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Estimating Paddy Field Water Requirements Using CROPWAT 8.0: A Case Study in Anai Irrigation Area, West Sumatra, Indonesia

Sutan Ikhsan Syahlevi*, Nurhamidah and Junaidi

Faculty of Engineering, Andalas University, West Sumatra, Indonesia

*Corresponding author's e-mail: sutanikhsan7@gmail.com

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Abstract: The accurate estimation of crop water requirements is critical for efficient water resource management, particularly in regions with limited irrigation resources. This study aims to evaluate the water requirements for rice crops using the CROPWAT 8.0 model and compare the results with the Penman Modification Calculation method, as specified in the Irrigation Planning Standards (KP-01). This research uses climatological data from the Kandang IV Station near the Batang Anai Irrigation area, focusing on key factors such as effective precipitation, air temperature, humidity, wind speed, sunshine duration, and topography. The representative Soil of the local area was incorporated into the analysis. The study finds that the average evapotranspiration (ETo) using CROPWAT 8.0 was 3.09 mm/day, with the peak water demand for rice occurring at the end of August, reaching 1.51 L/s·ha. These findings align with the study's objective of assessing irrigation demand for rice crops and offer a comparison of methodologies used to estimate water requirements. The results emphasize the need for improvements in the default crop and soil data used by CROPWAT 8.0 to better align with local agricultural conditions in Indonesia. This study contributes to developing more accurate models for water requirement estimation and highlights the importance of region-specific calibration in irrigation planning. Further research is needed to enhance the model's functionality and to explore alternative methods for improving water use efficiency in rice farming.

Keywords: CROPWAT 8.0, Eto, Batang Anai, Paddy Field Irrigation, Water Requirements Estimation.

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1. Introduction

Effective water management in agriculture ensures sustainable crop production, especially for water-intensive crops such as rice. In regions like Indonesia, where rice is a staple food, optimizing water use for paddy fields is essential to meet both agricultural demands and environmental sustainability goals. However, accurate estimation of water requirements for rice crops presents a challenge, particularly in areas with fluctuating climate patterns and limited water resources. Addressing these challenges requires reliable models supporting precise irrigation planning and management.

CROPWAT 8.0, 'Crop Water and Irrigation Requirements Program,' is a widely recognized tool developed by the United Nations Food and Agriculture Organization (FAO). This Windows-based software facilitates precise crop water and irrigation requirements calculations by integrating soil, climatic, and crop-specific data. Detailed information on CROPWAT 8.0 is available on the FAO Land & Water website. Based on the Penman-Monteith method (Smith, 1992), CROPWAT 8.0 provides a decision support system to estimate crop water requirements and develop irrigation schedules for various conditions (Tumiar *et al*., 2012). It allows users to input specific climate, soil, and crop data to simulate irrigation needs and assess crop performance under rainfed and irrigated conditions. CROPWAT 8.0 has been widely applied across agricultural regions globally, supporting effective water resource management. However, its application in specific local contexts, such as the Anai irrigation area of West Sumatra, Indonesia, remains underexplored.

Previous research has shown that irrigation water requirements calculated using CROPWAT 8.0 often yield different results than traditional methods like the KP-01 standard commonly used in Indonesia, which tends to overestimate water needs for rice (Shalsabillah *et al*., 2018). While CROPWAT offers potential benefits, understanding its performance in localized settings, such as West Sumatra, is critical to determining its reliability and practical utility for irrigation planning. This study addresses this gap by evaluating water availability and demand for paddy fields in the Anai irrigation area using CROPWAT 8.0, intending to provide insights into optimal water use strategies tailored to local agricultural conditions.

Recent studies underscore the importance of incorporating advanced models for effective water management under changing climate conditions (Jain & Singh, 2020; Sunil *et al*., 2021) CROPWAT 8.0 has been applied globally for estimating crop water requirements and has shown significant potential when tailored to local conditions (Poonia *et al*., 2021; Kumar *et al*., 2022). However, accurate input data, particularly for crops and soil characteristics, are critical for its successful application (Gabr, 2021).

