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THE OPTIMIZATION OF OPERATIONAL PATTERNS FOR THE CIPANUNJANG-CILEUNCA CASCADE RESERVOIR USING CONTINUOUS MODELS

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ABSTRACT: Cipanunjang-Cileunca Cascade Reservoir is the source of raw water for the drinking water supply system for the City and Regency of Bandung, West Java Province. Plengan, Lamajan, and Cikalong are three hydroelectric power plants (PLTAs) in the reservoir. The issue that is frequently faced in the reservoir is that excess water is lost to the spillway during the rainy season, but the water supply decreases in the dry season, disrupting the PLTA's performance. The optimization of the reservoir can be achieved if the conditions of the guidelines trajectory and the actual trajectory are close to 1, meaning that no water passes through the spillway but instead moves through the reservoir utility function. In this study, the simulation results of the operation pattern of the reservoir using continuous-model-obtained correlation values between guidelines trajectory and actual trajectory for a three-class and five-class operation pattern of the Cipanunjang Reservoir were 0.8 and 0.82, respectively. Meanwhile, the correlation values between guidelines trajectory and actual trajectory for three-class and five-class operation patterns of the Cileunca Reservoir were both 0.95. The results of this study show that the five-class operation pattern (very dry, dry, normal, wet, very wet) is better than the three-class operation pattern (dry, normal, wet) in the simulation of the operation pattern, so it is more suitable for use in facing uncertainty in the future.

Keywords: Cipanunjang-Cileunca Reservoir, Continuous model, Reservoir operation pattern, Reservoir optimization management, Spatial correlation model

1. INTRODUCTION

Referring to the National Medium-Term Development Plan (RPJMN) 2015–2019, one of the national development priorities is to achieve economic independence by moving strategic sectors of the domestic economy, for which there is a special article on water security. One of the targets is building a water reservoir with a capacity of 3 billion cubic meters and optimizing existing water reservoirs to increase per capita water storage capacity, provide renewable energy, and control flooding, with plans for the construction of 49 reservoirs and the development of raw water infrastructure as an attempt to support the achievement of drinking water services.

The hydrological component that is directly related to the reliability of raw water is the discharge, which depends on the rainfall and the land cover in a watershed. By knowing the discharge characteristics, the use of the raw water supply for downstream sectors such as hydroelectric power plants (PLTAs), irrigation, and drinking water supply systems (SPAMs) can be optimally carried out. One method for determining the characteristics of the discharge is using continuous Mock, NRECA, ARIMA, and Markov Chain models. The Markov chain is a stochastic process that can be measured by empirically estimating the probability of a transition to a discrete state in the observed system. In its application to supply problems, the Markov chain has been widely used to model various systems. This technique can be used to predict changes that occur in the future based on some information in the past. In the Markov chain, the sequence of processes of events means that the conditional probability of future events depends on current events. The main component in developing the Markov chain model is the state transition matrix and probability; both will summarize all the important parameters of dynamic change [1-4].

A study conducted by Utari [5] on a comparison of discharge models in the Cikapundung watershed concluded that the continuous model provides the best correlation value and relatively less error with historical discharge values because the continuous model calculates the value of rainfall and discharge (P, Q) in the period beforehand to predict future discharge. For the Cipanunjang-Cileunca Reservoir, the correlation value of the Discrete Markov Chain model used to generate the discharge was close to 1, indicating that the discharge forecast was conceptually close to the real condition (historical actual discharge) [6]. This study focuses on optimizing the operational simulation of the Cipanunjang-Cileunca Cascade Reservoir with a continuous model so that water demand downstream is met and no water is wasted through the spillway.

The continuous model, in this case, is a spatial correlation discharge prediction model, which can be conducted by correlating rain with discharge or discharge with ith several explanatory variables: one binary explanatory variable, two ternary explanatory variables, and three quaternary explanatory variables. The researcher then looks for the highest coefficient of determination; as the coefficient of determination approaches 1, the discharge forecast model approaches the actual discharge value. This model has been proven to be able to predict future discharge well [7-8].

