Analysis of the Operational Pattern of the Bili-Bili Reservoir in Gowa District, South Sulawesi Province

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ABSTRACT

The Bili-Bili Reservoir serves multiple purposes, including flood control, raw water supply, irrigation, and hydropower generation. In 2021, significant discrepancies were observed between the Annual Reservoir Operation Plan (AROP) and the actual Reservoir Operation Pattern (ROP). during the first 15 days of December 2021, the AROP targeted a rest water level (RWL) of +77.34 m with a planned discharge of 20.27 m³/sec. In contrast, the actual RWL reached +92.35 m with an actual discharge of 45 m³/sec. This study aims to analyze the causes of these differences and compare the reservoir operations outlined in the AROP with those reflected in actual utilization, using an operational pattern simulation based on variations in irrigation water requirement (IWR). Analysis using a dependable flow of 80% shows that the total IWR in the AROP is only 69% of the IWR calculated from actual reservoir utilization, likely due to declining inflow trends and an operational pattern that adjusts to inflow magnitude and rainfall. Meanwhile, the realized IWR is 32% greater than the utilization analysis and 91% greater than the AROP, indicating that the reservoir released more water than planned, following actual inflow conditions. This study highlights the need for more adaptive reservoir operation planning to ensure effective water resource management.

Keywords: Annual ROP, Irrigation Water Requirement, Actual Operation Pattern, Reservoir Operation, Simulation

1. INTRODUCTION

As the largest reservoir in South Sulawesi, the Bili-Bili Reservoir was built to control flood discharge from the Jeneberang River and supply water to Gowa, Takalar, and Makassar [1]. It serves multiple purposes, including flood control, raw water supply, irrigation over ±23,672 ha, and hydroelectric generation of 20.1 MW [2].

In 2021, significant discrepancies were noted between planned and actual operations, especially in early December. The Annual Reservoir Operation Plan (AROP) targeted a rest water level (RWL) of +77.34 m with an outflow of 20.27 m³/s, while the actual RWL reached +92.35 m with 45 m³/s outflow.

This deviation indicates a gap between long-term planning and field conditions. Higher storage and discharge may reduce flood buffering and disrupt water distribution. Since AROP is based on historical data, it remains vulnerable to hydrological and climatic variability [3].

Globally, reservoir studies increasingly address uncertainty and multi-sector needs using adaptive models. However, similar studies in Indonesia are limited. This research examines the causes of AROP deviations and evaluates irrigation water use to improve future reservoir operations.

2. THEORY AND METHODS

2.1 Theory

2.1.1 Dependable Flow Analysis

Dependable flow is defined as the river discharge available at a specific reliability level, associated with a probability or return period [4]. This study applied the monthly base planning method to capture seasonal variability [5]. Based on KP-01 [6] and SNI 6738 [7], 80% reliability is used for irrigation. The dependable discharge (Q_{80}) was calculated using the Weibull method [8].

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

where:
P = probability of exceedance
m = rank (position in descending order)
n = total number of data

2.1.2 Rainfall Data Consistency Test

A consistency test ensures the collected data is valid for use. Two commonly used methods are the double mass curve and the Rescaled Adjusted Partial Sums (RAPS) method. The double mass curve checks consistency by comparing cumulative annual rainfall at a test station with that of a reference station, while RAPS evaluates a single station's data based on cumulative deviation from the mean [9].

2.1.3 Potential Evapotranspiration (ETo)

The potential evapotranspiration (ETo) was calculated using the FAO-modified Penman–Monteith method, as it is suitable for a wide range of climatic conditions and provides detailed estimates. The ETo was calculated based on Equation (2) [10].

$$ET_0 = c \times (W \times R_n + (1 - W) \times (ea - ed) \times f(u)) \quad (2)$$

where:
ET0 = potential evapotranspiration (mm/day)
c = Penman correction factor
W = weighting factor based on temperature and elevation
R_n = net radiation equivalent to evaporation (mm/day)
e_a = saturated vapor pressure (mbar)
ed = actual vapor pressure (mbar)
f(u) = wind speed function

