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Hydrological Discharge and Hydropower Capacity Assessment for Sustainable Watershed Management

Utamy Sukmayu Saputri[1], Niar Armayanti[2], Thomasonan Lutfie Prananto[3]
[1,2]*Civil Engineering Study Program, Faculty of Engineering, Computer, and Design, Nusa Putra University Sukabumi.*
[3]*Civil Engineering Department, Universitas 17 Agustus 1945 Semarang.*
Email : [1] Utamy.sukmayu@nusaputra.ac.id . [2*] niar.armayanti_ts21@nusaputra.ac.id.*
[3]thomasonanlp@untagsmg.ac.id*

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ABSTRACT

The fluctuation of Cicatih River discharge presents a significant challenge in maintaining the operational performance of the Ubrug Hydropower Plant (HPP) in Sukabumi. Dependence on seasonal variations directly influences turbine efficiency and the continuity of electricity generation. This study aims to analyze the existing discharge of the Cicatih River, determine the efficiency of Ubrug HPP turbines, and evaluate the optimal discharge based on seasonal conditions. A quantitative approach was applied using the F.J. Mock hydrological simulation method to estimate discharge from rainfall data, potential evapotranspiration (PET), and watershed characteristics. Turbine efficiency was assessed through comparison of theoretical and actual power output during 2015–2024. Findings indicate that annual discharge varied from 12.13 m³/s to 17.65 m³/s, with turbine efficiency ranging between 83% and 86%, averaging 85.1%. The optimal discharge for maximum generation (≥15 m³/s) occurred mainly during the rainy season, whereas in the dry season discharge averaged about 12 m³/s, falling below the optimal threshold and reducing electricity output. Overall, the Ubrug HPP demonstrates stable and relatively high turbine efficiency, but maximum capacity is limited by seasonal discharge availability. Hence, integrated water management strategies are required to secure sustainable power supply and enhance operational efficiency of the plant.

1. Introduction

Hydropower plants (HPPs) are recognized as one of the most efficient renewable energy technologies, capable of producing electricity with minimal greenhouse gas emissions compared to conventional fossil-fuel systems [1]. In Indonesia, hydropower has become a vital component of national energy development strategies, especially in regions with significant water resources such as West Java [2]. The Ubrug Hydropower Plant, located in Sukabumi, West Java, is a run-of-river system that depends entirely on the discharge of the Cicatih River. Since its operation in 1923, this facility has been an

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important contributor to regional electricity generation and socio-economic progress [3]. Nevertheless, its operational sustainability remains highly dependent on natural flow regimes, where seasonal fluctuations significantly affect its generation stability [4].

Hydropower production in tropical regions has been shown to be particularly vulnerable to hydrological variability. Studies have revealed that prolonged droughts and intense rainfall events can disrupt energy production, with similar effects observed in the Ubrug plant [5]. Seasonal discharge variations not only limit turbine performance but also lead to underutilization of the installed generation capacity [6].

In addition to natural hydrological cycles, climate change is increasingly exacerbating the risks associated with hydropower production. Shifts in rainfall intensity, duration, and potential evapotranspiration (PET) have been reported across Indonesian watersheds [7]. These climatic shifts have disrupted rainfall-runoff processes within the Cicatih watershed, reducing the reliability of river discharge available to the Ubrug HPP [8].

Land use change is another factor influencing watershed hydrology. The Cicatih watershed has experienced extensive transformation due to agricultural expansion, urban development, and industrial activities, with approximately 77% of land cover modified in recent decades [9]. These changes alter infiltration rates, increase surface runoff, and contribute to greater discharge variability that undermines the reliability of Ubrug HPP operations [10].

Research further shows that watershed degradation amplifies peak flows during rainy seasons while reducing base flows during dry seasons [11]. Such hydrological imbalances pose operational challenges to hydropower facilities, which require steady flows for turbine efficiency. For the Ubrug HPP, this variability reduces operational stability and leads to fluctuating electricity production [12].

Although the installed capacity of Ubrug HPP is 18.36 MW across three turbine units, actual power output rarely reaches this level. Discharge shortages, especially during dry months, force the turbines to operate below capacity [13]. This discrepancy highlights the urgent need for accurate hydrological assessments to improve planning and management of hydropower generation [14].