Inflow forecasting is an important tool for reservoir operation [9]. The year forecast was determined using the Discrete Markov Chain method and the Standardized Precipitation Index (SPI). The Standardized Precipitation Index (SPI) is calculated based on precipitation (P). SPI normalizes precipitation accumulation (P) and climate water balance (P-ET) which represents the potential for evapotranspiration. This index is associated with its simple interpretation, low data requirements, and its multiscalar flexibility. The SPI provides a single numerical value for rainfall anomalies that can be compared across regions with very different climates. Technically, SPI is a standard deviation in which the observed value will deviate from the long-term mean for random variables that are normally distributed. SPI makes it possible to estimate agricultural, hydrological, and socio-economic drought by adjusting the index accumulation period [10-13]. SPI expresses actual rainfall as a standard deviation from the probability distribution function rainfall and makes this index an indicator of potential drought that allows comparisons across space and time [14]. SPI is recommended to show the calculated probability index to record the amount of rainfall, a negative index value of drought, and a positive wet index value. SPI can also be used to predict the monitoring of climate conditions at various times [15].

2. METHODOLOGY

Cipanunjang-Cileunca Cascade Reservoir is administratively located in Warnasari Village, Pengalengan Sub-District, Bandung Regency, West Java Province. These two reservoirs obtain water from the Cilaki River, which is part of the Cisangkuy and Citarum watersheds (Fig.1). Cipanunjang-Cileunca dam managed by Indonesia Power were constructed for hydropower generation purpose. Natural overflow through morning glory type spillway is practiced during flood control operation. The effective storage of the two dams is 16,900,000 m^3 and 11,230,000 m^3. A maximum of 5.5 m^3/s of water is released from Cipanunjang to the Cileunca reservoir throa an ugh gate installed in the water intake. Frothe m Cileunca reservoir, a maof ximum 6 m^3/s is supplied to the three micro hydropower plants (Plengan, Laand majan, Cikalong) located downstream, which are operated by PLTA. Cikalong Water Intake is located downstream of the Cikalong Micro Hydropower Plant [16].

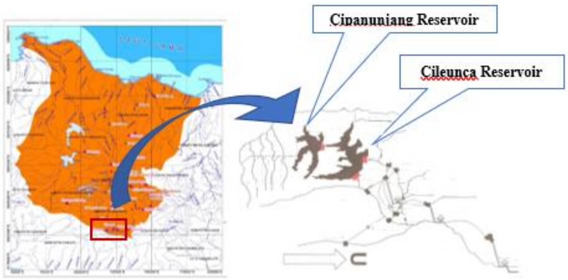

Fig.1 Map of the location of the Cipanunjang-Cileunca Reservoir (Plengan Hydroelectric Power Plant, 2018)

In this study, the hydrological component data needed were daily or monthly rainfall and discharge data from 1997 to 2017. Rainfall data were taken from six rain observation posts, four of which are located in the Cisangkuy watershed, while the other two are outside the watershed. The discharge data for the Cipanunjang-Cileunca Reservoir system are owned by Plengan Hydroelectric Power Plant as the reservoir manager.

2.1 Year Forecast of Reservoir Operation Pattern

A year forecast of the reservoir operation pattern consists of three classes (dry, normal, and wet years) and five classes (very dry, dry, normal, wet, and very wet years). The year forecast was determined using the Discrete Markov Chain method and the Standardized Precipitation Index (SPI) method developed by McKee, Doesken, and Kleist (1993), cited in [17]. The following equation is used to calculate SPI:

$$SPI = Q - \overline{\boldsymbol{Q}} \ / \ \boldsymbol{\sigma_j} \quad (1)$$

in which Q = annual rainfall (mm); $\overline{\boldsymbol{Q}}$ = average annual rainfall; and $\boldsymbol{\sigma_j}$ = standard deviation of annual rainfall.

The above equation was also used by Modarres [18] to determine dry, normal, and wet years based on discharge.

Table 1 Year classification for three-class guidelines trajectory

SPI Value	Category
1 to 2	Wet
0.99 to -0.99	Normal
-1 to -2	Dry

Year classification for three-class guidelines trajectory based on SPI value can be seen in Table 1. Year classification for the Five-class guidelines trajectory based on SPI value can be seen in Table 2 below.

Table 2 Year classification for five-class guidelines trajectory

SPI Value	Category
1 <<	Very Wet
0.51 to 1	Wet
0.5 to - 0.5	Normal
-0.51 to -1	Dry
-1 >>	Very Dry

2.2 Management Optimization of Cipanunjang Cileunca Reservoir

The reservoir was operated with management according to its needs.

