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Water Balance Analysis for Irrigation Sustainability in the Way Kelutum Irrigation Area

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Abstract

The sustainability of irrigated agriculture in regions with pronounced seasonal rainfall variability depends on maintaining a balance between water availability and crop water demand. This study evaluates the irrigation water balance in the Way Kelutum Irrigation Area, Pringsewu Regency, Lampung, Indonesia, through a semi-monthly analysis integrating crop water requirements and dependable river discharge. Crop water demand was estimated using the Penman–Monteith method, while dependable discharge at an 80% reliability level was calculated using the F.J. Mock model based on rainfall, climatological data, and watershed characteristics. The results indicate that effective rainfall contributes substantially to meeting crop water requirements during the early rainy season, whereas irrigation supply becomes the primary source of water during the dry season. The dependable discharge of the Way Kelutum River varies between 0.10 and 1.40 m^3/s throughout the year. Semi monthly water balance analysis shows that available water resources are sufficient to support two rice-growing seasons over an irrigated area of 42.04 ha, while water deficits occur for secondary crops during the peak dry period. By emphasising intra-seasonal water balance dynamics rather than annual-scale averages, this study provides practical insights for determining operational cropping patterns in small-to-medium irrigation schemes, particularly under conditions of limited dry-season water availability.

Keywords: crop water requirement; cropping pattern feasibility; dependable discharge; irrigation water balance; way kelutum irrigation area

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INTRODUCTION

Climate variability has increasingly emerged as a critical challenge for agricultural water management worldwide, particularly in regions where food production relies heavily on irrigation systems. Changes in rainfall patterns, increased frequency of dry spells, and heightened evapotranspiration rates have intensified competition for limited water resources among agricultural, domestic, and ecological users (Tian et al., 2018; Eisma & Merwade, 2020). In this context, irrigation water balance plays a central role in safeguarding food security by ensuring that water supply aligns with crop water demand across space and time. Failure to manage this balance effectively can lead to reduced crop yields, inefficient water use, and heightened vulnerability of farming systems to climate extremes, especially in tropical and subtropical regions where seasonal variability is pronounced (Meller, 2023).

Recent advances in hydrological and agricultural research have highlighted the importance of water balance analysis at multiple scales, ranging from river basins to on-farm irrigation schemes. At the watershed (DAS) scale, conceptual frameworks such as the Budyko approach have been widely applied to quantify the combined impacts of climate variability and human activities on streamflow dynamics, demonstrating that seasonal shifts in precipitation and evapotranspiration strongly influence water availability (Tian et al., 2018). At the irrigation and field scales, semi-monthly and seasonal assessments have been increasingly adopted to capture short-term hydrological responses to irrigation practices, water harvesting structures, and soil moisture dynamics (Eisma & Merwade, 2020; Risch & Frank, 2007). These studies consistently show that annual-scale water balance assessments tend to mask intra-annual variability, limiting their usefulness for operational irrigation management and cropping decisions.

Despite these advancements, several critical gaps remain in the existing literature. First, many studies continue to examine either water availability from a hydrological perspective or crop water demand from an agronomic perspective in isolation, resulting in fragmented insights that are insufficient for integrated irrigation planning (Cundaningsih et al., 2025). Second, intra-annual analyses particularly semi-monthly assessments that reflect actual irrigation scheduling and cropping calendars are still limited, especially in tropical regions where rainfall variability within seasons is substantial (Gichenje, 2019; Jordan et al., 2019). Third, empirical evidence from small-to-medium irrigation schemes remains scarce, even though such systems constitute the backbone of agricultural production in many developing countries and are often managed using a combination of formal infrastructure and local ecological knowledge (Goenster et al., 2015). These limitations constrain the development of adaptive, decision-oriented irrigation strategies under changing climatic conditions.

Positioned within this context, the present study contributes to bridging these gaps by applying an integrated, semi-monthly water balance framework at the operational irrigation scheme level. By explicitly linking dependable water availability with crop water requirements across cropping seasons, the study provides actionable insights for irrigation management decisions, including adjustments in cropping patterns and cultivated areas. This operational and seasonal focus aligns with recent calls for decision-support tools that translate hydrological analyses into practical irrigation planning under climate variability (Kusumastuti et al., 2021).

