JPPIPA 11(4) (2025)

Jurnal Penelitian Pendidikan IPA

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Assessment of Baseflow Characteristics and Environmental Flow Allocation in the Welo Sub-Watershed, Central Java

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Received: December 12, 2024
Revised: February 18, 2025
Accepted: April 25, 2025
Published: April 30, 2025

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DOI: 10.29303/jppipa.v11i4.11049

Abstract: This study assesses baseflow characteristics and environmental flow (EF) requirements in the Welo Sub-Watershed, Central Java, Indonesia—a region increasingly affected by land use change and climate variability. Using 30 years of daily streamflow data (1994–2023), baseflow was separated using the Fixed Interval Method with analysis conducted in Excel and the Hydrologic Engineering Center's Hydrograph Analysis (HEC-HMS). EF was estimated using both the Tennant Method and Flow Duration Curve (FDC) analysis. Results indicate that average dry-season baseflow is 0.79 m^3/s, while the reliable flow (Q80) averages 1.02 m^3/s. EF estimates are 0.43 m^3/s (Tennant) and 0.54 m^3/s (FDC). Under normal hydrological conditions, baseflow exceeds EF thresholds. However, peak irrigation demand reaching 1.30 m^3/s surpasses both baseflow and Q80 during dry periods. This suggests periods of ecological stress and potential conflict among water users. These findings underscore the need for integrating EF targets into local water resource planning to safeguard ecosystem function and ensure sustainable water allocation.

Keywords: Baseflow; Environmental flow; Flow duration curve method; Tennant method; Welo sub-watershed

Introduction

Sustainable water resource management in Indonesia is increasingly challenged by climate variability, land-use changes, and rising water demands, particularly in small-scale catchments such as the Welo Sub-Watershed in Central Java. The Welo Sub-Watershed, with an area of approximately 265 km², is crucial in supplying water for agriculture, domestic use, and environmental sustainability. This sub-watershed is characterized by a mix of agricultural land (predominantly rice fields and dryland farming), degraded forests in the upstream region, and an increasing rate of urban development in the downstream areas. The region experiences a monsoonal rainfall pattern with pronounced wet (November–April) and dry (May–October) seasons. This leads to seasonal fluctuations and prolonged low-flow periods during the dry months. These hydrological dynamics render the watershed vulnerable to ecological degradation and water scarcity.

Baseflow, defined as the portion of streamflow sustained primarily by groundwater, is essential for maintaining river health during dry seasons and for securing continuous water supply (Wang et al., 2016), which is primarily driven by groundwater contributions and serves as an indicator of ecological and hydrological integrity (Liu et al., 2019). However, in the Welo Sub-Watershed, this baseflow is under increasing pressure due to rapid land-use change, unsustainable irrigation practices, and the absence of integrated water management strategies (Randhir & Klosterman, 2024). Recent assessments in similar Indonesian sub-watersheds have shown a steady decline in baseflow reliability due to upstream deforestation, groundwater

How to Cite:
Sodikin, W., Juwono, P. T., & Sholichin, M. (2025). Assessment of Baseflow Characteristics and Environmental Flow Allocation in the Welo Sub-Watershed, Central Java. *Jurnal Penelitian Pendidikan IPA*, *11*(4), 672-684. https://doi.org/10.29303/jppipa.v11i4.11049

overexploitation, and unregulated surface water abstraction (Narulita, 2017; Taufik & Annisa, 2022).

Research demonstrates that the sustainability of baseflow is jeopardized by intense agricultural expansion and urban development, compounded by climatic variability (Wedajo et al., 2024). For instance, studies indicate that changing land-use patterns significantly alters baseflow dynamics, affecting overall water availability (Touseef et al., 2021). Environmental flow assessments present a promising approach by prescribing minimum flow thresholds to maintain and protect aquatic ecosystems (Granados et al., 2021). Despite numerous methodologies for assessing environmental flows globally (Hoan et al., 2020), practical application in Indonesia remains limited, stressing the need for effective integration into local water governance frameworks (Castellini et al., 2022).

Environmental flow (EF) frameworks, which aim to define minimum flow requirements to preserve aquatic ecosystems and hydrological balance, offer a strategic solution. However, EF implementation in Indonesia remains limited and poorly contextualized to the catchment scale. Most existing studies apply generalized global methods without adapting to local watershed characteristics. This gap underscores the importance of localized EF assessments that account for unique hydrological patterns, such as those observed at the Tapak Menjangan Weir in the Welo Sub-Watershed, where sharp discharge reductions occur annually during the dry season.

Localized EF assessments are critical because hydrological behavior can vary significantly from one region to another. Addor et al. (2017) highlight that a diverse set of catchments allows for a better understanding of localized ecohydrological processes and provides insights into how specific characteristics influence hydrological responses. Similarly, Sawicz et al. (2011) emphasize the importance of hydrologic similarity and spatial patterns of catchment behavior, suggesting that catchment classification based on local hydrologic responses can enhance the transferability of information and improve management strategies. This indicates that local hydrological responses, like those at the Tapak Menjangan Weir, must be considered when developing EF frameworks.

Furthermore, Karimi et al. (2012) stress the significance of identifying environmental flow requirements for maintaining aquatic habitats within specific river reaches. Their research indicates that understanding instream flow requirements is essential for effective river management and for supporting ecological integrity. This specific focus on local hydrological conditions aligns with the inherent variability of water flows, as discussed by Fenicia et al. (2011), who provide a flexible approach for hydrological modelling that accommodates the diverse characteristics of catchments. Such flexibility is paramount in adapting EF assessments to the unique hydrological signatures found in Indonesia.

