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Rainfall Prediction Model for the Real-Time Operation of the Batujai-Pengga Cascade Reservoir

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Abstract: Rainfall forecasting plays a crucial role in water resource management, especially in the context of reservoir operation. In this case, the Annual Plan for Reservoir Operation (RTOW) plays a crucial role in regulating the outflow under reservoir inflow conditions. The objective of this research is to develop an RTOW input prediction method and real-time operational rule curve for the Batujai-Pengga cascade reservoir in the Lombok River Basin. The optimal simulation of water balance was carried out on an annual basis (for RTOW) and every 10 days (for real-time operational) due to two different input conditions: deterministic inflow forecast based on the reliable discharge and stochastic inflow forecast generated from the rainfall forecast transformed into flow using the calibrated HEC-HMS model. The optimal simulation is facilitated by MS Excel-VBA based on the principle of equal sharing, with the K-factor serving as an indicator of water sufficiency and the S-factor serving as an indicator of the storage level in cascade reservoirs. This experiment compared the real reservoir water level (MAW) with the output from the simulation. The analysis yielded notable discrepancies between the stochastic and deterministic inflow inputs in the MAW simulation. The former exhibited a range of 0.39–1.26 m, while the latter spanned 0.66–1.23 m, both of which diverged significantly from the actual MAW condition. In accordance with the above results, it is recommended that when creating the reservoir rule curve, the input should be based on the updated rainfall prediction. The results of the simulation, conducted in accordance with the real-time rule curve and utilising rainfall updating on a per-period basis for a period of three months, indicate that the implementation incorporating stochastic inflow is more compatible with the actual reservoir water level than that incorporating deterministic inflow. Furthermore, the former exhibits a superior correlation coefficient and RMSE value.

Keywords: inflow, HEC-HMS, operational rule curve, reservoir.

巴都加-彭加梯级水库实时调度降雨预测模型

摘要：降雨预报在水资源管理中起着至关重要的作用，特别是在水库运行的背景下。在这种情况下，水库年度运行计划(起飞重量)在调节水库入流条件下的流出量方面起着至关重要的作用。本研究的目的是为龙目河流域的巴都加 - 彭加梯级水库开发起飞重量输入预测方法和实时运行规则曲线。由于两种不同的输入条件，每年（对于起飞重量）和每10天（对于实时运行）进行一次水平衡的最佳模拟：基于可靠流量的确定性流入预测和使用校准的羟丙

基甲基纤维素模型将降雨预报转化为流量而生成的随机流入预测。基于平等分享原则，Excel虚拟专用网络教程促进了最佳模拟，其中钾因子作为水充足性的指标，年代因子作为梯级水库的储水水平的指标。本试验将实际水库水位(金属加工用气体)与模拟输出进行了比较。分析发现，金属加工用气体模拟中随机和确定性流入输入之间存在显著差异。前者的范围为0.39–1.26米，而后者的范围为0.66–1.23米，两者均与实际金属加工用气体条件存在显著差异。根据上述结果，建议在创建水库规则曲线时，输入应基于更新后的降雨预测。根据实时规则曲线进行的模拟结果，利用三个月期间逐期更新的降雨量，结果表明，与采用确定性流入的实施相比，采用随机流入的实施与实际水库水位更兼容。此外，前者表现出更高的相关系数和均方根误差值。

关键词：流入，羟丙基甲基纤维素，运行规则曲线，水库。

1. Introduction

The operation of a reservoir entails a series of activities aimed at regulating the flow of water, conducted in accordance with established operational procedures. The operation of the reservoir to meet the irrigation water demand and other water demands often faces relatively limited water availability, especially during dry years [1, 2]; however, in flood conditions, flood emergency operation preparedness is required [3], so an accurate operating model is needed [4].

Water availability is essential for adapting to and mitigating the effects of climate change, promoting sustainable development, and ensuring life sustainability [5]. Climate change has impacted the variability of rainfall in the hydrological cycle, leading to an increase in extreme climatic events, seasonal shifts, and other related phenomena. This has affected water availability. The Intergovernmental Panel on Climate Change [6] stated that countries in Southern Asia, including Indonesia, are predicted to experience rainfall pattern changes as climate change occurs. Changes in water availability will naturally influence this condition. It has been found that larger reservoir capacity may even be needed for a situation with longer-horizon foresight on future inflows, depending on the system’s characteristics and hydrology, especially the position of low-flow sequences in stream flow time series [7]. Depending on the characteristics of the system and hydrologic conditions, particularly the location of low flows in the flow time series, a larger reservoir capacity is required to provide a longer-term view of future flows [7, 8].

Hydrologically, water availability is influenced by global and local climate. The global climate is influenced by a complex interplay of atmospheric circulation patterns that contribute to climate change. Meanwhile, the local climate phenomenon, namely the El Niño-Southern Oscillation (El-Nino and La-Nina), will also influence the duration of the season and result in alterations to water availability [9].

The Dodokan watershed is a utility watershed in the Lombok River Basin with a catchment area of 579 km^2, consisting of 8 river confluences. In the main river of this watershed, the Batujai and Pengga cascade reservoirs are located. The volume of water discharged into the river at the point of confluence is significantly greater than the capacity of the river to accommodate this flow. This condition renders Gerung Sub-district (the capital of West Lombok Regency) highly susceptible to the risk of inundation due to river overflow. Furthermore, the potential for flooding is exacerbated by the possibility of high tides in the sea. Almost 5% of the area downstream of the Dodokan River experiences flooding annually (BWS NT I, 2014).

In this case, the Annual Plan of Reservoir Operation (RTOW) plays a pivotal role in regulating the outflow discharge in accordance with the inflow conditions. It is capable of fulfilling the demand to the fullest extent possible for the forthcoming year due to the minimal requirements and the maximum reservoir storage capacity. Nowadays, the examination of the RTOW is predicated upon the assessment of water availability, employing the analysis of probability-dependent discharge, which exhibits a deterministic quality (constant value) in each period throughout the year. However, given the uncertainty associated with climate change, there is a need to develop a method for predicting stochastic water availability that optimizes reservoir operation patterns over a shorter period (10 days) to achieve optimal reservoir performance [10]. Based on the above cases, it is necessary to predict rainfall [11, 12] and reservoir inflow by using the discharge-rainfall model/hydrologic modeling system [13] to support reservoir operation decision-making in the Batujai and Pengga cascade reservoirs with inputs in the form of rainfall forecasts per period.

The objective of this research was to ascertain and propose a rule curve model for reservoir operation, with the aim of meeting 10 daily real-time water demands. This was to be achieved by taking into account the discrepancy between deterministic and stochastic inflow predictions over a given period.

