European Small Hydropower Association, 2004).

As P_t from Equation (20) would be constant in one hour, the energy of Wonorejo Power Plant in period j (MWh) was defined as $G_j = \sum_{t \in j} P_t$. The performances for electricity generation in all periods were simply determined to be the dependable energies at quartiles 0, 1, and 2, since the demands for electricity were undisclosed. It might be known that the three quartiles are respectively equivalent to 100%, 85%, and 50% exceedance probabilities.

2.6.3 Storage conservation of Wonorejo Reservoir

Based on consideration of the rule curves of Wonorejo ROR (Figure 3) and the periods on which rainy season changes to dry season, the starting time in the Monte Carlo simulations was set at the beginning of May (01/05). At this starting time of simulation, both storages of Wonorejo Multipurpose Dam and Tiudan Regulating Dam were conditioned to be full. The performance of Wonorejo ROR for the storage conservation of Wonorejo Reservoir was evaluated only at the end of simulations. In this case, it was assumed that the higher the frequency for the storage to be back in full condition, the better the performance of Wonorejo ROR. As in Equation (8), (9), (13) and (14), it can be recalled that when Wonorejo Reservoir is in full condition, there would likely be a water surplus in the daily storage of Tiudan Regulating Dam due to a spillover from Wonorejo Multipurpose Dam.

3 RESULTS

3.1 Inflows Distribution and Uncertainty

As shown in Figure 6(a), the determination of $\bar{I}_j$ and s_j in Equation (3) from non-outlier historical inflows was to generate synthetic inflows that have a similar histogram and periodic means to historical inflows. To further evaluate the performance of the Thomas-Fiering model, the Nash-Sutcliffe efficiency (NSE) can be examined from a standpoint of the periodic means of inflow. In this case, NSE is used to measure the performance of the Thomas-Fiering model to reproduce the variability and magnitude of historical inflow time series (Gupta et al., 2009). Its values range from $-\infty$ to 1, where an NSE of 1 represents perfect correspondence between the periodic means of synthetic and historical inflows (Nash and Sutcliffe, 1970). Based on the calculation, the NSE values of the periodic means of synthetic inflow for Segawe Regulating Weir and Wonorejo Multipurpose Dam are respectively 0.997 and 0.996. This can indicate that the Thomas-Fiering model had a very good performance in generating the synthetic inflows that fit the historical data distribution. However, it may be essential to explain that such synthetic inflows were not resulted only from the adjustment of historical $\bar{I}_j$ and s_j, but also from an inflow selection. This inflow selection was done after all the 72,000 inflows had been generated from the Thomas-Fiering model, where if a generated inflow was higher than the maximum limit or lower than the minimum limit, then the maximum or minimum limit was selected as synthetic inflow.

There were two types of maximum limits in the inflow selection, namely the historical maximum inflow that is lower than the high threshold for outliers (limit A) and the sum of $\bar{I}_j$ and s_j from all historical inflows (limit B). In Figure 6(a), the limit A was defined for Segawe Regulating Weir in periods May-1 to Sep-1, Sep-3 to Oct-3, and Nov-2 to Apr-3. For Wonorejo Multipurpose Dam, the limit A was defined in periods May-1 to Sep-1, Sep-3, Oct-1, Nov-1, Nov-3, and Dec-1 to Apr-3. For the two hydraulic structures, the limit B was defined in other periods. Meanwhile, the minimum limits in all periods were simply the low thresholds for outlier inflows. However, since the historical inflow time series were often continuously zero on the peak of dry season, there was an additional conduct in the inflow selection for Wonorejo Multipurpose Dam. The additional conduct was that if the frequency for historical inflow to be zero in periods j and $j+1$ was greater than 50%, then zero synthetic inflow in period j should be followed by zero inflow in period $j+1$. In Figure 6(a), this additional conduct was done in periods Aug-2 to Oct-1.