The sustainability of agricultural production is fundamentally shaped by the availability and governance of irrigation water (Putri et al., 2025). Irrigation plays a critical role in enhancing land productivity by enabling extended cropping seasons, as reflected in increased cropping indices, particularly in tropical countries with modern agricultural systems such as Indonesia (Wintyaswan et al., 2023). The effectiveness of irrigation depends not only on the volume of water supplied but also on equitable distribution and temporal alignment with crop water demands (Wulandari & Amal, 2024). Variability in rainfall often leads to inefficiencies in water utilization, with surpluses during the rainy season and deficits during the dry season, resulting in spatial and temporal mismatches between supply and demand (Palupi et al., 2024). Such patterns, including upstream surpluses and downstream deficits, have been documented in major irrigation basins, demonstrating that peak water availability does not necessarily coincide with periods of highest crop water demand (Kusumastuti et al., 2021).

The Way Kelutum Irrigation Area (DI), located in Pringsewu Regency, Lampung Province, represents a productive agricultural zone within the Way Sekampung watershed, where rice and secondary crops dominate local livelihoods. Although annual water availability appears relatively sufficient, farmers frequently experience water shortages during the dry season alongside underutilized surpluses during the rainy season. Previous studies in the region have predominantly focused either on hydrological water availability (Rahmawati et al., 2025) or on irrigation water requirements (Purwanto & Ikhsan, 2013; Permana & Ramadhan, 2022). Integrated water balance analyses that combine supply and demand variables at an operational scale remain limited, and most existing assessments rely on annual averages that obscure intra-seasonal dynamics critical for cropping pattern determination.

Accordingly, this study aims to: (1) estimate irrigation water requirements for rice and secondary crops using the Penman–Monteith method, a widely accepted approach for calculating reference evapotranspiration (Bunganaen et al., 2022); (2) simulate dependable river discharge using the F.J. Mock method, which has been validated for estimating reliable water availability under variable climatic conditions; and (3) analyze the semi-monthly irrigation water balance, including periods of surplus and deficit, across cropping seasons in the Way Kelutum Irrigation Area. The findings are expected to provide a scientifically robust and operationally relevant basis for adaptive irrigation management, supporting improved water use efficiency and sustainable agricultural planning in small-to-medium irrigation schemes under climate variability.

METHOD

Research Site

This study was conducted in the Way Kelutum irrigation area, located in Sukoharjo Sub-district, Pringsewu regency, Lampung province. As illustrated in **Figure 1**, from a hydrological perspective, the Way Kelutum irrigation area lies within the Way Sekampung watershed, which serves as one of the major food production zones in Lampung province. The irrigated area under investigation covers 42.04 ha, while the total area of the Way Kelutum watershed amounts to 5,969.71 ha.