2. Materials and Methods

2.1. Research Location

The research site is situated within the Dodokan Watershed (Fig. 1), where the Batujai and Pengga Dams are located. Dodokan is the largest watershed in the River Basin (WS) Lombok, comprising 93 irrigation structures, including 65 weirs, 26 small dams, and two larger dams. The Batujai Dam is located in Praya, the capital of Central Lombok Regency, and it services an irrigation area of 2,860 ha and raw water demand of 130 l/s. However, the Pengga Dam serves an irrigation area of 3,189 ha that is as a part of Central Lombok Regency and West Lombok Regency with raw water needs of 200 l/s. The Dodokan River is classified as an ephemeral river, exhibiting discontinuous flow. The Batujai Reservoir receives inflow from a catchment area of 37.15 km^2. The inflow to the Pengga Reservoir originates from a drainage area of 176.37 km^2 and is supplied by the Batujai Reservoir. The irrigation efficiency in both irrigation areas is around 40-55%.

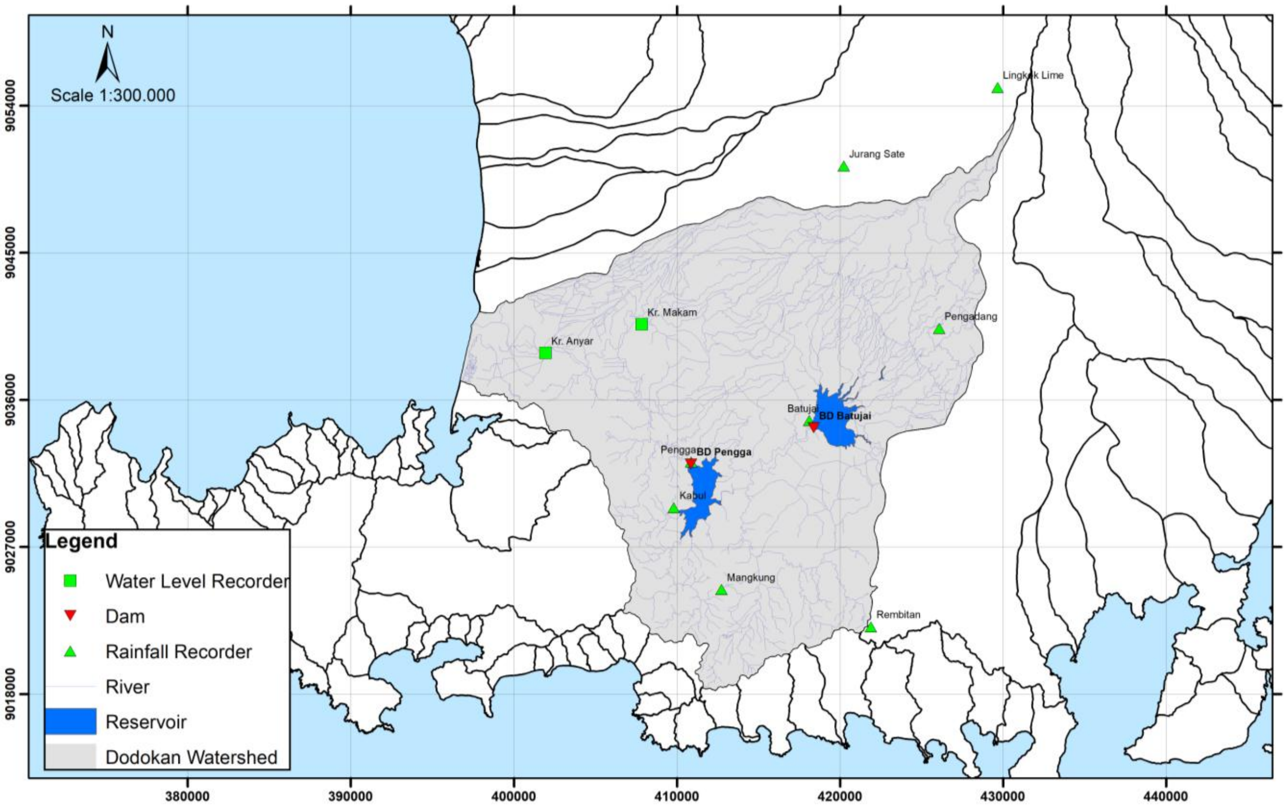

Fig. 1 Map of the Batujai-Pengga Reservoir in the Dodokan Watershed (BWS NT I)

2.2. Research Data

The following data were used for this research:

1. Information on the relationship between reservoir water level depth and storage volume in the inundation area (BWS NT-1);
2. Data on daily rainfall in rainfall stations (Batujai, Lingkok Lime, Mangkung, Pengga, Kabul, Jurangsate, Pengadang, and Rembitan) from 2000 to 2022 (BWS NT-I);
3. Data on daily discharge in water level records for Karang Makam from 2000 to 2022 (BWS NT-I);
4. Digital Elevation Model (DEM), river network, and topography map (BIG);
5. Map of land use in 2020 (Bappeda NTB Province);
6. Soil type map based on the Harmonized World Soil Database (HWSD) criteria;
7. Yearly Plan of Reservoir Operation (RTOW) in Batujai and Pengga for 2020/2021, 2021/2022, and 2022/2023 (BWS NT I);
8. Data on irrigation water demand and raw water demand (Yearly Water Allocation Plan of WS Lombok, BWS NT-I);
9. Reservoir water level depths of the Batujai and Pengga reservoirs from October to September 2020/2021, 2021/2022, and 2022/2023 (BWS NT I);
10. Initial estimation of the rainy season for 2020/2021, 2021/2022, and 2022/2023 (BMKG - first class of climatology station in Lombok Barat, NTB);
11. Estimation of monthly climatic conditions for 2020/2021, 2021/2022, and 2022/2023 (BMKG - first class of climatology station in Lombok Barat, NTB).

2.3. Methods

Fig. 2 presents the flow chart of the research.