This research is highly relevant to the field of agricultural water management as it explores the application of CROPWAT 8.0 in a specific regional context, contributing valuable data on the model's accuracy and effectiveness in Indonesia. By analyzing seasonal water requirements and exploring alternative irrigation schedules, this study supports sustainable water use practices and provides a replicable model for other regions facing similar water management challenges. The findings have potential implications for policymakers, agricultural engineers, and local farmers, offering practical guidelines for more efficient water use in rice cultivation.

Several studies have demonstrated the advantages of the Penman-Monteith method (Monteith, 1965) in calculating evapotranspiration with minimal error for reference crops, especially in tropical and subtropical climates (Pinos, 2022). However, studies also indicate that CROPWAT 8.0's effectiveness depends on accurate input data, particularly for crop and soil characteristics, which can impact water demand estimates if not carefully calibrated (Prastowo *et al*., 2016; Dasril *et al*., 2021). This study leverages recent advancements in CROPWAT 8.0 to assess its potential for optimizing irrigation practices, considering local environmental conditions in West Sumatra.

The CROPWAT 8.0 model was selected due to its flexibility in simulating various cropping systems and its robust estimation of evapotranspiration, which is essential for determining water requirements. This study incorporated climate data specific to the Anai irrigation area to provide accurate seasonal demand estimations and evaluate different planting dates for optimal water use. Limitations included the potential for user error in data input, which could affect results, particularly in areas where detailed soil and crop data may be limited.

Despite extensive use in various agricultural regions, CROPWAT's application in specific local contexts, such as the Anai irrigation area of West Sumatra, Indonesia, remains underexplored. This study addresses this gap by evaluating water availability and demand for paddy fields in the Anai irrigation area using CROPWAT 8.0, providing insights into optimal water use strategies tailored to local agricultural conditions. The findings contribute to sustainable water management practices and offer practical guidelines for policymakers and agricultural engineers (Kumar *et al*., 2022; Agrawal *et al*., 2023).

This research aims to assess the effectiveness of the CROPWAT 8.0 model in estimating irrigation water availability and requirements for the Batang Anai Irrigation Area, compared to manual calculations based on the Irrigation Planning Standards (KP-01).

2. Methods

This study employs an observational comparative design to evaluate irrigation water requirements in the Batang Anai Irrigation Area, utilizing both manual calculations following the Irrigation Planning Standards (KP-01) and the CROPWAT 8.0 software. The choice of this approach is informed by the need to test the robustness and accuracy of CROPWAT 8.0, a decision support tool developed by FAO, against traditional methods (Tumiar *et al*., 2012).

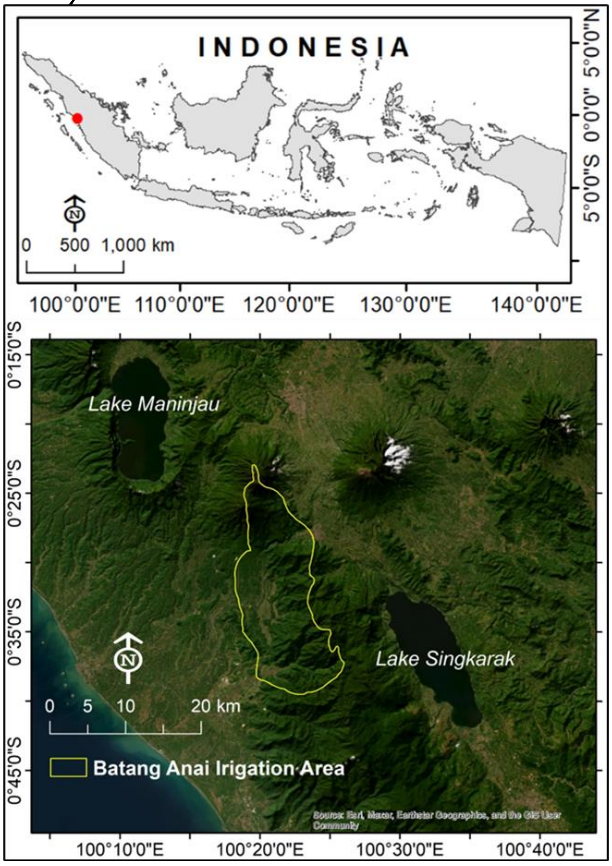

Figure 1. The study area map of Batang Anai Irrigation Area, in Padang Pariaman City, West Sumatera Province, Indonesia

2.1 Research Location

The research was conducted in the Batang Anai Irrigation Area in Padang Pariaman City, encompassing 8,421 hectares with a catchment area of 233 km². This site was selected for its significance in supporting regional agriculture and its comprehensive historical hydrological data, which is essential for robust analysis (Dasril *et al*., 2021). Figure 1 illustrates the layout of the catchment area.