2.1.4 Irrigation Water Requirement (IWR)

The irrigation water requirement (IWR) is analyzed by accounting for the natural water contribution from rainfall and groundwater [11]. The IWR is calculated using Equation (3) [12].

$$IWR = \frac{(ETc + P + WLR + IR - Re)}{IE} x\ A \quad (3)$$

where:
IWR = irrigation water requirement (L/s)
ET_a = crop consumptive use (mm/day)
P = percolation (mm/day)
WLR = soil water replacement requirement (mm/day)
IR = land preparation water requirement (mm/day)
Re = effective rainfall (mm/day)
IE = irrigation efficiency (%)
A = irrigated area (ha)

- Crop Consumptive Water Use (ETc)
  Crop consumptive water use refers to the amount of water required for evapotranspiration processes. ETc is calculated using Equation (4) [12].

$$ET_c = K_c \times ET_0 \tag{4}$$

where:
ETc = crop evapotranspiration (mm/day)
Kc = crop coefficient
ET_0 = potential evapotranspiration (mm/day)

- Percolation
  The percolation rate is influenced by soil properties, which are related to land use activities. For clay-type soils, the typical percolation rate ranges from 2 to 3 mm/day [13].

- Soil Water Replacement Requirement (WLR)
  The soil water replacement requirement refers to the amount of water needed to replenish the soil water layer lost due to crop evapotranspiration and field-level water losses. The replacement is typically applied twice, each with 50 mm of water, during the first and second months after transplanting, which is equivalent to 3.3 mm/day over a half-month period [12].

- Land preparation water requirement (IR)
  The land preparation water requirement is calculated using the method developed by Van de Goor and Zijlstra [14], as adopted by the Ministry of Public Works and Housing (2013). It is determined using Equation (5) [12].

$$IR = \frac{Me^k}{(e^k - 1)} \tag{5}$$

where:
IR = irrigation water requirement at the field level (mm/day)
M = water requirement to replace losses due to evaporation ($M = E_o + P$) (mm/day)
E_o = open water evaporation ($E_o = 1.1 \times ET_o$) (mm/day)
P = percolation (mm/day)
k = preparation factor ($k = M \times T / S$)
T = duration of land preparation (days)
S = soil saturation water requirement (200 mm) plus surface water layer (50 mm), in total 250 mm

- Effective Rainfall (Re)

Effective rainfall is the portion of dependable rainfall available for plant growth. For irrigation, 80% reliable rainfall is processed using the Weibull method. According to the Ministry of Public Works and Housing [5], 70% of R_{80} is considered effective, with 20% assumed lost. Effective rainfall is calculated using Equation (6) [15].

$$R_e = 0{,}7 \times \frac{R_{80}}{15} \tag{6}$$

where:
R_e = effective rainfall (mm/day)
R_{80} = dependable rainfall with 80% probability (mm)

- Irrigation Efficiency

  Irrigation efficiency is the ratio between the discharge released from the intake structure and the amount of water effectively used in the field, expressed as a percentage. Based on KP-01 guidelines [3], an irrigation efficiency value of 65% was used in this study.

2.1.5 Reservoir Water Losses

Water losses in a reservoir are generally caused by evaporation and seepage. Evaporation is calculated using the mass transfer method, which is based on diffusion transfer, as shown in Equation (7) [12].

$$E = 0{,}35(0{,}5 + 0{,}54u_2)(ea - ed) \tag{7}$$

where:
E = evaporation (mm/day)
u_2 = wind speed at 2 meters height (m/s)
e_a = saturated vapor pressure (mmHg)
ed = actual vapor pressure (mmHg)

2.1.6 Reservoir Operation Pattern (ROP)

The reservoir operation pattern (ROP) serves as a guideline for managing the reservoir in which the released discharge must be regulated according to specified rules to maintain the water level within the design range. The simulation of reservoir operation follows the mass balance equation shown in Equation (8) [14].

$$S_{t+1} = S_t + Q_t - O_t - E_t - L_t \tag{8}$$

where:
S_{t+1} = reservoir volume at time t+1
S_t = reservoir volume at time t
Q_t = reservoir inflow (m³)
O_t = reservoir outflow (total water demand) (m³)
E_t = evaporation loss (m³)
L_t = seepage loss (m³)

In this simulation, it is assumed that reservoir releases are used only to meet irrigation, raw water supply, and hydropower demands. Emergency releases or extreme conditions are not considered.

