BILINGUAL PUBLISHING GROUP

Research in Ecology
https://journals.bilpubgroup.com/index.php/re

ARTICLE

Crop Calendar Adjustments for Enhanced Rainwater Harvesting in Rice Cultivation of the Plain of Reeds Under Climate Variability

*Thai Duong Phung [1], Kieu Tram Thi Huynh [1], Van Tuan Phan [1], Dang Truong An [2]**

[1] *Faculty of Social Sciences Teacher Education, Dong Thap University, Cao Lanh City 81000, Vietnam*

[2] *Department of Oceanology, Meteorology and Hydrology, University of Science, Ho Chi Minh City 700000, Vietnam*

ABSTRACT

Climate variability significantly impacts agricultural water resources, particularly in regions like Vietnam's Plain of Reeds that heavily utilize rain-fed conditions. This study employs the FAO-AquaCrop model to estimate current and future irrigation water needs for rice cultivation in this critical subregion, aiming to identify optimal sowing schedules (OSS) that enhance rainwater utilization and reduce irrigation dependency. The model was driven by current climate data and future projections (2041-2070 and 2071-2099) derived from downscaled Global Circulation Models under RCP4.5 and RCP8.5 scenarios. The AquaCrop model demonstrated robust performance during validation and calibration, with d-values (0.82-0.93) and R^2 values (0.85-0.92) indicating strong predictive accuracy for rice yield. Simulation results for efficient irrigation water potential (IWP) under RCP4.5 revealed that strategic shifts in sowing dates can substantially alter water requirements; for instance, advancing the winter-spring sowing to December 5th decreased IWP by 15.6% in the 2041-2070 period, while delaying summer-autumn crop sowing to April 20th increased IWP by 48.6% due to greater reliance on irrigation as rainfall patterns shift. Similar dynamic responses were observed for the 2071-2099 period and for autumn-winter crops. These findings underscore that AquaCrop modeling can effectively predict future irrigation needs and that adjusting cultivation calendars presents a viable, low-cost adaptation strategy. This approach allows farmers in the Plain of Reeds to optimize rainwater use, thereby reducing dependency on supplementary irrigation and mitigating the adverse impacts of climate variability, contributing to more sustainable agricultural water management.

Keywords: Cultivation Calendar; Optimization; Irrigation Demand; Climate Variability; Shift; Rainwater Harvesting; AquaCrop

*CORRESPONDING AUTHOR:
Truong An Dang, Department of Oceanology, Meteorology and Hydrology, University of Science, Ho Chi Minh City, 700000, Vietnam; Email: dtan@hcmus.edu.vn

ARTICLE INFO
Received: 17 May 2025 | Revised: 30 May 2025 | Accepted: 5 June 2025 | Published Online: 19 June 2025
DOI: https://doi.org/10.30564/re.v7i2.10067

CITATION
Phung, T.D., Thi Huynh, K.T., Phan, V.T., et al., 2025. Crop Calendar Adjustments for Enhanced Rainwater Harvesting in Rice Cultivation of the Plain of Reeds Under Climate Variability. Research in Ecology. 7(2): 239–250. DOI: https://doi.org/10.30564/re.v7i2.10067

1. Introduction

Climate variability is rapidly reshaping the global agricultural landscape, imposing profound implications for food security and rural livelihoods [1, 2]. This impact is particularly acute in Southeast Asia, where rice cultivation forms the cornerstone of economic stability[3-5] and sustenance for millions [3, 6, 7]. The Vietnamese Mekong Delta (VMD), a region responsible for over half of Vietnam's rice production and home to more than 17 million people, is at the forefront of this climate-induced agricultural transformation [4, 8, 9]. Within the VMD, the Plain of Reeds subregion particularly exemplifies the complex challenges rice farmers face due to a changing climate [10-12]. This area, characterized by its expansive floodplains and intricate canal network, is inherently vulnerable to altered hydrological regimes and increasing drought frequency and intensity [10, 12, 13], making effective rainwater harvesting and water resource management critical [12, 14].