The Welo Sub-Watershed exemplifies the challenges faced by regions undergoing rapid transformations due to human activities and climate change, with indicators showing alarming reductions in water discharge during peak dry periods—evident from data collected at the Tapak Menjangan Weir (Wu et al., 2015; Zhang et al., 2019). These alarming trends necessitate an immediate policy response through a scientifically founded environmental flow framework that can accommodate the unique hydrological patterns of the area (Yang et al., 2017). Utilizing long-term hydrological data and methods like the Fixed Interval Method for baseflow separation, along with the application of Tennant and Flow Duration Curve (FDC) approaches, provides a robust basis for forming actionable guidelines aimed at balancing ecological and human water needs (Blanco-Gómez et al., 2019; Di Prima et al., 2018).

This study contributes to the growing body of hydrological research by offering a contextualized analysis of baseflow dynamics and environmental flow needs specifically in the Welo Sub-Watershed. Using 30 years of daily streamflow data (1994–2023), this research applies the Fixed Interval Method for baseflow separation and employs both the Tennant and Flow Duration Curve (FDC) methods for EF estimation. A key novelty lies in the integration of empirical hydrological data with region-specific challenges, providing scientific evidence to inform local water management policies. The ultimate goal is to develop actionable recommendations that support sustainable water allocation, balancing ecological preservation with agricultural and domestic water use in the Welo Sub-Watershed.

Method

This study adopted a quantitative research design with a descriptive-analytical approach to assess baseflow characteristics and environmental flow (EF) thresholds in the Welo Sub-Watershed, located in the Pekalongan Regency, Central Java, Indonesia. The study area, known as the Welo Sub-Watershed, covers approximately 36.08 km² and forms part of the larger Sengkarang Watershed (DAS Sengkarang). Administratively, it is situated within the sub-districts of Doro, Talun, and Petungkriyono in Pekalongan Regency, Central Java. The region is characterized by mixed land uses, including dryland farming, rice paddies, and forested highlands, with a monsoonal rainfall regime that causes pronounced seasonal variations in streamflow.