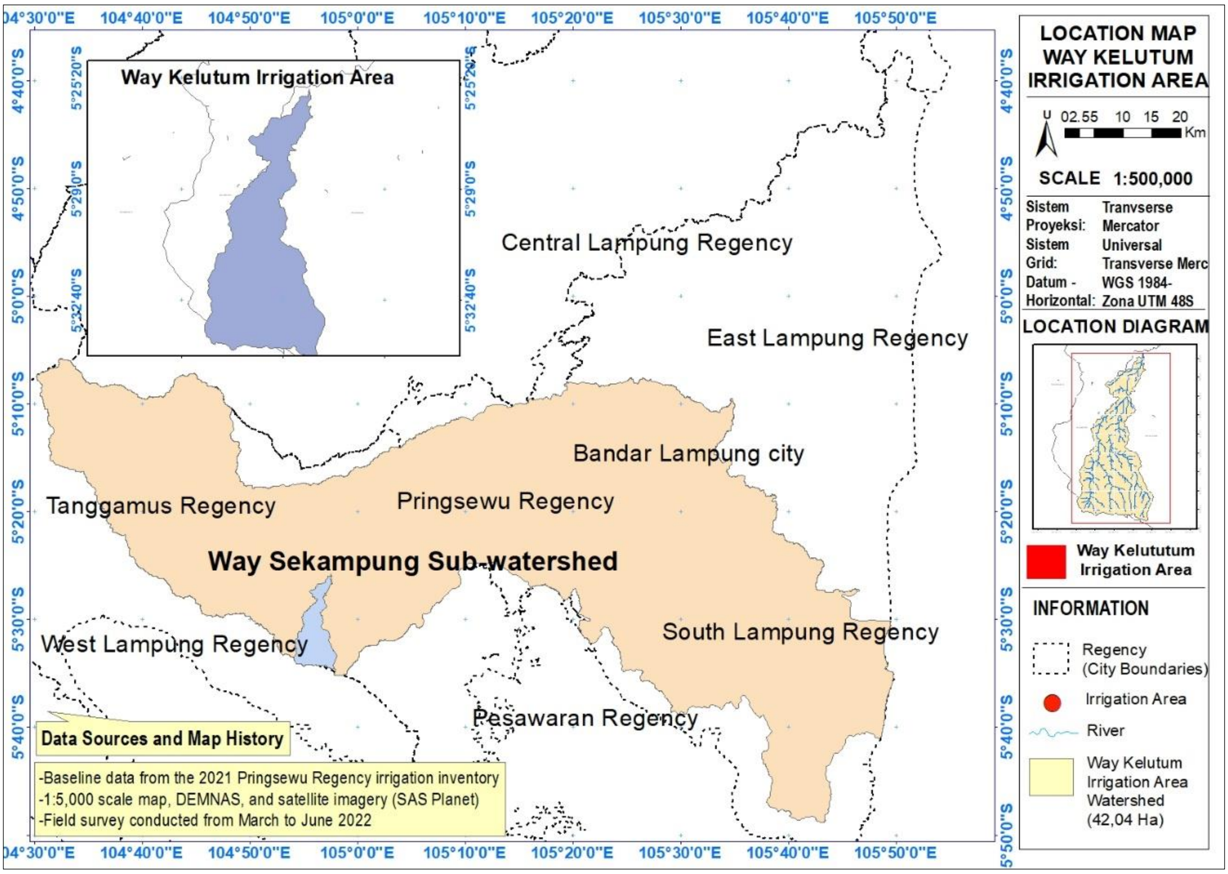

Figure 1. Way Kelutum irrigation area

Data Collection and Data Analysis

This study employed both primary and secondary data, detailed as follows:

1. **Primary data:** Field survey results through instantaneous discharge measurements of the Way Kelutum River.
2. **Secondary data included:**
   a. Daily rainfall records from four representative stations, namely PH.011 Way Guring Suka Agung–Bulok, PH.009 Kuto Dalem, R.040 Pematang Nebak, and PH.016 Pajar Esuk II, covering the period 1996–2017.
   b. Climatological data consisting of humidity, temperature, wind speed, and solar radiation obtained from BMKG stations at Branti, Gunung Megang, Reno Basuki, and Cisaat Natar over a 12-year period.

c. Watershed characteristics data, including hydrological parameters, watershed area, and land use.

The analytical method employed in this study was carried out through the following four stages:

Rainfall Data

The representative values from the four rainfall stations were calculated using the Thiessen Polygon method to obtain the watershed's average rainfall. Subsequently, the effective rainfall (Re) was determined at an 80% probability of occurrence (R80) using the Weibull distribution, in accordance with irrigation planning requirements.

Estimation of Evapotranspiration and Crop Water Requirements

Reference evapotranspiration (ETo) was calculated by considering temperature, humidity, and wind speed using the Penman–Monteith method. Actual crop evapotranspiration (ETc) was obtained by multiplying ETo with the crop coefficient (Kc). The net field water requirement (NFR) in paddy fields (Wulandari & Amal, 2024) can be determined using the mathematical equation as presented in Equation (1):

$$NFR = ET_c + P + WLR - R_e \quad (1)$$

The amount of water lost through the process of crop evapotranspiration is represented by the actual crop evapotranspiration (ETc), while water losses due to percolation into the soil are represented by P. The requirement to replenish the standing water layer in paddy fields is indicated by WLR, and Re denotes the effective rainfall that can be utilized by the crop. The additional water required by crops in the field, after accounting for the contribution of rainfall, is represented by the net field requirement (NFR) (Sabara et al., 2022).

Dependable Discharge Analysis

The dependable discharge was determined at an 80% reliability level to ensure water availability under operational irrigation conditions. Water availability analysis was conducted using the F.J. Mock method (Paski et al., 2017), which incorporates watershed characteristics, rainfall, and climatic data.