The rationale for adjusting cultivation calendars as an adaptation strategy to climate variability lies in the fundamental relationship between crop phenological development and prevailing climatic conditions[15, 16]. Optimal crop growth and yield are achieved when sensitive growth stages (e.g., flowering, grain filling) coincide with favorable environmental conditions, particularly adequate water availability and suitable temperatures, while avoiding periods of significant stress such as drought or extreme heat[16, 17]. Climate variability disrupts this synchrony by altering rainfall patterns (timing, amount, intensity) and temperature regimes[16, 18, 19]. Strategic shifts in sowing dates aim to realign the crop's lifecycle with these modified climatic windows, thereby maximizing the utilization of available rainwater (enhanced rainwater harvesting) and minimizing exposure to adverse conditions[20, 21]. This can lead to reduced demand for supplementary irrigation, lower input costs for farmers, and greater yield stability, representing a crucial low-cost adaptation measure [14, 15, 17].

Climate projections for the Plain of Reeds paint a concerning picture [8, 12]. Under mid- and high-emission scenarios (RCP4.5 and RCP8.5), models predict regional temperature increases of 1.5-4.3°C by 2100, accompanied by increasingly erratic rainfall patterns [9,10,15]. These shifts are anticipated to exacerbate existing water management challenges, particularly heightening irrigation water scarcity during dry seasons [10, 16]. For example, during the 2016-2017 growing season, unseasonal continuous heavy rains in Phu Duc commune (Tam Nong district, Dong Thap province) significantly damaged newly planted early winter-spring rice, necessitating widespread replanting [11, 12]. Furthermore, climate models predict a 15-30% decline in dry-season rainfall and a 25% increase in evapotranspiration by 2050 for the region [12, 13], directly threatening the viability of the VMD's intensive triple-cropping rice systems [13, 20].

In response to these multifaceted challenges, optimizing cultivation calendars emerges as a promising, low-cost, and scalable adaptation measure [19, 21, 22]. This approach, which involves adjusting planting times to better align rice phenology with evolving climatic conditions [16, 23, 24], aims to reduce irrigation dependency by maximizing the capture and use of seasonal rainfall and to mitigate yield reductions from climatic stressors like extreme heat events [17, 22, 23]. Studies from other tropical rice-growing regions corroborate the potential of this strategy [18, 19]. In Sri Lanka's Kurunegala District, for instance, delaying dry-season sowing by 30 days increased yields by 8-12% under RCP4.5 scenarios by helping crops avoid mid-season droughts[10, 15]. Similarly, in Vietnam's Ca Mau Province, advancing summer-fall cropping by just two weeks reduced heat-induced sterility by 20%[9, 13, 17]. The efficacy of cultivation calendar optimization lies in its ability to capitalize on early rainy-season moisture while avoiding peak temperatures during sensitive reproductive stages. Research indicates that even modest adjustments—such as a 10-15-day shift in transplanting dates—can reduce irrigation demand by 12–18% in tropical rice systems[20, 25, 26]. This approach represents a pragmatic adaptation solution, implementable with minimal additional resources, making it particularly suitable for smallholder farmers who may lack access to more capital-intensive adaptation measures[21, 26].

While previous research has highlighted the general benefits of calendar adjustments, a detailed, model-based assessment of optimal sowing schedules (OSS) specifically for the Plain of Reeds under future climate scenarios, focusing on enhancing rainwater utilization, is still needed. This study aims to fill this gap by employing the FAO-AquaCrop model. Developed by the Food and Agriculture Organization (FAO), AquaCrop is particularly well-suited for forecasting the effects of climate variability on crop production, especially in water-limited environments[22, 27, 28]. Its strength lies in its ability to simulate crop responses to water deficits and assess the impacts of various management solutions under changing environmental conditions. The primary objective of this research is to simulate future irrigation water potential (IWP) for rice cultivation in the Plain of Reeds and to determine OSS that enhance rainwater utilization under projected climate variability. This study specifically aims to: (1) assess the performance of the FAO-AquaCrop model for simulating rice yield in the Plain of Reeds; (2) simulate IWP for current and future climate scenarios (RCP4.5 and RCP8.5 for 2041-2070 and 2071-2099); and (3) identify adjusted crop calendars that can optimize the use of available rainwater, thereby reducing reliance on supplementary irrigation and enhancing resilience to climate variability.