From each 36,000 synthetic local inflows, the percent-

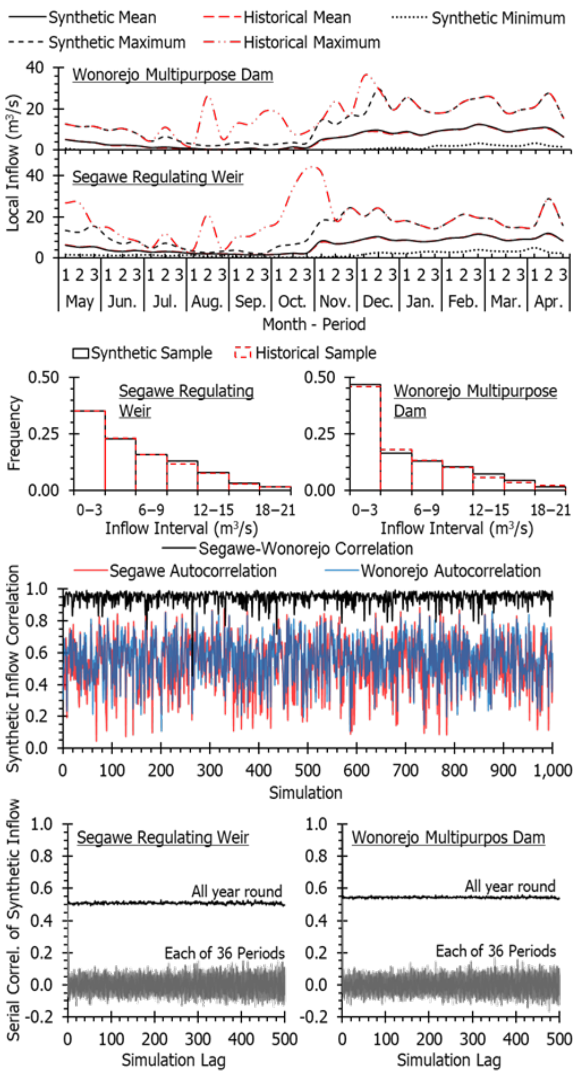

Figure 6. (a) Comparison of periodic statistical parameters and histograms between the synthetic and historical local inflows of Segawe Regulating Weir and Wonorejo Multipurpose Dam; (b) Correlation coefficients of the synthetic local inflows time series of Segawe Regulating Weir and Wonorejo Multipurpose Dam.

age of selection-affected inflows for Segawe Regulating Weir and Wonorejo Multipurpose Dam are respectively 9.37% and 24.53%. However, based on the correlation coefficients shown in Figure 6(b), the inflow time series in the Monte Carlo simulations can still be assumed to be uncertain (Haan, 2002). This is because, first, the correlation coefficients between the inflow time series in simulation y and those in simulation $y + 1$ (Segawe and Wonorejo autocorrelations) vary from 0.05 to 0.91. This means that two consecutive annual inflow time series were neither always strongly nor weakly correlated throughout all simulations. Second, the periodic serial correlation coefficients by 1 to 500 simulation lags vary only from -0.17 and 0.17. This means that the 1,000 inflows in every operational period were very weakly correlated, or hardly dependent on each other. Nevertheless, such an uncertainty does not necessarily implies that the inflow time series were completely vague. This is because the stability of the all-year-round serial correlation coefficients can indicate that the inflow time series had a consistent tendency to being high or low in rainy or dry season. Moreover, the high correlation coefficients between the two hydraulic structure's local inflow time series (Segawe-Wonorejo correlation) can indicate that the trends of the two local inflows were relatively similar in all simulations.

3.2 Output Convergency of Monte Carlo Simulations

Figure 7 shows the moving averages of annual irrigation, domestic water supply, and electrical energy resulting from the application of each ROR-D65 and ROR-D80 in the Monte Carlo simulations. It can be observed that the annual moving averages are unlikely to change significantly after 1,000 simulations, where the maximum relative errors in the last 100 simulations are less than 0.05%.

This is also the case when the moving averages of all purposes are examined within the rainy season, dry season, or each operational period. Therefore, the outputs of the Monte Carlo simulations can be assumed to have converged.