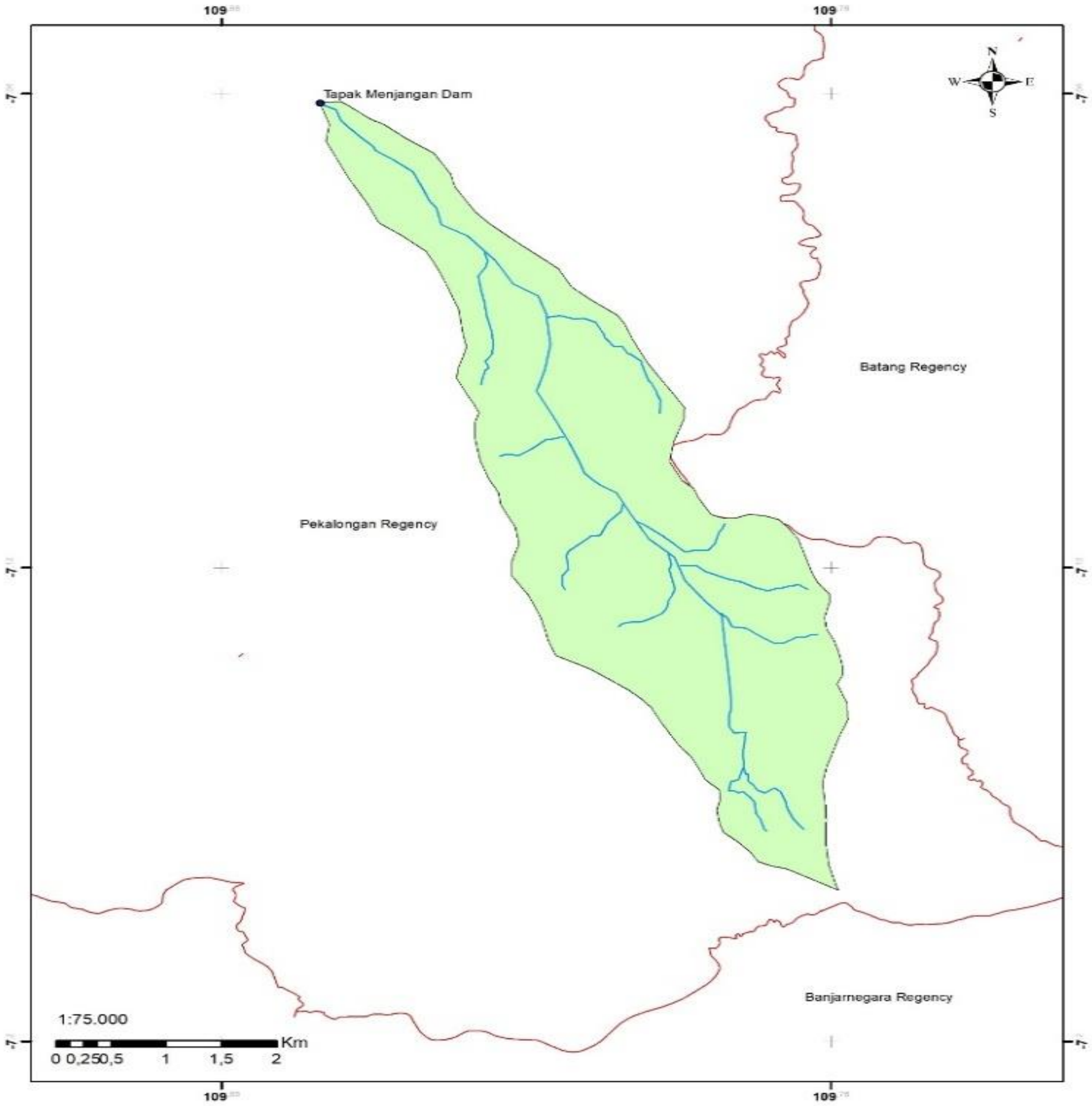

Figure 1. Location research

Data Collection

The study utilized 30 full years of daily streamflow data (January 1, 1994 – December 31, 2023), obtained from the Pemali-Comal River Basin Authority. Climatological data and catchment characteristics were also gathered to support hydrological assessment. Data for 2024 were excluded to ensure completeness and accuracy. Data pre-processing and analysis were conducted using Microsoft Excel, HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) for baseflow separation, and Python with Pandas and Matplotlib libraries for statistical processing and plotting of flow duration curves.

Baseflow Separation

Baseflow was separated using the Fixed Interval Method (FIM), where streamflow hydrographs were divided into fixed time intervals to identify minimum flows that represent groundwater contributions. The interval length NNN was determined using the empirical equation: $N = A^{0.2}$, is the catchment area in square kilometers. With A= 36.08 km^2, the resulting interval was approximately 4 days. Within each 2N-day window (8 days), the minimum discharge value was selected as baseflow. These values were connected to form the baseflow hydrograph. The method is preferred for its simplicity and suitability for long-term data analysis (Indarto, 2016).

Environmental Flow Estimation

Two hydrologic-based methods were applied: Tennant Method: EF was calculated as 10% of the Mean Annual Flow (MAF), representing the minimal flow required to sustain aquatic habitat during critical low-flow periods. MAF was computed by averaging all daily flow values from the 30-year dataset. The 10% threshold was chosen based on Tennant's classification for maintaining minimum ecological conditions, which has been adopted in several Indonesian catchment studies; Flow Duration Curve (FDC) Method: Daily discharge values were sorted in descending order and assigned exceedance probabilities using the Weibull formula:

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

where m is the rank, and n n is the total number of observations. The Q95 value (flow exceeded 95% of the time) was used as the EF threshold, commonly used in Indonesian water resource planning to represent extreme low-flow conditions essential for ecological protection.

Comparative Analysis

A comparative evaluation was conducted to assess the alignment between: Baseflow (dry season average); Tennant EF (10% of MAF); FDC EF (Q95 value); Q80 dependable flow (flow exceeded 80% of the time); and dry-season irrigation demand, obtained from local irrigation agency data (1.30 m^3/s).

The comparison was based on whether natural baseflow values exceeded the EF thresholds and irrigation requirements. The evaluation applied a compliance matrix to determine periods of surplus or deficit, indicating potential ecological stress or unmet anthropogenic demand.

Analytical Workflow

The analytical workflow is structured as follows: Data acquisition and preprocessing; Baseflow separation using FIM; MAF calculation and EF estimation using Tennant Method; FDC generation and extraction of Q95; Comparative analysis of EF, baseflow, Q80, and irrigation demand; and Interpretation of ecological and management implications.

A process flow diagram in Figure 2 is provided to illustrate this workflow.

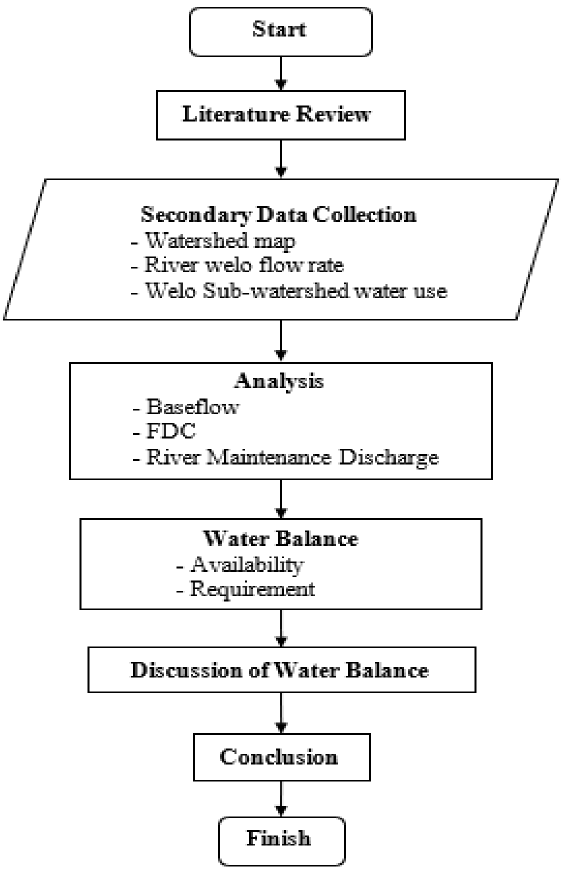

Figure 2. Research flow chart

Result and Discussion

Analysis of 30-year daily streamflow data (1994–2023) from the Welo Sub-Watershed reveals dynamic hydrological behavior influenced by climatic and anthropogenic factors. As summarized in Table 1 and illustrated in Figure 3, the average baseflow during the driest month (August) is 0.79 m^3/s, with fluctuations between 0.75 and 0.87 m^3/s. The dependable flow (Q80), calculated using the Flow Duration Curve (FDC), is 1.02 m^3/s. This indicates that baseflow contributes approximately 77% of the dependable flow, underscoring its critical role in sustaining minimum flows during dry periods.