2. Materials and Methods

2.1. The Study Area

The Plain of Reeds occupies a strategic agricultural position within the VMD, intersecting Dong Thap, Tien Giang, and Long An provinces[5, 7]. It spans from 10°04′56″ to 11°00′ N latitude and 105°03′15″ to 106°09′33″ E longitude (**Figure 1**). This expansive floodplain, characterized by elevations fluctuating between 0.0 and 2.5 meters above mean sea level, encompasses nearly 697,000 hectares of agricultural land, with rice cultivation being the dominant land use[5, 12]. Climatically, the region is governed by contrasting monsoonal systems: the Siberian high-pressure system drives arid conditions from December to April, while the Southwest monsoon instigates rainfall between May and November, accounting for approximately 90% of the annual precipitation[8]. These hydrological dynamics foster a relatively stable thermal regime, with mean annual temperatures ranging narrowly from 26.0 °C to 28.2 °C, coupled with persistent humidity levels near 80%[6, 21]. Such climatic consistency, alongside an average yearly rainfall of 1,500 mm, underpins the region's agricultural prowess, particularly its role as one of the VMD's primary rice-producing hubs[4]. However, the low-lying terrain renders the Plain of Reeds acutely vulnerable to climate-induced hydrological shifts, including erratic rainfall patterns and rising flood risks, which threaten both crop productivity and ecosystem stability[7, 20]. **Figure 2** illustrates the typical distribution of daily rainfall and temperature across the study area, highlighting the seasonal variability that agricultural practices, particularly rainwater-dependent ones, must navigate.

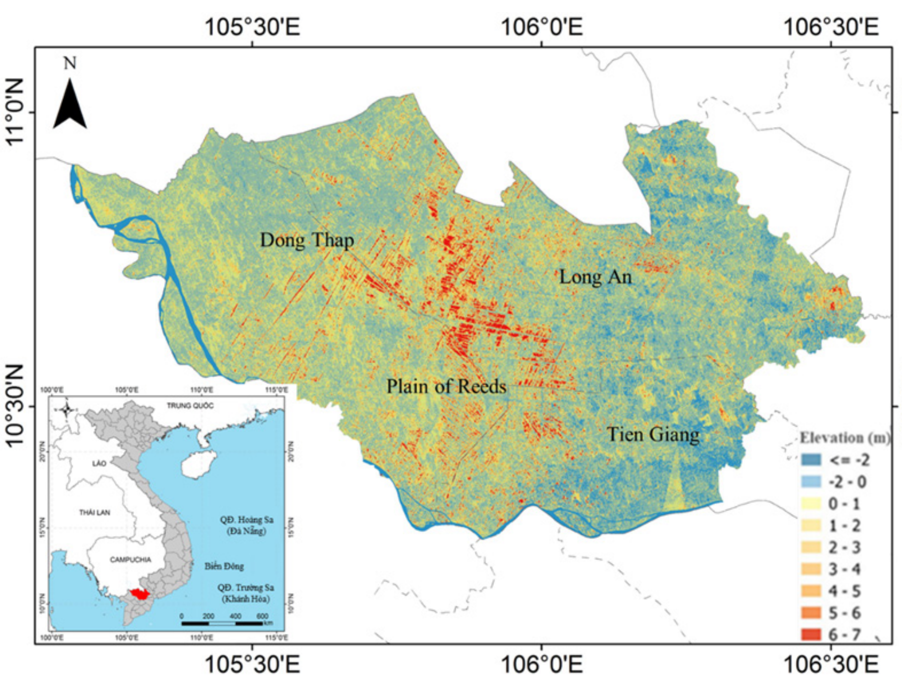

Figure 1. Map of the Plain of Reeds.