Water Balance Analysis

The amount of water surplus or deficit can be identified through water balance calculations (Kusumastuti et al., 2021). This analysis not only serves as a reference for optimizing water utilization but also provides important information for anticipating potential hazards arising from surplus or deficit water conditions (Wintyaswan et al., 2022). The water balance can be calculated using the mathematical equation presented in Equation (2):

$$WB = Q_{dep} - DR \quad (2)$$

where:
WB = water balance (m^3/s)
Qdep=dependable discharge (m^3/s)
DR = net water requirement at the intake (m^3/s)

RESULTS AND DISCUSSION

Rainfall Analysis

Rainfall data were collected from four stations that is PH.009 Kuto Dalem, PH.011 Way Guring Suka Agung–Bulok, PH.016 Pajar Esuk II, and R.040 Pematang Nebak. Areal average rainfall was calculated using the Thiessen Polygon method with coefficients ranging from 0.12 to 0.35. The largest contribution was from Station PH.016 Pajar Esuk II. Semi-monthly average rainfall exhibited a clear seasonal pattern **(Figure 2)** with peak values in January–March exceeding 150 mm per half-month, and a marked decline to below 40 mm per half-month during June–September. These observations indicate periods of potential water surplus during the rainy season and deficits during the dry season.

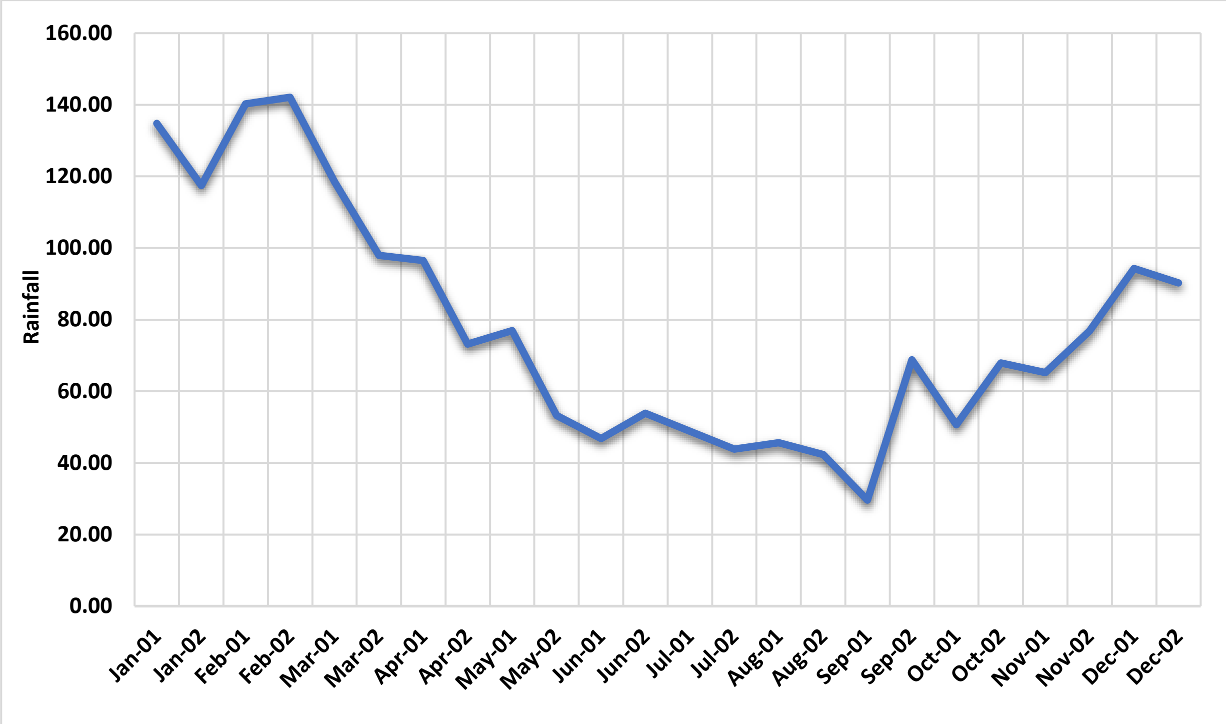

Figure 2. Semi-monthly average rainfall in Way Kelutum

While the rainfall patterns provide a descriptive overview it is essential to analyze the relative drivers of observed water surpluses and deficits. The surplus in the first rice season (January–March) coincides with peak rainfall whereas the second rice season exhibits the highest irrigation demand despite lower rainfall inputs. This higher water requirement in the second season can be attributed primarily to the cropping calendar rather than climatic factors. Specifically the growth stage of rice during the second season that characterized by peak evapotranspiration demands that overlaps with the transition from moderate rainfall to the dry season (June–September). Consequently, evapotranspiration demand dominates the water balance during this period, highlighting that crop water requirements, rather than rainfall variability alone are the main driver of irrigation needs. By integrating rainfall variability with crop evapotranspiration and the cropping calendar these findings underscore the importance of adaptive irrigation planning. The results suggest that water management strategies should prioritize efficient water allocation during the second rice season when evapotranspiration driven demand is highest to mitigate potential deficits and enhance water use efficiency (Sabara et al., 2020).