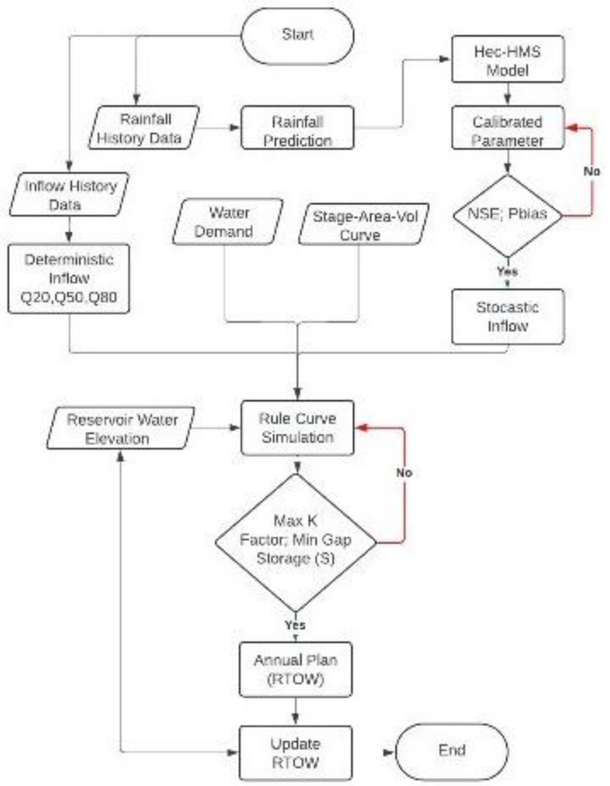

Fig. 2 Flow chart of the study (The authors)

2.3.1. Rainfal Prediction

The Institution of Meteorology, Climatology, and Geo-Physics (BMKG) publishes two books on seasonal prediction on an annual basis. The books include dry and rainy season predictions, which are published every March and August, respectively. The rainy season forecast book provides information on the prediction of the onset of the rainy season (AMH), a comparison between the AMH prediction and the average or normal rainfall over the past 30 years (1981-2010), prediction of rainfall characteristics (SMH) during the rainy season, prediction of the peak rainfall (PMH), and information on the expected range of rainfall from October to March in the following year.

In addition, the BMKG regularly publishes a bulletin on analysis and rainfall forecasts for the NTB province. This includes monitoring information and an overview of current climate conditions, particularly rainfall data for the preceding month and forecasts for the following three months. However, the rainfall forecast for the next three months is based on an analysis of rainfall data statistics, taking into account the physical conditions, atmospheric dynamics, and local circumstances in each region. This includes the initial forecast of the rainfall season (AMH), characteristics of the rainfall season (SMH), the peak of the rainfall season, and the range of rainfall predictions.

In this study, the stochastic forecasting method of the Markov chain is used to quantify rainfall prediction. The time series of rainfall station data from Batujai, Lingkok Lime, Mangkung, Pengga, Kabul, Jurangsate, Pengadang, and Rembitan are used, considering the SMH, AMH, and rainfall range published by the BMKG [14].

The characteristic of rainfall in a given area is the ratio of the cumulative amount of rainfall received over a specific period, compared to the average or normal amount during the same period (2000-2022), in the same month and location.

The rainfall characteristics can be divided into three categories [15]:

a. Over normal (AN): ratio > 115%;
b. Normal (N): ratio between 85% and 115%;
c. Under normal (BN): ratio < 85%.

In the Markov process, the probability in a certain period is dependent on or determined only from the previous period event. As posited by Soemarto [16], the stochastic model is a mathematically based hydrology model that generates a series of values, which can be understood as the output of a random process when probability is introduced as an input. The model simulation generates synthetic data comprising mean, variance, and standard deviation values that remain unaltered.

The most basic and commonly used method for creating hydrological data is the auto-regressive model. This model was named after the mathematician A.A. Markov (1856-1922). The general formula of the Markov model developed by Thomas and Fiering [17] is represented by the following equation:

$$X_{i+1} = \mu_X + r_i(X_i - \mu_X) + \sigma_X t_i \sqrt{(1 - r_i^{\,2})} \qquad (1)$$

Here, X_i is the rainfall (mm) in the i period, μ_X is the average of data series, r_i is the correlation coefficient, σ_X is the standard average deviation, and t_i is a random number.

Inflow prediction is carried out using the two following methods:

- Prediction of deterministic inflow based on the probability of the basic month dependable discharge, which is ranked by ten daily periods: The probability of discharge is categorized into three standard categories based on when water enters the reservoir. This calculation is derived from the average discharge observed in the data, with deviation ranging from 33% to 66.7%. A wet year is characterized by water discharge entering the reservoir at a rate higher than average, falling between 77.7% and 100%. Conversely, a dry year is defined by water discharge below the average, ranging from less than 0% to 33.3%. In accordance with these categories, the deterministic inflow is correlated with rainfall. Normal SMH prediction (N) corresponds to a normal year with a dependable discharge of 50%. An over-normal SMH (AN) aligns with a wet year, representing a dependable discharge of 20%. An under-normal year (BN) is associated with a dry year, reflecting a dependable discharge of 80%.
- The analysis of stochastic inflow prediction is conducted using the HEC-HMS flow-rainfall model,

with input in the form of the BMKG rainfall predictions quantified by the Markov chain model. The HEC-HMS model is a transformational tool that converts rainfall data into numerical hydrological flow, developed by the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers. Within the HEC-HMS software, there are features for calibration, distribution model simulation, model continuation, and the ability to read GIS data.

2.3.2. Water Demand

- *River maintenance flow:* In accordance with the circular letter published by the Directorate General of Water Resources of Indonesia in 2016, river protection is also carried out in conjunction with the maintenance flow (QM) to maintain the river ecosystem; 5% is taken from the available amount.
- *Irrigation water demand:* The equation used to determine the maximum irrigation water demand (Q D max) and crop water demand (NFR) is based on the KP-02 (2013: 123) methodology. This methodology involves analyzing the irrigation water demand based on several factors, including rainfall, evapotranspiration, irrigation area, crop type, crop group, and irrigation efficiency. These factors are then incorporated into the Cropping Pattern Plan (RTT) within the Yearly Water Allocation Plan (RAAT)-BWS Nusa Tenggara I. However, the aforementioned equation does not account for water demand outside of irrigation, which includes raw water provided through flat rates and PLTMH in accordance with the local irrigation operation pattern.

2.3.3. Optimization and Simulation of the Reservoir

Reservoir operation entails the storage of river water flows within the reservoir and the release of the stored water for the achievement of specific objectives [18]. However, the operational pattern is the operational benchmark for a reservoir, which means that the outflow from the reservoir must follow a certain pattern to maintain the desired elevation according to the design [19].

Reservoir equation is expressed as follows [20]:

$$S_{t+1} = S_t + I - O \quad (2)$$

where:
S_{t+1} - storage at the end of period t
t - time interval
S_t - storage in initial period t
I - total volume of inflow into reservoir during period t
O - total volume of outflow from the reservoir during period t

This research employs two approaches to simulation optimization, as outlined below:

1) The simulation optimization of RTOW design is conducted each September (annually) to direct the implementation of hydrology for the subsequent year (t + 1). A review of the input data reveals that this simulation is distinguished between inflow predictions based on the probability of dependable discharge (deterministic inflow) and stochastic inflow predictions based on the SMH-rainy season prediction from October until March of the following year. To predict rainfall data for stochastic inflow and 10-day reliable probability discharge, SMH-dry year-inflow prediction (period after March) is employed. This is achieved by analysing the equialization condition of year type for deterministic inflow.

2) Simulation optimization of rule curve implementation for each 10-day period is conducted on a periodic basis, with SMH updated based on the next three rainfall predictions published annually by the BMKG.