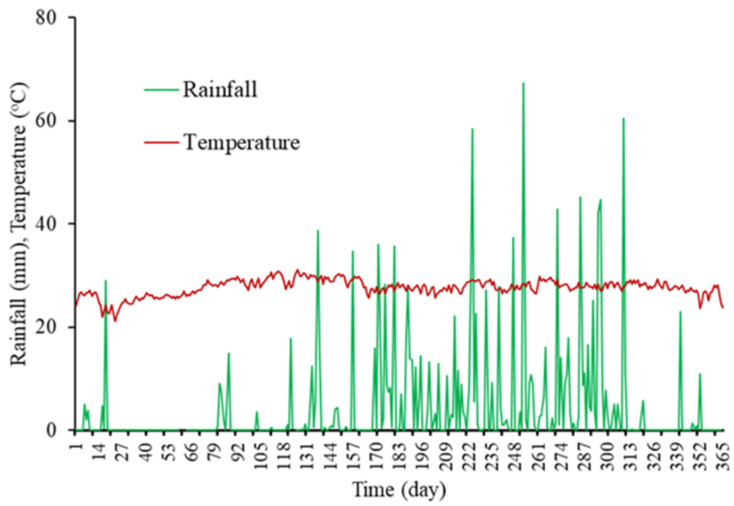

Figure 2. Distribution of daily rainfall and temperature across the study area.

2.2. FAO-Aquacrop Model Description

The FAO-AquaCrop model, developed by the Food and Agriculture Organization (FAO), serves as a powerful and efficient tool for crop growth simulation, particularly in water-limited environments[22, 28]. Its primary strength lies in accurately modeling crop responses to water availability, making it particularly valuable for studies on climate change adaptation in agriculture, including the optimization of rainwater harvesting[15, 18]. The FAO-AquaCrop model requires a relatively small number of input parameters that are generally obtainable, enhancing its accessibility and applicability across diverse agricultural contexts[5, 17]. A key feature of FAO-AquaCrop model is its use of the Penman-Monteith formula to calculate reference evapotranspiration (ETo). This, combined with its simulation of actual crop evapotranspiration (ETc), provides a robust foundation for assessing crop water use efficiency and irrigation requirements[8, 24]. AquaCrop's versatility is further demonstrated by its successful application in a wide range of studies, from drought severity evaluation to assessing the impacts of water quality deterioration and soil salinization[4, 9]. Its ability to incorporate both historical data and long-term climate scenarios enables researchers to generate robust forecasts of future crop production trends, making it an essential tool for developing adaptive strategies, such as optimizing cultivation calendars for enhanced rainwater capture in regions like the Plain of Reeds.

In the FAO-AquaCrop model, ETo is based on the Penman-Monteith formula:

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

In the Eq.(1), Rn represents the net radiation at the soil surface, measured in $MJ.m^{-2}.d^{-1}$; G denotes the soil heat flux density, expressed in $MJ.m^{-2}.d^{-1}$; T signifies the mean air temperature in degrees Celsius; u_2 indicates wind velocity at a height of 2.0 m, measured in $m.s^{-1}$; es stands for the saturation vapor pressure in kPa; e_a refers to the actual vapor pressure, also in kPa; Δ symbolizes the slope of the vapor pressure curve, expressed in $kPa.°C^{-1}$; γ represents the psychrometric constant, measured in $kPa.°C^{-1}$.

The calculation of ETc is derived from the ETo and the crop coefficient (Kc). The formula for determining ETc is as follows:

$$ET_C = ET_O{*}K_C \quad (2)$$

In Eq.(2), the Kc coefficient varies according to the specific plant species and its developmental phase. The FAO-AquaCrop model determines grain yield (GY) by multiplying biomass yield (Bi) with the harvest index (HI). The formula for computing grain yield is expressed in Eq.(3).

$$GY = B_i{*}HI \quad (3)$$

In the Eq.(3), Bi is derived from the formula $B_i = WP^* \sum \frac{Tr_i}{ET_{oi}}$, ($kgha^{-1}$) where WP* represents crop water productivity ($g.m^{-2}$), Tri denotes daily plant transpiration (mm), and EToi signifies the daily reference evapotranspiration (mm). The HI is treated as a relatively stable parameter. Within the crop module, HI undergoes continuous adjustment throughout the process of grain formation.

