Journal of the Civil Engineering Forum, May 2024, 10(2):163-172
DOI 10.22146/jcef.7913
Available Online at https://jurnal.ugm.ac.id/v3/jcef/issue/archive

Optimization of Pengga Reservoir in The Mandalika Special Economic Zone for Irrigation and Water Supply

Dewandha Mas Agastya*, I Wayan Yasa, I Dewa Gede Jaya Negara
Department of Civil Engineering, Faculty of Engineering, University of Mataram, Mataram, INDONESIA
Jalan Majapahit No 62 Mataram
*Corresponding author: dewandhamas96@mail.ugm.ac.id

SUBMITTED 19 May 2023 **REVISED** 1 March 2024 **ACCEPTED** 13 March 2024

ABSTRACT Mandalika Special Economic Zone is tourism area that is expected to improve the economy in West Nusa Tenggara Province. To support these activities, an allocation of domestic water needs of 200 liters second^{-1} is needed. The potential availability of water in the Pengga Reservoir is planned to be a source of domestic water needs in the Mandalika Special Economic Zone. Pengga Reservoir has an effective storage volume of 17.26 MCM. Potential water resources in Pengga Reservoir are obtained from reservoir outflow upstream and lateral inflow from several tributaries. The study was carried out to determine the reservoir storage capacity to meet domestic water needs and irrigation water needs covering an area 3189 ha. The cropping pattern used in the Pengga irrigation area is Paddy – Paddy/Secondary Crops – Paddy/Secondary Crops. To optimize the potential of water resources in the Pengga Reservoir, a linear programming optimization method is used. Indicators of the success of optimization calculations are indicated by the value of cropping intensity, k factor and reliability that have met the minimum limit value. The k factor value for irrigation water needs is 0.70 and domestic water needs is 0.85. Based on the optimization results, it is known the largest annual cropping intensity value occurs in the November I planting season. This conclusion can be seen from the comparison of annual cropping intensity values for the November I and November II planting schedules for the dry year inflow discharge scenario of 99.98% and 97.22% respectively. The cropping intensity value in the November I planting season is greater than November II, namely 100% and 97.25%, for the normal year discharge inflow scenario. This study provides an information for policy makers can use the November I planting schedule to obtain values for maximum cropping intensity and domestic water requirements.

KEYWORDS Mandalika Special Economic Zone; Domestic Water; Cropping Intensity; k Factor; Rule Curve

1 INTRODUCTION

The Pengga Reservoir is a key water infrastructure project on Lombok Island, fulfilling multiple functions including supplying water for domestic use, irrigation, tourism, and maintaining ecosystem flows. This initiative stemmed from a study on Water Resources Development on Lombok Island carried out by Canadian consultants in 1994. The discovery of significant water resource potential by the Implementing Agency of the Brantas River Multipurpose Master Project between 1975 and 1977 prompted feasibility studies and detailed design efforts. The construction of the Pengga Reservoir, which took place from 1994 to 1999, is located along the Penujak River, downstream of the Batujai Reservoir. The availability of water in the Pengga Reservoir is influenced by both the natural inflow from the local area and the regulated flow from the Batujai Reservoir (Agastya, 2022). The creation of the Pengga Reservoir seeks to meet the irrigation and domestic water demands of Lombok Island's southern region. Optimizing water resource potential in reservoirs is crucial for enhancing benefits for irrigation and domestic uses, ensuring equitable and efficient operations (Azamathulla et al., 2009). The southern region of Lombok Island, characterized by extensive agricultural fields, often experiences crop failures due to a brief rainy season and low rainfall intensity.

At the commencement of its operations, Pengga Reservoir had a storage capacity of 21 million cubic meters (MCM). This capacity was allocated to satisfy the irrigation requirements of approximately 3189 hectares, domestic water supply at a rate of 150 liters per second, and to generate electricity with a capacity of 400 KVA. Although the reservoir continues to contribute to electricity generation, this research predominantly addresses the irrigation and domestic water demands within the Mandalika Special Economic Zone. Echosounding measurements conducted in 2020 revealed that Pengga Reservoir's effective storage volume has decreased to 17.26 MCM, primarily due to sediment accumulation within the reservoir's inundation area. A study in 2018 simulated the reservoir's capacity to irrigate 3585 hectares under a crop rotation of rice-rice-vegetables, without considering the domestic water requirements (Qomah et al., 2018). Presently, there is an increased demand for domestic water supply in the Mandalika Special Economic Zone from Pengga Reservoir. The Mandalika area spans 1035.67 hectares and hosts the Mandalika International Street Circuit, which is a venue for the Superbike World Championship (WSBK) and Moto Grand Prix (MotoGP) events, highlighting its geo-economic and geostrategic significance. The Mandalika Special Economic Zone benefits from its marine tourism attractions, including beaches with white sand and exotic vistas, and its strategic location near the Lombok International Airport, emphasizing environmentally sustainable tourism development.

