Water use optimization of Benel Reservoir in Jembrana Regency, Bali Province

by Paper Icwrdep

Submission date: 18-Apr-2024 10:16AM (UTC+0700)
Submission ID: 2353457846
File name: 21.pdf (328.98K)
Word count: 3954
Character count: 20731

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Abstract. Benel Reservoir has a storage capacity of 1.71 million cubic meters (MCM) and has been supplying water for irrigation purposes. In line with population growth, the Benel Reservoir is projected to be capable of meeting the domestic water demand in the Jembrana Regency. As a result, this research aimed to determine the optimal water use in the Benel Reservoir for irrigation and domestic uses. The irrigation water requirements are necessary for an area of 1,047.3 hectares, while the domestic water demands are 64 l/s. F.J Mock Method of rainfall-runoff model is used to calculate water availability using 10 years of daily rainfall data and has been calibrated using observed discharged data from the Benel water level gauge station. The optimization model is formulated using linear programming. During wet years, the optimization result for water utilization with inflow discharge yields a cropping intensity value of 300%. The cropping intensity value of 287.50% in the scenario of normal inflow discharge. Furthermore, the cropping intensity value is 275% in the case of dry-year inflow discharge. Irrigation and domestic water demand met the minimum value limit of 0.70 and 0.85 for the k-factor. The reliability in supplying irrigation and domestic water reached 100%.

Keywords: Benel Reservoir, optimization, reliability, water balance, water use

1. Introduction

Benel Reservoir is located in the 18.86 km^2 catchment area of the Tukad Aya river basin. The water potential in this basin is sufficient to support Jembrana Regency's water needs, particularly for agriculture. The reservoir's construction was planned to meet the water needs of 1,047.30 hectares of land for irrigation [1]. According to the projections for the Jembrana Regency's population growth, the Benel Reservoir should be able to meet the demand for domestic water demand. The required amount of domestic water demand is 64 l/s [2]. The reservoir's potential availability of water can help mitigate the reduction in spring discharge. However, this issue has an impact on the water imbalance between irrigation and domestic water demands, potentially reducing its availability. An optimization analysis is then carried out to maximize the use of water from the Benel Reservoir to satisfy domestic and irrigation water demands to solve this issue.

The Benel Reservoir has the characteristics of 1.61 million m^3 of effective storage capacity and 305,000 m^3 of dead storage space. This capacity can be used to meet the water demand in the Jembrana Regency. Using linear programming, an irrigation and domestic water allocation optimization approach can be used to enhance its performance [3]. This study aims to maximize the annual cropping intensity by optimizing the release of water in the reservoir. Reservoir optimization uses a linear programming method by considering water availability, water supply priorities, storage characteristics, cropping patterns, and planting schedules [4]. Linear programming is an optimization method widely used in water resource planning and management problems. This method uses decision variable parameters, constraints, objective functions, and a solver to determine optimal operating decisions [5]. Linear programming can be used to provide effective solutions for reservoir operations to meet irrigation and domestic water needs [6].

2. Materials and Methods

2.1. Study Site

In Jembrana Regency, Benel Reservoir is administratively located between Berambang Village and Melaya Village. It covers an area of 18.7 km^2 and receives its water from the 8.87 km long Tukad Aya River. It is situated at 8'17'6.75" S and 114'36'16.86" E. The research's location is shown in Figures 1 and 2 below.

Figure 1. Benel Reservoir

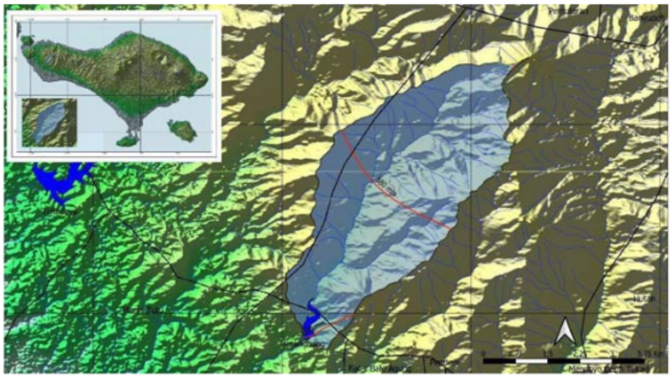


Figure 2. Map of Benel Reservoir Catchment Area

2.2. Secondary Data

The data for this study came from Balai Wilayah Sungai Bali Penida and The Meteorology, Climatology, and Geophysics Agency (BMKG) of Indonesia, specifically from the Jembrana Regency. The secondary data that was used are described below.

a) Benel Reservoir technical information

b) Daily rainfall data from Automatic Rainfall Recorder stations (ARR) Dauh Waru Station, Jembrana Station, Palasari Station, and satellite data from Japan Aerospace Exploration Agency (JAXA).
c) Climatological data of Jembrana Regency from Palasari Station.

