JTEP Jurnal Keteknikan Pertanian,
Vol. 14 No. 2, p258-268, 2026
P-ISSN 2407-0475 E-ISSN 2338-8439

Available online:
http://journal.ipb.ac.id/index.php/jtep
DOI: 10.19028/jtep.014.2.258-268

Research Article

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Spatial-Temporal Assessment of Water Balance in the Barugbug Irrigation Command Area

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Article Info

***Submitted:* 8 May 2026**
***Revised:* 15 Juni 2026**
***Accepted:* 29 Juni 2026**
***Available online:* 29 June 2026**
***Published:* June 2026**

Keywords:
Barugbug Irrigation Command Area, Penman-Monteith, SISCROP, Spatial Modelling, Water Balance

How to cite:
Nurkhaida, R., Liyantono., Adi. S. H.(2026). Spatial-Temporal Assessment of Water Balance in the Barugbug Irrigation Command Area. Jurnal Keteknikan Pertanian, 14(2): 258-268. https://doi.org/10.19028/jtep.014.2.258-268.

Abstract

Efficient irrigation management requires accurate information regarding the spatial and temporal dynamics of water availability and irrigation requirements. However, water balance assessments in many irrigation systems are still commonly conducted using aggregated approaches, which provide limited information on the spatial-temporal distribution of water shortages within an irrigation command area. To address this limitation, this study evaluated irrigation water requirements, water availability, and water balance condition in Barugbug Irrigation Command Area using spatial approach. Effective rainfall was estimated through spatial interpolation using the Inverse Distance Weighting method. The irrigation water requirement was estimated using the Penman-Monteith method combined with pixel-based calculations. Water availability was estimated using the 80% dependable discharge (Q80) derived from operational records from 2014 to 2024. The analysis showed that irrigation water requirements consistently increased during the land preparation period, particularly in March and October. The highest Q80 value was recorded in March at 22.30 m3/s, whereas the lowest value occurred in October at 0.22 m3/s. Water balance analysis showed that surplus conditions generally occurred during the wet season, whereas water deficits emerged from the second period of August to the second period of October.

Doi: https://doi.org/10.19028/jtep.014.2.258-268

1. Introduction

The Barugbug Irrigation Command Area is part of the Jatiluhur Irrigation Scheme, which supplies irrigation water to approximately 2,870 ha of agricultural land in the Karawang and Subang Regencies. Despite its important role in supporting agricultural production, irrigation management in this area faces several challenges, particularly high water losses caused by damaged irrigation

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infrastructure, canal leakage, and uneven water distribution (Rizal et al., 2019). Water availability is influenced by seasonal discharge fluctuations and its hydraulic connection to the Tarum Timur Canal, resulting in dynamic water supply conditions throughout the year (Azmeri et al., 2019; Lubis et al., 2018).

An accurate assessment of the irrigation water balance is essential for managing these fluctuations and ensuring reliable water delivery. Previous studies have assessed irrigation water balance using Penman-Monteith to estimate crop water requirements and the 80% dependable discharge to estimate water availability (Maulida et al., 2022; Saputri & Saves, 2023; Tubani et al., 2025). However, most of these studies estimated irrigation water requirements at the scheme level using aggregated approaches. Consequently, they provide limited information on the spatial variability of water surplus and deficit conditions within the irrigation service area. This limitation is particularly important because irrigation water demand is influenced by variations in cropping patterns, land characteristics, microclimatic conditions, and field position within the irrigation network (Ahmadpour et al., 2022; Olivera-Guerra et al., 2023; Smith et al., 2009). Consequently, potential water surplus and deficit conditions are not evenly distributed across the irrigation areas.

This study addresses these limitations by combining dependable operational discharge analysis with raster-based irrigation water requirement modelling derived from the Sistem Informasi Standing Crop (SISCROP). Unlike previous studies that primarily assesses irrigation water balance temporally at scheme level, the proposed approach evaluates water balance at pixel level, enabling simultaneous analysis of spatial and temporal variations in water availability and irrigation requirements. This approach enables the identification of field-scale water surplus and deficit patterns, providing more detailed information for operational management across the irrigation command area.