2.3. Input Data for Model Simulation

To simulate IWP for current conditions (baseline) and future periods (2041-2070 and 2071-2099) under RCP4.5 and RCP8.5 scenarios in the Plain of Reeds, we employed the FAO-AquaCrop mode l[12, 24]. Current climate data (sunshine duration, relative humidity, wind speed, temperatures, and rainfall) for the baseline period (2010-2024, as indicated in **Table 1**) were sourced from the Hydrometeorological Forecasting Station in Dong Thap province. Future climate projections were derived from downscaled outputs of five Global Circulation Models (GCMs): cIWRF, PRECIS, CCAM, regCM, and MRI-AGCM. These GCMs were selected for their proven utility in agricultural research within the VMD and their ability to provide plausible future climate trajectories. **Table 1** presents the baseline climate characteristics and the projected changes in temperature and precipitation for the future scenarios.

Table 1. Baseline climate (2010-2024) and future scenarios in temperature and precipitation across the study area (standard errors show the uncertainty range in projection due to applying. other GCMs).

Baseline (2010-2024)	Period Windows	Representative Concentration Pathway (RCP)			
		RCP 4.5	Change	RCP 8.5	Change
Mean temperature 27.6 (^{o}C)	2041-2070	29.0 ± 0.9^{o}C	1.4^{o}C	29.5 ± 1.4^{o}C	1.9^{o}C
	2071-2099	29.5 ± 1.2^{o}C	1.9^{o}C	31.0 ± 2.7^{o}C	3.4^{o}C
Mean rainfall 1488.5 (mm)	2041-2070	1795.1 ± 7.8 mm	20.6%	1728.1 ± 9.2 mm	16.1%
	2071-2099	1737.0 ± 2.9 mm	16.7%	1784.7 ± 11.6 mm	19.9%

To ensure robust simulation results from the FAO-AquaCrop model, comprehensive soil and crop data were meticulously collected and analyzed for the study area. Soil samples were obtained from representative locations within the Plain of Reeds to characterize the pedological properties crucial for crop growth. The soil analysis yielded essential hydrological parameters, including volumetric soil water content (SWC) at field capacity (FC) and permanent wilting point (PWP), and total available water (TAW). Additionally, the soil's saturated hydraulic conductivity (K) was determined (**Table 2**). These parameters collectively provide a detailed representation of the soil's water retention and transmission characteristics, fundamental for accurately simulating crop-water interactions.

Table 2. Soil characteristics of the study area (Dang, 2021).

Soil Characteristics	Values	Unit
Volumetric soil water content (SWC)	47	%
Field capacity (FC)	32	%
Permanent wilting point (PWP)	20	%
Soil's hydraulic conductivity (K)	120	Mm/m
Total available water (TAW)	225	Mm/day

Crop cultivation data were referenced from Dang (2021) and local agricultural extension services, encompassing key growth stages such as sowing, transplanting (if applicable, though direct seeding is common), flowering, maturity, and harvesting dates for typical rice cultivation calendars (**Table 3**). This temporal information was complemented by data on typical irrigation water application practices and fertilizer usage, allowing for a comprehensive representation of rice cultivation in the region. The integration of these detailed soil and crop datasets ensures a high-fidelity simulation of rice growth and water use efficiency under various climate scenarios, forming the basis for evaluating calendar adjustments.

Table 3. Cultivation calendar and seed densities applied for rice crop seasons.

Cultivation Practices	Cultivation Crops		
	Winter-Spring	**Summer-Autumn**	**Autumn-Winter**
Sowing	15-December	5-April	10-Aug
Harvesting	20-March	10-July	20-Nov
Seeds	160 kg/ha	180 kg/ha	kg/ha

3. Results

This section details the findings of the study, beginning with an assessment of the FAO-AquaCrop model's performance in simulating rice yield in the Plain of Reeds. This is followed by an analysis of simulated irrigation water needs under current weather conditions and projected future climate scenarios. Finally, an evaluation of efficient irrigation water potential achievable through strategic crop calendar adjustments is presented.