2.2 Data Collection

Hydrological and Climatological Data:
Daily Rainfall Data (mm/day): Sourced from the Kandang IV station, covering 10 years from 2012–2021. This extended period ensures a representative sample for calculating average and effective rainfall (Prastowo *et al*., 2016).
Climatological Data:
They were collected from nearby meteorological stations, including Air Temperature (°C), Humidity (%), Sunlight (radiation in MJ/m²), and Wind Speed (m/s). These variables were chosen based on their relevance for evapotranspiration calculations and their impact on irrigation needs (Pinos, 2022).

2.3 Data Analysis

The analysis involved multiple stages to determine irrigation water requirements:
Evapotranspiration (ETo) Calculation: Conducted using the Penman-Monteith equation, integrated into CROPWAT 8.0. This method is recommended by FAO for its accuracy in a variety of climates and its comprehensive consideration of meteorological data (Allen *et al*., 1998). The equation inputs temperature, humidity, radiation, and wind speed to provide a reliable estimate of ETo.
Effective Rainfall Calculation: Rainfall data from Kandang IV station were analyzed using the R80 method, where effective rainfall was calculated as 70% of the R80 value (Tumiar *et al*., 2012). The formula used is:

$$Re = \frac{0.7\ x\ R80}{10} \quad ...(1)$$

$$\text{R80} = \frac{N}{5} + 1\text{R} \quad ...(2)$$

Planting Schedule and Crop Coefficients (Kc): Inputs were determined based on local cropping patterns and growth stages of rice, which is crucial for accurately assessing crop water needs (FAO, 2009).

Soil Type Data were assessed to determine water retention and infiltration characteristics. The soil type, such as sandy loam or clay, impacts water-holding capacity, a critical factor in irrigation planning (Wardana & Saputra, 2019). Manual Calculations with KP-01: Manual irrigation requirements were calculated following KP-01 standards, which involve empirical methods to estimate evapotranspiration and effective rainfall. The

KP-01 approach was a benchmark for evaluating the CROPWAT 8.0 outputs (Shalsabillah *et al*., 2018).

2.4 Statistical Analysis

A comparative analysis was conducted to evaluate discrepancies between the results obtained from CROPWAT 8.0 and KP-01 calculations. To ensure the **study's validity and reliability**, data sources were cross-referenced with regional meteorological records to confirm accuracy. Second, pre-processing involved data cleaning to remove anomalies or outliers, ensuring consistent analysis. Lastly, a pilot test was conducted with a subset of data to validate the CROPWAT 8.0 setup before full-scale analysis.

3. Result

3.1. Irrigation Water Requirements with Penman Modification (KP-01)

Potential evapotranspiration with Penman Modification (KP-01)

Table 2 illustrates the fluctuations in monthly Evapotranspiration Potential (Eto) values calculated using the Penman Modification (KP-01) method, which represents the atmospheric water demand and is crucial for understanding crop water requirements. In the Batang Anai Irrigation Area, the lowest Eto was recorded in July at 3.07 mm/day (approximately 95.3 mm/month), while the highest was observed in March at 3.57 mm/day (approximately 110.6 mm/month). The average evapotranspiration over the study period was 3.26 mm/day. These values reflect the impact of varying climatic conditions, such as temperature and solar radiation, directly influencing crops' water needs.

The seasonal variation in Eto indicates how crop water requirements shift throughout the year. For instance, March's highest monthly Eto value corresponds to increased solar radiation and higher temperatures, leading to greater evaporation and water demand. On the other hand, the lowest values in February and September, and notably in July, coincide with periods of reduced solar radiation and cooler temperatures, resulting in lower evapotranspiration rates. Such data underscores the necessity of incorporating climatic conditions into irrigation planning to optimize water use, reduce crop stress, and enhance water-use efficiency.