1. Reservoir Economic Environment
   During its operation, reservoir management had several constraints, including:
   a. Water mass balance, in which there was a water volume limit in the reservoir according to the following mass balance equation
   $$S_{t+1} = S_t + Q_{in} - Q_{out} - E \quad (2)$$
   S_{t+1}= Reservoir water volume at time t + 1 (m^3); S_t = Reservoir water volume at time t (m^3); Q_{in} = incoming water discharge (m^3/day); Q_{out} = outgoing water discharge (m^3/day); E = Evaporation (mm)
   b. Limit of reservoir storage volume, Smin < S < Smax
   c. Limit of incoming and outgoing discharge, in which incoming discharge < reservoir capacity by removing excess water via the spillway while outgoing discharge was adjusted to downstream water needs.
   d. Operational constraints of various kinds, such as the maximum allowable turbine discharge, operational costs, as well as equipment and river maintenance.
2. Optimal Operation (*Avenir Aleatoire*)
   This operation is used to anticipate the randomness of future discharge forecasts by utilizing accounts of the spatial correlation of the main hydrological components [19].

3. RESULTS AND DISCUSSION

3.1 Year Forecast of Three-Class and Five-Class Operation Patterns

Determination of wet, dry, and normal years for optimal reservoir management simulations was carried out using the three-class Markov discrete method; discharge data were classified based on the cumulative curve (less than) and continuous methods. Annual discharge data were divided into three classes [20, 21]:

1. Class 0, i.e., dry year class;
2. Class 1, i.e., normal year class;
3. Class 2, i.e., wet year class.

First, it was necessary to identify the conditions in year t with the discrete method and SPI method. For the discrete method, the annual discharge data were sorted from largest to smallest and then divided into three classes (dry, normal, and wet). The average discharge value for each class was sought. The type of year was determined by looking at the annual discharge value. Annual discharge value that exceeded the average value for the wet class was categorized as wet year; annual discharge was categorized as normal if it was between the mean value of the wet class and the normal class; and so on. For the SPI method, there were two scenarios for year identification:

1. SPI calculation with the average value and standard deviation of rainfall at Cileunca Rain Gauge Station (P1)
2. SPI calculation with annual historical input discharge value

Historical discharge and rainfall, which have been classified into three classes (dry, wet, and normal), were then searched for the probability value of the annual transition matrix. The first-order transition matrix is used to predict the discharge of the n + 1 month based on the events/history of the nth month. The annual transition matrix is used for determining trajectory type. An example of the annual transition matrix can be seen in Table 3 for the three-class operation pattern and in Table 4 for the five-class operation pattern.

Table 3 First order annual Markov Transition Matrix for three-class operation pattern of Cipanunjang Reservoir, the highlight is a significant result as it is the biggest number comparing the others, both vertically and horizontally.

Condition in Year (t-1)	Condition in Year (t)				
	0	1	2		
0	0.70	0.30	0.00	1	P0N
1	0.33	0.56	0.11	1	P1N
2	0.00	0.50	0.50	1	P2N
	1.03	1.36	0.61	3	PNN
	PN0	PN1	PN2	PNN	

Table 4 First order annual Markov Transition Matrix for five-class operation pattern of Cipanunjang Reservoir, the highlight is a

significant result as it is the biggest number comparing the others, both vertically and horizontally.

Condition in Year (t-1)	Condition in Year (t)						
	1	2	3	4	5		
1	0.33	0.33	0.17	0.17	0	1	P1N
2	0.33	0.33	0	0.33	0	1	P2N
3	0.33	0	0.33	0.33	0	1	P3N
4	0.2	0	0.2	0.4	0.2	1	P4N
5	0	0	0.5	0	0.5	1	P5N
	1.19	0.66	1.2	1.23	0.7	5	PNN
	PN1	PN2	PN3	PN4	PN5	PNN	

The use of this annual transition matrix will serve as a guide in establishing a guidelines trajectory. If historically, the incoming discharge (Qin) in year t-1 is in the dry discharge class, we make the first drawdown in that year with code 0. Here, we can see that the probability of incoming discharge next year is the greatest—namely, dry year. Thus, there will likely be dry conditions next year. Furthermore, the normal year is indicated by code 1 and the wet year is indicated by code 2. For the five-class operation pattern, a very dry year is indicated by code 1; a dry year is indicated by code 2; a normal year is indicated by code 3; a wet year is indicated by code 4, and a very wet year is indicated by code 5. The results of the year forecasting using the Discrete Markov method for three-class and five-class operation patterns of Cipanunjang Reservoir can be seen in Table 5 and Table 6, while those for Cileunca Reservoir can be seen in Table 7 and Table 8.