2.2 Methods

2.2.1 Research Location

The study was conducted at the Bili-Bili Reservoir in Bili-Bili Village, Gowa Regency, South Sulawesi. Built on the Jeneberang River, the reservoir functions as key infrastructure for flood control, raw water supply, and irrigation. The river merges with the Jenelata River before discharging into the Makassar Strait.

Technical specifications of the reservoir, obtained from BBWS Pompengan Jeneberang (2024), are presented as follows:

- Catchment area : + 384.40 km^2
- Normal Water Level (NWL) : EL. +99,50 m
- Lowest Water Level (LWL) : EL. +65,00 m
- Supplementary Water Level (SWL) : EL. + 101,6 m
- Total Storage Capacity : 305,55 million m^3
- Effective Storage Capacity : 248.18 million m^3

The Bili-Bili Reservoir serves multiple purposes, including irrigation over ±23,672 ha, hydropower generation, and raw water supply. Its location is shown in Figure 1.

Figure 1. Location of Bili-Bili Reservoir

2.2.2 Research Data

The data used in this study are secondary data obtained from official institutions relevant to the research. The types of data and their sources are presented in Table 1.

Table 1. Types and Sources of Research Data

Data Type	Data Source	Description
Bili-Bili reservoir technical data	BBWS Pompengan Jeneberang	Elevation, volume, inundation area
Climatological data		Bontobili Station, 2012–2021
Jeneberang River daily discharge		Daily discharge, 2013–2021
Reservoir operation pattern		AROP and Actual Operation, 2021
Planting pattern (Jeneberang Catchment)		Year 2021
Reservoir water utilization data		Allocation for irrigation and hydropower (PLTA)
Bathymetry and inundation area		Survey results, 2020
Daily rainfall data	South Sulawesi Provincial Water Resources Agency	Malino & Sungguminasa Stations, 2012–2021

2.2.3 Research Procedure

This study analyzed Bili-Bili Reservoir operations using a water balance approach at 15-day intervals. The simulation evaluates the effectiveness of the Annual Reservoir Operation Plan (AROP) in meeting actual water demands and compares it with real operational conditions. Three simulation approaches used in this study are as follows:

1. Simulation based on water demand and utilization: Based on actual data for irrigation, raw water, and hydropower (PLTA) demand during 2021.
2. Simulation based on the Annual Reservoir Operation Plan (AROP) 2021: Uses planned elevation and outflow data as from the AROP document.
3. Simulation based on actual reservoir operation in 2021: Uses recorded actual elevation and discharge data during 2021 operations.

Each simulation applies a water balance model considering inflow, demand, evaporation, and storage volume based on the elevation–volume curve. The research steps are shown in Figure 2.