3.1. Performance Assessment of the FAO-AquaCrop Model

The performance of the FAO-AquaCrop model was appraised using standard statistical indicators to evaluate the agreement between simulated and observed rice yield data from the Plain of Reeds. The coefficient of determination (R^2), index of agreement (d), and root mean square error (RMSE) were employed. The R^2 is calculated as follows:

$$R^2=\frac{\sum_{i=1}^{n} S_i * O_i-\sum_{i=1}^{n} S_i * \sum_{i=1}^{n} O_i}{\sqrt{\sum_{i=1}^{n} S_i^2-\left(\sum_{i=1}^{n} S_i\right)^2} * \sqrt{\sum_{i=1}^{n} O_i^2-\left(\sum_{i=1}^{n} O_i\right)^2}} \tag{4}$$

where *Si* and *Oi* are the simulated results and observed data, respectively and is the average value of the observed data series

The index of agreement (d) is defined by the Equation (5)

$$d=1-\frac{\sum_{i=1}^{n}\left(S_i-O_i\right)^2}{\sum_{i=1}^{N}\left(S_i-\bar{O}_i\right)^2} \tag{5}$$

and root mean square error (RMSE) is calculated by the Equation (6)

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(S_i-O_i\right)^2}{n}} \tag{6}$$

In most practical applications, the RMSE is used as a measure of absolute error between the calculated results and observed data[23].

The AquaCrop model demonstrated robust applicability and strong predictive accuracy across both calibration (2015–2024 data, if these are the years from your methods – OCR says 2024, but **Table 4** says 2024) and validation (2005–2014 data) procedures for rice yields in the Plain of Reeds. During validation, statistical coherence between observed and simulated yields was strong, with d-values spanning 0.82–0.89, exceeding the 0.75 threshold generally considered acceptable for agricultural model performance. R^2 metrics (0.85–0.92) further confirmed this strong predictive accuracy. RMSE values (0.20–0.31 t/ha) remained below 5% of mean observed yields, indicating precise estimation capabilities. Calibration outcomes further enhanced model performance, with d-index values improving to 0.84–0.93 through parameter optimization (**Table 4**). The R^2 range of 0.85–0.92 post-calibration suggests stable predictive relationships, even when considering evolving climatic conditions. **Figure 3** visually represents the model's performance for the winter-spring crop season during both validation and calibration phases.

Table 4. Performance of the AquaCrop model through the validation and calibration procedures based on the RMSE, d and R^2

Sowing Crop	Validation (2005-2014)			Calibration (2015-2024)		
	d	**RMSE**	**R^2**	**d**	**RMSE**	**R^2**
Winter-spring	0.87	0.21	0.85	0.93	0.19	0.92
Summer-autumn	0.82	0.31	0.89	0.84	0.33	0.85
Autumn-winter	0.85	0.24	0.87	0.85	0.28	0.88

Notably, RMSE fluctuations (0.19–0.33 t/ha) during calibration fell within acceptable margins for rice systems across all sowing crop seasons considered. These error indices collectively confirm AquaCrop's aptitude for simulating crop cultivation under the Plain of Reeds conditions. While minor underestimations (2-3%) were observed during years with extreme El-Niño events, the overall model performance satisfies FAO-recommended thresholds for crop modeling (d > 0.8, $R^2 > 0.75$, and RMSE < 10% of mean observed yield), supporting its use for subsequent scenario analysis.