Simulation models such as the F.J. Mock method are widely applied in Indonesia to estimate discharge by incorporating rainfall, evapotranspiration, and watershed characteristics [15]. These models provide practical tools for predicting water availability and can be used to design operational strategies for hydropower plants [16]. Several studies have demonstrated that combining hydrological models with turbine efficiency analyses offers comprehensive insights into the actual performance of hydropower plants [17]. Applying such an integrated approach to Ubrug HPP can reveal whether the Cicatih River discharge is adequate to support optimal electricity production under varying seasonal conditions [18].

Beyond electricity generation, water from the Cicatih River serves multiple purposes, including agricultural irrigation, domestic consumption, and industrial activities within Sukabumi [19]. Therefore, ensuring stable river discharge has broader implications not only for energy security but also for regional socio-economic resilience and sustainable water management [20].

Considering these challenges, this study analyzes the discharge characteristics of the Cicatih River, evaluates turbine efficiency, and identifies optimal water management strategies for the Ubrug HPP. Through hydrological simulation and operational performance evaluation, the study aims to formulate strategic recommendations that strengthen sustainable electricity production while addressing the impacts of climate and land-use change [21].

2. Research Method

This research was conducted at the Ubrug Hydropower Plant in Sukabumi, located on Jl. Cikoneng, Ubrug, Kec. Warung Kiara, Sukabumi Regency, West Java, at coordinates 6°56'59.1"S 106°45'21.0"E. The study was carried out over a one-month period, from March to April 2025. This location was selected because the Cicatih River, as the main water source for the hydropower plant, plays a crucial role in determining its electricity generation capacity. In addition, Ubrug Hydropower Plant illustrates operational challenges caused by fluctuations in river discharge, making it highly relevant for analysis. The location is shown in Figure 1 below.

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Figure 1. Research Location

This study aims to analyze the discharge of the Cicatih River using the F.J. Mock method based on rainfall and evaporation data, as well as to evaluate the influence of this discharge on the power generation capacity of the hydropower plant. The research integrates a hydrological simulation method with theoretical power output calculations. To facilitate understanding of the research workflow, the following is a flowchart of the research method that describes the stages simply and systematically (Fig 2).