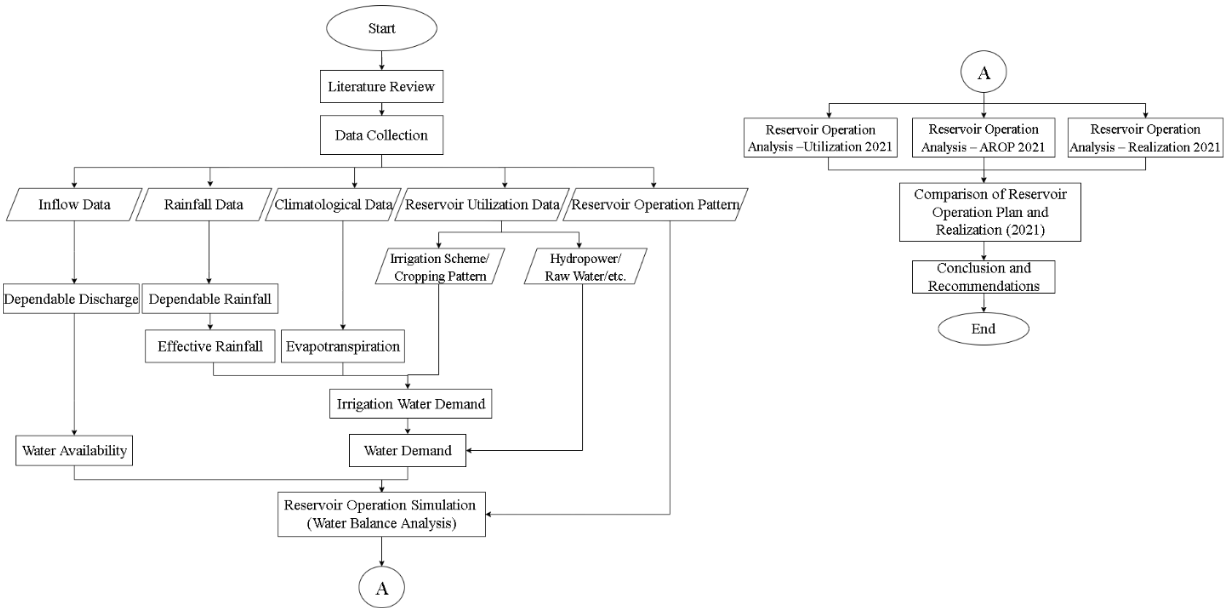

Figure 2. Research Flowchart

3. RESULTS AND DISCUSSION

3.1 Rainfall Consistency Test

Rainfall data consistency was tested using the RAPS method, as both stations were analyzed individually. RAPS yields unitless statistical values indicating the stability of annual rainfall trends by comparing calculated Q values to critical thresholds at a given confidence level. Results for Malino and Sungguminasa stations are shown in Table 2.

Table 2. Consistency Test of Rainfall Stations in the Jeneberang Catchment Area

Station	Q_{calc} vs $Q_{critical}$ (95%)	Result	R_{calc} vs $R_{critical}$ (95%)	Result
Malino	0,806 < 1,114	Consistent	0,698 < 1,114	Consistent
Sungguminasa	0,113 < 1,28	Consistent	0,135 < 1,28	Consistent

3.2 Potential Evapotranspiration

Potential evapotranspiration was calculated using the FAO-modified Penman-Monteith method with climatological data from Bonto Bili Station (2012–2021). Average monthly values are shown in Figure 3, with the highest rate in October at 4.664 mm/day.

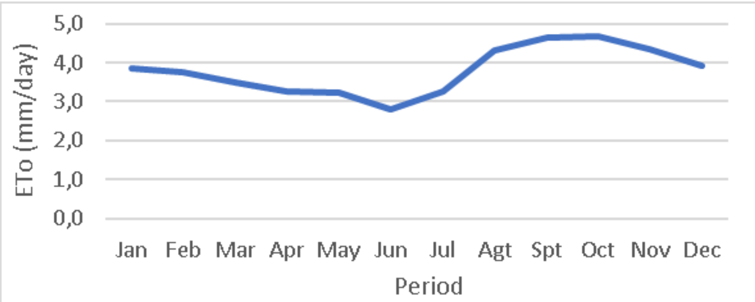

Figure 3. Jeneberang Catchment Potential Evapotranspiration

3.3 Dependable Flow

The dependable flow analysis of the Jeneberang Catchment was conducted using daily discharge data from the Jeneberang River for the period 2013–2021. Using the Weibull method, the dependable flow with 80% reliability was found to be 19.46 m^3/s, and with 90% reliability was 14.55 m^3/s. The dependable flow was calculated using the planning base-month method and is illustrated in Figure 4.