To optimize the simulation, iterations of the K-factor (release portion) and C-factor (storage portion) must be conducted to obtain a maximum and equal result. The K-factor is defined as the weight of the water allocation, which represents the supply/demand ratio. The ratio K-factor indicates two key aspects of the water allocation system: the volumetric reliability of the water allocation and the schedule of water distribution in the irrigation area. The classification of the K-factor in Table 1 is based on the irrigation practices observed in the Lombok river basin [21].

Table 1 K-factor standard for irrigation operation (The authors)

Class Range of the K-Factor	**%**	**Deficit Operation Categories**	**Interlude of Water Distribution**
K1	80–100	Zero-Very low	Continuous
K2	60–79	Low Rotation 1	Medium
K3	40–59	Medium Rotation 2	Medium
K4	20–39	High Rotation 3	Long
E	0–20	Very high	Emergency priority is inter-irrigation areas.

The S-factor is required as an indicator for the storage capacity of water distribution in multiple reservoirs. Water cannot be claimed by a single reservoir but must be distributed among reservoirs in the system. If the S-factor of the inter-reservoir is the same, the interspace containing water can be considered equal. Moreover, it is essential to consider not only the immediate need for water, but also the future requirements. This necessitates an understanding of the final volume of water that will be required as an inter-time inventory [21]. The anticipated volume is the expected final volume, calculated from period to period based on the predicted hydrological conditions or approached from the planned reservoir rule curve.

In reservoir simulation, the objective is to optimize the K-factor (release part) and C-factor (storage part) through iteration to maximize the value. The process is constrained by the following factors:

1) The maximum allowable water supply for a given water demand is constrained by the maximum channel capacity.

2) The ratio K-factor (FK) is from 20% to 100% for all simulations.

3) The maximum allowable discrepancy in FK between reservoirs within a given period is 5%. This value is determined through trial and error in the simulation update of the rule curve implementation for the RTOW design.

4) The maximum S-factor (SK) of the reservoir in the same period is 10% for the simulation of the RTOW design and by trial and error in the simulation of the rule curve implementation.

The water level of the reservoir as indicated by the simulation results is ≥ LWL.

3. Results and Discussion

3.1. Rainfall Prediction

3.1.1. Historical Area Rainfall

Rainfall forecast indicates the predicted area of rainfall in the catchment areas of the Batujai and Pengga reservoirs. The area rainfall in the two catchment areas of the dams is presented in Tables 1 and 2, based on the percentage weight of the Thiessen coefficient at each rainfall station.

Table 2 Weight of the Thiessen coefficient in the Batujai and Pengga dam catchment areas (Own study)

No.	Rainfall Station	Weight of Thiessen in the Batujai Dam	Weight of Thiessen in the Pengga Dam
1	Batujai	0.29	0.22
2	Jurangsate	0.06	-
3	Pengadang	0.61	-
4	Lingkok Lime	0.04	-
5	Pengga	-	0.12
6	Kabul	-	0.14
7	Rembitan	-	0.55
8	Mangkung	-	0.37

Based on the forecast of the rainy season for the period from October to the following year-March, the characteristics of the rainy seasons in 2020-2021, 2021-2022 and 2022-2023 for the catchment areas of Batujai and Pengga Dams are normal (N). This forecast is employed to anticipate the stochastic inflow for the forthcoming year, with a view to simulating and optimizing the RTOW schedule (every September). Fig. 3 presents the precipitation trends.

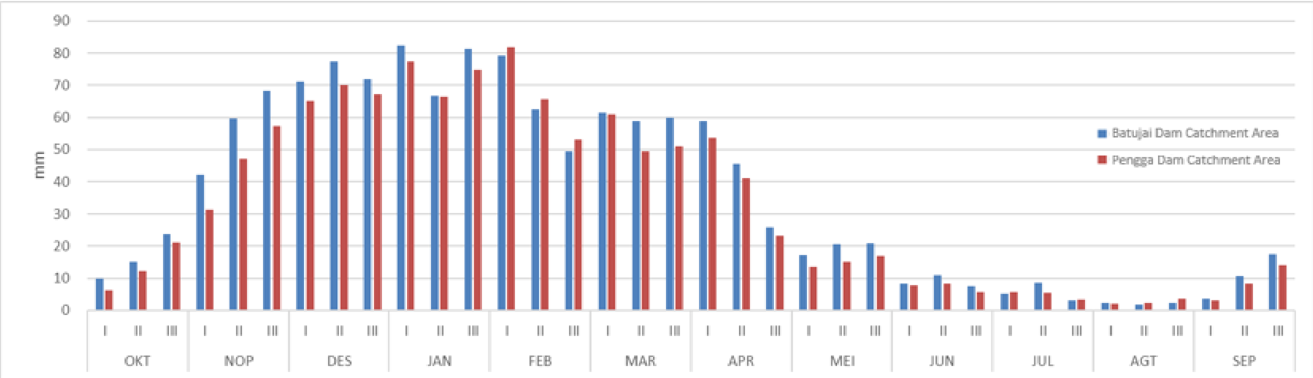

Fig. 3 Rainfall per 10-day period in the Batujai and Pengga dam catchment areas (Own study)

3.1.2. Area Rainfall Prediction

Based on the forecast of the rainy season from October to the following year-March, the characteristics of the rainy seasons in 2020-2021, 2021-2022, and 2022-2023 in the Batuja and Pengga dam catchment areas are normal (N). This forecast is used to predict the subsequent one-year stochastic inflow for the simulation optimization of the RTOW (each September in each year).

To forecast the stochastic inflow and arrange the RTOW under the normal SMH condition, the predicted rainfall using the Markov chain method for 2020/2021, 2021/2022, and 2022/2023 in the Batujai catchment area was 1,307, 1,304, and 1,284 mm, while in the Pengga catchment area, it was 1,149, 1,164, and 1,193 mm, with the RMSE and correlation values as follows:

i) Rainfall in the Batujai catchment area: RMSE = 0.22-0.74, correlation = 95%-99%.

ii) Rainfall in the Pengga catchment area: RMSE = 0.02-1.50, correlation = 99%.

The verification of the rainfall prediction values over a 10-day period revealed a pattern that was consistent with the 10-day historical average pattern. The rainfall prediction analysis results are presented in Table 3 and Fig. 4 and 5.