Table 1. Automatic Rainfall Record Stations and Climatological Stations

Station	Coordinate		Parameter	Interval Data	Period
	E	N			
Palasari	114.547483	-8.252083	Rainfall & Climatological	Daily	2012-2021
Benel	114.604117	-8.284883	Rainfall	Daily	2012-2021
Dauh Waru	114.647650	-8.318900	Rainfall	Daily	2012-2021
Jembrana	114.617600	-8.341000	Rainfall & Climatological	Daily	2012-2021
JAXA			Rainfall	Hourly	2012-2021

d) Observed discharged data from Automatic Water Level Record (AWLR) in the Benel Reservoir (2010-2019).
e) Irrigation water demands data for 13 irrigation areas/ subak, namely Upper East Manistutu (42 ha), Lower East Manistutu (85 ha), Skak I (15 ha), Skak II (5.3 ha), Benel (170 ha), Tibu Paras (55 ha), Pangkung Buluh (135 ha), Peh (88 ha), Yeh Anakan (130 ha), Tegal Jati (147 ha), Kaliakah Munduk (55 ha), Pangkung Liplip (140 ha) and Tegal Brekis (93 ha). There are 1,047.3 ha of irrigation area.
f) Domestic water demand constantly (0,06 m^3/s) [2]

2.3. Reservoir Water Availability

The Tukad Aya River's flow provides the Benel Reservoir with its water supply. The F.J. Mock method is used to predict the upcoming discharge by modeling rainfall-runoff relationships. Utilizing rainfall information from the rain gauge stations at Palasari, Benel, Dauh Waru, and Jembrana, calibration of the Tukad Aya Watershed characteristics is done. The catchment area's features, rainfall data, evapotranspiration, infiltration coefficients, and soil moisture all contribute to an impact on how rainfall-runoff is calculated. The FJ. Mock equations that followed were used to calculate rainfall-runoff [7]

$$\Delta E = \frac{PET.m(18-n)}{20} \quad (1)$$

$$AET = PET - \Delta E \quad (2)$$

Equation (1) and Equation (2) show ΔE is the difference between actual and potential evapotranspiration, AET is actual evapotranspiration, PET is potential evaporation, m is the percentage of unvegetated land, n is the number of rainy days.

$$ER = P - AET \quad (3)$$

Where ER is the amount of excess rainfall (mm) and P is the amount of monthly precipitation (mm) as shown in Equation (3).

$$WS = ER - SM \quad (4)$$

Equation (4) shows SM indicates soil moisture (mm) and WS represents excess water (mm).

$$I = DIC \times WS; I = WIC \times WS \quad (5)$$

$$DRO = WS - 1 \tag{6}$$

The infiltration coefficients for the dry and wet seasons are represented in the equation above by *DIC* and *WIC*, respectively, while the runoff coefficient is denoted by *DRO* (mm).

$$GWS = 0.5 \times (1 + K) \times 1 + K \times IGWS \tag{7}$$

$$BF = 1 - (GWS - IGWS) \tag{8}$$

In this equation, *GWS* represents groundwater storage (mm), *K* for soil recession factor, *IGWS* for initial groundwater storage (mm), and *BF* for baseflow (mm).

$$TRO = DRO + BF \tag{9}$$

$$Qcal = \frac{A \times TRO \times 1000}{H \times 24 \times 60 \times 60} \tag{10}$$

TRO represents total runoff (mm), *Qcal* is calculated runoff discharge (m^3/s), The catchment area (km^2) is indicated by *A*, and the number of days in a calculation month is symbolized by *H*. Furthermore, the F.J. Mock method requires calibration with measured discharge data from the Benel Reservoir's Automatic Water Level Record to produce results consistent with the specific conditions and characteristics of the location.