Table 5 Year classification based on Markov discrete forecast method for three-class operation pattern of Cipanunjang Reservoir

Year	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
SPI of Cileunca Rainfall	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SPI of Cipanunjang Historical Discharge	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
Discrete Markov	0	1	1	1	2	1	1	1	1	1	0	0	0	0	1	0	1	0	0	0	0

Table 6 Year classification based on Markov discrete forecast method for five-class operation pattern of Cipanunjang Reservoir

Year	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
SPI of Cileunca Rainfall	3	3	3	3	3	2	3	1	3	3	3	3	3	3	3	3	3	2	2	3
SPI of Cipanunjang Historical Discharge	4	4	4	4	5	3	4	4	4	2	3	2	3	3	4	3	2	1	1	1
Discrete Markov	4	4	4	4	5	3	3	5	4	1	2	2	1	2	4	2	1	1	1	2

Table 7 Year classification based on Markov discrete forecast method for three-class operation pattern of Cileunca Reservoir

Year	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
SPI of Cileunca Rainfall	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SPI of Cipanunjang Historical Discharge	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
Discrete Markov	0	1	1	1	2	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0

Table 8 Year classification based on Markov discrete forecast method for five-class operation pattern of Cileunca Reservoir

Year	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
SPI of Cileunca Rainfall	3	3	3	3	3	2	3	1	3	3	3	3	3	3	3	3	3	2	2	3
SPI of Cipanunjang Historical Discharge	4	4	4	4	5	3	2	4	4	2	2	2	2	2	4	2	2	1	1	1
Discrete Markov	2	4	4	4	5	3	3	3	3	3	2	2	1	2	4	2	1	1	1	2

3.2 Determination of Guidelines Trajectory Using Continuous Method

The reservoir trajectory is created to explain the phenomenon of the reservoir filling with a certain input discharge to the determined discharge according to the mass balance equation in the reservoir: $S_{t+1} = S_t + Q_{in} - Q_{out}$. Q_{in} is a random variable of the river discharge that will fill the reservoir, while Q_{out} is a determining variable. By comparing the actual trajectory of forecasted discharge and the guidelines trajectory of a certain return period, it is possible to know the dry probability and the amount of discharge that can be forecast for the coming months. Accordingly, the reservoir can be managed optimally, in part by anticipating the reservoir variables. In this study, discharge data used were forecasted discharge data that were built with a continuous rain-discharge spatial correlation model. Fig.2 is a chart of guidelines trajectories for three-class operation patterns with continuous input discharge of Cipanunjang Reservoir; Fig.3 charts those trajectories for Cileunca Reservoir.

3.3 Monthly Discharge Forecast Using Continuous Method

The model used to predict the monthly discharge is the method of spatial correlation of hydrological components, commonly known as the continuous method. Discharge at time t + 1 is constructed by discharge and rainfall at time t with multiple linear regression.

Figures 4 and 5 are a comparison between the historical discharge and the estimated/forecasted discharge for Cipanunjang Reservoir and Cileunca Reservoir (Cilaki Beet); based on statistical tests between the historical discharge and the forecasted discharge, the correlation value reached 0.87, and 0.83. Absolute relative error (KAR) was 0.004 for both reservoirs, root means square error (RMSE) obtained was 0.064 and 0.063, and the coefficient of the determination reached 0.76 and 0.7. This indicates that the spatial correlation method can be used to forecast future discharge, which is shown by the correlation value between the historical discharge and the forecasted discharge approaching 1.

3.4 Optimization of Reservoir Management

The discharge data used were forecast discharge data that was built with a rain-discharge spatial correlation model. Year forecast of three-class and five-class operation patterns was made using Discrete Markov and continuous methods. Simulations carried out were adjusted to the objectives of the downstream reservoir and its constraints, which were categorized in the reservoir economic environment. The constraints included 1) water mass balance equation, 2) maximum water level, 3) downstream water needs, and 4) turbine propulsion limit [22].