Table 3 Rainfall prediction for the Batujai and Pengga catchments (Own study)

No.	Prediction Year	Batujai Dam			Pengga Dam		
		Rainfall (mm/year)	RMSE	Correlation	Rainfall (mm/year)	RMSE	Correlation
1	2020/2021	1307	0.74	95%	1149	0.02	99%
2	2021/2022	1304	0.41	99%	1164	1.50	99%
3	2022/2023	1284	0.22	99%	1193	0.17	99%

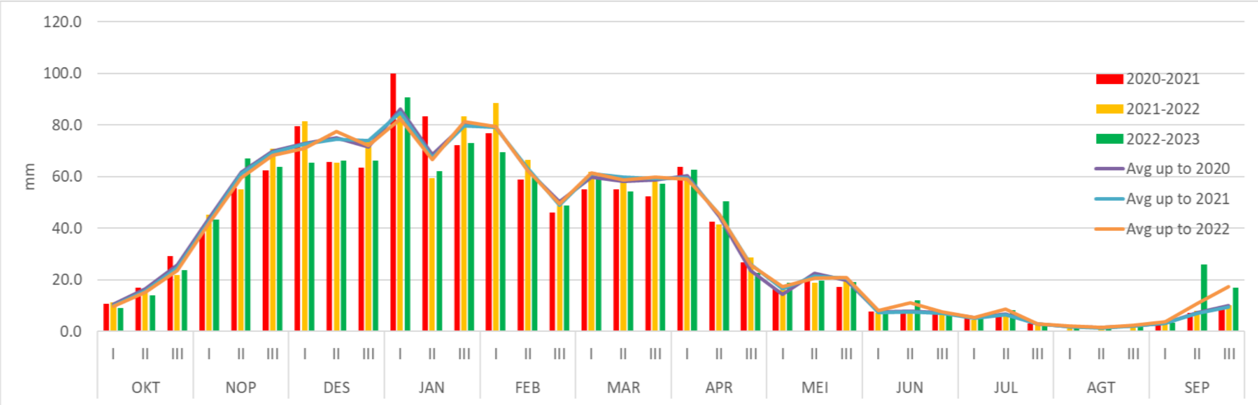

Fig. 4 Prediction of rainfall trends in the Batujai catchment (Own study)

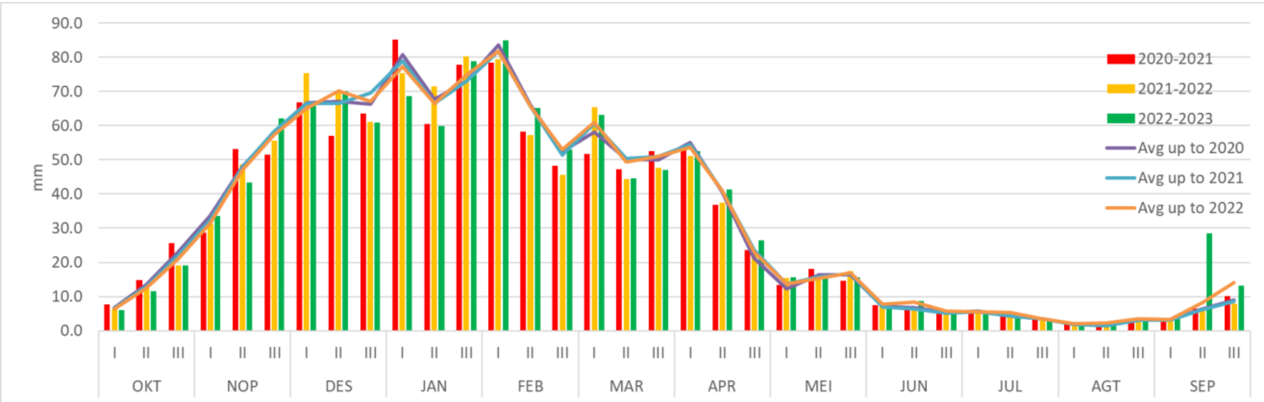

Fig. 5 Prediction of rainfall trends in the Pengga catchment (Own study)

To forecast the stochastic inflow for the purpose of arranging the curve due to real-time implementation, rainfall predictions are updated every period based on the next 3-month SMH prediction. For example, at the end of September III, rainfall forecasts for October I to December III are made, and at the end of October I, rainfall forecasts for October II to January I are made, etc., until next year's September III. The basis for predicting the following three months, for instance, in hydrological year 2020, can be seen in Table 4-SMH for one of the Batujai and Pengga rainfall stations in Praya Barat District.

Table 4 SMH matrix for 2020-2021, with a focus on the next three months in the Praya Barat district area (Own study)

Period	Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Sep.	2020	N	N	N									
Oct.	2020		N	N	AN								
Nov.	2020			AN	N	AN							
Dec.	2020				AN	AN	AN						
Jan.	2021					AN	N	N					
Feb.	2021						AN	N	N				
Mar.	2021							N	N	AN			
Apr.	2021								N	AN	BN		
May	2021									BN	BN	BN	
Jun.	2021										BN	BN	BN
Sep.	2021	AN	N	N									
Oct.	2021		N	N	N								

Based on the analysis of rainfall predictions using the Markov chain method, considering the next 3 months of SMH at each rainfall station for each period, it can be concluded that the rainfall prediction for the next 3 months shows a generally high gap, mainly for June, November, and December, as illustrated in Fig. 5.

The thick black line represents the trend of actual rainfall, while the colored lines represent the predictions for each period of the next 3 months, which are updated every period. Fig. 6 presents the rainfall prediction per period and the actual rainfall for 2020/2021.

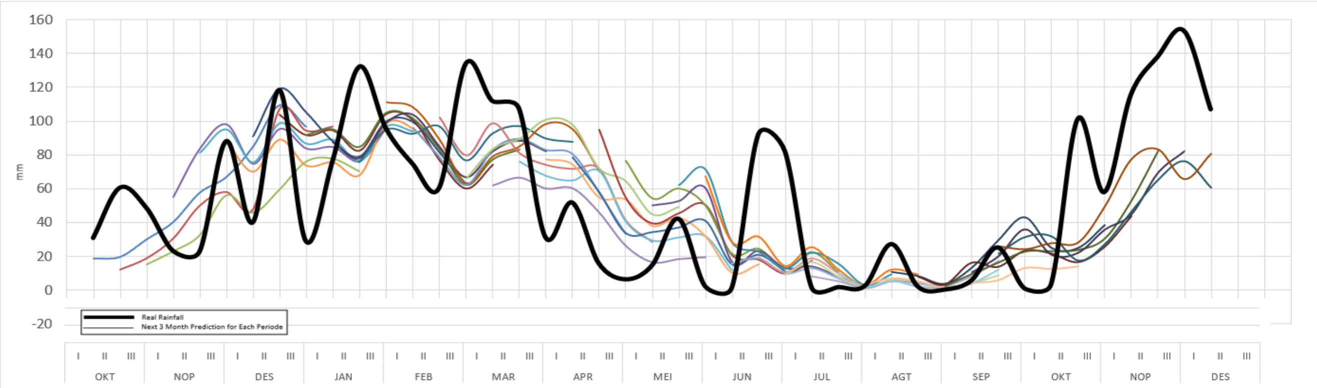

Fig. 6 Rainfall trend: prediction per period versus real rainfall for 2020/2021 (Own study)

3.2. Inflow

3.2.1. Deterministic Inflow (Probability of Dependable Discharge)

Deterministic inflows based on measured inflows at the Batujai and Pengga dams for each period from October to September, from 2013 to 2022, are presented. The 10-day average measurable inflow ranges as follows:

i) Batujai Dam: 347 to 5,687 l/s

ii) Pengga Dam: 205 to 9,152 l/s.