Accordingly, this study aims to estimate spatiotemporal irrigation water requirements using raster-based SISCROP data, evaluate water availability using the 80% dependable discharge (Q80) as an indicator of reliable water supply, and assess water balance conditions across the Barugbug Irrigation Command Area to identify the timing and locations of areas vulnerable to irrigation water deficits.

2. Material and Methods

2.1 Study Area and Period

This study was conducted in the Barugbug Irrigation Command Area located in the Karawang and Subang Regencies. The Barugbug Weir is the primary water source for the irrigation system. The research was conducted from March 2025 to March 2026, covering data collection, processing, analysis, and report preparation.

2.2 Data and Tools

This study used secondary data obtained from relevant agencies, including climatological data consisting of air temperature, relative humidity, solar radiation, and wind speed for the 2022–2024

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period, rainfall data for 2015–2024, operational discharge data from the Barugbug Weir for 2014–2024, irrigation network and service area maps, and cropping pattern and crop growth phase data from the ((SISCROP) for 2022–2024. Numerical data were processed using Microsoft Excel, and spatial analysis was conducted using ArcGIS Pro 3.6. The research workflow is illustrated in Figure 1.

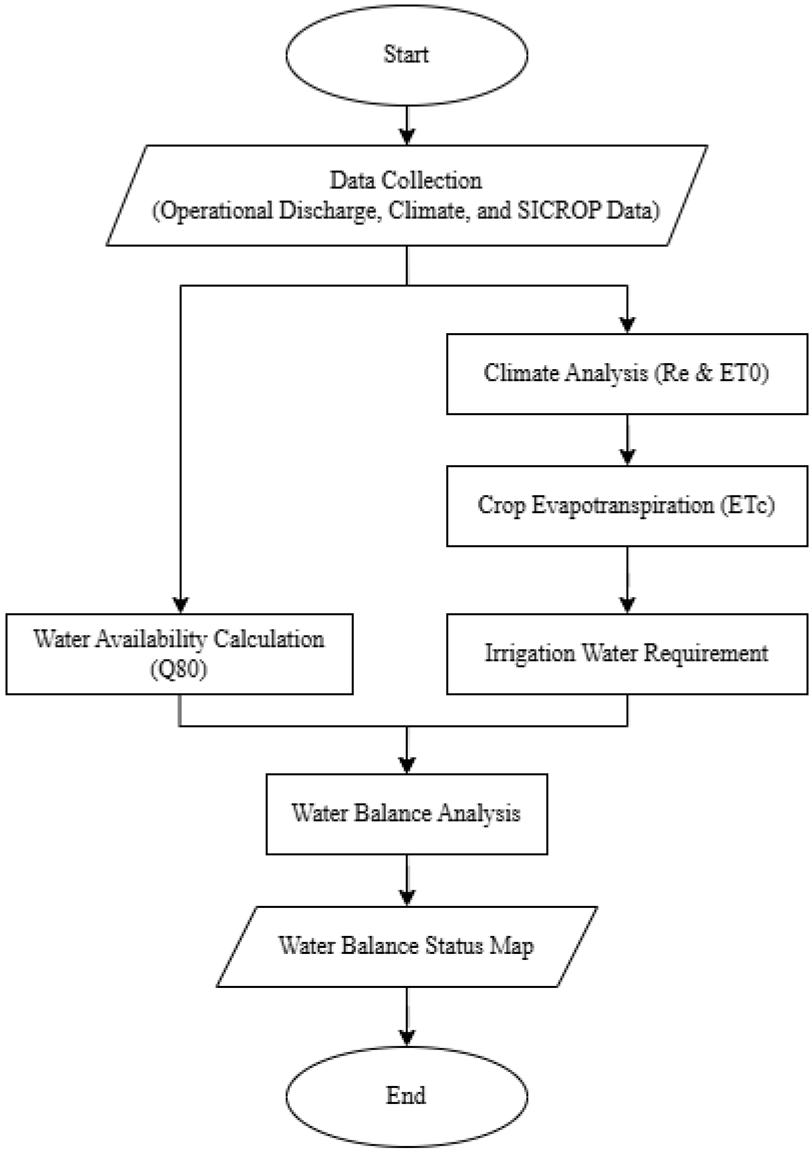

Figure 1. Flowchart of the study.

A raster-based spatiotemporal approach was applied, with each pixel treated as an analysis unit at 15-days interval. Climate data, crop growth phases, and irrigation boundaries were integrated to analyze the spatial and temporal distribution of irrigation water requirements in the Barugbug Irrigation Command Area. Crop growth phases from SISCROP were converted into crop coefficients

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(Kc) to calculate the crop evapotranspiration (ETc), net field requirement (NFR), irrigation requirement (IR), and discharge requirement (DR) using the Raster Calculator tool in ArcGIS Pro 3.6.

2.3 Climate Data Analysis

1. Effective rainfall (Re) was derived from the 80% dependable rainfall (R80). The spatial rainfall distribution was interpolated using the Inverse Distance Weighting (IDW) method in ArcGIS Pro.

$$Z(x) = \frac{\Sigma \frac{Zi}{d_i^p}}{\Sigma \frac{1}{d_i^p}} \quad (1)$$

where Z(x)is the rainfall at location x, Z_iis the rainfall at observation point i, d_iis the distance between the observation point and location x, and p is the power parameter.