As shown by these results, the monthly distribution of Eto highlights the importance of adapting irrigation practices according to seasonal trends. Months with high Eto, such as March, August, and October, indicate the need for more intensive water management to meet crop requirements. Meanwhile, months with lower Eto suggest a potential reduction in irrigation needs. Further, the data reveals the importance of monitoring factors like temperature, solar radiation, and humidity, which can influence these variations. A comprehensive understanding of these trends allows for better irrigation scheduling and resource management, ensuring efficient water use throughout the year. Cross-referencing Eto values with local climate data could further refine irrigation strategies and support adaptation to potential climate changes.

Table 1. Potential evapotranspiration with Penman Modification (KP-01)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (^{0}C)	25.5	25.5	25.7	26.0	26.0	25.8	25.6	25.6	25.9	25.2	25.8	25.9
Humidity (%)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Solar-Radiation (%)	31.1	31.3	37.3	32.0	33.8	44.1	37.8	35.4	29.4	32.9	30.9	30.7
Wind speed (m/s)	1.1	1.2	0.9	0.8	0.7	0.8	0.8	0.7	0.7	0.6	0.6	0.6
Eto/day (mm/day)	3.2	3.3	3.6	3.3	3.1	3.3	3.1	3.4	3.2	3.3	3.3	3.3
Number of days	31	28	31	30	31	30	31	31	30	31	30	31
Eto/month (mm/month)	98.4	92.0	110.6	97.6	96.0	97.6	95.3	104.4	94.6	103.0	100.3	101.2

3.2. Irrigation Water Availability with F.J. Mock

Irrigation water availability is crucial in determining optimal cropping patterns, as it directly impacts the ability to meet crop water requirements. This availability is influenced by climatic conditions, with effective rainfall serving as a primary source. The F.J. Mock method estimates water contributions from rainfall, accounting for these climatic factors. The results outlined in Figure 2 and the data presented on half-monthly water availability provide a comprehensive view of how seasonal and annual rainfall variations impact irrigation planning.

The analysis shows significant variability in irrigation water availability throughout the year, with peaks in early December (31.39 units), late November (28.41 units), and early April (26.93 units), indicating periods of abundant water resources likely due to increased rainfall. Conversely, the lowest water availability is seen in late June (2.97 units), with other low points in early February (5.99 units) and early October (6.59 units), suggesting drier weather and potential water shortages. These fluctuations underscore the importance of understanding seasonal rainfall patterns to align irrigation strategies with periods of high and low water availability, ensuring crop water needs are met efficiently while avoiding water wastage.

Effective rainfall can complement or exceed irrigation requirements, particularly when it aligns with crop water demand. Recognizing these seasonal trends in water availability enables better irrigation scheduling and resource conservation, especially during periods of surplus rainfall. For example, during high water availability periods like November, December, and April, farmers may reduce reliance on supplemental irrigation, conserving resources and minimizing costs. On the other hand, proactive water management strategies, such as using stored water or adjusting planting cycles, become essential during low-availability periods like late June and early February. This adaptive approach to water management can optimize water use throughout the growing season, promoting sustainable agriculture and resilient irrigation practices.