2.4. Water Demands

Several factors, including irrigation area, evapotranspiration, percolation, crop efficiency, cropping pattern, irrigation efficiency, rainfall, and land preparation, were considered to estimate irrigation water demand [6]. A cropping pattern of paddy-paddy and paddy-secondary crops in the Benel Reservoir irrigation area, with planting schedules for the first week of November (I), the second week of November (II), and the first week of December (III). This equation is used to calculate the amount of water required for irrigation.

$$NFR = Etc + LP + P - Reff + WLR \tag{11}$$

NFR represents irrigation water requirement (mm/day); *Etc* symbolizes evapotranspiration (mm/day); and *LP* for land preparation water requirement (mm/day). The effective rainfall (mm/day) is indicated by *Reff*. Using this equation, the discharge of water demand at the intake gate could be calculated.

$$DR = \frac{NFR}{EI} \times A \times T \tag{12}$$

Water demand at intake is represented by *DR* (l/s/ha), water demand in paddy fields is symbolized by *NFR*, and irrigation efficiency is shown by *EI* (%).

2.5. Reservoir Simulation and Optimization

Reservoir operation simulation has a simpler analysis than optimization analysis used for continuity reservoirs. Simulation using the standard operating rule method can divide water needs into irrigation water needs and domestic water needs [8]. Reservoir simulation is determined to be successful if the reservoir water release can meet the minimum value of the k factor for domestic water needs of 0.85 and the irrigation water needs of 0.75 [9]. The simulation operation is conducted to assess the reservoir's current reliability under the implemented operational system [10], [11]. Furthermore, to establish the rule curve zones of the Benel Reservoir for different conditions. The analysis is performed using the following formula.

$$R(t) = 0\text{ ; where } S(t) + I(t) - E(t) - EF(t) \le DS \tag{13}$$

$$R(t) = S(t) + I(t) - E(t) - EF(t) - DS\,;\text{ where } S(t) + I(t) - E(t) - EF(t) - DS \leq RT \quad (14)$$

$$R(t) = RT\,;\text{ where } RT < S(t) + I(t) - E(t) - EF(t) - DS \leq RT + K - DS \quad (15)$$

$$R(t) = S(t) + I(t) - E(t) - EF(t) - K\,;\text{ where } S(t) + I(t) - E(t) - EF(t) > RT + K \quad (16)$$

The formulas for storage capacity (K), minimum storage (DS), initial storage (S), inflow (I), and losses from evaporation (E) define the correlation between release and the potential amount of water to be used. The equation below illustrates how reservoir storage, inflow, and outflow were all included in the water balance equation.

$$S(t+1) = S(t) + I(t) - E(t) - EF(t) - RI(t) - RB(t) \quad (17)$$

According to Equation (17) *S(t+1)* refers to reservoir storage volume (MCM), *S(t)* means reservoir storage at the start of the period (MCM), It symbolizes inflow (MCM), *E(t)* symbolizes evaporation (MCM), *EF(t)* is environmental water release (MCM), *RI(t)* is irrigation water release (MCM), and *RB(t)* indicates domestic water release (MCM). The optimization model included three critical components: the objective function, decision variables, and constraints [12], [13]. *RI(t)*, *RB(t)*, and planting area (ha) are decision variables in reservoir operation optimization with linear programs. The study's was to maximize the intensity of annual planting and to fulfill domestic water. Linear program constraints are used to calculate the release of irrigation water, domestic water, reservoir storage volume, and reservoir water level [14], [15].

3. Result and Discussion

3.1. Reservoir Storage Characteristics

Benel Reservoir has a normal water level of +171.50 m with a storage volume of 1.64 million m^3 and an inundation area of 17.39 ha. The floodwater level of Benel Reservoir is at an elevation of +173.64 m with a storage of 2.03 million m^3 and an inundation area of 18.87 ha. Figure 3 shows the relation between elevation, inundation area, and storage volume of the reservoir.