Climatological Analysis

Figure 3 presents the monthly variation of rainfall, evapotranspiration (ETP), and the rainfall–evapotranspiration balance (P–ETP) in the Way Kelutum Irrigation Area, highlighting the seasonal interaction between water supply and atmospheric demand. Variability in crop evapotranspiration is primarily controlled by climatic factors, including air temperature, relative humidity, wind speed, and solar radiation.

Climatological data indicate that the annual average air temperature ranges from 24–29 °C, relative humidity from 76–84%, solar radiation from 7–10 h/day, and wind speed from 2–12 km/day. These parameters strongly influence reference evapotranspiration (ETo), as calculated using the Penman–Monteith method **(Figure 3)**. The highest ETo values occur during August–October, corresponding to high solar radiation, lower relative humidity, and increased wind speed, which collectively enhance atmospheric water demand. In contrast, the lowest ETo values are observed during January–March, coinciding with high rainfall and elevated humidity, which suppress evapotranspiration rates. This climatic control is clearly reflected in the water balance pattern. During the wet season (January–March and November–December), rainfall exceeds evapotranspiration, resulting in positive P–ETP values and water surplus conditions. These conditions are favorable for irrigation sustainability, as crop water requirements are largely met by precipitation, allowing excess water to contribute to soil moisture replenishment and hydrological storage (Wulandari & Amal, 2024).

From April to August, a marked decline in rainfall combined with relatively stable or increasing evapotranspiration leads to a progressive reduction in P–ETP values. Negative P–ETP values during August–September indicate water deficit conditions, when irrigation supply becomes highly dependent on river discharge and effective water management. The most critical period occurs in September–October, when high ETo and low precipitation coincide, increasing the risk of irrigation water shortages. The return to surplus conditions in November–December reflects increased rainfall and reduced evapotranspiration, supporting recovery of soil moisture and water storage (Paski et al., 2017). Overall, the results demonstrate that irrigation sustainability in the Way Kelutum Irrigation Area is strongly governed by seasonal climatic variability and its control on evapotranspiration and rainfall balance. Monthly water balance analysis, integrated with climatological parameters, provides a robust basis for adaptive irrigation planning and sustainable water resource management under changing climate conditions (Permana & Ramadhan, 2022).