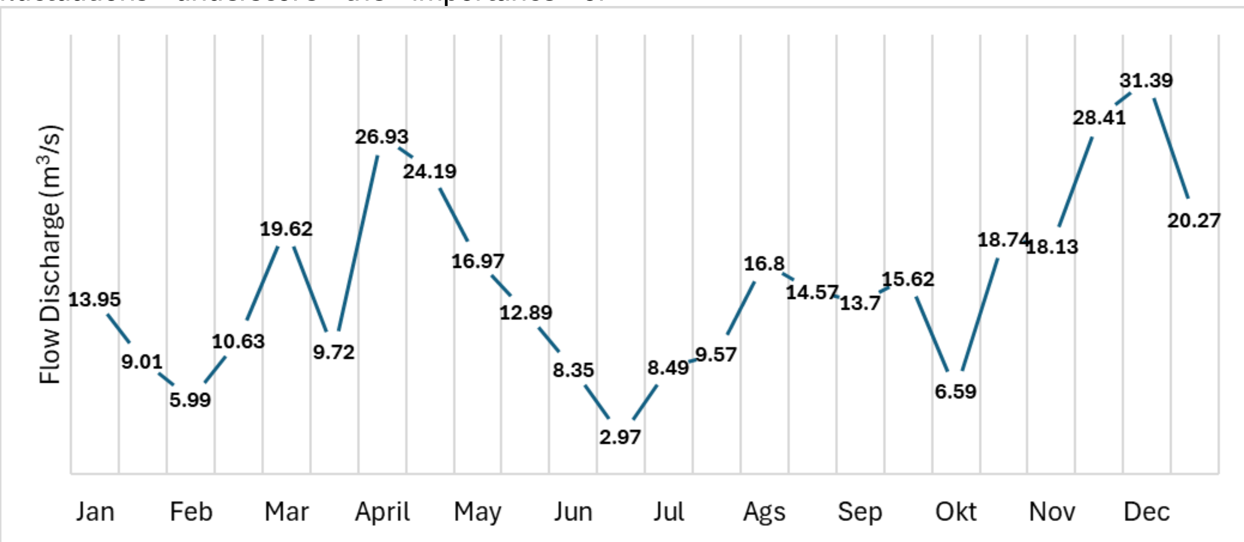

Figure 2 Irrigation Water Availability calculated using F.J. Mock method

3.3. Irrigation Water Requirement using Penman Modification

Estimating irrigation water requirements is essential for managing water resources in paddy fields. Using the Penman Modification (KP-01), the water demand is calculated for each half-month period, considering climatic variables and crop water consumption. This empirical approach, incorporating weather data and crop growth stages, helps ensure accurate irrigation planning. The irrigation water demand fluctuates during the study period based on climatic conditions, as shown in Figure 3. For example, in the first half of

January, the irrigation demand is relatively low (0.4 mm). Still, it increases significantly in February (7.2 mm for the first half and 13.9 mm for the second half), highlighting the impact of temperature and precipitation variations on crop water requirements.

In the seasonal analysis, three distinct cropping periods are observed: October to February, February to May, and June to September. The water requirement during these periods reflects the changing weather conditions and the growth cycle of the rice crop. The irrigation demand varies from 2.9 mm to 3.5 mm from February to May, indicating a stable water requirement during this phase. However, from June to September, the demand significantly drops, with negative values such as -6.2 mm in the second half of September, indicating periods of reduced water needs, possibly due to rainfall or lower evaporation rates during cooler weather conditions. Such variations emphasize the need for adaptive irrigation strategies that respond to seasonal fluctuations and maintain crop health without excessive water usage.

The results underscore the importance of adjusting irrigation practices based on seasonal patterns and daily climatic conditions. For instance, the irrigation demand in May (around 3.4 mm) is relatively moderate, yet there is a considerable increase in the later months. These seasonal variations in water demand highlight the need for well-managed irrigation systems to optimize water use throughout the cropping season. Ensuring water availability during peak demand periods and conserving it during lower-demand phases is key to sustainable water resource management in rice cultivation. As illustrated by the seasonal water demand data, this calculation provides valuable insights for optimizing irrigation scheduling and promoting efficient water use in paddy fields.