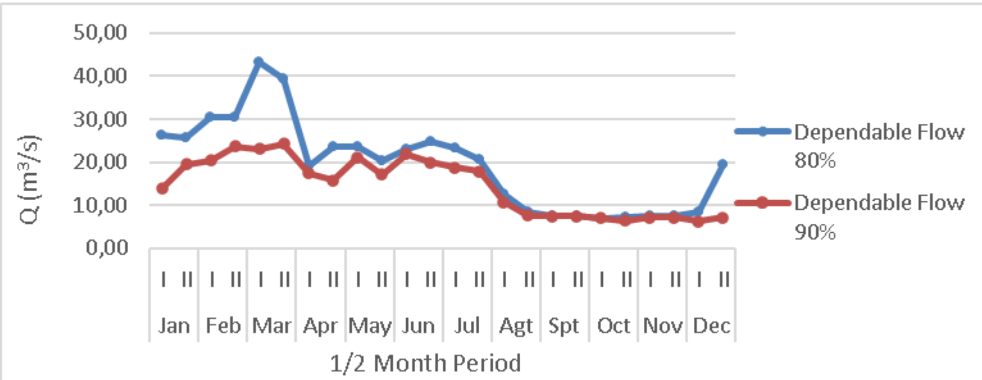

Figure 4. Jeneberang Catchment Dependable Flow

3.4 Effective Rainfall

Using the Weibull method, the average dependable rainfall (R_{80}) was determined to be 4.28 mm. This dependable rainfall was then used to analyze effective rainfall. An effective rainfall of 80% was applied for paddy fields, while 50% was used for secondary crops. The results of the effective rainfall analysis are shown in Figure 5.

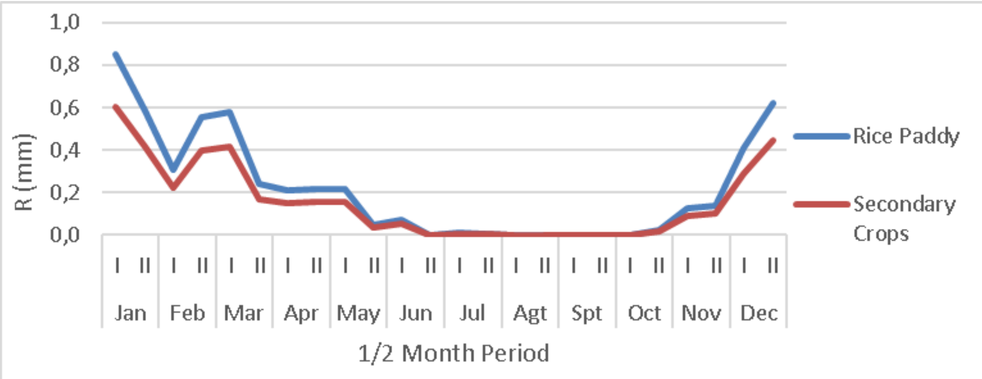

Figure 5. Jeneberang Catchment Effective Rainfall

3.5 Irrigation Water Requirement

The irrigation water requirement was calculated based on the cropping pattern in the Jeneberang Catchment, covering three irrigation areas: Bili-Bili (2,342 ha), Bissua (10,785 ha), and Kampili (10,545 ha), as shown in Figure 6.