3.3 Performances of Wonorejo ROR

Reliabilities and resiliencies for the PF Blader–Kluwih–Gelang irrigation according to ROR-D65 are identical to those according to ROR-D80. Figure 8 shows that the lowest reliability is 69.5% in period Oct-3, while the lowest resiliency is 4.26% in period Oct-2. It can also be observed that the vulnerabilities under the two ROR alternatives are relatively similar, with the same highest value of 97.1% in period Nov-1.

This is because the local inflow of the Segawe Regulating Weir was prioritized for the Song River's duty flow, as defined in Equation (4) and (5), where the actual release for the PF Blader–Kluwih–Gelang irrigation was completely dependent on it.

Figure 8 also shows that for the PF Paingan irrigation, the reliabilities according to ROR-D80 only reach 99.8% in period Jan-3 and 99.9% in period Feb-1, while those according to ROR-D65 reach 100% in all periods. The resiliency in period Jan-3 according to ROR-D80 is 50.0%, whereas the vulnerabilities in periods Jan-3 and Feb-1 are 38.9% and 38.2%, respectively. Meanwhile, the highest and second-highest vulnerabilities according to ROR-D65 are 7.7% in period May-3 and 7.6% in period Jun-2.

These differences arise because the application of ROR-D80 causes the Tiudan Regulating Dam to stop releas-

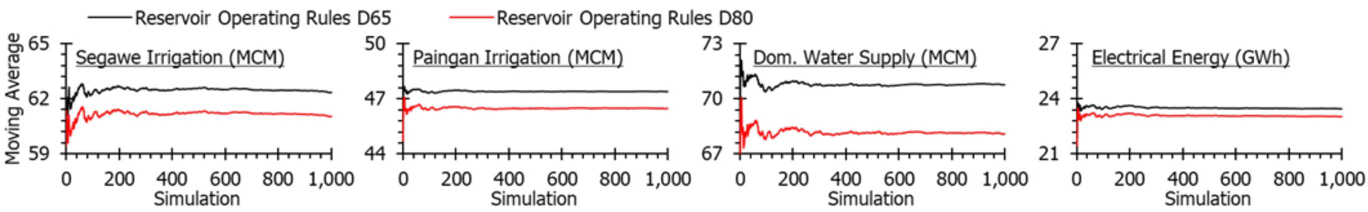

Figure 7. Moving averages of annual irrigation, domestic water supply, and electricity generation according to the application of each ROR-D65 and ROR-D80 in 1,000 Monte Carlo simulations.

ing its storage during certain hours, as defined in Equation (11) and (12), when the release from Wonorejo Multipurpose Dam fails to conserve the daily storage of the Tiudan Regulating Dam.

As for domestic water supply, both ROR alternatives result in good performance during the peak of the dry season, when the lowest inflows and highest water demands occur (Figure 3). As shown in Figure 8, the reliabilities reach 100% in periods May-1 and Sept-2 to Oct-2 under ROR-D65, and in periods Aug-2 to Sept-2 and Oct-1 under ROR-D80. However, the two alternatives yield less satisfactory performance in other periods, where the lowest reliabilities are 73.9% (ROR-D65, period May-3) and 52.4% (ROR-D80, period May-1).

In terms of resiliency, ROR-D65 results in 0% in period Mar-1, while ROR-D80 results in 10.7% in period Jan-2. The highest vulnerabilities under ROR-D65 and ROR-D80 are 59.0% (period May-3) and 59.8% (period Jun-1), respectively.

As also shown in Figure 8, the dependable energies of the Wonorejo Power Plant under ROR-D65 and ROR-D80 are relatively similar at the second quartile (Q2). The lowest Q2 energy for both alternatives is 500.8 MWh in period Feb-3. However, the dependable energies differ significantly at quartiles 0 and 1 (Q0 and Q1). The lowest Q0 energies under ROR-D65 and ROR-D80 are 275.6 and 159.2 MWh in periods Dec-2 and Jan-1, respectively, while the lowest Q1 energies are 480.1 and 457.9 MWh in periods Dec-2 and May-2.