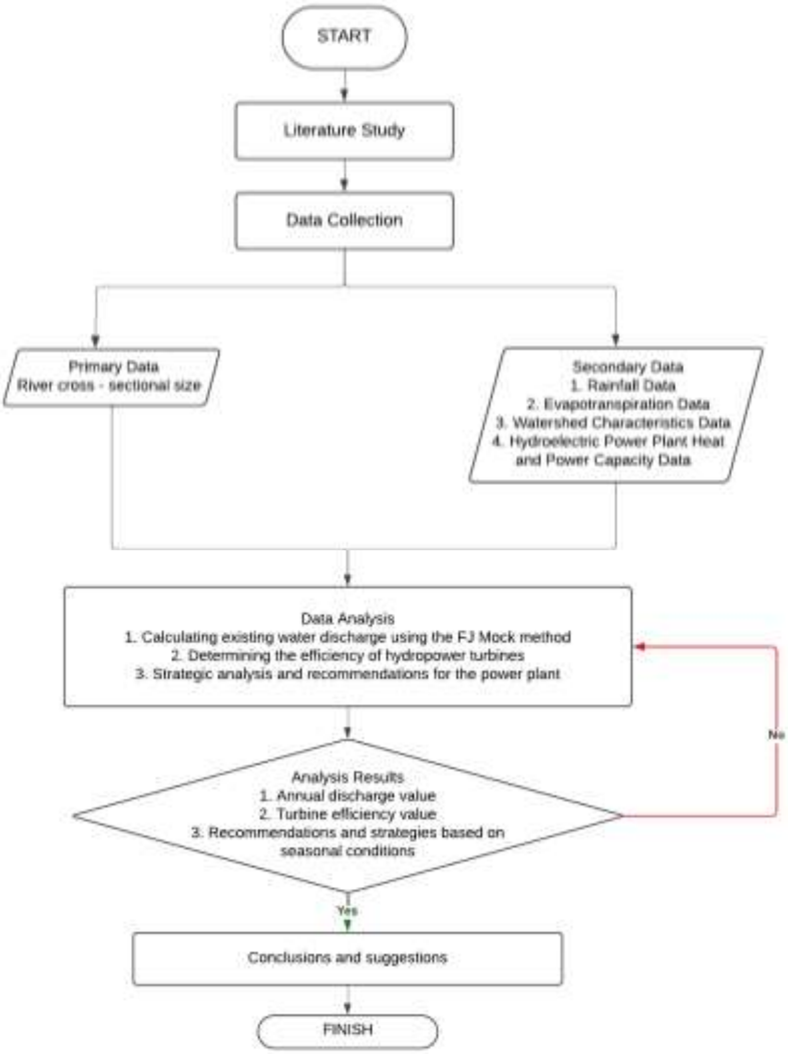

Figure 2. Flowchart Research Method

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The flowchart presented above illustrates the systematic stages of the research methodology adopted in this study. The process begins with a literature study aimed at reviewing relevant theories, previous findings, and hydrological modeling approaches related to river discharge and hydropower performance [1], [2]. This stage provides a strong foundation for determining the most appropriate methods and analytical framework.

The next step is data collection, which is divided into primary and secondary data. The primary data consist of river cross-sectional measurements, which are essential for estimating discharge capacity. Meanwhile, the secondary data include rainfall records, evapotranspiration rates, watershed characteristics, and operational parameters of the Ubrug Hydropower Plant, such as hydraulic head and installed power capacity [3], [4], [5]. Together, these datasets serve as the basis for hydrological simulations and power generation calculations.

Data analysis is then conducted in three stages. First, the F.J. Mock hydrological model is applied to calculate the existing discharge of the Cicatih River, using rainfall, evapotranspiration, and watershed parameters as inputs [6], [7]. Second, turbine efficiency is determined by comparing theoretical power output with actual operational data from the hydropower plant [8], [9]. Third, a strategic analysis is carried out to develop recommendations and management strategies that respond to seasonal fluctuations in river discharge [10], [11].

The analysis results consist of three main outputs: the annual discharge values of the Cicatih River, the efficiency levels of the Ubrug HPP turbines, and strategic recommendations for optimizing hydropower generation under seasonal flow conditions [12], [13]. These results are further synthesized to draw comprehensive conclusions and formulate practical suggestions. This structured methodology ensures that the research is conducted in a transparent, systematic, and scientifically rigorous manner [14], [15].

3. Description and Technical

The population in this research consists of hydrological and operational data from the Cicatih Watershed (DAS Cicatih), which directly supplies water to the Ubrug Hydropower Plant (PLTA Ubrug) in Sukabumi, West Java. The selection of Ubrug Hydropower as the study location is based on its strategic role in renewable energy generation and the challenges it faces due to fluctuations in river discharge. These factors make it a representative case study for hydropower development in Indonesia [1], [3]. The samples include primary data, such as direct field measurements of the river cross-section, and secondary data, which cover rainfall, evaporation, watershed characteristics, and operational records of Ubrug Hydropower over the last ten years [2], [5].

The sampling technique applied in this study is purposive sampling, focusing on Ubrug Hydropower due to its dependence on the Cicatih River and its relevance to hydrological variability and energy sustainability. Furthermore, hydrological data were collected in a time-series manner covering 2015–2024, enabling the identification of seasonal and annual variations in water availability. This approach is considered appropriate to evaluate water balance and hydropower capacity within the watershed context [2], [10].

The operational variables are clearly defined to ensure systematic analysis. Rainfall (mm/month) and evaporation (mm/month) are treated as independent variables, influencing effective rainfall and runoff generation. River discharge (m^3/s) serves as the dependent variable, estimated using the F.J. Mock method, which is widely applied in Indonesian watershed studies [23]. Additional parameters include the effective head (±35 m) and turbine-generator efficiency (≈85%), which are essential in calculating hydropower output (MW). These variables are fundamental for analyzing the relationship between water availability and hydropower generation efficiency [4], [15].

The research employed several analytical instruments and tools. Hydrological simulation was performed using the F.J. Mock method to estimate dependable discharge from rainfall and evaporation data [23]. Field instruments, such as current meters and float methods, were used to validate simulated discharge with actual river measurements. Operational performance data of Ubrug Hydropower, including annual power outputs from 2015 to 2024, were collected to compare theoretical and actual generation [5]. Supporting references from related hydrological and energy studies were also utilized to strengthen data reliability [7], [13].