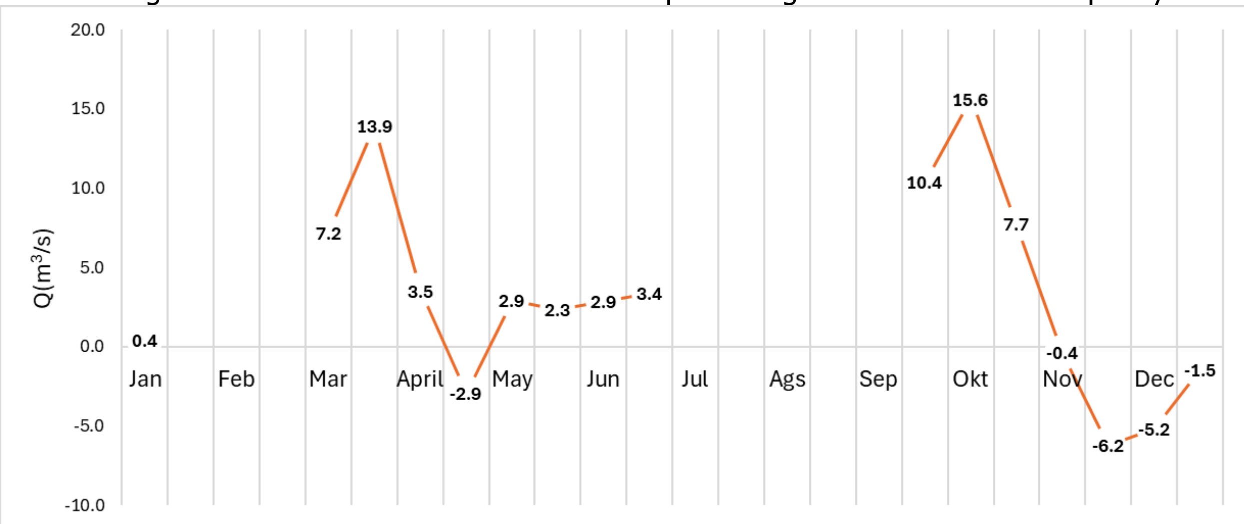

Figure 3. Irrigation Water Requirement calculated using Penman Modification (KP-01)

3.4. Irrigation Water Requirements with CROPWAT 8.0

The CROPWAT 8.0 model is another widely used tool for estimating irrigation water requirements. This study assumed that three planting cycles occur annually, each with specified start and harvest dates. This study assumes that planting cycles occur three times per year, each with specific start and harvest dates. Planting Season I (MT1) commences on January 1 and continues until the harvest on April 30. Planting Season II (MT2) follows, beginning on May 1 and concluding with harvest on August 28. Finally, Planting Season III (MT3) starts on September 1 and is harvested on December 29. The analysis indicates that the peak water demand is observed in August, with a maximum requirement of 12.75 m³/second. In specific periods, the irrigation water demand reaches 0 m³/second, signifying that the effective rainfall during these times is sufficient to meet the irrigation needs without additional water input. This finding emphasizes the importance of accurately assessing rainfall and integrating it into irrigation scheduling to reduce water consumption when natural resources are adequate.