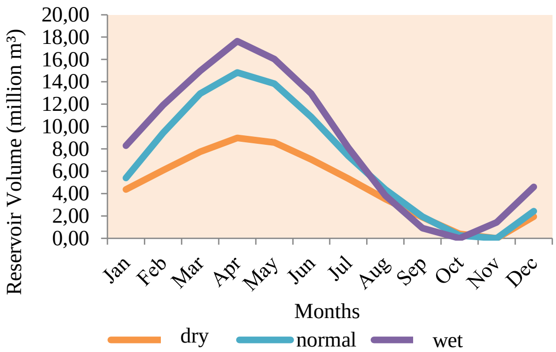

Fig.2 Chart of guidelines trajectory for three-class continuous discharge of Cipanunjang Reservoir

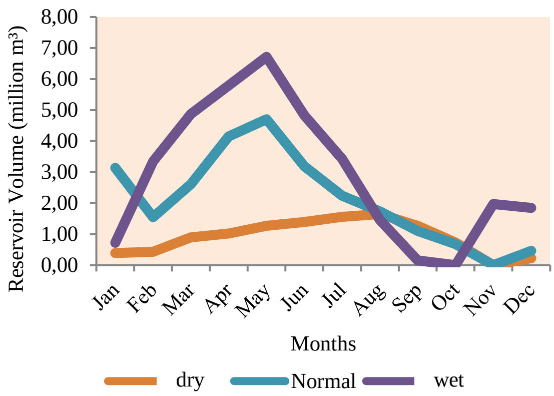

Fig.3 Chart of guidelines trajectory for three-class continuous discharge of Cileunca Reservoir

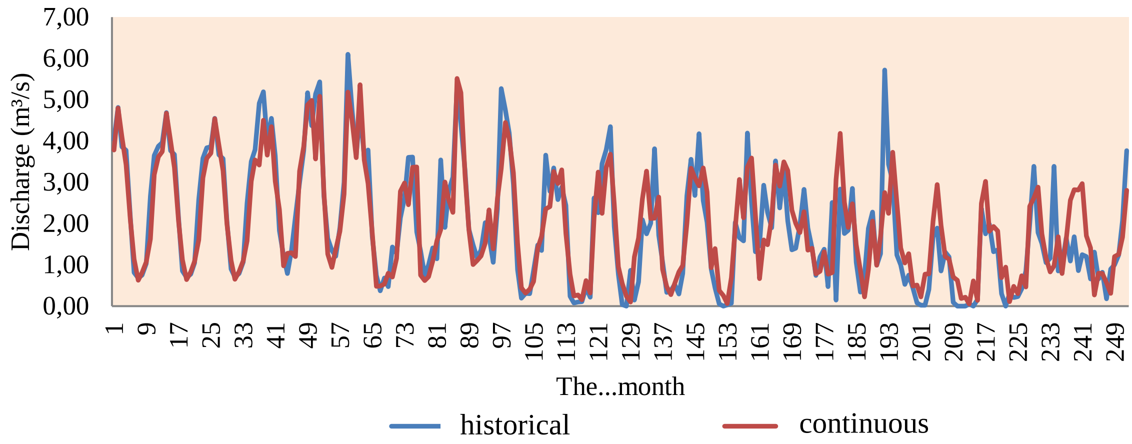

Fig.4 Comparison of historical discharge and forecasted discharge of Cipanunjang Reservoir