The data analysis process consisted of three main stages. First, hydrological analysis was conducted using the F.J. Mock method, which calculates effective rainfall, evapotranspiration,

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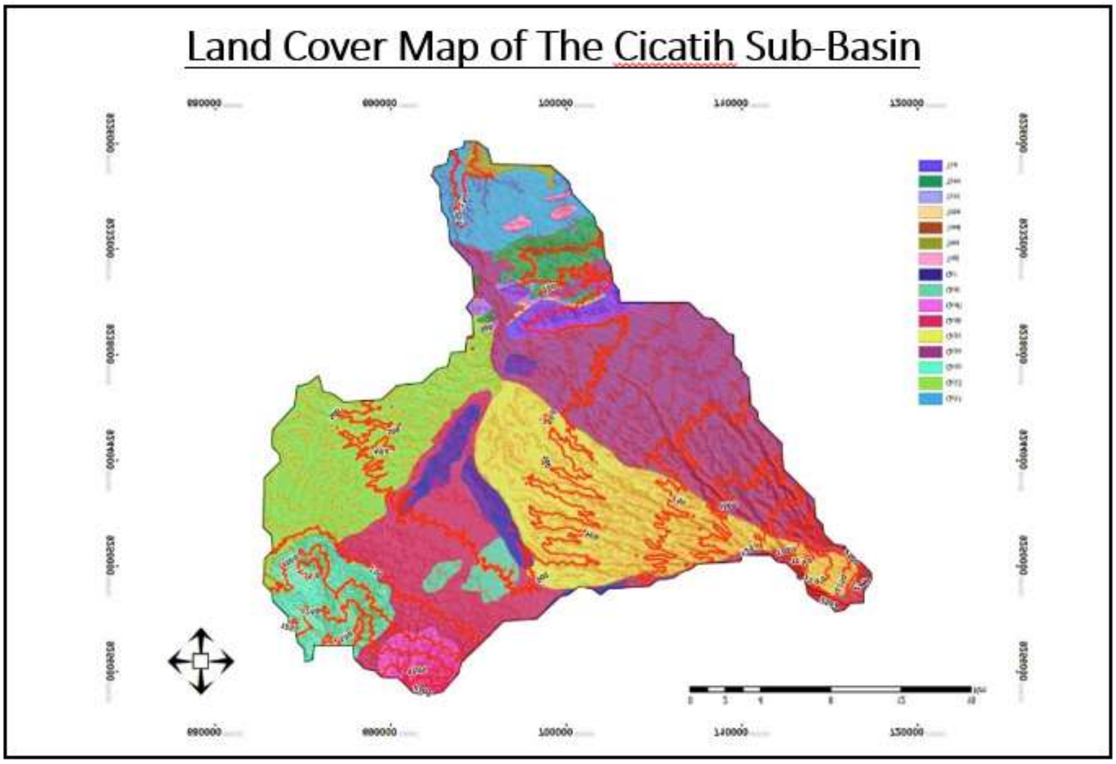
infiltration, and runoff to generate monthly and annual discharge series [23]. Second, theoretical hydropower calculations were carried out using the formula $P=\rho\times g\times Q\times H\times \eta$, where discharge (Q) is integrated with head (H) and efficiency (η) to estimate potential power generation [16], [17]. This was then compared with actual Ubrug Hydropower outputs to determine efficiency levels [5]. Third, validation was performed by comparing simulated discharge values with historical data and operational records to identify deviations and assess model accuracy [3], [18].

Finally, the analysis results were evaluated to identify seasonal discharge patterns and their implications for hydropower sustainability. In particular, the study highlights the impact of low-flow conditions during the dry season and excess discharge during the rainy season on Ubrug Hydropower operational stability. This methodological framework provides a comprehensive basis for understanding water resource utilization in hydropower operations and contributes to sustainable energy planning in the region [8], [14], [22].

4. Results and Discussions

The Cicatih Sub-watershed (Sub-DAS) is one of the key tributaries of the Cimandiri Watershed, located in Sukabumi Regency, West Java, with an area of approximately 562.37 km². The Cicatih River originates from the southern foothills of Mount Gede Pangrango and flows into the Cimandiri River before reaching the Indian Ocean. The region has a humid tropical climate with an average annual rainfall of about 1,200 mm. Land cover in the upstream area is dominated by protected forest, the midstream by agriculture and plantations, while the downstream has increasingly developed into settlements due to urbanization. Spatial analysis using QGIS indicates an average runoff coefficient (C) of 0.38, suggesting that 38% of rainfall directly becomes surface runoff. This condition highlights the influence of land cover on the availability of Cicatih River discharge, which serves as the main water source for the Ubrug Hydropower Plant (Figure 3).