The aim of this study is to evaluate the Pengga Reservoir's capacity to accommodate the domestic water requirements of the Mandalika Special Economic Zone by analyzing the reservoir's operational patterns. This analysis is critical for ensuring that the reservoir maximizes its water resource potential effectively, which is measured by factors such as annual cropping intensity, the k factor's value for both irrigation and domestic water needs, and the overall reliability of the reservoir. The ultimate objective of optimizing reservoir storage is to guarantee that all designated irrigation and domestic water demands are met, while also maintaining the ecological flow requirements downstream of the reservoir (Mehta et al., 2023). To achieve these optimal results, the study employs a linear programming method, recognized for its straightforward mathematical model and its frequent use in managing water resources systems (Heydari, Othman and Qaderi, 2015). The practice of optimal reservoir management, through the application of a rule curve, provides a systematic approach to assist operators in making informed decisions about water distribution and resource management (Rediasti et al., 2023).

2 METHODS

2.1 Research Location

Administratively, the Pengga Reservoir is situated in the West Praya District of the Central Lombok Regency, within the West Nusa Tenggara Province, Indonesia. Geographically, it is positioned at coordinates 8°45' N latitude and 116°11' E longitude. The reservoir is built on the Penujak River, with its water primarily sourced from Mount Kendo. Upstream of the Penujak River lies the Batujai Reservoir, which plays a significant role in the operational dynamics of the Pengga Reservoir. The Mandalika Special Economic Zone, on the other hand, is located administratively within the Pujut District, also part of the Central Lombok Regency in West Nusa Tenggara Province, Indonesia. The distance from the Pengga Reservoir to the Mandalika Special Economic Zone (SEZ) is approximately 37.50 km, and it is about 51 km away from Mataram City. Figure 1 illustrates the geographic locations of the Pengga Reservoir, Batujai Reservoir, and the Mandalika Special Economic Zone (SEZ) in the Central Lombok Regency, West Nusa Tenggara Province, Indonesia.

2.2 Data Availability

The secondary data required for this research on the Pengga Reservoir were obtained from the River Basin Organization of Nusa Tenggara I and the Meteorology, Climatology, and Geophysical Agency. The utilized secondary data include:

a. Technical data of Pengga Reservoir, which are essential for determining the maximum, normal, and minimum storage capacities, as well as for ascertaining the elevation of the main dam's crest, spillway, and intake.

b. Historical inflow discharge data, employed to assess water availability for the Pengga Reservoir and to develop inflow discharge scenarios for a wet year (Q35%), a normal year (Q50%), and a dry year (Q65%). This analysis is based on 23 years of historical data, spanning from 1997 to 2020.

c. Rainfall data, used to calculate the average rainfall, effective rainfall for irrigation water needs, and evapotranspiration. The data were collected from the ARR Kabul and Kuripan rain stations, covering a period of 26 years from 1994 to 2020.

d. Evapotranspiration and evaporation calculations at Pengga Reservoir, which utilize climatological data provided by the Meteorology, Climatology, and Geophysics Agency in West Lombok Regency and the River Basin Organization of Nusa Tenggara I. This climatological data set includes temperature, relative humidity, sunshine duration, and wind speed, spanning a duration of seven years.