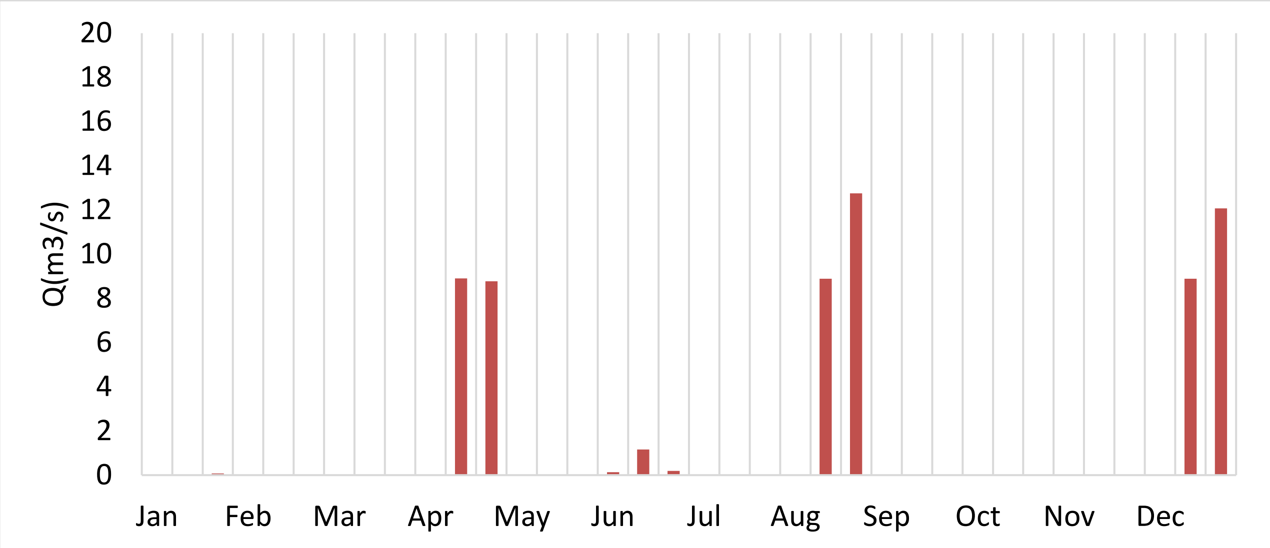

Figure 4. Irrigation Water Requirement calculated using CROPWAT 8.0

3.5. Statistical analysis

3.5.1. Comparison of Potential Evapotranspiration Results of Penman Modification Method and CROPWAT 8.0 Calculation

The comparison results show that the potential evapotranspiration (ETo) value using the Penman modification method is higher, at 3.26 mm/day, compared to the value obtained with the CROPWAT 8.0 method, which is 3.01 mm/day. Both methods used the same climatological data from the Kandang IV Station over 10 years, from 2012 to 2021. The climatological data used includes temperature (°C), wind speed (km/day), humidity (%), and solar radiation duration (%). The differences in the results between the two methods can be attributed to using different albedo values, representing the ratio of incoming solar radiation to the radiation reflected into the atmosphere (Purnomo, 2003). In the Penman modification method, the albedo value is 0.25, while in the CROPWAT 8.0 method, the albedo value is 0.23 (Anggraeni and Kalsim, 2013). These variations in albedo values lead to differences in the estimated potential evapotranspiration (ETo) values obtained by each method.

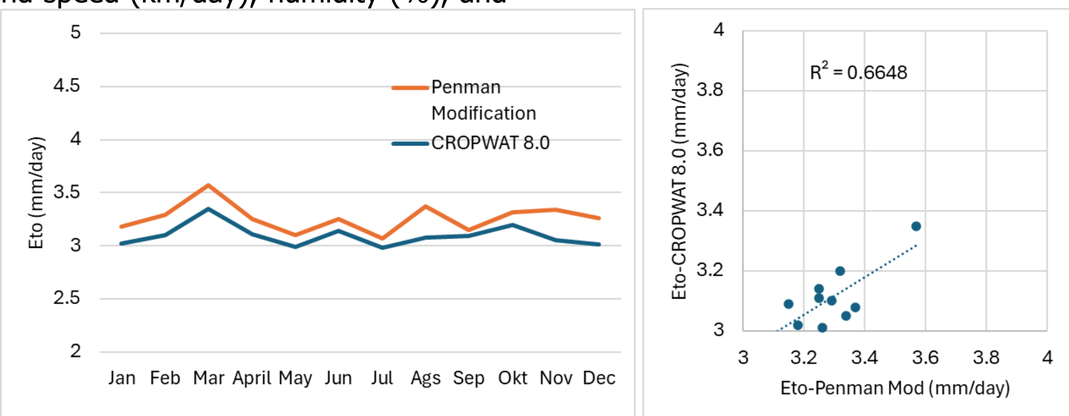

Figure 5. Comparison and scatterplot of Potential Evapotranspiration (Eto) calculated using Penman modification method and CROPWAT 8.0

3.5.2. Comparison of Irrigation Water Requirement by Penman Modification Method and CROPWAT 8.0 Calculation

The comparison of irrigation water requirements calculated using the Penman Modification Method and CROPWAT 8.0 (Table 2) reveals that the CROPWAT 8.0 method estimates a higher water requirement, at 1.51 L/day/ha, compared to the 0.73 L/day/ha estimated by the Penman modification method. This discrepancy in results can be attributed to differences in the handling of soil characteristics and crop data between the two methods. While both methods utilize general soil data, particularly clay soil, applying soil data in CROPWAT 8.0 can be further refined by using more localized data derived from specific field studies, which would more accurately reflect the natural conditions of agricultural land. Additionally, CROPWAT 8.0 considers various factors, such as soil saturation depth, irrigation scheduling, and the volume of irrigation water applied, all of which contribute to more precise and realistic water requirement estimations for rice crops. In contrast, the Penman method does not incorporate these additional factors, leading to lower water demand estimates. Therefore, the results suggest that the CROPWAT 8.0 method offers a more detailed and adaptable approach for calculating irrigation needs, potentially providing more reliable data for efficient irrigation management.