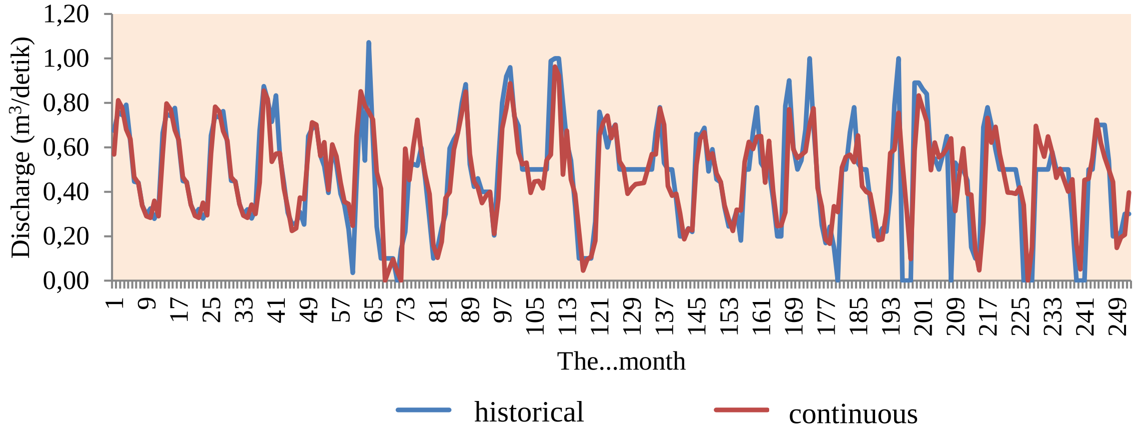

Fig.5 Comparison of historical discharge and forecasted discharge of Cileunca Reservoir

3.4.1 Reservoir economic environment

The reservoir economic environment provides information about the storage limits used (constraint). Cipanunjang and Cileunca Reservoirs function to meet the needs of PLTAs in Plengan, Lamajan, and Cikalong, as well as the need for drinking water of the regional drinking water company (PDAM) in the City and Regency of Bandung. Objectives: meet the raw water needs in the dry season, meet the water needs downstream, and prevent the loss of water through the spillway.

Cipanunjang Reservoir Constraints:

1. Conservation of mass: St+1 = St + Qin – Qout
2. Stock: 0 < S < 22 million m^3
3. Water Level: 1422 m < TMA < 1446.5 m
4. Qout: Q Raw Water 0.86 m^3/second< Qout

Cileunca Reservoir Constraints:

1. Conservation of mass: St+1 = St + Qin – Qout
2. Stock: 0 < S < 11 million m^3
3. Water Level: 1407 m < TMA < 1418.5 m
4. Qout: Q Raw Water 1.2 m^3/second< Qout < Q 5 Turbine 10.09 m^3/second

3.4.2 Optimal Management of Three-Class Operation Pattern

Running the three-class operation pattern involved following a guidelines trajectory from three-class Discrete Markov and five-year continuous discharge models, the continuous future discharge forecast model, and the dry, normal, and wet year forecast that was determined using Discrete Markov and continuous methods. The forecasted discharge, guidelines trajectory, year classification, and reservoir constraint were all combined in an optimal reservoir simulation with the principle of the mass water balance. The output discharge constraint of Cipanunjang Reservoir was Q R5 Dry of 0.86 m^3/second, while the output discharge constraint of Cileunca Reservoir was 1.2 m^3/second, which was the sum of the output of Cipanunjang Reservoir and the reliability of raw water from Cilaki Beet, with the maximum output of Q 5 Plengan PLTA turbine at 10.09 m^3/second.

3.4.3 Optimal Management of Five-Class Operation Pattern

The operation of the five-class pattern followed a guidelines trajectory from five-class Discrete Markov and 10-year continuous discharge models, a continuous future discharge forecast model, and the very dry, dry, normal, wet, and very wet year forecast that was determined using Discrete Markov and continuous methods. The forecasted discharge, guidelines trajectory, year classification, and reservoir constraint were all combined in an optimal reservoir simulation with the principle of the mass water balance. The constraints of both reservoirs were the same as those under optimal management of the three-class operation pattern.

3.5 Optimal Reservoir Management Simulation

The optimal operation simulation of Cipanunjang Reservoir using the continuous model is shown in Figure 6 for the three-class operation pattern and Figure 7 for the five-class operation pattern. The correlation value between guidelines trajectory and actual trajectory was close to 1, namely 0.8, for the three-class operation pattern and 0.82 for the five-class operation pattern. The chart demonstrates the difference between guidelines trajectory and actual trajectory due to the anticipated discharge forecasted by a continuous model based on the rainfall-discharge hydrological component, in which the two components could be random and sometimes did not match the actual conditions. The component in the hydrological cycle can be stochastic and deterministic variables. Hence, the occurrence cannot be predicted by humans. Meanwhile, the output and saved components are influenced by human activities. Thus, their occurrence can be estimated and controlled by humans [23].