2.3 Reservoir Water Availability

The water availability in the reservoir is defined as the dependable flow (Yekti, 2017). For Pengga Reservoir, the calculation of water availability is based on historical discharge data spanning 23 years, from 1997 to 2020. The concept of dependable flow is crucial for identifying a discharge level that consistently exists in the river, serving as the inflow to the reservoir during its operational phase (Farriansyah et al., 2018). To optimize the utilization of water, calculations incorporate three inflow discharge scenarios: dry, normal, and wet years (Xu and Zhang, 2018). According to the reservoir operation pattern rules, probabilities of 35% for wet year inflow discharge, 50% for normal year inflow discharge, and 65% for dry year inflow discharge are applied (Ginting et al., 2017). The inflow discharge accounts for two primary sources: runoff from upstream reservoirs or watersheds and lateral inflow from tributaries (Wang et al., 2019). The probability of water availability in the reservoir is determined using the Weibull method (Li et al., 2017), with the equation presented as follows:

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

Where $P(x)$ is the probability value of water availability (%), m is the order of discharge data from the highest to the lowest value, and n is the total number of discharge data points.

2.4 Irrigation Water Requirement

The calculation of irrigation water requirements follows the guidelines from the Standard Irrigation Planning Criteria-01 (Jayadi et al., 2019). Rainfall data impacting the Pengga Reservoir's water catchment area derive from the Kabul and Kuripan ARR, spanning 26 years from 1994 to 2020. The cropping pattern in the Pengga irrigation area is Paddy-Paddy-Secondary Crops, with planting schedules set for November-I and November-II. Factors influencing irrigation water requirements include meteorology, agronomy and soil, and irrigation canal conditions (Heydari, Othman, Qaderi, Noori and Shahiriparsa, 2015). Percolation and seepage rates on clay soil types post-inundation range between 1 mm day^{-1} and 3 mm day^{-1} (Samosir et al., 2015). The duration allocated for land preparation is 1.5 months according to the tertiary map (Yasa et al., 2023). In instances of water availability deficit, potential solutions may involve reducing the irrigation area, modifying cropping patterns, or adjusting technical group rotations (Mboyerwa et al., 2022). Equation 2 delineates the water requirement for land preparation, with equation 3 specifying the water requirement during this phase:

$$PWR=\frac{\left(S_a-S_b\right)N.d}{10^4}+Pd+F1 \quad (2)$$

Where PWR is the water requirement for land preparation (mm), S_a is the degree of soil saturation before land preparation starts (%), S_b is the soil saturation degree before land preparation begins, N is the soil porosity percentage at average soil depth, d is the assumed soil depth after land preparation work (mm), Pd is the inundation depth after land preparation work (mm), and $F1$ is the water loss in the field for one day (mm).

$$IR=M.e^k/\left(e^k-1\right) \quad (3)$$

Where IR is the irrigation water requirement at the paddy field level (mm day^{-1}), M is the water requirement to replace water loss due to evaporation (mm day^{-1}), Eo is open water evaporation taken during land preparation (mm day^{-1}).

2.5 Domestic Water Requirement

The calculation of domestic water requirements within a region is based on its current population and anticipated population growth rates (Zhou et al., 2019). Several factors influence the demand for domestic water, including the population, industrial activities, agriculture, livestock, and tourism (Fang et al., 2014). In the context of this study, the domestic water demand designated for the Mandalika Special Economic Zone (SEZ) is established at 200 liters per second. This requirement was derived from a report by the River Basin Organization of Nusa Tenggara I, which focused on the development of a domestic water supply system at the Pengga Dam to support the Mandalika SEZ.

2.6 Optimization of Single Reservoir Operation

Linear programming optimization techniques are applicable for addressing operational challenges in reservoir management (Jamil et al., 2019). This approach encompasses three critical components: the objective function, decision variables, and constraint functions (Raju et al., 2020). The aim of the objective function in these optimization calculations is to achieve the highest possible annual cropping intensity (Maliwal et al., 2019). Decision variables represent the determinants that, when optimized, contribute to achieving the objective function most effectively (Long Le Ngo, 2007). These variables include the area of the irrigated land, the actual amount of irrigation water released, and domestic water requirements (Turner et al., 2021). Constraint functions represent the boundaries within which the optimization must operate to achieve the desired outcomes (Nandalal and Bogardi, 2007). The equation for the constraint function is provided below.

a) Planting area at the beginning of planting season I, II, and III

$$A_i\leq AI \quad (4)$$

Where A_i is the planting area in planting season i, i = I, II, III and AI is the irrigation area.

b) Storage volume of the reservoir

$$S_{min}\leq S\leq S_{max} \quad (5)$$

Where S_{min} is the minimum storage of the reservoir, S is the effective storage of the reservoir, and S_{max} is the maximum storage of the reservoir.