The inflow in the Batujai and Pengga Dams (Fig. 7) is employed as a reference point for the analysis of the deterministic inflow prediction for the period from October to September in 2020/2021, 2021/2022, and 2022/2023. The deterministic inflow prediction is based on the characteristics of the normal rainy season in the Batujai and Pengga dam catchments. To account for potential variability, the prediction is adjusted using the normal dependable discharge. Accordingly, the deterministic inflow is derived and presented in Table 5.

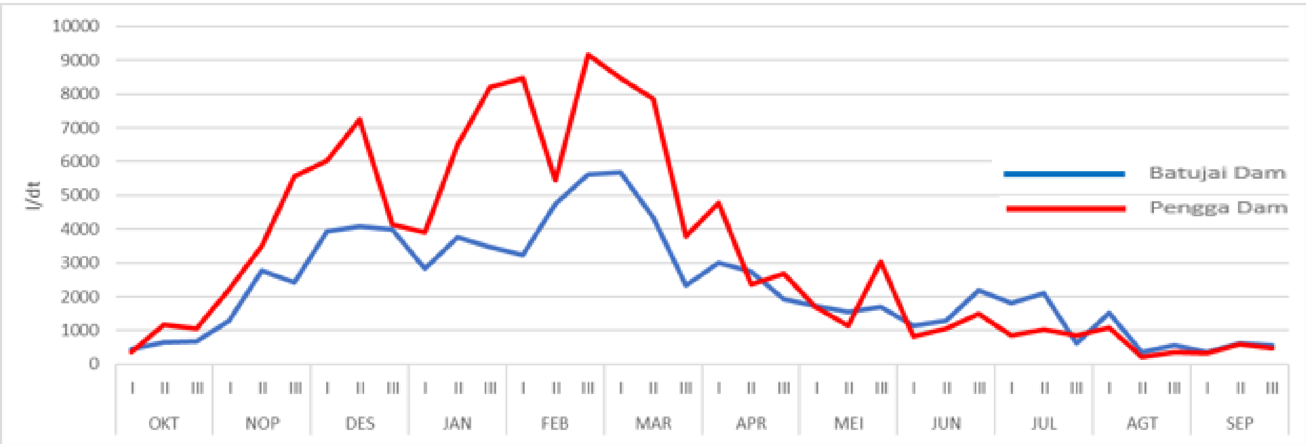

Fig. 7 Dependable inflow averages in the Batujai and Pengga dams (Own study)

Table 5 Deterministic inflow prediction for the Batujai and Pengga catchments (Own study)

No.	Prediction Year	Batujai Dam			Pengga Dam		
		Minimum	Average	Maximum	Minimum	Average	Maximum
1	2020/2021	0	1408	3619	0	1307	3689
2	2021/2022	0	1263	3583	0	1224	3689
3	2022/2023	0	1568	3837	0	1453	3729

3.2.2. Stochastic Inflow

Stochastic inflow was analyzed using the HEC-HMS software. The calibration of the model parameters was conducted by assessing the degree of similarity between the model output and the observational data collected from the AWLR Karang Makam. The calibration result of HEC-HMS modeling shows that the NSE value is 0.42 due to a percent bias of 9.52%; the RMSE is 0.8, which indicates that the model accurately represents transformation of rainfall into streamflow.

The analysis of the Batujai and Pengga dam catchments with the input parameters predicts the rainfall for each period from October until September in 2020/2021 and 2021/2022. Furthermore, the 2022/2023 data are based on the updated seasonal predictions for each region provided by the BMKG. The analysis of rainfall prediction considers both SMH and AMH (Fig. 8 and Table 6).

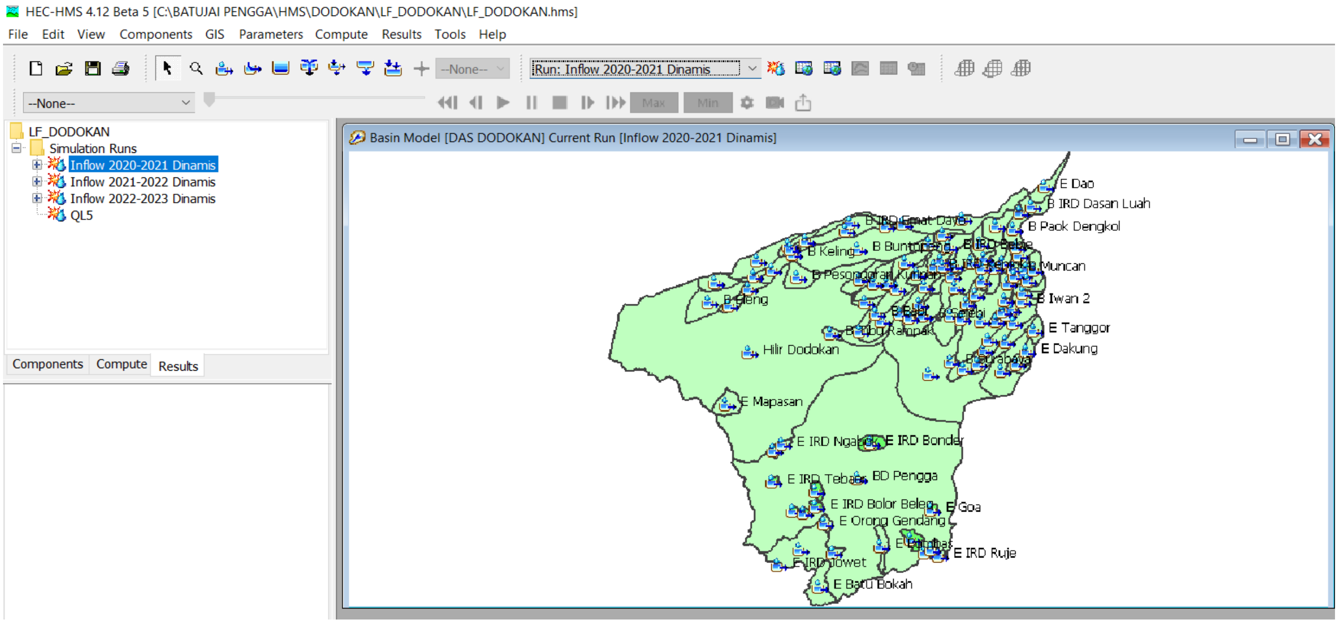

Fig. 8 The Dodokan watershed basin model (location in the Batujai and Pengga dams) (Own study)