Hydrograph analysis and baseflow separation were conducted using HEC-HMS software, with graphical plotting and statistical interpretation completed in MS Excel. This digital workflow ensured consistency and transparency in processing long-term time series data.

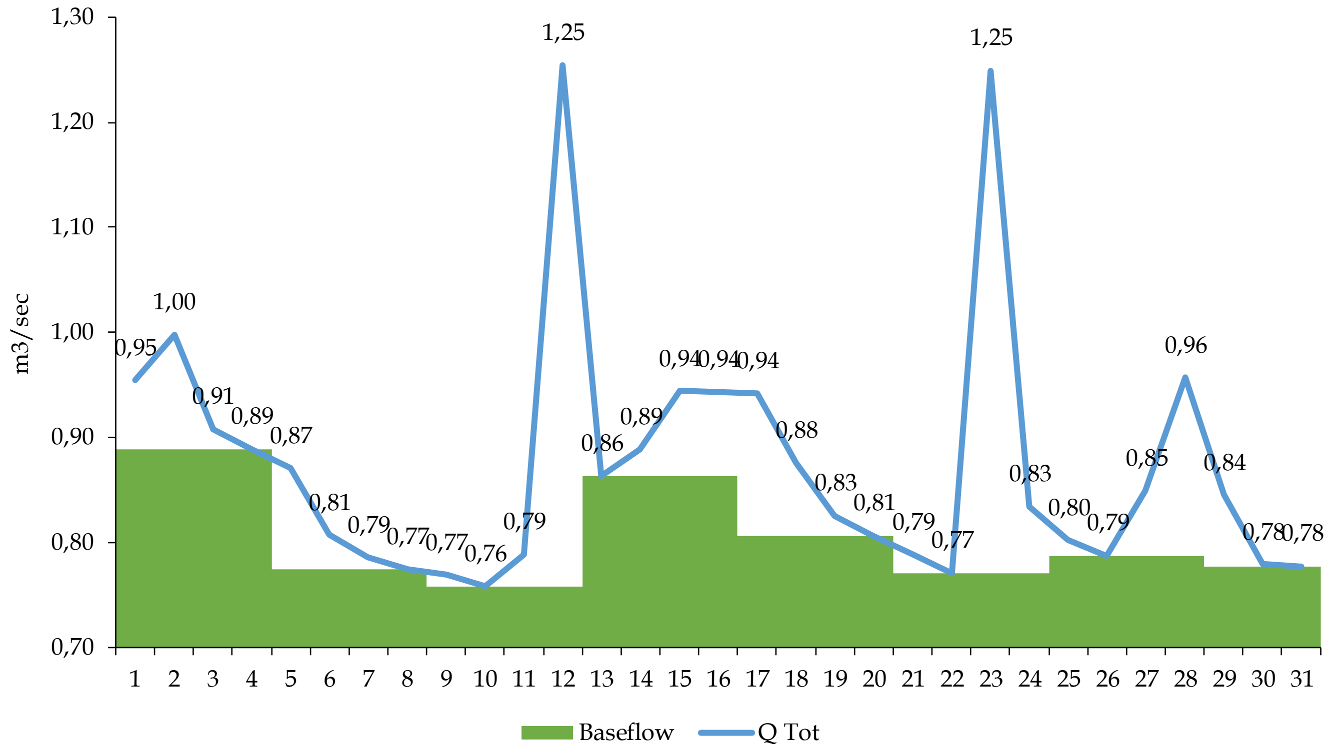

Figure 3. Hydrograph and baseflow of Welo River in August (1994-2023)

Table 1. Average daily discharge in August (1994–2023) and baseflow estimation using fixed interval method

Date	River Discharge (m^3/s)	Interval	Baseflow (m^3/s)
1	0.94	1	0.87
2	0.98		
3	0.89		
4	0.87		
5	0.86	2	0.76
6	0.80		
7	0.77		
8	0.76		
9	0.76	3	0.75
10	0.75		
11	0.78		
12	1.23		
13	0.85	4	0.85
14	0.87		
15	0.93		
16	0.93		
17	0.93	5	0.79
18	0.86		
19	0.81		
20	0.79		
21	0.78	6	0.76
22	0.76		
23	1.22		
24	0.82		
25	0.79	7	0.78
26	0.78		

Date	River Discharge (m^3/s)	Interval	Baseflow (m^3/s)
27	0.84		
28	0.94		
29	0.83	8	0.77
30	0.77		
31	0.77		
Avg	0.86	Avg	0.79
Min	0.75	Min	0.75
Max	1.23	Max	0.87

Environmental Flow Interpretation

Table 2. Recommended river maintenance discharge FDC and Tennant method (m^3/s)

Year	FDC	Tennant
1994	0.14	0.29
1995	0.14	0.53
1996	0.76	0.40
1997	0.16	0.38
1998	0.95	0.40
1999	0.42	0.34
2000	0.34	0.35
2001	0.46	0.30
2002	0.16	0.31
2003	0.19	0.21
2004	0.16	0.32
2005	0.00	0.29
2006	0.19	0.25
2007	0.22	0.31
2008	0.27	0.44
2009	0.27	0.36
2010	2.49	0.68
2011	0.43	0.72
2012	0.21	0.53
2013	0.62	0.47
2014	0.44	0.45
2015	0.14	0.35
2016	1.84	0.46
2017	0.64	0.43
2018	0.28	0.33
2019	0.22	0.31
2020	0.82	0.48
2021	0.82	0.62
2022	2.62	1.03
2023	0.14	0.55
Average	0.55	0.43