c) Actual release value

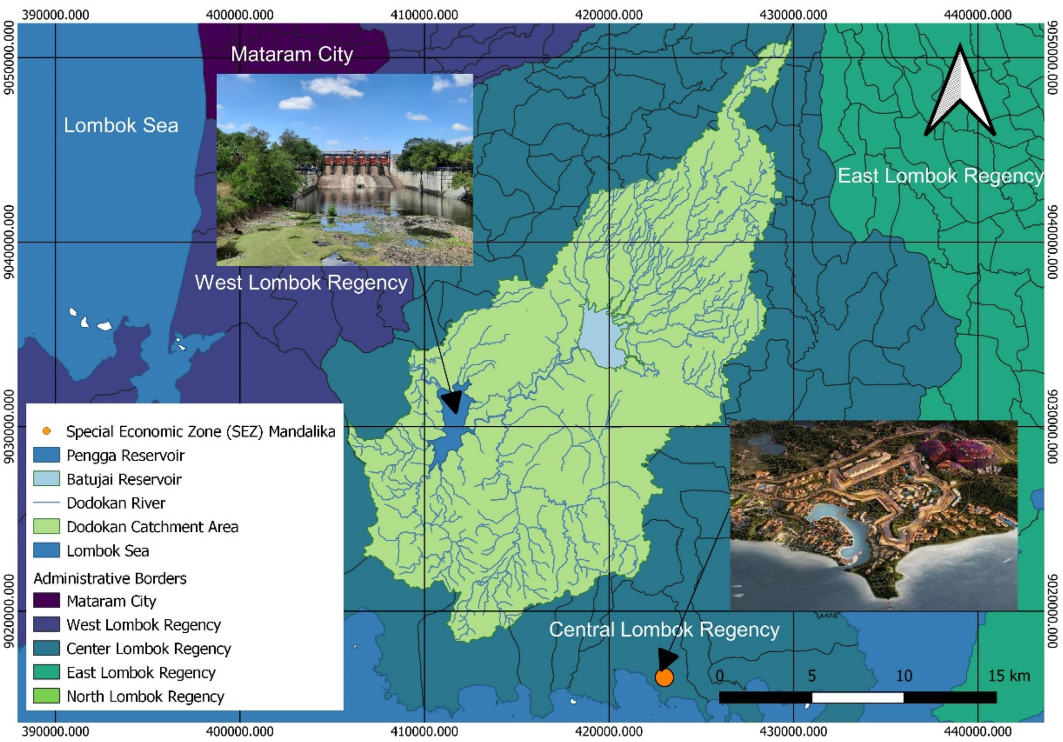

Figure 1 Map depicting the locations of Pengga Reservoir, Batujai Reservoir, and the Mandalika Special Economic Zone in Central Lombok Regency, Indonesia

$$AR \leq TR \tag{6}$$

Where AR is the actual release value of the reservoir and TR is the target release value of the reservoir.

d) The value of the k factor as a factor for meeting irrigation water and domestic water needs

$$k_t = \frac{AR_t irrigation}{TR_t irrigation} \tag{7}$$

$$k_t = \frac{AR_t domesticwater}{TR_t domesticwater} \tag{8}$$

Where k_t is the factor for meeting the needs of irrigation water and domestic water for period t, AR_t is the actual release for period t (MCM), TR_t is the target release for period t (MCM), and t is the release period.

e) Reservoir reliability

$$RI_{irrigation} = \frac{s_{irrigation}}{N} \times 100\% \tag{9}$$

$$RI_{domesticwater} = \frac{s_{domesticwater}}{N} \times 100\% \tag{10}$$

Where RI is the reservoir operation reliability (%), s is the number of times the reservoir release meets the conditions, and N is the unit length of the simulation or optimization calculation period.