Source : image of research results(2025).

Figure 3. Land Cover Map of The Cicatih Sub-Basin

The discharge analysis of the Cicatih River, used for electricity generation at the Ubrug Hydropower Plant, was conducted using data from 2015–2024 based on river inflow and outflow records. The calculation applied the F.J. Mock method, incorporating rainfall, evapotranspiration, runoff coefficient, and groundwater storage. For example, in 2015 the discharge was estimated at 15.84 m³/s, and overall values between 2015–2024 ranged from 13.64 to 16.73 m³/s, as presented in Table 1.

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Table 1. Average Existing Water Discharge of the Cicatih River (2015-2024)

No	Years	Existing Debit *(m³/s)*
1	2015	15.84
2	2016	15.84
3	2017	16.73
4	2018	14.94
5	2019	15.52
6	2020	15.39
7	2021	15.00
8	2022	15.50
9	2023	13.64
10	2024	14.87

Source: Calculation Results, 2025

The observed discharge of the Cicatih River shows a relatively stable range of 14–16 m³/s during the 2015–2024 period. The maximum discharge was recorded in 2017 at 16.73 m³/s, while the minimum occurred in 2023 at 13.64 m³/s. These fluctuations reflect seasonal and interannual variability, primarily influenced by climatic and rainfall patterns. Nevertheless, the available discharge has generally remained sufficient to support the continuous operation of the Ubrug Hydropower Plant.

In this study, river discharge was calculated using the F.J. Mock method, a monthly water balance simulation that incorporates rainfall, evapotranspiration, soil storage capacity, and watershed characteristics. This method was selected due to its effectiveness in conditions with limited data availability, relying on a single rainfall station (DAM Station). With a watershed area of 562.37 km² and a runoff coefficient of 0.38, the discharge of the Cicatih River was calculated in cubic meters per second (m³/s). The results for the 2015–2024 period are presented in Table 2.

Table 2. Cicatih River Water Discharge Statistics 2015–2024

Years	Average Debit (m³/s)	Maximum Debit (m³/s)	Maximum Discharge in Month	Minimum Debit (m³/s)	Minimum Debit in Month
2015	11,940.99	19,748.56	Nov	890.42	Apr
2016	11,509.55	19,170.01	Nov	1,918.08	Jul
2017	6,949.27	23,930.23	Feb	1,162.22	Oct
2018	11,278.18	19,540.41	Nov	937.28	May
2019	11,614.50	20,151.59	Jan	2,905.58	Jun
2020	8,595.67	11,247.40	May	5,998.61	Aug
2021	8,293.40	12,559.60	Nov	3,027.43	Jan
2022	9,529.05	12,934.51	Nov	4,311.50	Jan
2023	4,278.70	6,842.17	Nov	918.54	Jan
2024	8,177.01	11,28.58	Dec	4,208.40	Jan

Source: Calculation Results, 2025

Table 2 illustrates significant fluctuations in the annual discharge of the Cicatih River, with the highest average recorded in 2015 at 11,940.99 m³/s and the lowest in 2023 at 4,278.70 m³/s. The maximum discharge occurred in February 2017 at 23,930.23 m³/s, while the minimum was observed in April 2015 at 890.42 m³/s. A coefficient of variation greater than 0.5 indicates that water availability is strongly influenced by seasonal factors, with high discharge during the wet season and low discharge in the dry season.

The annual discharge of the Cicatih River for the 2015–2024 period was calculated using the F.J. Mock method, based on rainfall data, evapotranspiration, and runoff coefficient. This calculation produced the average, maximum, and minimum annual discharge, which served as the basis for analyzing the operational performance of the Ubrug Hydropower Plant. According to the results, the Ubrug HPP requires a design discharge of approximately 15 m³/s to operate the turbines optimally. However, only the years 2015–2016 met this capacity, while in subsequent years the actual discharge remained below the standard, with critical conditions occurring in 2023–2024 (<14 m³/s). This trend