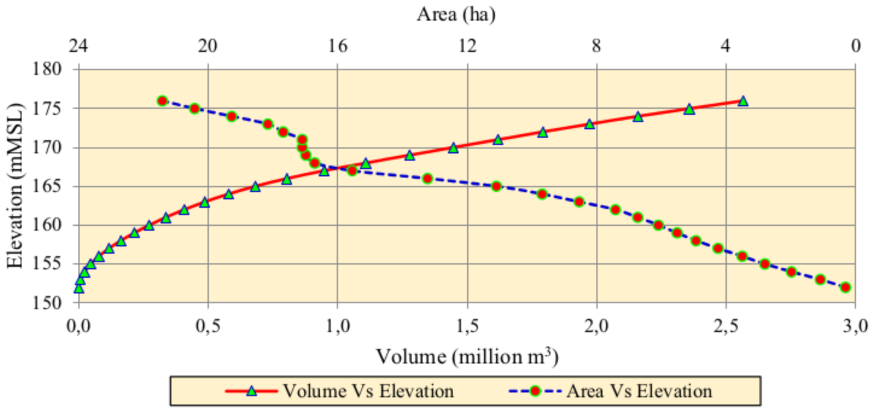


Figure 3. The characteristics curve of Benel Reservoir

3.2. Reservoir Water Availability

The analysis of water availability at the Benel Reservoir using the FJ.Mock method, transforming rainfall into runoff. Rainfall data are obtained from the Palasari station, Benel station, Dauh Waru station, Jembrana station, and satellite rainfall data sourced from JAXA. To determine the hydrological characteristics of the Benel Watershed, calibration is executed using the solver program in Microsoft Excel. The measured discharge employed for calibration is the recorded discharge from AWLR spanning the years 2010 to 2019. The calibration results reveal a strong correlation value of 0.816, as illustrated in Figure 4.

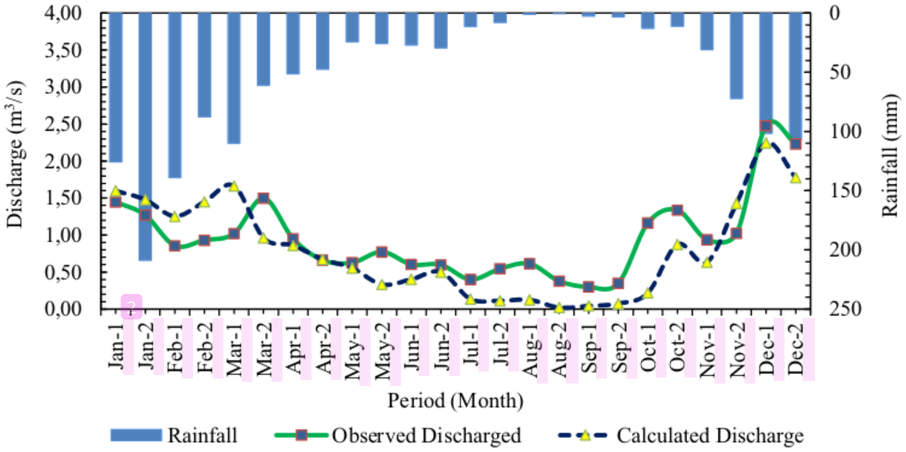


Figure 4. Parameter Calibration Graph

3.3. Potential Reservoir Inflow

According to the Figure 5, the analysis uses the basic month method by sorting the inflow value from the largest to the smallest value each month. The analysis is used to obtain wet-year discharge with an exceedance probability of 35%, normal-year discharge with an exceedance probability of 50%, and dry-year discharge with an exceedance probability of 65% using the Weibull continuous probability distribution method. The results of the calculation of the inflow discharge for the flow conditions of the wet, normal, and dry years will be used as input in the calculation of the simulation and optimization of the release by the priority policy of water demand services.

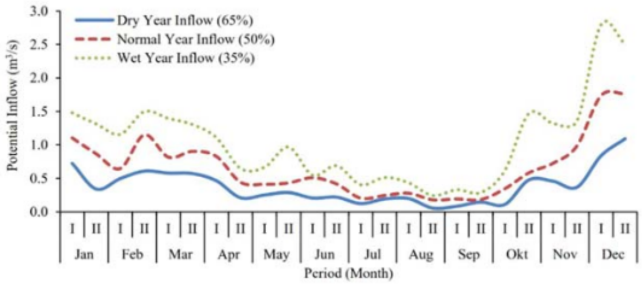


Figure 5. Reservoir Inflow for Dry, Normal, and Wet Years

3.4. Evapotranspiration

Analysis of potential evapotranspiration using the Penman-Monteith method with climatological data at Jembrana Station. The climatological data used are temperature, humidity, sunlight, and wind speed. The following Table 2 shows the results of the study.