Figure 9 generally shows that ROR-D80 results in better performance in terms of storage conservation of the Wonorejo Reservoir than ROR-D65. The frequencies for the reservoir to return to full condition at the end of April (30/04) are 76.4% and 81.3% under ROR-D65 and ROR-D80, respectively. More specifically, the lowest final water levels are 176.6 and 181.3 mMSL for ROR-D65 and ROR-D80, respectively.

These differences occur because the dry release rules and rule curve of ROR-D80 are significantly lower than those of ROR-D65 Figure 3. However, since the frequency of the reservoir returning to full condition does not reach 100%, the dependency of reservoir operation in period May-1 on that in period Apr-3 cannot be definitively established. This is because the inflow time series in all simulations are independent and do not occur consecutively. Consequently, as shown in Figure 8, the resiliencies in period Apr-3 are not determined using Equation (1).

4 DISCUSSION

4.1 Motivations for Proposing the Application Concept of ROR

It is widely recognized that the main challenge in annual reservoir operation lies more in the uncertainty of the inflow time series than in the operational plan itself (Kasprzyk et al., 2013; Giuliani et al., 2014).Clearly, a reliable prediction model for inflow time series over an entire future year would substantially improve the effectiveness of reservoir operation planning. However, in the absence of such a model, the achievement of operational objectives remains highly sensitive to inflow uncertainty.

This forms the basis for the application of the ROR concept, as presented in Table 2, where release decisions are determined in real time without considering the reservoir's actual inflow.

Prescribing release decisions based on the rule curves of ROR and the actual storage condition, as shown in Table 2, helps preserve the consistency of releases by allowing storage variations to follow probabilistically safe temporal conditions (Ahmadi et al., 2015). In this way, reservoir operation becomes more transparent, as each release decision can be evaluated against predefined storage criteria rather than relying on unrestricted judgment (Ilich, 2024).

Moreover, a properly optimized ROR can maximize reservoir performance in meeting varying periodic water demands while maintaining storage conservation (Tang et al., 2024). It also helps ensure that water demands are satisfied with minimal waste and balanced trade-offs among competing demands (Jibat et al., 2024).