2. Reference evapotranspiration (ET0) was calculated using the FAO Penman–Monteith method (Allen et al., 1998).

$$ET_0 = \frac{0{,}408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0{,}34 u_2)} \quad (2)$$

where Δ is the slope of the vapor pressure curve (kPa/°C), Rn is the net radiation at the surface (MJ/m²/day), G is the soil heat flux (MJ/m²/day), which is often negligible in daily calculations, γ is the psychrometric constant (kPa/°C), T is the mean air temperature (°C), u2 is the wind speed at a height of 2 m (m/s), es is the saturation vapor pressure (kPa), and ea is the actual vapor pressure (kPa).

3. Crop evapotranspiration (ETc) was calculated as

$$ETc = ET_0 \; x \; Kc \quad (3)$$

where ETc is the crop evapotranspiration, ET_0 is the reference evapotranspiration, and Kc is the crop coefficient.

2.4 Irrigation Water Requirement

Irrigation water requirements were analyzed in accordance with the KP-01 Criteria for Irrigation Network Planning ((Kementerian Pekerjaan Umum, 2013). The calculation included the Net Field Requirement (NFR), Irrigation Requirement (IR), Discharge Requirement (DR), and Land Preparation (LP) using the following equations:

1. The Net Field Requirement (NFR) was calculated as follows:

NFR = ETc + P + WLR -Re (4)

where ETc is the crop evapotranspiration, P is percolation, WLR is the water layer requirement, and Re is effective rainfall.

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2. The irrigation Requirement (IR) was calculated as follows:

$$IR = \frac{NFR}{e} \tag{5}$$

   where e is the overall irrigation efficiency (65%)

3. The discharge Requirement (DR) was calculated as follows:

$$DR = \frac{\frac{IR}{(1{,}000\ x\ 99.89)}}{(15\ x\ 86{,}400)} \tag{6}$$

   where DR is water withdrawal requirement at the source (m^3/s/pixel), IR is irrigation requirement (mm/15 days), 1,000 is the conversion factor from mm to m^3, 99.89 is pixel area in SISCROP (m^2), 15 is the SISCROP period (days), and 86,400 is the conversion factor from mm/15 days to m^3/day

4. The Land Preparation Requirement was calculated using Van De Goor and Zijlstra's (1968) equation:

$$LP = \frac{M\ x\ e^k}{(e^k - 1)} \tag{7}$$

   where LP is the irrigation water requirement for land preparation (mm/day), M is the water requirement to replace the water lost due to evaporation and percolation in saturated paddy fields (M = Eo + P), Eo is the open-surface evaporation (mm/day), P is percolation (mm/day), k is M × T divided by S, T is the soil preparation period (days), and S is the water requirement (mm).