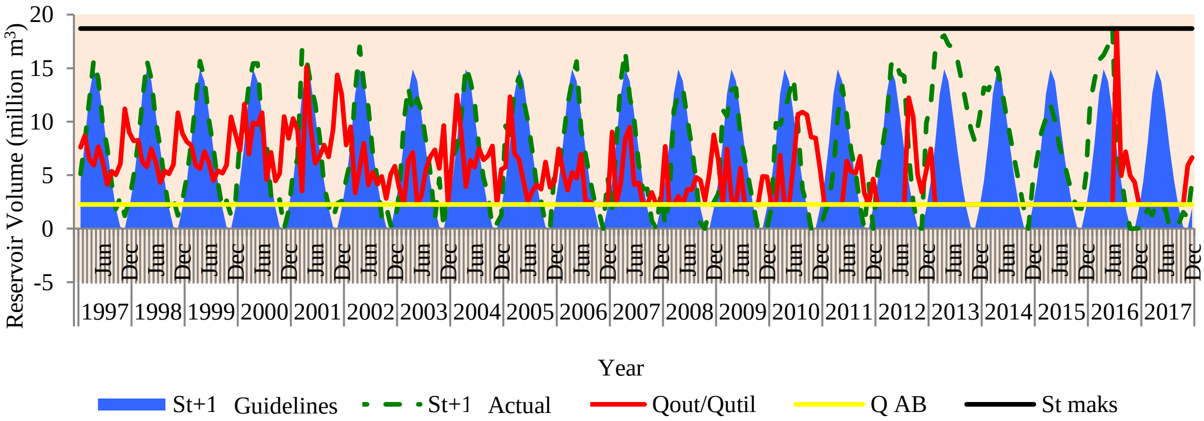

Fig.6 Chart of optimization of three-class operation pattern of Cipanunjang Reservoir using continuous model, 1997–2017

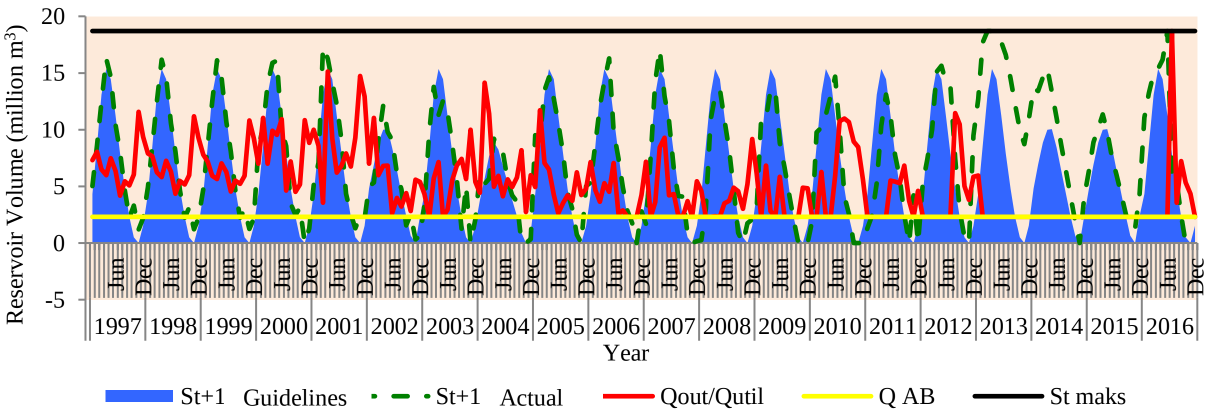

Fig.7 Chart of optimization five-class operation pattern of Cipanunjang Reservoir using continuous model, 1997–2017