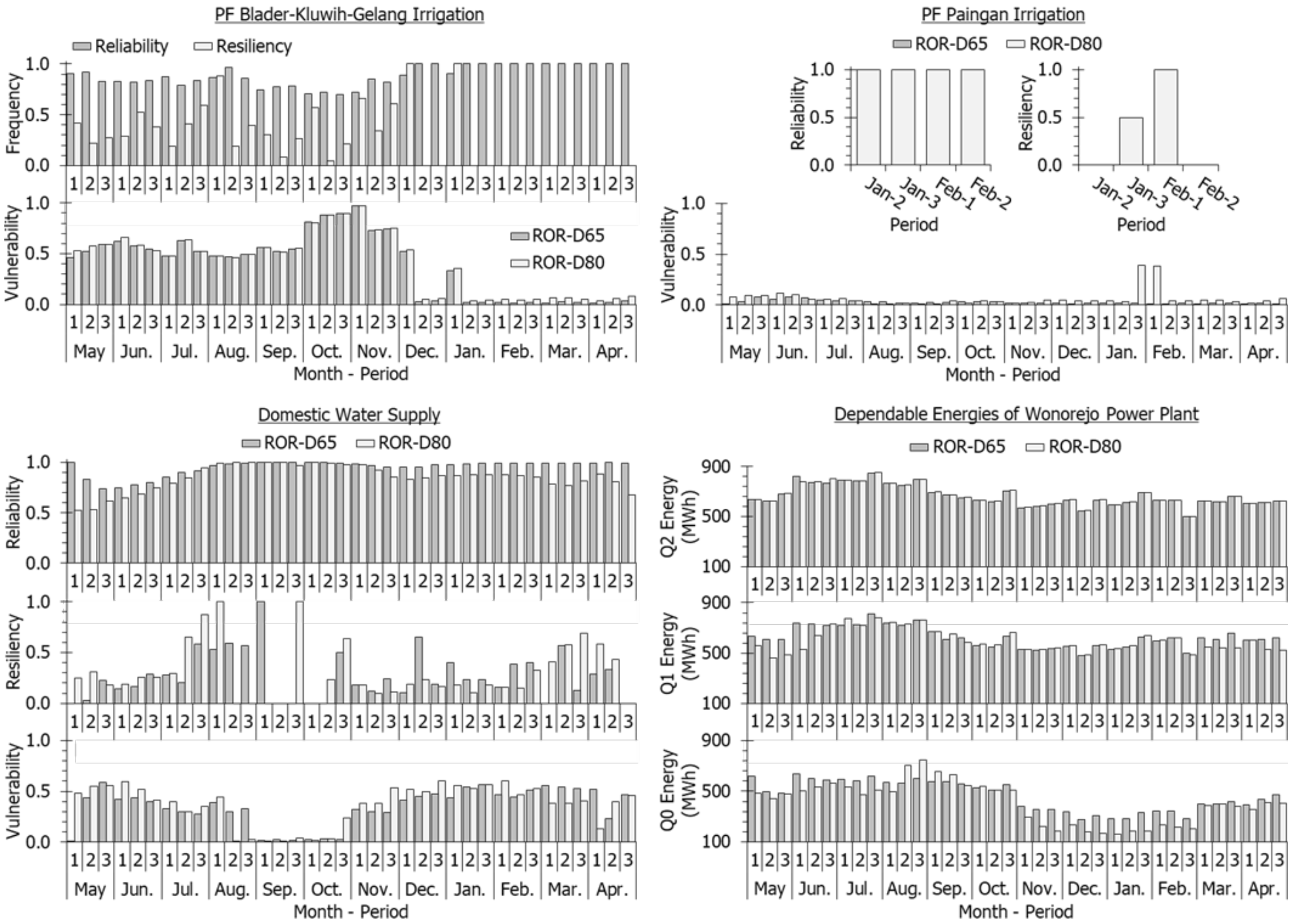

Figure 8. Performances of ROR-D65 and ROR-D80 for the demand satisfactions and the electricity generation.

4.2 Differences and Advantages of the Proposed Application Concept of ROR

The release decisions that vary throughout the year may give the impression that the ROR application concept in this study is somewhat similar to that of APRO, as described by Pusat Pendidikan dan Pelatihan SDA dan Konstruksi (2017). However, as shown in Figure 9 and Table 2, reservoir operation under ROR does not focus solely on storage conservation.

This is because there is no requirement for the actual water level to remain within specific rule curves Table 2. Instead, there is a considerable possibility for it to remain between two rule curves, or above one of them, for extended periods Figure (9). If the ROR has been derived through an optimization process, the release decisions in all periods can be considered appropriate, since the application of ROR does not rely on the actual inflow, which is often unknown in real time due to operational limitations.

Furthermore, the ROR application concept is more relevant and transparent for reservoir operation than APRO. This is because ROR does not assume certainty in dependable inflow, nor does it ignore inflow uncertainty. Instead, it adopts a conservative approach: when the actual water level lies between two rule curves, the release rule corresponding to the lower rule curve is selected.

4.3 Comparative Review of Similar Studies

Studies on reservoirs outside Indonesia have primarily focused on deriving or optimizing operating rules, but have rarely examined their real-time application as required in practice (Kangrang et al., 2018; Wan et al., 2019; Kosasaeng and Kangrang, 2023; Tang et al., 2024). Similarly, although Monte Carlo simulations have been employed in several studies to evaluate reservoir performance (Feng et al., 2017; Liu et al., 2019; Yaghoubi et al., 2020; Zhao et al., 2026), they have not been applied to the implementation of ROR.