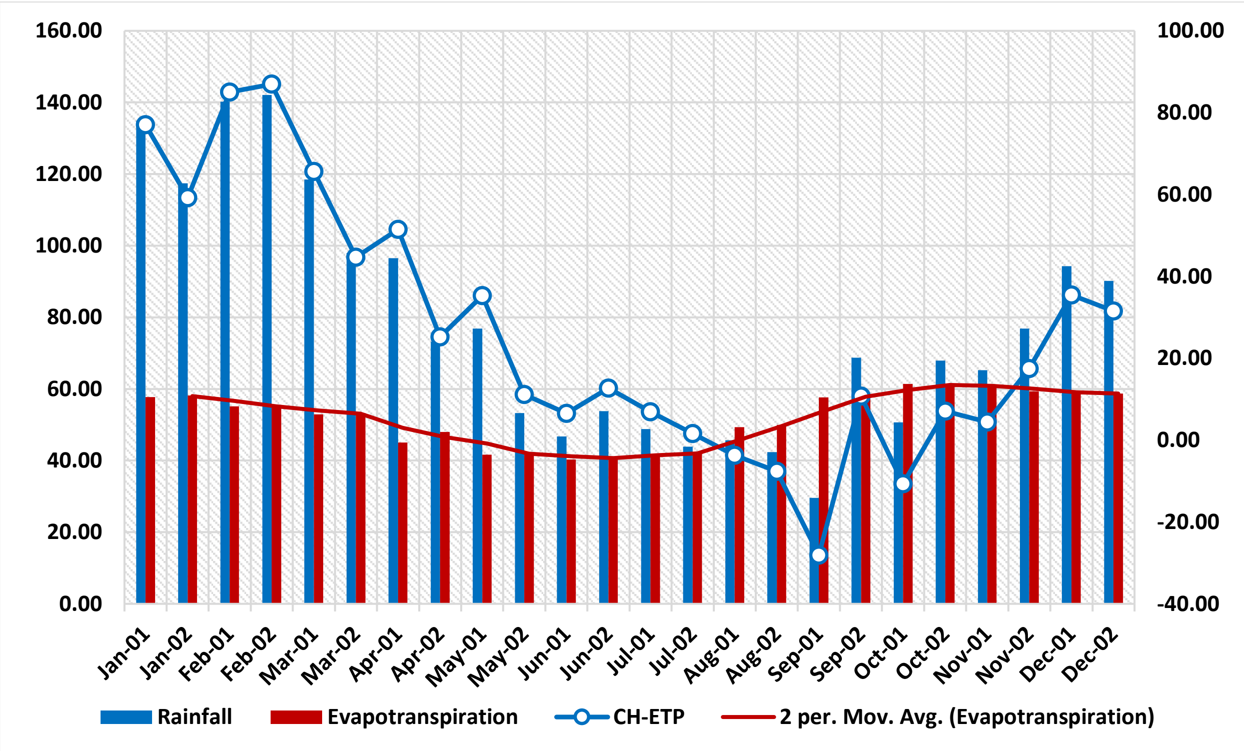

Figure 3. Semi-monthly average rainfall, evapotranspiration, and the difference between rainfall and land evapotranspiration

Dependable Discharge Analysis

The dependable discharge was calculated using the F.J. Mock method at an 80% probability level. The simulation results presented in **Figure 4** show that the discharge of the Way Kelutum River ranges from 0.10 to 1.40 m^3/s, with the lowest values occurring at the peak of the dry season, namely in August–September. The instantaneous discharge measurement conducted in May 2022 was 0.1861 m^3/s, which is relatively consistent with the simulated results for the dry period. This agreement reinforces the validity of the F.J. Mock model in representing actual field conditions.

High discharge values are observed during January–March and June–August, reaching up to approximately 1.2–1.3 m^3/s, which correspond to periods of relatively high rainfall and positive or near-neutral rainfall–evapotranspiration balance (P–ETP). During these months, surface runoff and baseflow contributions are sufficient to sustain irrigation water supply, reducing the dependency on strict water allocation measures. A pronounced decline in discharge occurs during September–October, when values drop to below 0.1 m^3/s. This sharp reduction coincides with the peak evapotranspiration period and negative P–ETP values, as previously discussed, indicating severe water deficit conditions. During this critical dry-season phase, irrigation sustainability becomes highly vulnerable, as river flow alone may be insufficient to meet crop water requirements without prior storage or demand management (Purwanto & Ikhsan, 2016).

The gradual recovery of discharge during November–December reflects the onset of the rainy season, consistent with increasing rainfall and decreasing evapotranspiration. This recovery highlights the strong control of seasonal climatic variability on river flow dynamics and confirms that river discharge acts as an integrated indicator of basin-scale water balance conditions. Overall, the discharge pattern reinforces the conclusion that irrigation sustainability in the Way Kelutum Irrigation Area is strongly constrained during the late dry season, particularly in September–October. Integrating river discharge analysis with rainfall–evapotranspiration balance provides a robust framework for identifying critical water stress periods and supports the implementation of adaptive irrigation scheduling and water resource management strategies (Rahmawati et al., 2025).

Irrigation Water Requirement Analysis

The calculation of irrigation water requirements was conducted for land preparation, the first rice planting season (January–March), the second rice planting season (May–July), and the secondary crop season (September–November). The results indicate that:

a. Land preparation: 2,457–2,722 m^3/ha
b. Rice season I: 7,832.62 m^3/ha/season
c. Rice season II: 8,187.10 m^3/ha/season
d. Secondary crops: 7,548.77 m^3/ha/season

The highest water demand occurs during the second rice planting season, which coincides with the dry period, in line with increased evapotranspiration.