Environmental flow thresholds were evaluated using both the Tennant Method and the FDC Method, and the results are presented in Table 2 and visualized in Figures 4 and 5. The Tennant method, based on 10% of Mean Annual Flow (MAF), produced an average EF of 0.43 m^3/s, while the FDC method using Q95 yielded 0.55 m^3/s. While the Tennant method reflects ecologically conservative thresholds (Dwi et al., 2025; Nuraya et al., 2025; Putra et al., 2025), the FDC method shows greater sensitivity to annual variability, especially in extremely dry or wet years. For instance, in 2005, the FDC value approached zero, while Tennant remained more stable.

The comparison of both methods shows that under average hydrological conditions, both EF thresholds fall below the baseflow value, indicating that ecological water requirements can generally be met (Hizazi & Subagyo, 2025; Indaryani et al., 2025; Soares & Sudaryanti, 2025). However, under stress conditions—such as irrigation demand reaching 1.30 m^3/s at Tapak Menjangan Weir—there is a clear deficit.

The analysis results show significant fluctuations in the value of river maintenance discharge over the 30 years, especially in the FDC method, which has higher variability. The FDC method resulted in an average maintenance discharge of 0.55 m^3/s, while the Tennant method showed a slightly lower value of 0.43 m^3/s. This difference reflects the different characteristics of the approach in determining the river's minimum flow requirement, where the FDC method is based more on a statistical analysis of time series data. In contrast, the Tennant method uses a percentage of the annual average discharge according to the classification of flow conditions.

The temporal patterns of the results of both methods show some interesting differences. The FDC method shows higher sensitivity to extreme hydrological conditions, with significantly higher values in wet years (such as 2010, 2016, and 2022) and values close to zero in some dry years (such as 2005). In contrast, the Tennant method shows a more stable pattern and tends to follow the trend of the annual average discharge.

The trends in the maintenance discharge values obtained from both methods show patterns consistent with the streamflow characteristics of the Welo Subwatershed. The higher values in the last decade (2015-2023) compared to the previous decade indicate changes in hydrological patterns that may be influenced by land use changes and climate variability, as expressed in the background of the study.

The environmental flow values in Figure 5 were estimated using two different hydrological methods. The Flow Duration Curve (FDC) method yielded an average minimum environmental flow requirement of 0.54 m^3/s, while the Tennant method recommended a slightly lower value of 0.43 m³/s. Both values fall below the baseflow average, suggesting that under average conditions, the ecological requirements of the river can be met. However, irrigation demand in the region, particularly at Tapak Menjangan Weir, was recorded at 1.30 m³/s, which surpasses both baseflow and Q80 flow, posing a challenge for water allocation during drought conditions.

To obtain a comprehensive understanding of the Welo Subwatershed's ability to meet the needs of river maintenance discharge, a comparative analysis was conducted between the availability of water (mainstay discharge Q80) and irrigation needs and maintenance discharge. The base flow discharge analysis results showed a value of 0.80 m³/s with a probability of 86.29%. Referring to Limantara (2010) in "Practical Hydrology" and reinforced by Hatmoko (2012), optimal irrigation planning uses an 80% probability standard that balances water supply security and resource efficiency. Thus, the analysis of water availability in the Welo Subwatershed for irrigation purposes uses the mainstay discharge Q80 based on the FDC analysis of 1.03 m³/s.