3 RESULTS and DISCUSSION

3.1 Water Availability in Pengga Reservoir

The water availability in Pengga Reservoir is determined by the outflow from Batujai Reservoir and lateral inflow from several tributaries. Situated within the Dodokan watershed, the Pengga Reservoir benefits from a catchment area that spans approximately 550 km^2, with its own direct catchment area covering 352.65 km^2. The analysis of inflow discharge data for the reservoir, spanning from 1997 to 2023, utilizes half-month average discharge figures. Key tributaries contributing lateral inflow to the upstream area of Pengga Reservoir include the Serau, Mangkung, Mbau, and Rurut rivers. The geographical relationship between Pengga Reservoir, Batujai Reservoir, and the Mandalika Special Economic Zone is depicted in Figure 1. The lateral inflow volume is calculated by subtracting the outflow discharge from Batujai Reservoir from the inflow discharge to Pengga Reservoir. The calculation of water availability for Pengga Reservoir employs the Weibull method to establish the probability of inflow discharge under wet, normal, and dry year scenarios. This involves sorting 26 years of historical discharge data from highest to lowest and assigning probabilities of 35% for wet year, 50% for normal year, and 65% for dry year inflow discharge scenarios. The inflow discharge scenarios for Pengga Reservoir are illustrated in Figure 2, indicating that the maximum inflow for wet and normal years typically occurs in the first half of February, with peak values of 6.320 m^3 s^{-1} and 5.622 m^3 s^{-1}, respectively. For dry years, the maximum inflow discharge peaks in the first half of January, reaching 3.529 m^3 s^{-1}. Minimum inflow discharges for wet, normal, and dry year scenarios are recorded at 1.520 m^3 s^{-1}, 0.803 m^3 s^{-1}, and 0.424 m^3 s^{-1}, respectively.

3.2 Evapotranspiration and Evaporation at Pengga Reservoir

From 2016 to 2022, evapotranspiration and evaporation data were analyzed for Pengga Reservoir. The evapotranspiration rate was determined using the Penman-Monteith method. Subsequently, the evaporation rate was calculated by applying an evaporation coefficient of 1.10 to the evapotranspiration values (Rediasti et al., 2023). The peak values for evapotranspiration and evaporation were observed in the first mid-month of November, registering at 6.18 mm day^{-1} and 6.80 mm day^{-1}, respectively. These values are visually represented in Figure 3, which illustrates the evapotranspiration and evaporation trends at Pengga Reservoir.

3.3 Irrigation Water Needs in Pengga Irrigation Area

Irrigation areas in Central Lombok Regency and West Lombok Regency get irrigation water supply from Pengga Reservoir. Some indicators of irrigation utilization used in the Pengga Reservoir optimization calculation are:

a. The cropping pattern within the Pengga irrigation sector follows a Paddy-Paddy/Secondary Crops-Paddy/Secondary Crops rotation, with respective planting ratios of 100%-70%/30%-50%/50%.

b. Alternative planting schedules used are November I and November II.

c. The existing planting area for Pengga irrigation area is 3189 ha.

Table 1 displays the calculated irrigation water requirements for the Pengga irrigation area. The peak irrigation water demand for the November I planting season is determined to be 1.065 l s^{-1} ha^{-2}, occurring in mid-December. For the November II planting season, the maximum irrigation water requirement is recorded at 0.866 l s^{-1} ha^{-2}.

Table 1. The Value of Irrigation Water Demand in Planting Season I and II

No	Period		Day	Nov-I	Nov-II
				l s^{-1} ha^{-2}	l s^{-1} ha^{-2}
1	January	I	15	0.848	0.866
		II	16	0.734	0.862
2	February	I	14	0.687	0.760
		II	14	0.375	0.721
3	March	I	15	0.515	0.394
		II	16	0.519	0.633
4	April	I	15	0.675	0.458
		II	15	0.604	0.768
5	May	I	15	0.636	0.609
		II	16	0.647	0.695
6	June	I	15	0.631	0.612
		II	15	0.471	0.634
7	July	I	15	0.372	0.444
		II	16	0.378	0.377
8	August	I	15	0.542	0.363
		II	16	0.474	0.551
9	September	I	15	0.508	0.490
		II	15	0.466	0.532
10	October	I	15	0.488	0.500
		II	16	0.331	0.453
11	November	I	15	0.174	0.356
		II	15	0.174	0.174
12	December	I	15	0.885	0.112
		II	16	1.065	0.805

3.4 Domestic Water Needs in Mandalika Special Economic Zone

The Pengga Reservoir's potential is effectively harnessed to satisfy the domestic water demands within the Mandalika Special Economic Zone. Information regarding domestic water requirements was sourced from the River Basin Organization of Nusa Tenggara I. Currently, Pengga Reservoir is designated to fulfill the domestic water needs of the Mandalika Special Economic Zone, allocating 150 l s^{-1}, with an additional provision of 50 l s^{-1} for residential purposes. This allocation supports the Mandalika Special Economic Zone's infrastructure development for the Drinking Water Supply System in Pengga Reservoir, aimed at addressing the clean water requirements for the World Superbike and MotoGP events.