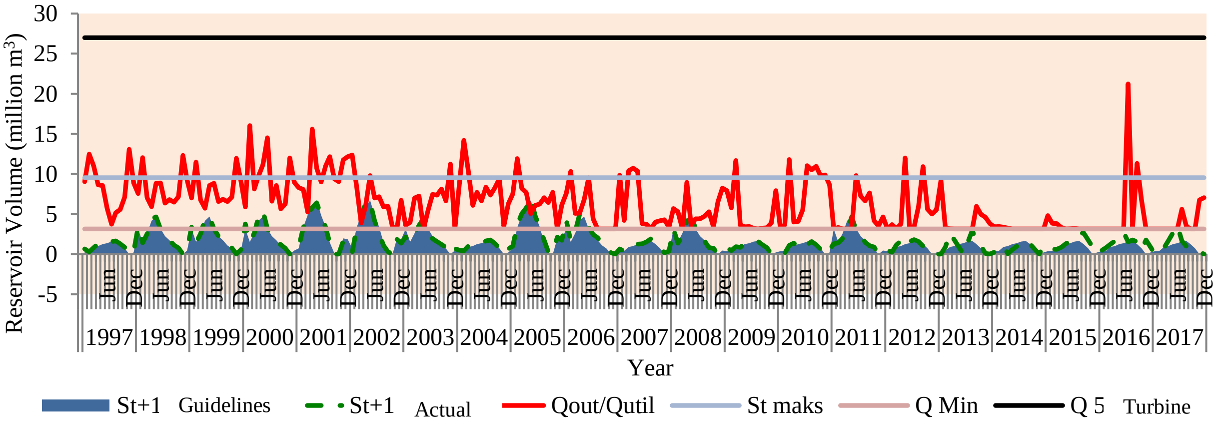

Fig.8 Chart of optimization of the three-class operation pattern of Cileunca Reservoir using the continuous model, 1997–2017

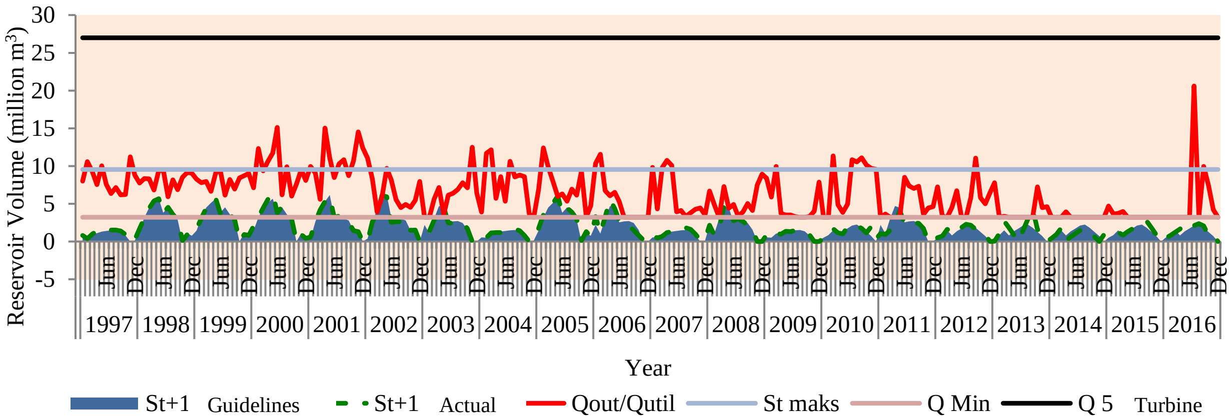

Fig.9 Chart of optimization of the five-class operation pattern of Cileunca Reservoir using the continuous model, 1997–2017

The optimal operation simulation of Cileunca Reservoir using the continuous model is shown in Figure 8 for the three-class operation pattern and Figure 9 for the five-class operation pattern. The correlation value between guidelines trajectory and actual trajectory was close to 1, namely 0.95, for the three-class operation pattern and the five-class operation pattern. The figure shows there is a difference between the guidelines trajectory and the actual trajectory, which still exceeds the maximum volume of the reservoir, causing runoff, which was due to the anticipated discharge forecasted by the continuous model, in which the actual incoming discharge could be smaller or greater than the forecasted discharge.

The input discharge is strongly influenced by the rainfall intensity, and every region has different characteristics depending on the type of rainfall. This will affect the amount of flow in the watershed [23]. The flow is used as input to identify the planning discharges in the development of the water supply system in Indonesia. Moreover, an accurate analysis of discharge that closely approximates the facts is crucial to the efficiency of water resource systems in fulfilling water use demands [24].

4. CONCLUSION

The optimization of the reservoir is achieved with guidelines trajectory and actual trajectory that are close to 1. This means that no water passes through the spillway; instead, it is sent through the reservoir utility function for raw water for drinking water downstream. The correlation values between guidelines trajectory and actual trajectory for three-class and five-class operation patterns of Cipanunjang Reservoir were 0.8 and 0.82, respectively. In addition, the correlation values between guidelines trajectory and actual trajectory for three-class and five-class operation patterns of Cileunca Reservoir were both 0.95. Therefore, the five-class operation pattern (very dry, dry, normal, wet, very wet) is better than the three-class operation pattern (dry, normal, wet) in the simulation of the operation pattern, so it is more suitable for facing uncertainty in the future.

5. ACKNOWLEDGMENTS

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