2.5 Water Availability Analysis

Water availability was evaluated using the 80% dependable discharge (Q80) derived from operational discharge data from 2014 to 2024 at 15-day intervals. The probability was calculated using the Weibull equation:

$$P = \frac{m}{n+1}\ x\ 100\% \tag{8}$$

Where P is the probability, m is the rank order, and n is the number of observations. The discharge corresponding to an 80% probability was defined as Q80.

2.6 Water Balance Analysis

The water balance in the Command Area was evaluated by comparing the dependable discharge (Q80) with the discharge requirement (DR) at a 15-day temporal resolution, representing the balance between the water supply and irrigation requirement.

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3. Results and Discussion

3.1 Irrigation Water Requirements and Water Availability

Figure 2 shows the spatial distribution of effective rainfall (Re) across the irrigation command area during the peak wet season (the first period of February) and the peak dry season (the second period of July). A clear spatial gradient was observed during the wet season, where lighter colors represented higher effective rainfall and darker colors represented lower values. The western area recorded the highest Re (131.40 mm/day), whereas the eastern region recorded lower values (96.47 mm/day). The gradient indicates the spatial variability of effective rainfall across the study area. This finding suggests that effective rainfall was not uniformly distributed throughout the irrigation command area, resulting in varying contributions to crop water requirements at different locations. In contrast, effective rainfall decreased substantially during the dry season, reaching 0 mm/d in all areas. Consequently, irrigation water has become the primary source of water supply for crop production during periods of low rainfall (Paski et al., 2018).