Table 2. Result of Evapotranspiration Analysis

Month	Period	Eto mm/day	Month	Period	Eto mm/day
January	I	5.63	July	I	3.96
	II	5.28		II	3.81
	III	5.67		III	4.07
February	I	5.63	August	I	4.86
	II	5.79		II	4.90
	III	7.42		III	4.95
March	I	5.60	September	I	5.45
	II	5.82		II	5.68
	III	6.02		III	5.70
April	I	4.60	October	I	5.94
	II	4.52		II	5.58
	III	4.50		III	5.66
May	I	4.33	November	I	5.39
	II	4.20		II	5.98
	III	4.25		III	5.62
June	I	4.01	December	I	5.00
	II	3.92		II	4.96
	III	3.85		III	5.01

3.5. Irrigation and Domestic Water Needs

A simulation analysis of Benel Reservoir was conducted to determine the reservoir's ability to meet irrigation and domestic water needs in wet, normal, and dry year discharge conditions. Optimization analysis was carried out using a linear programming method to get maximum cropping intensity and planting area. Some constraints when conducting optimization analysis are that the actual release of irrigation and domestic does not exceed the target release value. The k-factor values should not be less than 0.7 for irrigation water needs and 0.85 for domestic water needs. The potential for reservoir storage can increase cropping intensity for the Benel irrigation area of 1,047.3 ha. The irrigation area will use three planting seasons with a cropping pattern of paddy-paddy/paddy-corn/corn.