Table 6 Stochastic inflow prediction for the Batujai and Pengga catchment areas based on the HEC-HMS results (Own study)

No.	Prediction year	Batujai Dam (l/s)			Pengga Dam (l/s)		
		Minimum	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
1	2020/2021	1239	2412	5586	1509	4771	6549
2	2021/2022	986	1742	3707	987	1975	4342
3	2022/2023	542	1823	7261	548	2583	4850

3.3. Water Demand

The dam's primary water demand services are irrigation and raw water provision. The irrigation water demand in the Batujai and Pengga irrigation areas is determined by the cropping pattern outlined in the RAAT-WS Lombok document. The average cropping pattern consists of rice crop followed by a second crop, with a ratio of 300%. However, the raw water demand for the Batujai Dam is 130 l/s, and the Pengga Dam has not yet been operationalised for raw water operations until the end of 2023 (the plan is for 150 l/s for the Special Economic Area of Mandalika). Table 7 presents the irrigation water demand.

Table 7 Irrigation water demand (Own study)

No.	Dam	Water demand			
		Maximum NFR (l/s/ha)	**Max. (l/s)**	**Min. (l/s)**	**Average (l/s)**
1	Batujai	1.23	4469	0	2081
2	Pengga	1.21	1852	0	1010

3.4. RTOW Simulation

The simulation of the RTOW design is based on deterministic inflow (static) and stochastic inflow (dynamic). The results of this simulation are outlined in Table 8:

i) The K-factor with deterministic inflow ranges from 20% to 100%, while the K-factor with stochastic inflow ranges from 30% to 100%.

ii) The reservoir filled with deterministic inflow ranges from 6% to 100%, whereas with stochastic inflow, it ranges from 26% to 100%.

iii) The average gap percentage to the real condition with deterministic inflow ranges from 0.66 to 1.23 m, and with stochastic inflow, it ranges from 0.39 to 1.26 m.

Table 8 Recapitulation of the RTOW design simulation results (Own study)

No.	Location	Period	Static			Dynamic		
			K-Factor	**S-Factor**	**Gap (m)**	**K-Factor**	**S-Factor**	**Gap (m)**
1	Batujai Dam	2020-2021	20-100%	6-100%	0.04-2.17 (avg. 0.69)	30-100%	16-100%	0.02-1.36 (avg. 0.56)
		2021-2022	25-100%	18-100%	0.04-2.36 (avg. 0.89)	30-100%	50-100%	0.06-2.39 (avg. 1.26)
		2022-2023	30-100%	37-100%	0.01-2.18 (avg. 0.67)	30-100%	42-100%	0.03-1.63 (avg. 0.86)
2	Pengga Dam	2020-2021	30-100%	13-100%	0.00-3.70 (avg. 123)	30-100%	26-100%	0.04-2.49 (avg. 0.66)
		2021-2022	47-100%	27-100%	0.01-2.62 (avg. 0.82)	40-100%	54-100%	0.02-0.98 (avg. 0.39)
		2022-2023	35-100%	36-100%	0.03-1.70 (avg. 0.66)	35-100%	46-100%	0.01-1.33 (avg. 0.51)

Furthermore, an evaluation of the sustainability of reservoir operation for design simulation (Fig. 9) reveals the following metrics:

- Reliability: 100%
- Resiliency: 100%
- Vulnerability: 0%.

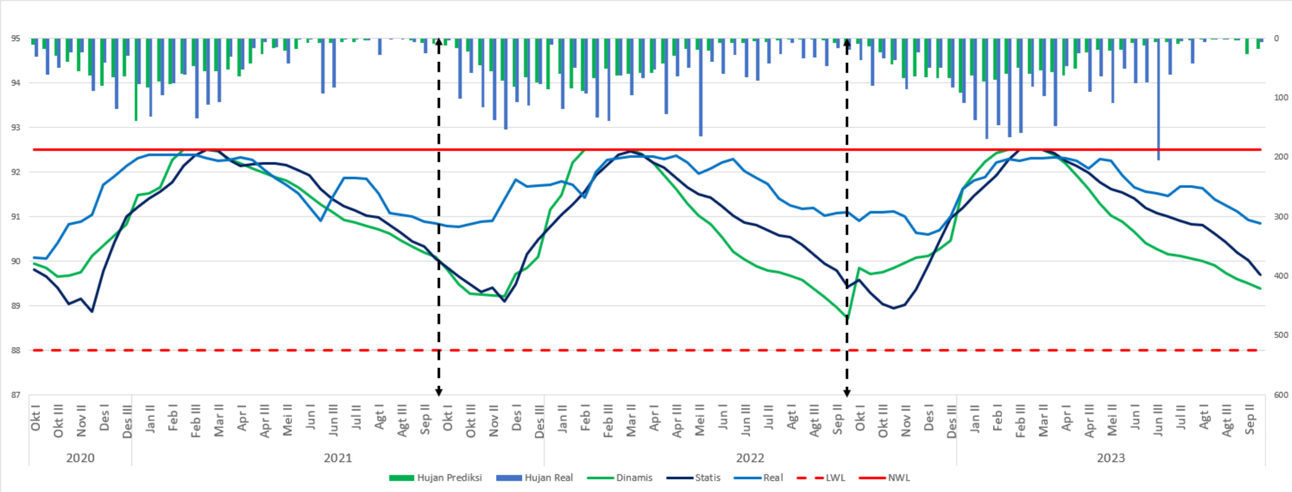

Fig. 9 Sustainability of reservoir operation for design simulation (Own study)

The trend of reservoir water levels, as per the design simulation analysis, can be seen in Fig. 10. Fig. 10 illustrates that the reservoir water level in actual conditions is typically higher than that of the RTOW reservoir. This is based on the forecast provided by the BMKG. This phenomenon can be attributed to the influence of climate change, such as the occurrence of La Niña, which manifests for three consecutive years and results in an increase in rainfall levels that exceed the projected levels.