This study is the first to demonstrate a fully operational real-time implementation of ROR. It is also the first to statistically evaluate the performance of ROR for an integrated system of three hydraulic structures. Therefore, this study provides both conceptual clarity and

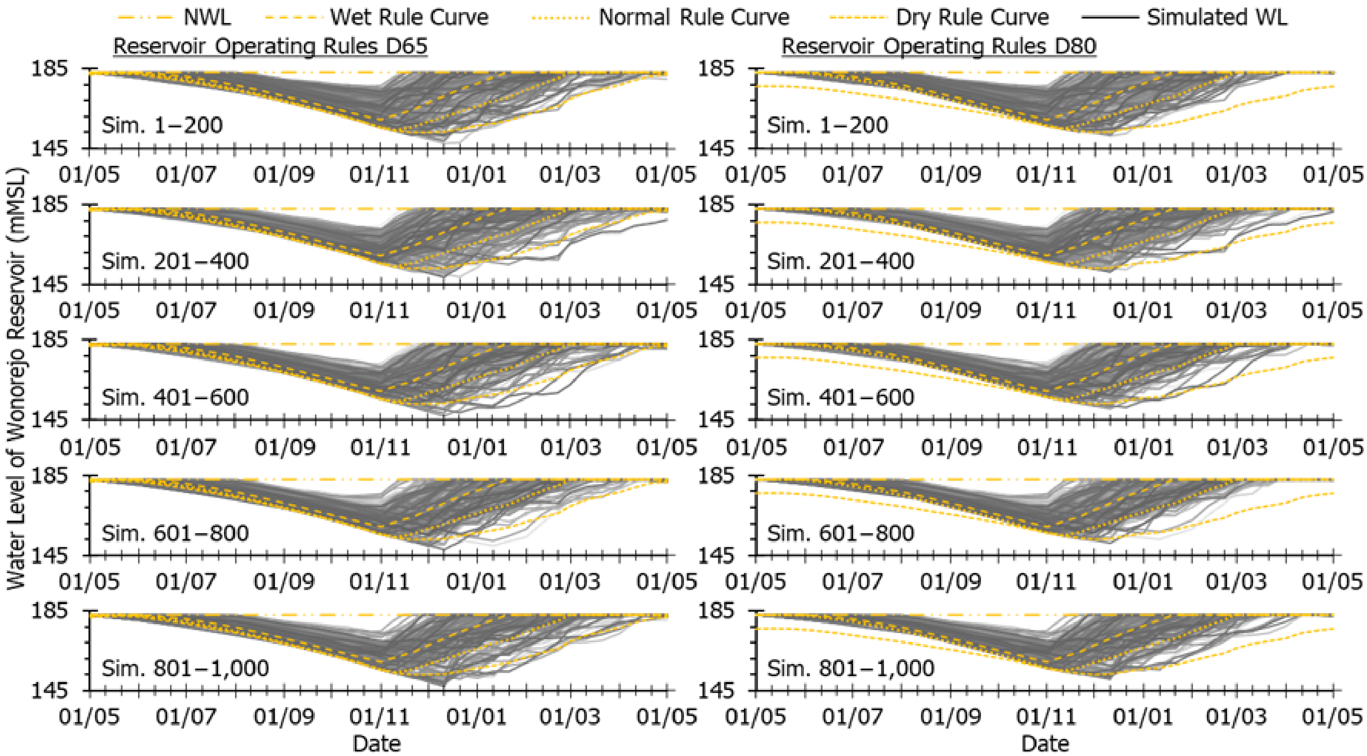

Figure 9. Changes in the storage of Wonorejo Reservoir according to the application of each ROR-D65 and ROR-D80.

statistical evidence regarding the real-time applicability of ROR, even in the context of integrated hydraulic systems.

4.4 Recommendations on the Application of ROR

The Monte Carlo simulations in this study show that the application of the Wonorejo ROR results in relatively good performance in terms of periodic demand satisfaction and annual storage conservation. However, as the findings are specific to the Wonorejo ROR, several general recommendations for the application of ROR need to be discussed.

First, three key factors are involved in the derivation of an ROR: storage capacity, water demand, and dependable inflow. As illustrated in Figure 3, these factors may be interdependent due to optimization constraints on release rules and rule curves. Among them, dependable inflow can be considered the most independent factor, as water demand is typically determined from established methods or historical data, while storage capacity is fixed for a given year.