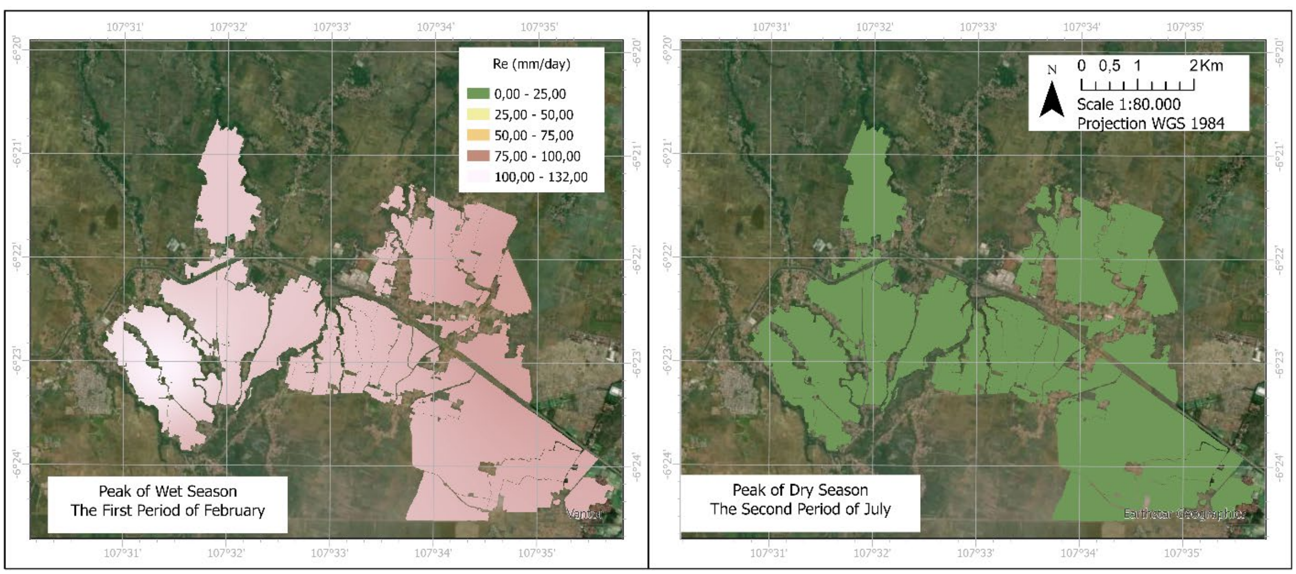

Figure 2. Spatial-temporal variability of effective rainfall (Re).

Figure 3 presents the temporal variation in irrigation water requirements and dependable discharge in the Barugbug Irrigation Command Area. The net field (NFR) and irrigation (IR) requirements generally decreased during the wet season, when effective rainfall contributed substantially to meeting crop water requirements. Consequently, the amount of irrigation water required was lower, which is consistent with the findings of September et al. (2021). The discharge requirement (DR) reached its highest values in the second period of March (2.73 m^3/s) and the second period of October (2.81 m^3/s). This increase was associated with land preparation and initial field inundation, which require a significant water supply (Azmeri et al., 2019; Saputra, 2018). These

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conditions suggest that irrigation scheduling during the wet season can be minimized to improve overall water-use efficiency.

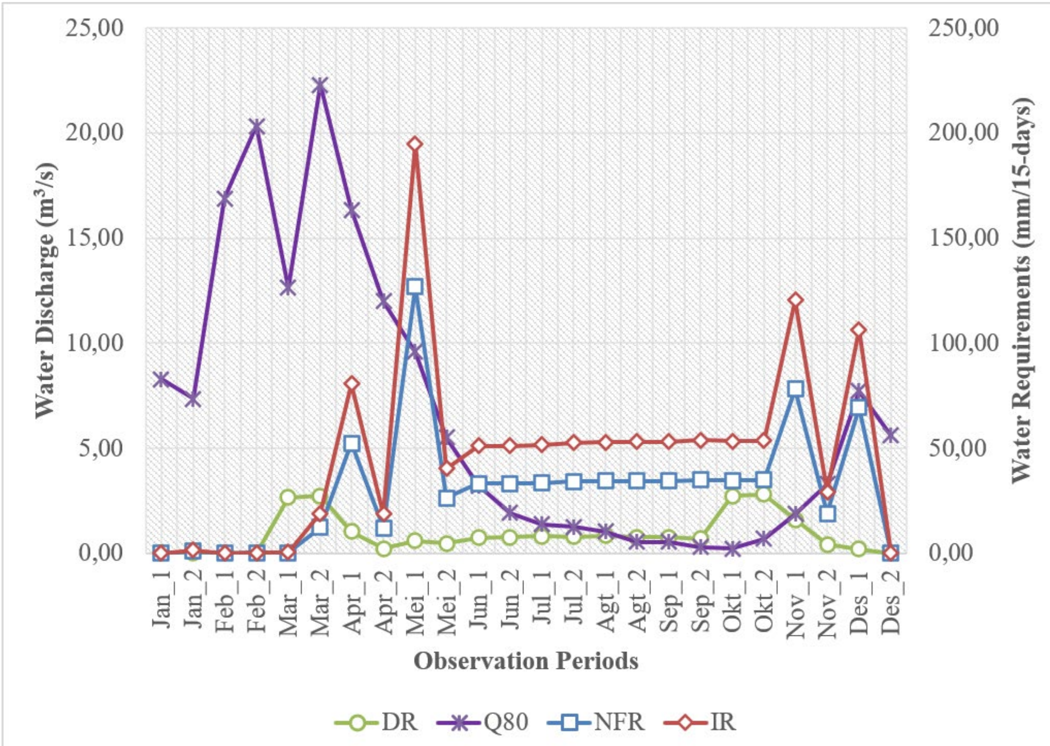

Figure 3. Comparison of NFR, IR, DR, and Q80.