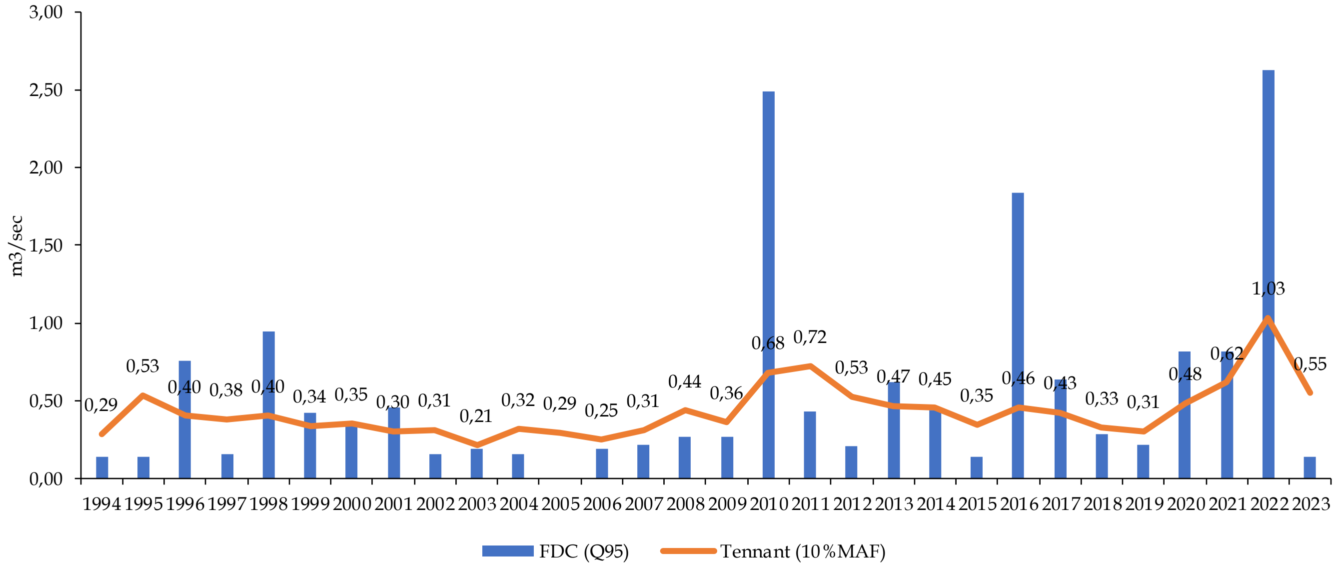

Figure 4. River maintenance discharge of FDC and Tennant method

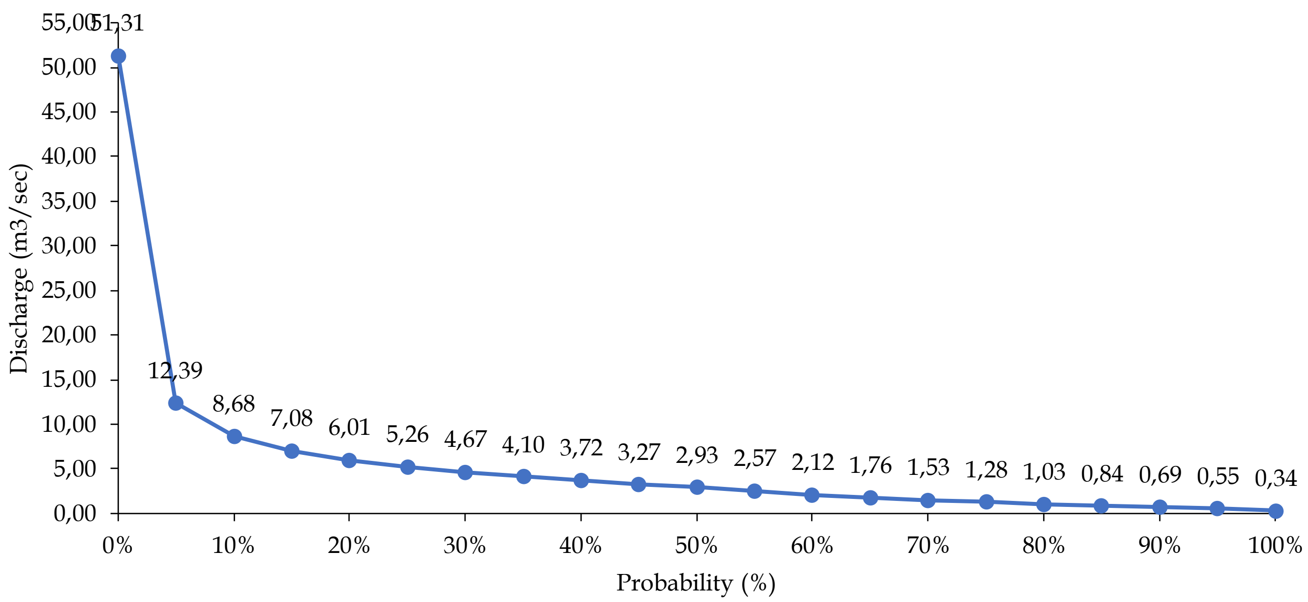

Figure 5. FDC analysis chart of Welo Subwatershed

Based on the Tennant method analysis, a discharge of 0.43 m³/s was obtained, with a probability of 97.94%. However, regarding Government Regulation No. 38/2011 on Rivers, the river maintenance discharge is determined using a 95% probability (Q95). Thus, for regulatory compliance, the maintenance discharge used is 0.55 m³/s, equivalent to Q95, which has a larger amount to be more optimal in maintaining river ecosystems and ecology.

In addition to the river maintenance discharge at the Tapak Menjangan Dam control point, there are other uses, namely for irrigation of the Tapak Menjangan Irrigation Area (D.I.) with an allocation of 1.30 m³/second (water allocation document from the Central Java Province Water Resources and Spatial Planning Public Works Office in 2023). The water balance calculation can be seen in the following figure.

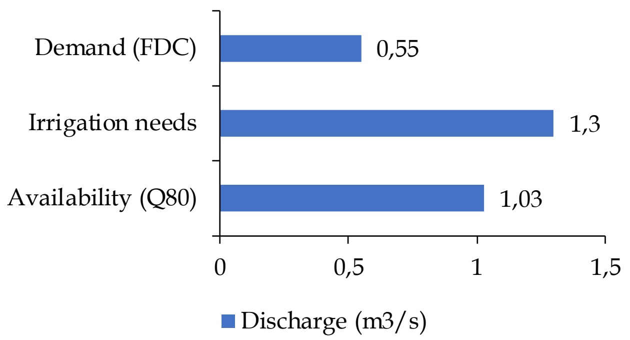

Figure 6. Comparison of water availability and demand in the Welo Sub-Watershed

Water Balance and Deficit

As illustrated in Figure 6, a water balance comparison between Q80 (1.03 m³/s) and total water demand (1.85 m³/s: 1.30 m³/s for irrigation + 0.55 m³/s for EF) reveals a deficit of 0.82 m³/s. This mismatch requires immediate policy attention. Referring to Limantara (2010) and Hatmoko (2012), the use of Q80 is justified for irrigation design due to its reliability.