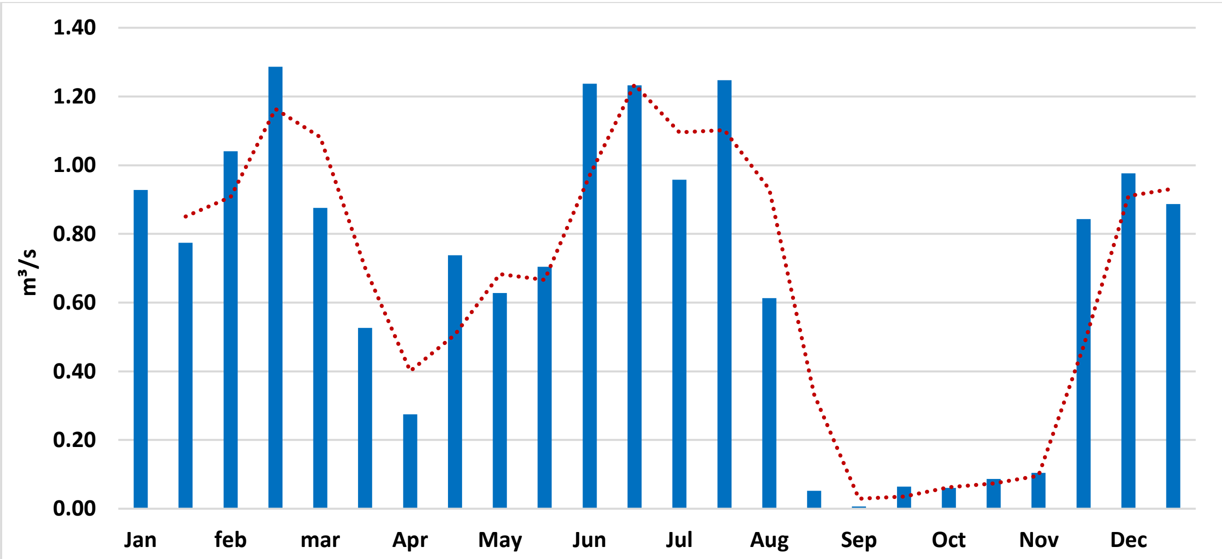

Figure 4. Reliable discharge

Irrigation Water Balance

Figure 5 presents a comparison between reliable discharge and irrigation water demand with all quantities expressed consistently on a semi-monthly and seasonal basis. The analysis indicates that:

a. The irrigation system can operate optimally during the two primary rice-growing seasons as water availability is sufficient to meet irrigation requirements for 42.04 ha in both Rice Season I and II in accordance with the planned cultivation area.
b. During the secondary crop season, a water deficit is observed indicating that available water is insufficient to fully meet crop requirements under current scheduling. Mitigation options include reducing the irrigated area, adjusting planting schedules, or selecting secondary crop varieties that are more tolerant of limited water availability (Wintyaswan et al., 2023).