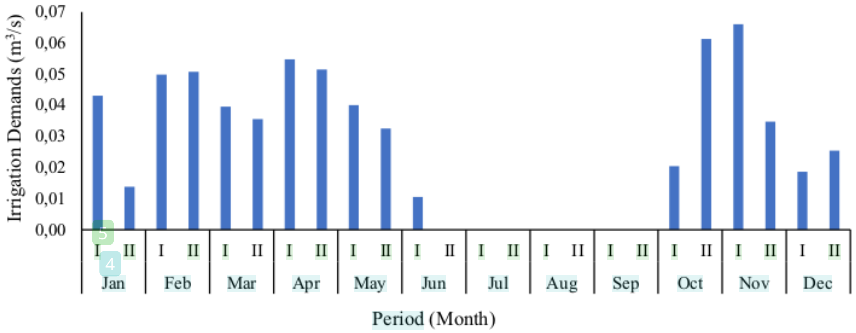


Figure 6. Irrigation Water Demands Upper Intake

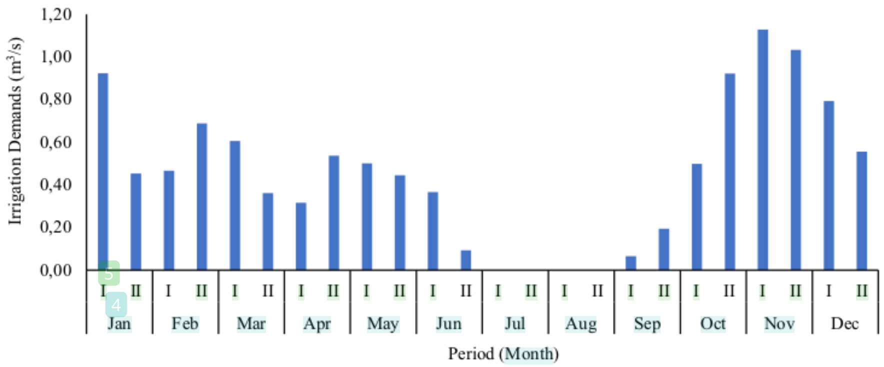


Figure 7. Irrigation Water Demands Lower Intake

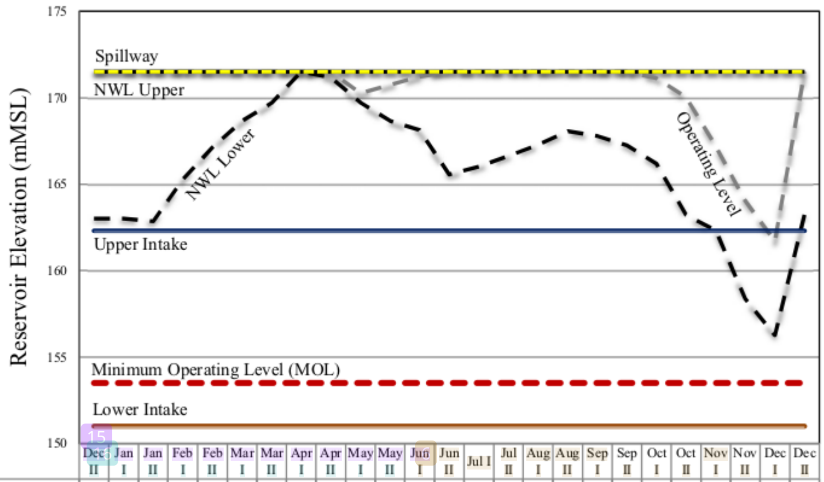
Based on Figure 6, the highest irrigation water demand at the upper intake of the Benel Reservoir amounts to 0.07 m^3/s. This upper intake serves the irrigation areas of Subak Manistutu Timur and Subak Tibu Paras. According to Figure 7, it showed the highest irrigation water demand at the lower intake, totaling 1.13 m^3/s. The lower intake of the Benel Reservoir caters to the irrigation areas of Subak Skak I, Subak Skak II, Subak Benel, Subak Pangkung Buluh, Subak Peh, Subak Yeh Anakan, Subak Tegal Jati, Subak Kaliakah, Subak Munduk, Subak Pangkung Lipip, and Subak Tegal Brekis. Furthermore, the domestic water requirement for drinking water is also sourced from the lower intake of the reservoir, amounting to 0.064 m^3/s for each period.

3.6. Reservoir Optimization

The irrigation and domestic water demand information became an indicator for optimizing reservoir water utilization. The reservoir water utilization review considered water availability during dry, normal, and wet years. The optimization result showed that the maximum annual cropping intensity for dry, normal, and wet years was 275%, 287.50%, and 300%, respectively. For dry, normal, and wet years, irrigation reliability was 91.7%, 95.8%, and 100%, respectively. Furthermore, domestic water demand was 100% reliable for all three years. The k-factor value was kept to a minimum of 0.70 for irrigation and 0.85 for domestic water demand.

3.7. Rule Curve

The optimal utilization of reservoir water has become effective in accommodating the specific cropping patterns for each irrigation region or subak, along with the domestic water needs. Rule curves delineate the regulations governing the operational water level limits of the Benel Reservoir. Based on the optimization outcomes, a planned water level, referred to as the operating level, is established for the operational use of the Benel Reservoir. Figure 8 illustrates the Minimum Operation Level (MOL), Upper Normal Water Level (NWL), Lower Normal Water Level (NWL), and the elevations of the spillway, upper intake, and lower intake. It is anticipated that this approach will enhance the operational performance of the Benel Reservoir, enabling reservoir operators to conduct operations in alignment with the designated operating level. This will ensure the fulfillment of both irrigation water and domestic water requirements.



	Dec II	Jan I	Jan II	Feb I	Feb II	Mar I	Mar II	Apr I	Apr II	May I	May II	Jun I	Jun II	Jul I	Jul II	Aug I	Aug II	Sep I	Sep II	Oct I	Oct II	Nov I	Nov II	Dec I	Dec II
NWL Lower	163,	163,	162,	165,	167,	168,	169,	171,	171,	169,	168,	168,	165,	166,	166,	167,	168,	167,	167,	166,	163,	162,	158,	156,	163,
Operating Level	171,	171,	171,	171,	171,	171,	171,	171,	171,	170,	170,	171,	171,	171,	171,	171,	171,	171,	171,	171,	170,	167,	164,	161,	171,
NWL Upper	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,
Spillway	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,	171,
MOL	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,	153,
Lower Intake	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151	151
Upper Intake	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162	162

Figure 8. Rule Curve of Benel Reservoir

4. Conclusion

The highest inflow discharge for dry, normal, and wet years is determined to be 1.091 m^3/s, 1.735 m^3/s, and 2.794 m^3/s, respectively, based on an analysis of Benel Reservoir water availability using the FJ. Mock method. The water utilization optimization analysis of Benel Reservoir yields guidelines for effective reservoir operation, which can be used as a reference for operational decisions. For dry, normal, and wet years, the maximum annual cropping intensity is 275%, 287.50%, and 300%, respectively. The dry year inflow scenario has the lowest irrigation reliability of 91.7%, while the wet year inflow scenario has the highest irrigation reliability of 100%. Domestic water demand was provided at 100% in all inflow scenarios. The k-factor values also meet the minimum requirements for irrigation and domestic water needs, which are 0.70 and 0.85, respectively. Furthermore, operational rule curves must be used with the designated operating level to meet the planned water requirements.

Acknowledgments

The author would like to express gratitude to the Bali Penida River Council for supporting the secondary data and also to Warmadewa University for financial support of this research.

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