Meanwhile, on the water demand side, two main components were considered. First, the water demand for irrigation reaches 1.30 m³/s, which indicates a considerable water demand for the agricultural area served. Second, the need for river maintenance based on the Flow Duration Curve (FDC) is 0.55 m³/s, which must be allocated to maintain the sustainability of the river ecosystem.

By comparing the water availability value of 1.03 m³/s with the total water demand of 1.85 m³/s (the sum of irrigation and river maintenance needs), a water deficit of 0.82 m³/s occurs. This deficit indicates that water availability is insufficient to meet all the necessary needs. Therefore, a more efficient water management strategy is needed to find alternative water sources to overcome the shortage.

In the face of a water deficit of 0.82 m³/s, while maintaining the priority allocation of river maintenance discharge (0.55 m³/s), several integrated solutions can be implemented to overcome these challenges—modernization of irrigation systems through the application of water-saving technologies such as drip irrigation and sprinkler systems. In addition, developing water storage infrastructure in small-scale bung or reservoir construction as a storage facility for surplus water during the rainy season is a strategic solution to be utilized during deficit periods. Through the integrated implementation of a series of solutions, the problem of a water deficit of 0.82 m³/sec can be progressively overcome without sacrificing vital allocations for the sustainability of river ecology, thus ensuring the achievement of an optimal balance between the fulfillment of agricultural irrigation needs and the preservation of river ecosystems as valuable environmental assets.

The comparative analysis in Figure 6 shows that the mainstay discharge of the Welo Subwatershed (1.02 m³/s) can meet the river ecosystem's maintenance needs very well, according to the FDC and Tennant methods standards (Stahl et al., 2008). This mainstay discharge is almost double the requirement set by the FDC method and more than double the requirement according to the Tennant method. This indicates that most of the time (at least 80%), the Welo Subwatershed has sufficient capacity to maintain the river ecosystem while supporting water utilization for domestic, agricultural, and other needs.

However, the situation changes significantly when the analysis is focused only on baseflow. With a value of 0.79 m³/s, baseflow is sufficient to meet the river environment's minimum needs, according to the FDC method (0.54 m³/s) and the Tennant method (0.43 m³/s). This finding contrasts with the critical phenomenon that has occurred at the Tapak Menjangan weir over the past decade, where there was a weir runoff discharge of zero m³/s at the peak of the dry season in some years, as revealed in the background of the study.

Moreover, significant fluctuations in annual FDC values indicate vulnerability to hydrological extremes, such as low-flow events recorded in 2005 and other dry years. In contrast, the Tennant method offered more stable year-to-year estimates but may underrepresent extreme variations in flow, which are critical for planning under climate variability.

This study reveals important dynamics related to baseflow discharge characteristics and the determination of stream maintenance discharge in the Welo Subwatershed (Arnell, 1999). The average baseflow value of 0.79 m^3/s obtained during the dry season indicates a stable groundwater contribution to river flow. This finding aligns with McMahon & Nathan (2021), who emphasize that baseflow is a key indicator of water supply sustainability during the dry season. However, when compared to the mainstream discharge value Q80 of 1.02 m^3/s, there is a heavy reliance on surface flow during the wet season (Laaha et al., 2017). This demonstrates the limited groundwater storage capacity in the region, as described in a study by Tallaksen et al. (2023), which states that watersheds with low storage capacity tend to have smaller baseflow to total flow ratios and are more vulnerable to drought.

Year-to-year baseflow fluctuations ranging from 0.75 to 0.87 m^3/s suggest temporal variability influenced by climate and land cover changes. Zhang et al. (2017) found that forest conversion and growth of residential areas can reduce infiltration and increase surface flow, thereby reducing baseflow contribution. Something similar was observed in the Welo Subwatershed, where land use pressures and a changing climate have worsened the watershed's natural capacity to maintain baseflow. This finding reinforces the report by Permatasari et al. (2019) on watershed degradation in Indonesia that significantly reduces baseflows, increases the risk of drought, and decreases the resilience of freshwater ecosystems.

The assessment of maintenance discharge using the FDC and Tennant methods showed complementary results. Although the average calculation results were within a similar range (0.54 m^3/s for FDC and 0.43 m^3/s for Tennant), their methodological characteristics led to mixed results in extreme years. Based on discharge time-series statistics, the FDC method is more sensitive to extreme hydrological conditions (Liu et al., 2020). In contrast, the Tennant method, which is based on a percentage of annual discharge, produces more stable and conservative estimates. This finding is consistent with the studies of Choi et al. (2019), who highlighted that the sensitivity of FDC to annual fluctuations makes it a more suitable method for historical analysis, while Tennant is more suitable for practical applications with limited data.

Toward Ecosystem-Based Flow Allocation: ELOHA Approach

While this study used Tennant and FDC as practical tools, a more comprehensive approach such as the Ecological Limits of Hydrologic Alteration (ELOHA) could provide robust guidance for integrating ecological flow regimes into regional planning (Wardani et al., 2023; Zaini et al., 2023). ELOHA, as introduced by Poff et al. (2007), combines hydrological classification, ecological response modelling, and stakeholder engagement. Although currently limited by ecological data in Welo, ELOHA remains a promising future direction, particularly as citizen-science and remote sensing improve local ecological monitoring.

While both methods have been widely used in environmental flow studies, more holistic approaches, such as ELOHA (Ecological Limits of Hydrologic Alteration), developed by Opperman et al. (2018), offer a more adaptive and ecosystem-based framework. However, in the context of the Welo Subwatershed, which has limited ecological data, the FDC and Tennant methods can still provide an adequate technical basis for determining the minimum value of river maintenance discharge (Arief et al., 2019; Purwanto & Paiman, 2023), as also suggested by Arthington et al. (2018).