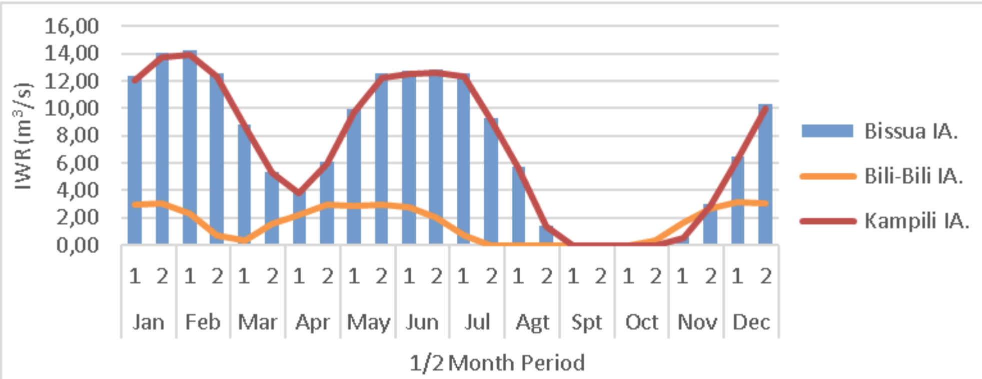

Figure 2. Jeneberang Catchment Irrigation Water Requirement

3.6 Reservoir Water Utilization Demand

Other water demands related to reservoir use include hydropower (8 m^3/s per turbine), raw water supply (3.3 m^3/s), industrial needs (0.5 m^3/s), and environmental flow for river maintenance (0.86 m^3/s).

3.7 Reservoir Water Losses

Water loss from the reservoir due to evaporation is shown in Figure 7. The highest evaporation occurred in September, reaching 0.561 mm/day.

The average annual seepage rate of the reservoir, as reported by BBWS Pompengan Jeneberang, is 0.24 m^3/s.

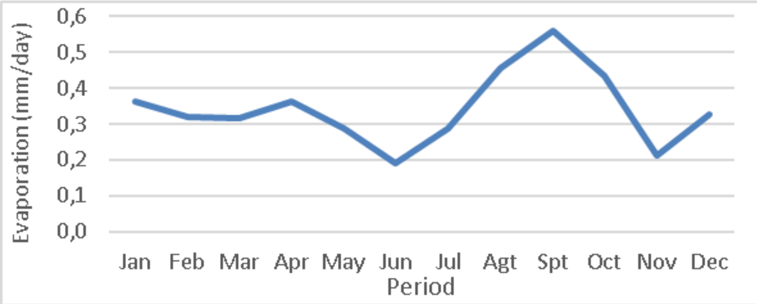

Figure 3. Jeneberang Catchment Evaporation

3.8 Reservoir Operation

Reservoir operation was analyzed using the water balance method with three simulation approaches, each differing in irrigation demand assumptions. The first two (utilization-based and 2021 AROP) used 80% dependable flow (Q_{80}), while the third (actual 2021 operations) used observed inflow. Results are shown in Table 3.

Table 3. Summary of Bili-Bili Reservoir Operation Simulations

		Reservoir Storage			**Reservoir Water Demand**		**Reservoir Reliability Rate**
		Elevation (m)	**Volume** (million m^3)	**Period**	***Outflow*** (m^3/det)	**Period**	
Utilization	Highest	96,11	192,24	Apr II	35,70	Jan II	96%
	Lowest	65,00	110,41	Dec II	12,45	Sep II	
AROP	Highest	99,50	242,18	Mar I-II, Apr I-II, May I-II	28,83	Jun I-II, Jul I-II	100%
	Lowest	86,52	136,72	Dec II	12,45	Sep II	
Actual	Highest	99,50	242,18	Jan II, Feb I-II, Maret I, April I-II, Nov I-II, Dec I-II	45,00	Jan I-II, Feb II, Maret II, Oct II, Dec II	100%
	Lowest	96,25	194,16	Jan I	10,00	Oct I	

3.9 Analysis of Reservoir Operation Differences

Differences in reservoir operation are compared based on irrigation water requirements (IWR). Any excess or spilled water is considered part of the irrigation demand.

- Utilization-Based Operation vs. AROP

  As shown in Figure 8, the IWR from AROP is relatively lower than the utilization-based approach, especially during the early and mid-year periods. Annually, AROP meets only 69% of the utilization-based IWR, indicating underestimation in planned allocations.