3.5 Water Balance in Pengga Reservoir

Analyzing the reservoir water balance is crucial for assessing the reservoir's capacity to meet both irrigation and domestic water demands. Figure 4 presents a graph depicting the annual water balance of the reser-

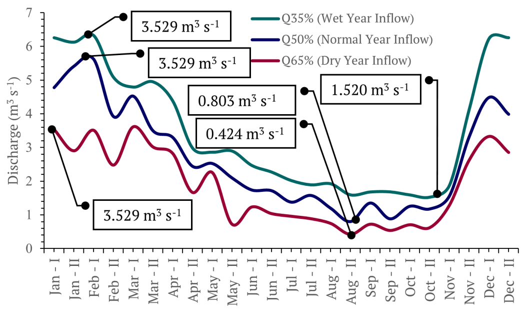

Figure 2 Graphs of Dry, Normal, and Wet Year Inflow Discharge Scenarios in Pengga Reservoir

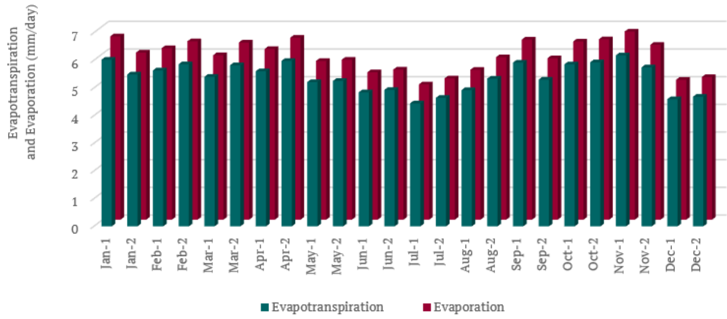

Figure 3 Evapotranspiration and Evaporation Values in Pengga Reservoir

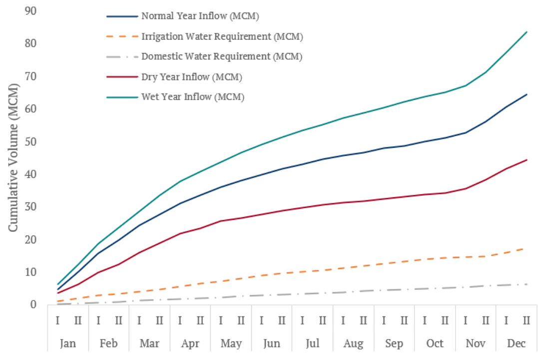

Figure 4 Water Balance for Water Availability, Irrigation Water Needs and Domestic Water in the Pengga Reservoir

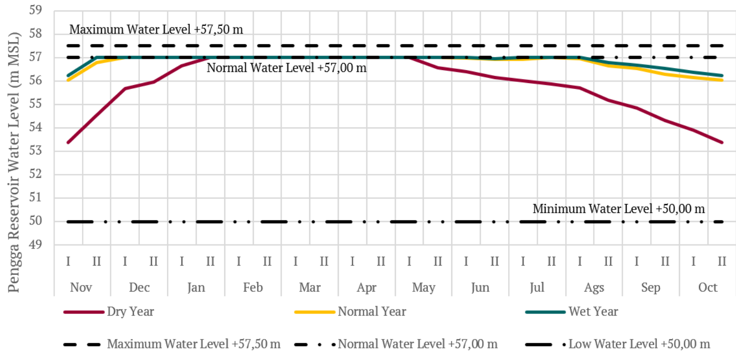

Figure 5 Graph of the Rule Curve for the November I Planting Schedule in Pengga Reservoir

voir, showcasing the cumulative total of annual water demands against the cumulative total of annual water availability. The graph illustrates that the water availability within Pengga Reservoir is adequate to satisfy the needs for both irrigation and domestic water.