One of the most important implications of this study is the imbalance between baseflow availability and maintenance discharge requirements in the dry season. While the mainstem discharge Q80 is theoretically sufficient to meet ecological and irrigation needs, field conditions show that the remaining baseflow is slightly above the ecological minimum discharge threshold in the dry season. Some years even record zero discharge at the Tapak Menjangan weir, indicating the potential for severe disruption to the river ecosystem. This phenomenon is consistent with the "flow disturbance regime" concept promoted by Grizzetti et al. (2017), which explains that disturbances to the low flow regime can result in ecosystem dysfunction even if the total annual water volume does not change significantly (Mardyansyah et al., 2024). Under these conditions, the inability of rivers to maintain ecological minimum flows can threaten aquatic habitats, reduce biodiversity, and disrupt other ecosystem functions, as also emphasized by Reid et al. (2019).

The imbalance between anthropogenic demand and ecosystem sustainability is the main challenge in managing the Welo Subwatershed. Water demand for irrigation, which reaches 1.30 m^3/s, far exceeds the baseflow value and even exceeds the mainstay discharge Q80. This imbalance poses a high risk of conflict over water allocation, especially in the dry season. This situation is not unique to the Welo Subwatershed; similar pressures have been reported in many watersheds worldwide due to land use change and increased climate variability, as Albert et al. (2021) described. This condition is exacerbated by IPCC (2023) projections that predict an increase in the frequency and intensity of future droughts. Loon & Laaha (2015) also warned that increasing climate variability will reduce the ability of watersheds to maintain low flows sustainably.

In that context, the findings of this study make an important contribution to the formulation of data-driven policies that are more adaptive to local conditions. Compared to previous studies, this research provides a more detailed quantitative picture of the relationship between natural water availability, ecological demand, and water utilization pressure (Albert et al., 2021; Poff et al., 2017). Thus, this study not only strengthens the results of Ilmi (2022) on watershed degradation in Indonesia but also provides specific metrics that can be used to evaluate and design future sustainable and climate-resilient water resources management strategies.

Strategic Recommendations

To address the recurring dry-season deficit, this study recommends: Modernization of irrigation infrastructure, including micro-irrigation (e.g., drip or sprinkler systems); Development of small reservoirs to capture excess wet-season flow for later use; Implementation of flow allocation regulations that prioritize minimum ecological flow before irrigation abstractions; Hydro-ecological zoning based on ELOHA to support flexible allocation under variable climate conditions.

Critical Reflection and Limitations

Although the Q80 discharge is generally sufficient to meet both EF standards, baseflow alone remains borderline, especially in extreme dry years. Cases of zero discharge observed at Tapak Menjangan in 2012 and 2015 affirm the vulnerability of the system—consistent with Grizzetti et al. (2017) and Reid et al. (2019), who emphasize the cascading ecological consequences of low-flow interruptions.

The dominance of surface-based irrigation, limited retention capacity, and watershed degradation—confirmed by Zhang et al. (2017), Zhang et al. (2017), and Permatasari et al. (2019)—further aggravate the sustainability of water resources in the region.

Conclusion

This study concludes that the Welo Sub-Watershed exhibits a moderate baseflow capacity, averaging 0.79 m^3/s, which is a critical indicator of groundwater contributions and a reliable flow source during the dry season. The application of the Fixed Interval Method over a 30-year data period enabled consistent identification of baseflow dynamics, while environmental flow values derived from the Flow Duration Curve (0.54 m^3/s) and Tennant Method (0.43 m^3/s) suggest that ecological flow requirements can generally be fulfilled under average hydrological conditions. However, the irrigation demand—up to 1.30 m^3/s—significantly exceeds baseflow and the dependable Q80 discharge (1.02 m^3/s), especially during drought-prone periods, leading to potential ecological stress and increasing competition over water resources. To mitigate this imbalance, the study recommends a combination of strategic measures, including modernization of irrigation infrastructure with water-saving technologies, development of small-scale water storage facilities such as reservoirs to retain excess wet-season runoff, and enforcement of regulatory policies that ensure minimum environmental flow is secured before water is allocated for irrigation. If these adaptive strategies are not adopted, the watershed is at risk of experiencing more frequent disruptions in river flow, including dry-season zero discharge events as previously recorded, which may result in biodiversity loss, degradation of aquatic ecosystems, and heightened conflicts among stakeholders. These findings underscore the urgency of adopting an integrated and ecologically informed water resource management policy and suggest that frameworks such as ELOHA (Ecological Limits of Hydrologic Alteration) could provide a more comprehensive and adaptive foundation for sustaining environmental flows in hydrologically vulnerable regions like the Welo Sub-Watershed.

Acknowledgments

The authors would like to thank the Welo Sub-Watershed Authority for providing access to the long-term hydrological data used in this study. Thanks to the Department of Irrigation Engineering, Faculty of Engineering, Universitas Brawijaya, for technical and administrative support during the research process.

Author Contributions

Conceptualization, W.S. and P.T.J.; methodology, software, formal analysis, investigation, data curation, writing—original draft preparation, visualization, W.S.; validation, W.S., P.T.J., and M.S.; resources, project administration, P.T.J.; writing—review and editing, supervision, P.T.J. and M.S.; funding acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

Funding

This research was independently funded by researchers. This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

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