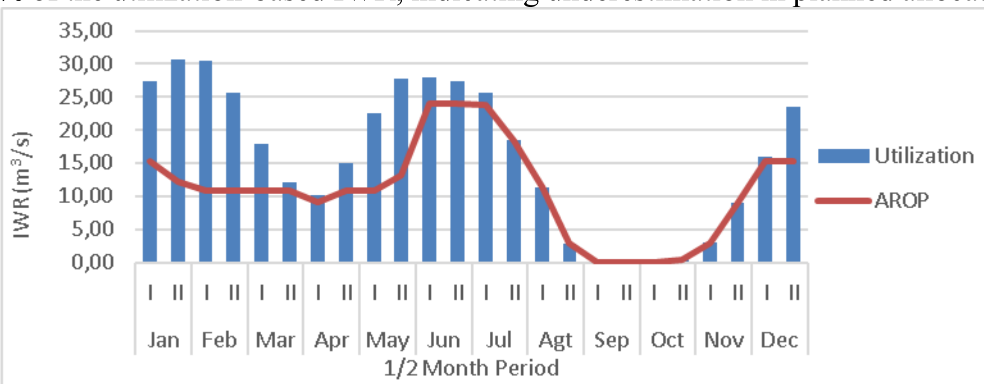

Figure 8. Comparison of IWR: Utilization-Based vs. AROP

The difference in IWR is caused by:

1. Declining reservoir inflow

As shown in Figure 9, average inflow from 2013 to 2020 shows a downward trend. Fully meeting IWR could risk reservoir depletion, as Table 3 indicates only 96% reliability. Thus, discharge in the operation plan is reduced to avoid operational failure.

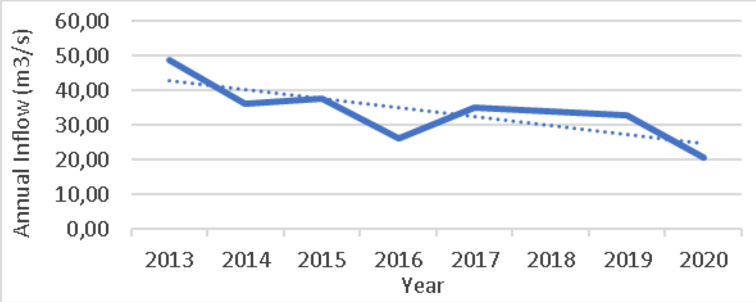

Figure 9. Inflow Trend of Bili-Bili Reservoir

2. The reservoir operation plan is influenced by inflow and rainfall patterns

As shown in Figure 10, from late January to early May, IWR in the AROP is lower than in the utilization-based analysis despite high inflow. This is because outflow is reduced during the peak rainy season, when rice fields can rely on rainfall. Consequently, the reservoir stores more water during this time and increases releases later, especially entering the dry season around July I.

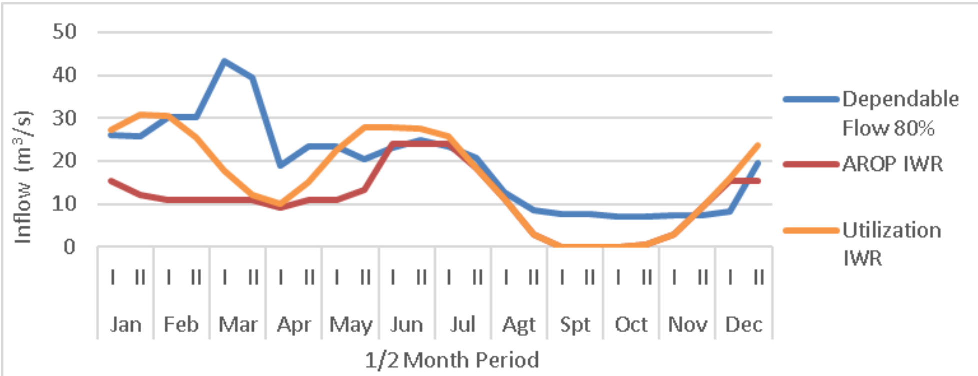

Figure 10. Comparison of IWR Based on Dependable Flow, AROP, and Utilization Analysis

- Comparison of Reservoir Operations: Utilization, AROP, and Actual

In 2021, the actual irrigation water demand (IWR) served was 90% higher than the planned AROP values and 29% greater than the demand estimated in the utilization analysis. This comparison is shown in Figure 11.