This study demonstrates that different exceedance probabilities of dry inflow lead to different operational outcomes: ROR-D80 performs better in terms of storage conservation Figure (9), whereas ROR-D65 performs better in terms of demand satisfaction (Figures 7 and 8).

If one of the ROR alternatives must be selected, a multi-criteria decision-making approach may be applied. However, dependable inflows do not necessarily need to be categorized as "dry," "normal," and "wet." These terms are conceptual and do not fully represent the variability of actual inflow time series over a year (Mateus and Tullos, 2017; Li et al., 2024).

In this study, the application of ROR assumes that release rules and their corresponding rule curves act as real-time anticipatory controls (Table 2). This implies that increasing the number of release-rule sets and rule curves may improve reservoir performance. Therefore, provided that storage capacity is sufficient, an ROR can be derived using more than three dependable inflow levels—such as exceedance probabilities of 35%, 50%, 65%, and 80%—to enhance both demand satisfaction and storage conservation. The naming of corresponding release rules and rule curves can follow the conventions of reservoir management. However, it should be noted that water demand may exceed feasible supply, and that higher dependable inflows correspond to lower exceedance probabilities (Figure 3).

Second, the application of ROR may lead to critical storage conditions, particularly when the actual water level falls below the lowest rule curve (Figure 9). In this context, it is important to recall that the primary purpose of a reservoir is to meet water demand. Under inflow uncertainty, excessively restricting releases to maintain storage levels may be undesirable, especially when substantial storage is still available. Moreover, Figure 9 shows that the release decisions defined in Table 2 can often restore storage to safe conditions. This is largely because the ROR is derived such that the initial water level of each rule curve corresponds to its final water level (Figure 3c).

To assess the risk of low storage in the upcoming year, reservoir operators can apply ROR within Monte Carlo simulations, as demonstrated in this study. The simulation start time can be aligned with the actual operational start, while the initial water level can be set based on estimated end-of-year conditions. The performance of ROR in terms of storage conservation can then be evaluated using the simulated final water levels. In general, a higher frequency of final water levels being equal to or greater than the initial level indicates better performance.

Given that ROR is typically applied over at least one year, Monte Carlo simulations are a reasonable and practical approach. They can also be computationally efficient, as the number of simulations is largely determined by the number of release decisions at each time step (Table 2; Figure 7). Furthermore, performance indicators derived from these simulations—such as electricity generation and demand satisfaction—can support financial planning for reservoir operation in the coming year, which is essential for the sustainability of multipurpose dams in Indonesia.

However, it should be emphasized that the reliability of Monte Carlo simulation outputs depends on the quality of the assumed inflow distributions and their associated uncertainties (Figures 2 and 6).

5 CONCLUSION

Inflow uncertainty remains a major challenge in annual reservoir operation and is often difficult to overcome in real time. However, it does not necessarily render reservoir operation conceptually unclear or practically complicated, as operational convenience is as important as its relevance.

This study therefore proposes a practical application concept of ROR as a set of real-time anticipatory rules for annual reservoir operation. Under this concept, release decisions can be made conveniently without considering the reservoir's actual inflow. At the same time, because decisions are based on the actual storage condition and the rule curves of ROR, the clarity and consistency of reservoir operation can be maintained under varying hydrological conditions.

Based on the application of ROR-D65 and ROR-D80 in Monte Carlo simulations of an integrated system consisting of the Segawe Regulating Weir, Wonorejo Multipurpose Dam, and Tiudan Regulating Dam, the proposed ROR concept demonstrates relatively good performance. In 1,000 simulations, ROR-D65 and ROR-D80 achieve reliabilities of 76.4% and 81.3%, respectively, for annual storage conservation, and minimum reliabilities of 73.9% and 52.4% for periodic demand satisfaction.

However, if the ROR concept is to be applied to other real reservoir systems, operators should recognize that its performance is influenced by storage capacity, water demand, and, most importantly, dependable inflow. Furthermore, it is recommended that reservoir operators first apply ROR within Monte Carlo simulations to estimate its performance and to assess the likelihood and extent to which it may lead the reservoir to critical low-storage conditions.

DISCLAIMER

The authors declare no conflict of interest.

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