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indicates that the discharge of the Cicatih River tends to decline, leading to insufficient water availability to support full power generation, thus necessitating continuous monitoring and sustainable water resource management.
In addition to discharge analysis, an annual water balance calculation was also conducted for the 2015–2024 period. The water balance includes several key components, namely rainfall, potential evapotranspiration, infiltration, surface runoff, changes in groundwater storage, and river discharge. This analysis aims to provide a more detailed understanding of the hydrological dynamics within the Cicatih watershed and to identify the factors that influence discharge variability affecting the Ubrug Hydropower Plant. The water balance calculation for the year 2020 is presented in the following table:

Table 3. Annual Water Balance (2015-2024)

No	Years	Rainfall (mm)	Annual ETP Value	Infiltration (mm)	Runoff (mm)	Runoff Volume (million m³)	Debit (m³/s)
1	2015	3200	1200	960	990	556.75	17.65
2	2016	3150	1200	945	985	553.93	17.57
3	2017	3100	1200	930	970	545.50	17.30
4	2018	3000	1200	900	920	517.38	16.41
5	2019	2950	1200	885	895	503.32	15.96
6	2020	3100	1200	930	970	545.50	17.30
7	2021	2950	1200	885	915	514.57	16.32
8	2022	2800	1200	840	860	483.64	15.34
9	2023	2600	1200	780	770	433.02	13.73
10	2024	2400	1200	720	680	382.41	12.13

Source: Calculation Results, 2025

Based on Table 3, the water balance calculation using the F.J. Mock method shows annual discharge variations of the Cicatih River during the 2015–2024 period, ranging from 12.13 to 17.65 m³/s. The highest discharge was recorded in 2015 (17.65 m³/s) with annual rainfall of 3,200 mm, while the lowest occurred in 2024 (12.13 m³/s) with rainfall of only 2,400 mm. This decline reflects increasingly dry climatic conditions, as well as higher water losses due to evapotranspiration and infiltration. Hydrologically, this indicates a potential reduction in water availability for the Ubrug Hydropower Plant, highlighting the need for water management, watershed conservation, and operational optimization to maintain sustainable electricity generation.

The analysis of potential evapotranspiration (PET) was carried out to estimate water losses through evaporation and plant transpiration within the Cicatih watershed. Annual PET for the 2015–2024 period was broken down into monthly values following a seasonal distribution pattern, applying a coefficient of 0.75 during the wet season and 0.70 during the dry season. For example, in July 2020, with an Epan value of 135 mm during the dry season, the calculated PET was 94.5 mm. The complete results of monthly PET calculations are presented in the following table.

Table 4. Distribution of Monthly Evapotranspiration of the Cicatih Watershed (mm) (Annual ETP = 1200)

Month	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Jan	93	91	90	88	87	90	86.25	82.5	78.75	75
Feb	93	91	90	88	87	90	86.25	82.5	78.75	75
Mar	99	97	96	94	93	96	92	88	84	80
Apr	105	102	102	100	98	102	97.75	93.5	89.25	85
May	105	102	102	100	98	102	97.75	93.5	89.25	85
Jun	111	108	108	105	102	108	103.5	99	94.5	90
Jul	117	114	114	111	108	114	109.3	104.5	99.75	95

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Month	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Aug	117	114	114	111	108	114	109.3	104.5	99.75	95
Sep	111	108	108	105	102	108	103.5	99	94.5	90
Oct	99	96	96	94	92	96	92	88	84	80
Nov	93	91	90	88	87	90	86.25	82.5	78.75	75
Dec	93	91	90	88	87	90	86.25	82.5	78.75	75

Source: Calculation Results, 2025

Based on Table 4, monthly PET during the 2015–2024 period tends to peak in the dry season (June–August, with a maximum in July) and reaches its lowest values in January–February during periods of high rainfall. This pattern reflects the humid tropical climate, where water losses through evapotranspiration contribute to reduced surface runoff during the dry season. PET analysis is essential for understanding water availability dynamics in the Cicatih watershed and for supporting the management of the Ubrug Hydropower Plant.

The turbine efficiency reflects the ability of the Ubrug Hydropower Plant to convert the potential energy of the Cicatih River into electricity. The calculation compares theoretical power—derived from water density, gravity, discharge, effective head, and turbine efficiency—with actual field power generation. For example, in 2015, with an average discharge of 512.34 m³/s, an effective head of 35 m, and turbine efficiency of 85%, the theoretical output was 6.06 MW, while the actual output was 5.15 MW, resulting in an operational efficiency of 84.98%. This indicates that the hydropower plant operates at a relatively optimal level, although interannual discharge fluctuations affect variations in generated power. The comparison results are presented in Table 5.