Table 2. Comparison of Irrigation Water Requirement

Calculation Method	**Irrigation Water Requirements (L/s/ha)**
Penman Modification	0.73
CROPWAT 8.0	1.51

While both methods use general soil data (clay soil), CROPWAT 8.0 can be further refined by incorporating site-specific soil data from field studies. Moreover, CROPWAT 8.0 considers additional factors such as soil saturation depth, irrigation timing, and water application volume, contributing to more precise water requirement estimations. In contrast, the Penman method does not account for these factors, leading to lower water demand estimates. As such, the results suggest that CROPWAT 8.0 provides a more detailed and adaptable approach to estimating irrigation needs, which may be more suitable for real-world irrigation management and optimization.

The findings of this study highlight the importance of selecting appropriate models and methods for estimating irrigation water requirements. The comparison between the Penman Modification method and CROPWAT 8.0 reveals similarities and differences, with CROPWAT 8.0 providing more detailed estimations due to its incorporating additional factors. This study emphasizes the need for accurate modeling of evapotranspiration and irrigation water requirements to optimize water resource management and ensure efficient irrigation practices, particularly in regions with fluctuating climatic conditions like Batang Anai.

This study's findings are consistent with previous research indicating that CROPWAT 8.0 often estimates higher irrigation water requirements than traditional methods such as the Penman Modification method. However, the current study’s use of specific soil data and cropping patterns provides a more tailored approach that reflects the unique conditions of the Batang Anai Irrigation Area, offering insights that could be applied to similar agricultural regions.

The results of this study have significant implications for irrigation management in regions with varying climatic conditions. The ability to accurately estimate water requirements using models like CROPWAT 8.0 can help optimize irrigation schedules, reduce water wastage, and improve crop yields. Integrating effective rainfall data further enhances the model's applicability by reducing the reliance on irrigation when natural water resources are sufficient.

One limitation of this study is the use of general soil data, which may not fully capture the variability of soil properties across different Batang Anai Irrigation Area areas. Future studies should consider incorporating more localized soil data to refine the estimations of water requirements. Additionally, the analysis assumes a constant cropping pattern, which may not always align with real-world agricultural practices.

Future research could explore the use of remote sensing and soil sensors to gather more accurate data on soil moisture and evapotranspiration, improving the precision of irrigation water requirement models. Additionally, further studies could investigate the impacts of climate change on water availability and irrigation needs, particularly in regions vulnerable to extreme weather events.

In conclusion, this study provides valuable insights into estimating irrigation water requirements using the Penman Modification method and CROPWAT 8.0. The results underscore the importance of incorporating accurate soil and climatic data and considering local agricultural practices when planning irrigation strategies. The findings contribute to the ongoing efforts to optimize water use in agriculture and enhance sustainable farming practices.

4. Conclusion

This study evaluated the irrigation water needs of the Batang Anai Irrigation Area using the Penman Modification and CROPWAT 8.0. The Penman Modification estimated a Potential Evapotranspiration (PET) of 3.26 mm/day, while CROPWAT 8.0 calculated 3.09 mm/day, with irrigation requirements of 0.73 l/dt/ha and 1.51 l/dt/ha, respectively. CROPWAT 8.0 also identified months with no irrigation need, indicating sufficient rainfall. The findings underscore the importance of accurate water requirement estimations for optimizing water management in areas with variable rainfall. While both models provide valuable insights, CROPWAT 8.0 offers more detailed results by incorporating localized data. Future research should refine these models with more specific data and advanced technologies like remote sensing to improve irrigation efficiency, particularly in regions with climate variability.

Data availability statement

Data will be made available on request.

Conflict of interest

The authors claimed there is no conflict of interest.

Author contribution

SIS: conceptualization, methodology-investigation-validation, writing—original draft, **N** and **J**: supervising, reviewing, and editing. All authors have read and agreed to the published version of the manuscript.

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