3.6 Results of Reservoir Operation Optimization in Pengga Reservoir

The optimization calculation for Pengga Reservoir operations utilizes a wet year inflow discharge scenario with a probability of 35%, a normal year inflow discharge scenario with a probability of 50%, and a dry year inflow discharge scenario with a probability of 65%. The purpose of this optimization is to determine Pengga Reservoir's capacity to allocate water to the Mandalika Special Economic Zone and enhance the intensity of annual planting. Some of the variables determined in the optimization of reservoir operations include the size of the irrigation area and the actual release values for domestic and irrigation water needs in Pengga Reservoir. The results of the Pengga Reservoir operation calculations can be seen in Table 2.

The success of the optimization results in leveraging the potential availability of water in the reservoir is evident from the annual cropping intensity, the adequacy in meeting irrigation and domestic water needs, and reliability (Thomas et al., 2021). The total value of annual cropping intensity at the start of the November I planting season for dry, normal, and wet year inflow scenarios is 99.98%, 100%, and 100%, respectively. This total value of annual cropping intensity exceeds that of the November II planting season schedule. The maximum irrigated area achievable with the dry year inflow discharge scenario is 3188.38 ha, which is larger than the area during the November II planting season. The k factor values for irrigation and domestic water requirements meet the minimum limits of 0.70 and 0.85, respectively.

3.7 Rule Curve at Pengga Reservoir

The goal of the optimization calculation for reservoir operation is to develop a rule curve model aligned with the inflow probabilities influenced by climate change (Digna, 2021). The rule curve is defined by the upper normal operating limit curve and the lower normal operating limit curve (Agastya et al., 2023). Indicators for creating the rule curve include river flow conditions during the rainy season for the upper limit graph and the dry season for the lower limit graph (US Army Corps of Engineers, 1991). The maximum water level of Pengga Reservoir is set at elevation +57.50 m, and the minimum water level is at elevation +50.00 m. In formulating the rule curve, an important consideration is

Table 2. Optimization Results of Dry, Normal and Wet Year Inflow Discharge Scenarios in Pengga Reservoir

Indicators	Planting Season Schedule					
	November I			November II		
	Dry	Normal	Wet	Dry	Normal	Wet
Irrigation Planting Area (ha)	3188.38	3189.00	3189.00	3100.38	3101.26	3189.00
Crop Intensity (%)	99.98	100	100	97.22	97.25	100
k Factor Irrigation	0.71	0.79	1.00	0.70	0.72	0.70
k Factor Domestic Water	0.91	0.85	0.85	0.85	0.85	0.85
Irrigation Water Reliability (%)	100	100	100	100	100	100
Domestic Water Reliability (%)	100	100	100	100	100	100
Minimum Storage Volume (MCM)	5.67	13.15	14.07	6.41	13.93	17.09
Maximum Storage Volume (MCM)	17.26	17.26	17.26	17.26	17.26	17.26

ensuring that both the upper and lower normal operating limit curves revert to the initial water level (Wesli, 2015). The lower, middle, and upper normal operating limit curves have initial and final water levels of 53.37 m, 56.02 m, and 56.24 m, respectively. Policymakers are recommended to use the rule curve for the November I planting schedule, as depicted in Figure 5.

4 CONCLUSION

Based on the results of the reservoir operation optimization calculations for Pengga Reservoir, it has been determined that the optimal values of cropping intensity, k factor, and reliability are achieved in the November I planting season. This conclusion is drawn from comparing the cropping intensity values of the dry year inflow discharge scenario between the November I and November II planting seasons. In the November I planting season, the cropping intensity value reaches 99.98%, compared to 97.22% in the November II planting season. Considering the total domestic water demand of 200 liters per second for the Mandalika Special Economic Zone and Central Lombok Regency, Pengga Reservoir is capable of meeting the domestic water needs in the region. This conclusion is supported by the domestic water demand k factor meeting the required limit of 0.85 and a reliability of 100%. The rule curve graph for the November I planting season can serve as a guideline for reservoir operation.

DISCLAIMER

The authors declare no conflict of interest.

ACKNOWLEDGMENTS

Acknowledgments are due to the Ministry of Public Works and Housing – River Basin Organization of Nusa Tenggara I; Meteorology, Climatology, and Geophysical Agency and Indonesia Tourism Development Corporation (ITDC) for provided hydrological data and technical data for the Pengga Dam to complete this research.

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