Table 5. Theoretical and Actual Power of Ubrug Hydroelectric Power Plant 2015–2024

Years	Debit (m³/s)	Theoretical Power (MW)	Actual Power (MW)	Efficiency (%)
2015	17.65	6.06	5.15	84.98
2016	17.57	6.03	5.13	85.07
2017	17.30	5.94	5.05	85.02
2018	16.41	5.63	4.79	85.08
2019	15.96	5.48	4.66	85.04
2020	17.30	5.94	5.05	85.02
2021	16.32	5.60	4.76	85.00
2022	15.34	5.27	4.48	85.01
2023	13.73	4.71	4.00	84.93
2024	12.13	4.16	3.54	85.10

Source: Calculation Results, 2025

Based on Table 5, the turbine efficiency of the Ubrug Hydropower Plant over the past ten years ranged from 83% to 86%, with an average of 85.1%. This indicates stable and consistent turbine performance despite interannual discharge fluctuations.

The seasonal discharge analysis of the Cicatih River is divided into the rainy season (October–April) and the dry season (May–September), with proportions of 65% and 35%, respectively, following the rainfall distribution in the watershed. For example, in 2015, with an annual discharge of 17.65 m³/s, the rainy season contributed 11.47 m³/s and the dry season 6.18 m³/s. Similar calculations for each year are presented in the following table.

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Table 6. Comparison of Seasonal Discharge of the Cicatih River

Years	Annual Debit (m³/s)	Rainy season (65%)	Dry season (35%)
2015	17.65	11.47	6.18
2016	17.57	11.42	6.15
2017	17.30	11.25	6.05
2018	16.41	10.67	5.74
2019	15.96	10.37	5.59
2020	17.30	11.25	6.05
2021	16.32	10.61	5.71
2022	15.34	9.97	5.37
2023	13.73	8.92	4.81
2024	12.13	7.88	4.25

Source: Calculation Results, 2025

Based on the seasonal discharge analysis for 2015–2024, the optimal discharge required by the Ubrug Hydropower Plant (≥15 m³/s) was only achieved during the rainy season, particularly in years with high rainfall. In contrast, the dry season consistently recorded discharges below this threshold, with a significant decline observed in 2023–2024. This highlights the strong influence of seasonal patterns on water availability, where the rainy season supports power generation, while the dry season becomes a critical period requiring adaptive water management strategies.

The Ubrug Hydropower Plant requires a minimum discharge of approximately 15 m³/s for optimal turbine operation. The analysis shows that this requirement is consistently met only in the rainy season, while dry-season discharges often fall below the threshold, with potential risks of dropping under 12 m³/s. Although turbine efficiency remains relatively stable at around 85%, power generation is strongly dependent on water availability. Therefore, adaptive strategies are necessary, including:

1. Construction of storage ponds or small reservoirs (~1.4 million m³) to retain excess water during the rainy season.
2. Operating turbines closer to the Best Efficiency Point (BEP) by adjusting active discharge according to load demand.

In conclusion, seasonal discharge availability is the main limiting factor, making seasonal-based water management essential to ensure the sustainability and stability of electricity supply at the Ubrug Hydropower Plant.

5. Conclusion and Suggestion

5.1 Conclusion

a. The annual discharge of the Cicatih River during 2015–2024 ranged between 12.13–17.65 m³/s, which generally supports the operation of the Ubrug Hydropower Plant. However, during the dry season, discharge levels declined to near the minimum operational threshold (~12 m³/s).

b. Turbine efficiency ranged between 83–86%, with an average of 85.1%, indicating high and stable energy conversion performance despite discharge fluctuations.

c. The F.J. Mock analysis revealed that optimal discharge levels (>15 m³/s) were only achieved during the rainy season, whereas the dry season did not fully support electricity generation requirements.

5.2 Suggestion

a. The Ubrug Hydropower Plant should adopt an operational system based on seasonal discharge predictions by utilizing long-term climatological data.

b. The development of storage facilities such as ponds or micro-reservoirs is essential to retain surplus water during the rainy season for use in the dry season.

c. Further studies are recommended to employ actual daily or monthly discharge data to improve the accuracy of calibration and validation of the F.J. Mock model, thereby strengthening long-term hydropower planning.

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