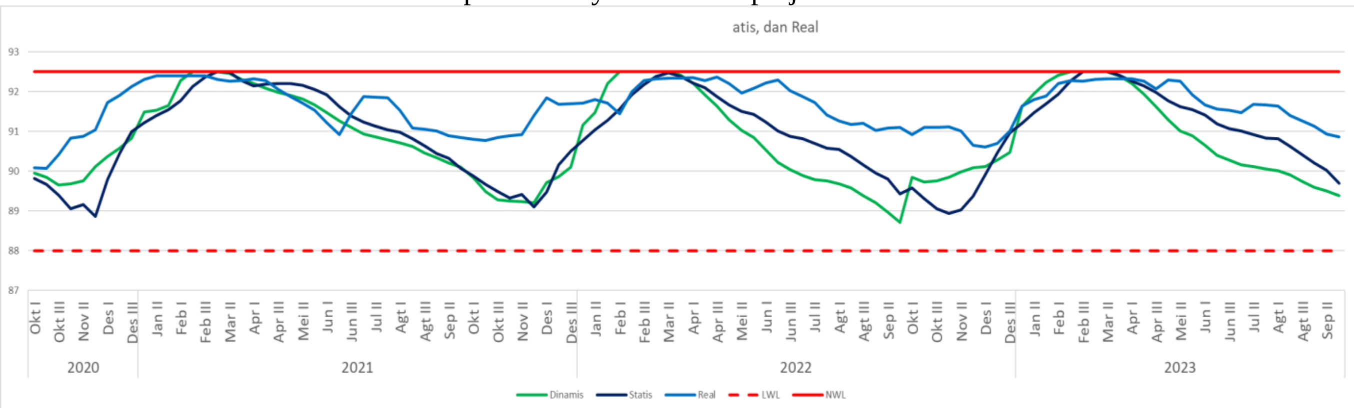

Fig. 10 Comparison of the RTOW: deterministic, stochastic, and real (Own study)

3.5. Implementation of Real-Time Simulation

The real-time implementation of the rule curve simulation for regulating reservoir operation every 10 days involves using rainfall predictions from the BMKG, based on a target condition determined by the elevation in the RTOW, for each period. The simulation is based on the initial storage conditions for the period, predicted reservoir inflow, and water demand. The results of the implementation simulation and sample rule curves for 2020/2021, 2021/2022, and 2022/2023 are presented in Table 9 and Fig. 11 and 12.

Table 9 Comparison of implementation simulation results (Own study)

Scenario	Year of 2020/2021				Year of 2021/2022				Year of 2022/2023			
	Correlation		RMSE		Correlation		RMSE		Correlation		RMSE	
	Batujai	Pengga	Batujai	Pengga	Batujai	Pengga	Batujai	Pengga	Batujai	Pengga	Batujai	Pengga
Static	98.9%	94.6%	0.34	0.48	94.0%	71.4%	0.32	0.73	93.2%	97.3%	0.44	0.36
Dynamics	99.3%	98.6%	0.24	0.16	94.9%	99.3%	0.43	0.28	94.6%	98.7%	0.30	0.25

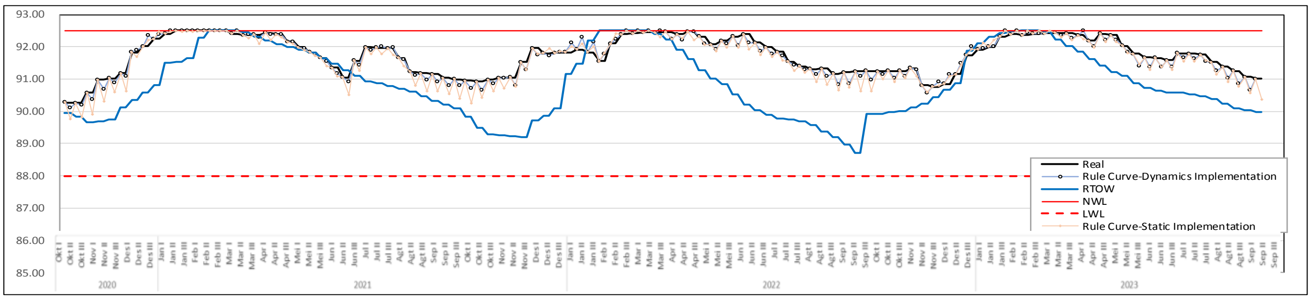

Fig. 11 Rule curve of the real-time implementation in the Batujai Reservoir (Own study)

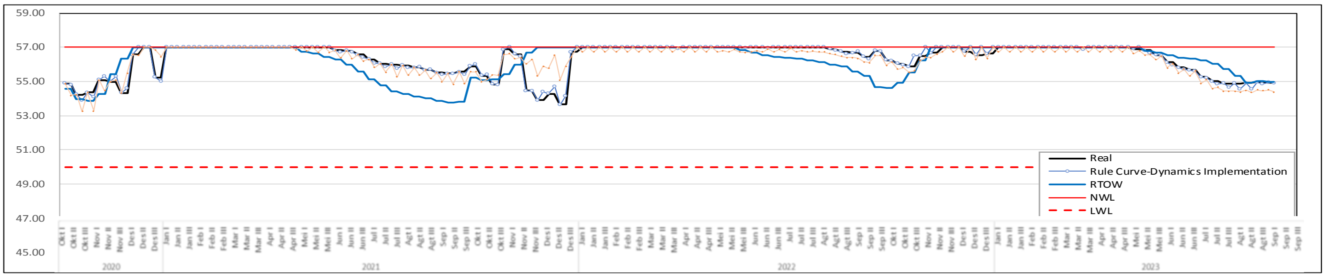

Fig. 12 Rule curve of the real-time implementation in the Pengga Reservoir (Own study)

Based on the results of the simulation comparison, the use of stochastic inflow for the reservoir is more appropriate than the use of deterministic inflow, in terms of the actual water level in the reservoir (as evidenced by the correlation analysis and the RMSE value). The planned RTOW is lower than the actual conditions. This is due to the impact of La Niña, which was observed in 2020-2023.

4. Conclusions

This research intended to determine an RTOW input prediction method and real-time operational rule curve of the Batujai-Pengga cascade reservoir in the Lombok River Basin.

The results demonstrate that the MAW simulation outcomes, both with stochastic and deterministic inflow inputs, exhibit a notable discrepancy. The former range from 0.39 to 1.26 m, while the latter range from 0.66 to 1.23 m, which are significantly different from the actual MAW condition. In accordance with the above results, it is recommended that when creating the reservoir rule curve, the input should be based on the updated rainfall prediction. The results of the simulation, conducted in accordance with the real-time rule curve and utilising rainfall updating on a per-period basis for a period of three months, indicate that the implementation incorporating stochastic inflow is more compatible with the actual reservoir water level than that incorporating deterministic inflow. Furthermore, the former exhibits a superior correlation coefficient and RMSE value.

Based on the analysis and discussion above, the method of designing and implementing reservoir operation using stochastic inflow is more optimal than deterministic inflow. It is verified from the correlation coefficient and RMSE, which are produced for every period in every year. However, in the future, it will be necessary to implement this method in years when the rainfall forecast is below or above normal, not just when it is normal.

The findings of this study are anticipated to inform real-time monitoring and decision-making at the dams, with the potential for application to the operation of the Bajuai and Pengga dams in the Nusa Tenggara I River Basin.

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