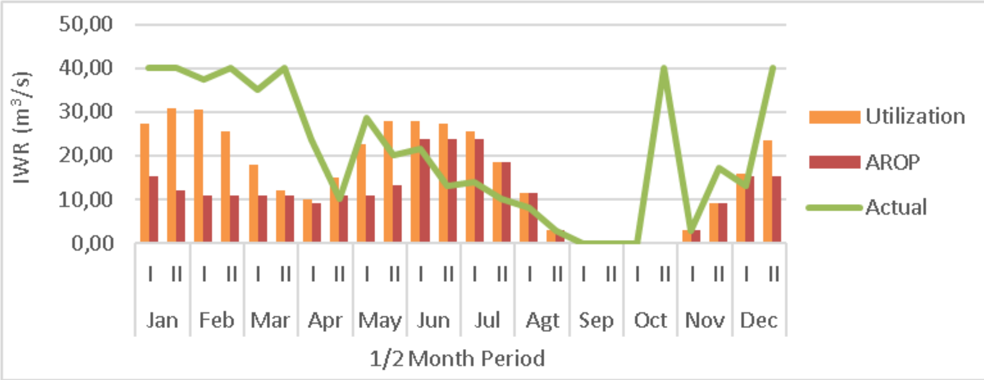

Figure 11. IWR Based on Utilization Analysis, AROP, and Actual Reservoir Operation

Causes of IWR Differences:

1. Irrigation supply exceeded the planned discharge

   The actual reservoir operation provided more irrigation water than planned in the AROP, which only partially targeted irrigation demand. As shown in Figure 11, higher water releases were achieved without operational issues. Between January I and April I, additional outflow was likely intended to maintain storage elevation within safe operational limits.
2. Reservoir operation follows inflow pattern

   Irrigation discharge in 2021 closely followed inflow trends. As shown in Figure 12, during high inflow periods (January I to April I), actual discharge exceeded the AROP plan, despite the rainy season. This was likely a regulated release to manage reservoir storage levels in response to increased inflow and rainfall.

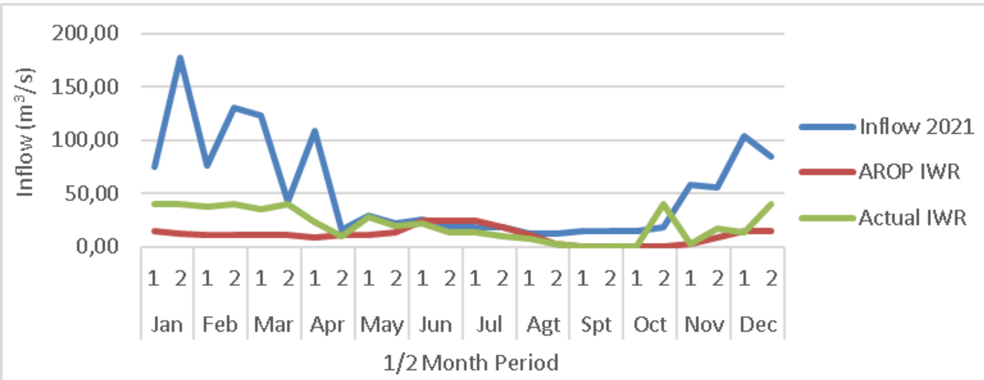

Figure 12. Comparison of Inflow, AROP IWR, and Actual 2021 Operation

4. CONCLUSIONS

With an 80% dependable flow of 19.46 m³/s, Bili-Bili Reservoir can meet irrigation demand at 100% reliability. Actual operation yielded the highest IWR—29% above utilization-based and 90% above AROP—due to declining inflows, AROP assumptions, and discharge adjustments responding to real-time inflow conditions.

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