The analysis of dependable discharge (Q80) in the Barugbug Irrigation Command Area showed strong seasonal variations following annual rainfall patterns. Water availability peaked at 22.30 m³/s in the second period of March, coinciding with the wet season, and gradually declined to its lowest value of 0.22 m³/s in the first period of October during the dry season. This pattern reflects the strong influence of seasonal rainfall on river flow and the reduced contribution of base flow during prolonged dry conditions (Miranti & Rahmadania, 2021; Sudinda, 2021). The variation in water availability between the wet and dry seasons indicates the importance of effective irrigation management to ensure an adequate water supply under varying seasonal conditions.

3.2 Spatial - Temporal Water Balance Status

Surplus conditions generally occurred during the wet season (January to June and November to December). The highest surplus condition was observed in the second period of February, when effective rainfall reduced irrigation water requirements, whereas deficit conditions developed from the second period of August to the second period of October. This period coincided with reduced water availability and relatively high irrigation requirements, resulting in an imbalance between the water supply and crop water requirements. These findings indicate that the water balance status

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within the command area is strongly influenced by rainfall variability, which impacts water availability and irrigation water requirements.

Figure 4 illustrates the spatial and temporal distribution of the water balance conditions across the Barugbug Irrigation Command Area. The raster-based analysis derived from SISCROP data revealed a marked shift in the water balance status between the first and second periods of August 2024. During the first period of August, most areas remained under surplus conditions, indicating that the available water was still sufficient to meet the crop water requirements. However, by the second period of August, deficit conditions became widespread across the irrigation command area, reflecting the rapid decline in water availability during the dry season.

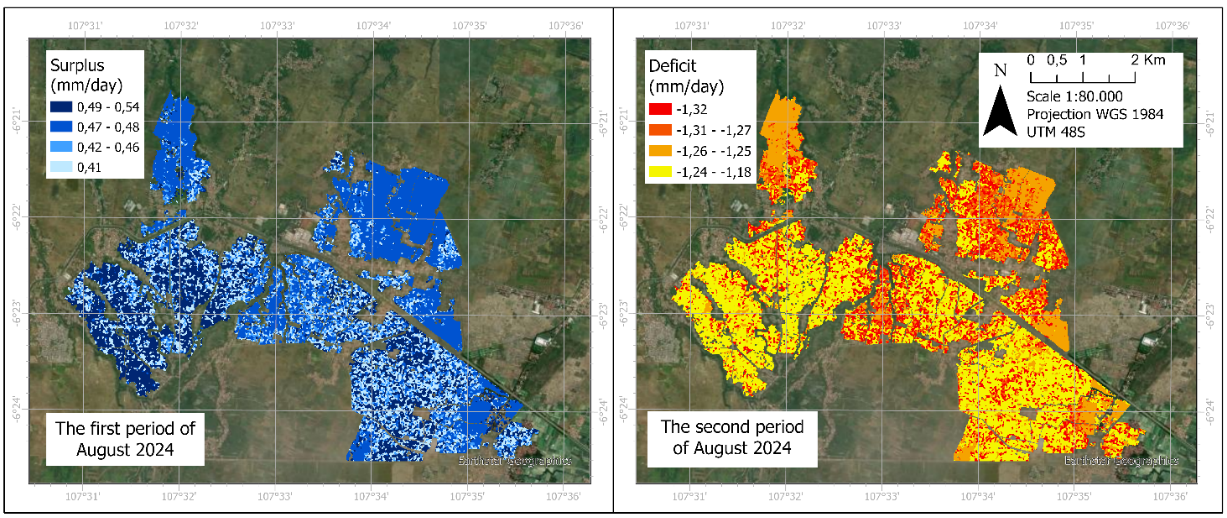

Figure 4. Spatial-temporal distribution of water balance conditions in the Barugbug Irrigation Command Area.