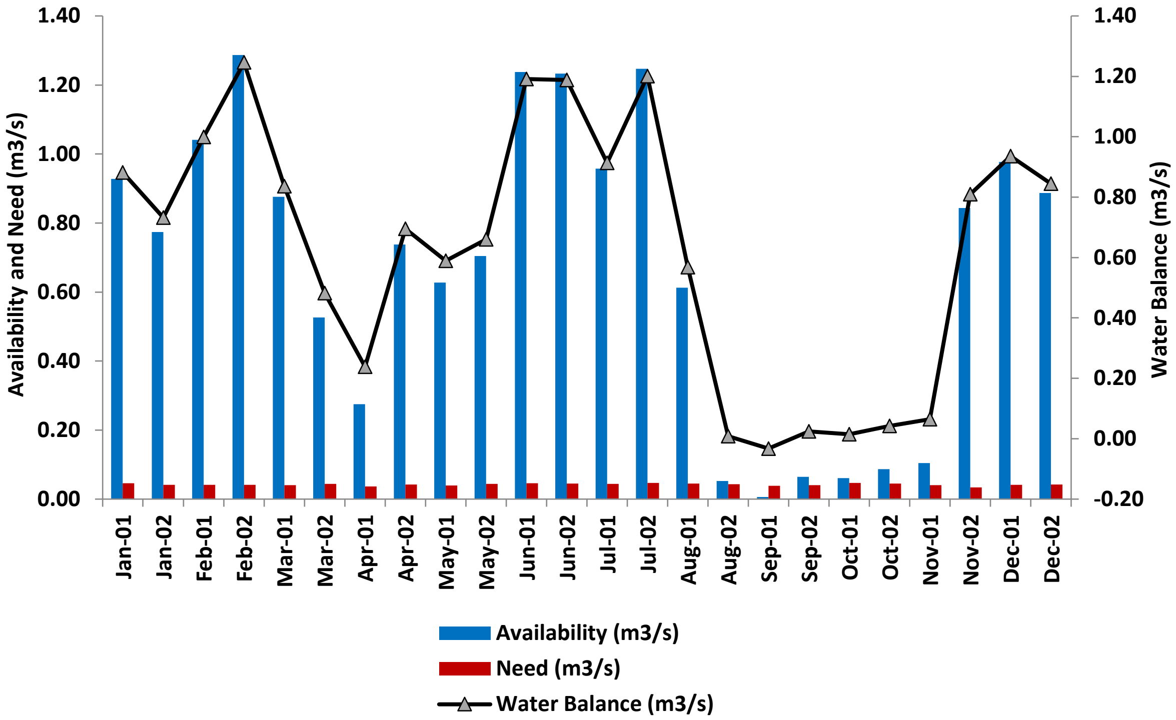

Figure 5. Comparison of reliable discharge and irrigation water demand in the Way Kelutum irrigation area illustrating periods of surplus and deficit and their implications for seasonal irrigation management decisions

The findings suggest that rice cultivation in the Way Kelutum Irrigation Area is largely secure from water deficit risks across the two main cropping seasons. The statement regarding "potential rice productivity" has been rephrased to emphasize water-limited productivity potential rather than absolute yield, as direct productivity or yield measurements were not reported in this study. In contrast, secondary crop development is constrained by limited water availability during the dry season (Risch & Frank, 2007). This observation aligns with previous research that highlighted that mismatches between water availability and crop water requirements often limit irrigation performance in tropical regions (Doipuloh *et* al., 2019). These results underscore the importance of adaptive irrigation management strategies including modifications in cropping patterns, the adoption of water-saving technologies, and diversification of cultivated commodities, to enhance the efficiency and resilience of irrigation water use (Tian et al., 2018). By explicitly linking water availability, crop water demand, and irrigation planning these insights provide actionable guidance for seasonal irrigation management decisions.

CONCLUSION

This study demonstrates that irrigation water management in the Way Kelutum Irrigation Area is strongly governed by seasonal variability in water availability and crop water demand. The integration of rainfall, climatological, and dependable discharge analyses indicates a clear temporal imbalance between wet and dry seasons, which directly affects irrigation water supply. Simulation of dependable discharge using the F.J. Mock method at an 80% reliability level shows that water availability is sufficient to support two consecutive rice-growing seasons over an irrigated area of 42.04 ha, although river discharge declines markedly during the dry period. Water balance analysis reveals that while rice cultivation in the first and second planting seasons can be reliably supported, secondary crop cultivation experiences water deficits during the dry season. This finding highlights the need for operational adjustments, such as limiting the cultivated area, modifying planting schedules, or selecting drought-tolerant secondary crops. Although the irrigation system demonstrates potential for sustaining intensive rice cultivation, its capacity to support secondary crops is constrained under dry-season conditions. The results underscore the importance of adaptive irrigation management based on seasonal water balance information. However, this study is limited by the use of modelled discharge and a single reliability criterion, and future research should incorporate multi-level reliability analysis, observed flow data, and irrigation efficiency assessments to further refine management recommendations

AUTHOR CONTRIBUTIONS

Conceptualization, RP and DIK; methodology, FYM; software, RP; validation, RP, DIK, and FYM; formal analysis, RP; investigation, DIK; resources, FYM; data curation, RP; writing—original draft preparation, DIK; writing—review and editing, FYM; visualization, RP; supervision, DIK; project administration, FYM; funding acquisition RP.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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