The spatial pattern of the deficits was not uniformly distributed. Areas with more severe deficits were concentrated in several parts of the irrigation system, whereas other areas experienced relatively lower deficit levels. This spatial heterogeneity suggests that the availability and distribution of water are influenced by local hydraulic conditions within the irrigation network. Differences in conveyance efficiency, water loss along canals, operational water distribution practices, and the relative location of service areas within the network may contribute to the observed variability in water balance conditions.

The severity of these deficits was reflected in the spatial distribution of water balance values, where downstream areas consistently showed larger negative deficits reaching up to -1,32 mm per day per pixel compared to upstream areas during lower discharge periods. This pattern indicates that water shortages became more pronounced toward the tail-end of the irrigation system, where water delivery may be affected by cumulative losses along the conveyance networks. Similar observations have been reported by Aryani et al. (2024), who found that declining network efficiency and water losses along distribution canals can reduce water availability in the downstream areas. Consequently, the available supply may be insufficient to fully meet crop water requirements during the dry season, thereby increasing the risk of water stress in the affected areas.

The observed spatial disparities emphasize the importance of improving irrigation water distribution, particularly during periods of limited availability. Management measures, such as rotational irrigation scheduling, rehabilitation of conveyance structures, reduction of water losses along canals, and improvements in distribution control, could improve water distribution efficiency and reduce inequalities in water distribution across the irrigation network.

In contrast, the southern parts of the command area maintained relatively stable water conditions during the dry season. The water balance evaluation results indicated that water availability in the Barugbug Irrigation Command Area is influenced not only by river discharge but also by the conditions of the irrigation network and local water distribution arrangements. Field observations and information from the agricultural extension officer indicated that the southern region was receiving additional water supply from the Tarum Timur Canal system. However, the exact diversion structure could not be verified during this study. These findings are consistent with those of Mulyadi et al. (2014), who reported a connection between the Barugbug irrigation network and the Tarum Timur Canal through the BTT 21 and BTT 22 structures. Therefore, the presence of supplementary water sources may contribute to the relatively stable water balance observed in the southern area, even during periods of reduced discharge.

4. Conclusion

Irrigation water requirements increased significantly during the land preparation period, particularly in March and October, when crop water requirements were at their peak. Simultaneously, reliable discharge (Q80) reached its highest value of 22.30 m^3/s during the wet season and declined to only 0.22 m^3/s in the dry season, reflecting substantial seasonal fluctuations in water availability. Water balance analysis showed that irrigation water was generally sufficient during the wet season, resulting in surplus conditions across most of the command area. In contrast, water shortages emerged between the second half of August and the second half of October, as water availability decreased, while irrigation demand remained relatively high. Spatial analysis further revealed that these deficits were unevenly distributed. Specifically, the downstream areas of the irrigation network experienced more severe water stress.

5. Acknowledgement

The authors would like to express their sincere gratitude to Perum Jasa Tirta II for providing hydrological data, Badan Meteorologi, Klimatologi, dan Geofisika (BMKG) for climate data support, and the Indonesian Center for Agricultural Development and Modernization of Land Resources

Available online:
http://journal.ipb.ac.id/index.php/jtep
DOI: 10.19028/jtep.014.2.258-268

(ICADM Land Resources) for providing access to the SISCROP data. The authors also extend their appreciation to Mr. Eko Ginanjar K., A.Md, the agricultural extension officer (PPL) in Pabuaran Village, Patokbeusi Sub-district, Subang Regency, for his valuable assistance and field support during this study.

6. AI Writing Statement

The author used Generative AI (ChatGPT, GPT-5.5) solely to assist with language translation, language editing, and paraphrasing during the preparation of this manuscript. All research design, analyses, data interpretation, discussion, and conclusions are the author's own work and responsibility.

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