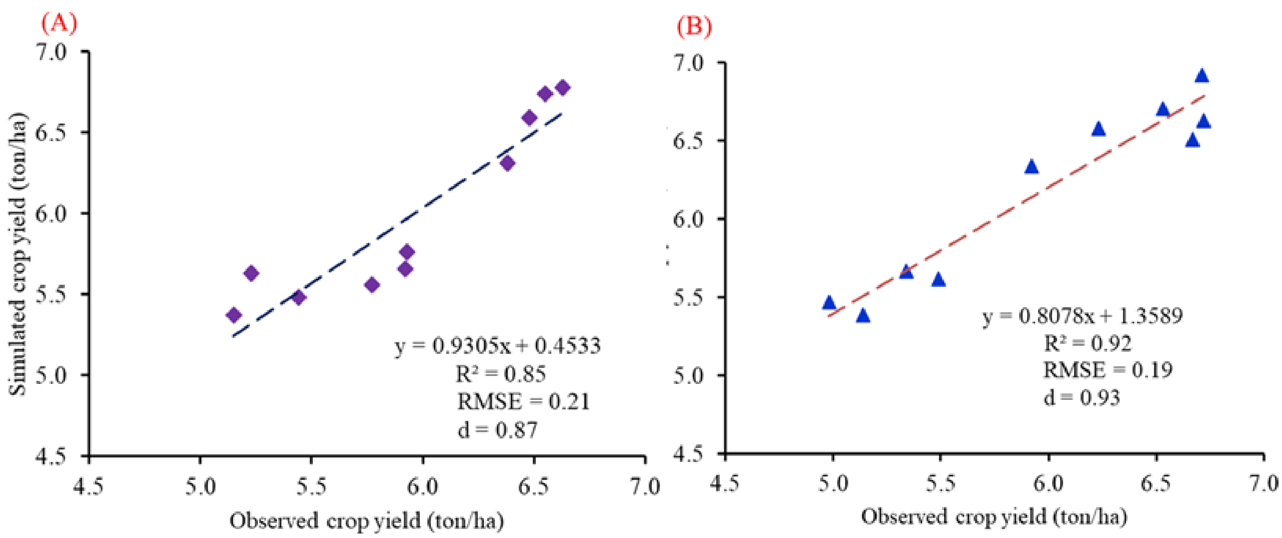

Figure 3. The performance of the FAO AquaCrop assessed through (A) validation process and (B) calibration process for winter-spring crop season in the study area.

3.2. Analysis of Simulated Irrigation Water Potential Under Current Weather Conditions and Future Climate Scenarios

AquaCrop model simulations reveal significant potential shifts in Irrigation Water Potential (IWP), interpreted here as the net irrigation water need, under projected climate scenarios (RCP 4.5 and RCP 8.5) compared to current conditions (**Table 5**). Under current conditions, the baseline IWP reflects region-specific agroclimatic constraints, with notable intra-annual variability tied to precipitation distribution and atmospheric evaporative demand (influenced by temperature and vapor pressure deficits). In seasons where precipitation deficits coincide with peak crop water requirements, IWP naturally increases, consistent with AquaCrop's water balance calculations.

Projections for the 2041-2070 period indicate a median increase in IWP ranging from 3.8% to 8.6% under the RCP4.5 scenario, primarily attributable to heightened evaporative demand resulting from an average temperature rise of approximately +1.4 °C. For the later period of 2071-2099 under RCP4.5, IWP is projected to be 11.1% to 15.1% higher than current demands, driven by more significant warming (average $\Delta T \sim +1.9$ °C). Similar increasing trends, though often of greater magnitude, are observed under the RCP8.5 scenario due to higher projected temperature increases (**Table 5**).

Figure 4 (previously **Table 4** in OCR text, but likely refers to the bar chart visual) illustrates these projected increases across the different rice cultivation seasons. The results consistently show that winter-spring crops have the highest irrigation demand, as this season typically aligns with the driest period. This is followed by the summer-autumn crop, and then the autumn-winter crop, which benefits most from monsoonal rainfall. The increase in IWP is generally more pronounced in the later future period (2071-2099) across all seasons due to more significant projected temperature increases compared to the 2041-2070 period.

Table 5. Simulation results of irrigation water need in the current weather conditions and future scenarios rice cultivation crops across the study area.

Crop	Current	RCP 4.5 Scenario		RCP 8.5 Scenario	
		2041-2070	2071-2099	2041-2070	2071-2099
Winter-spring	806.4	849.9	908.6	866.9	895.9
Summer-autumn	530.4	550.8	589.0	561.8	580.7
Autumn-winter	254.4	276.3	294.4	281.8	290.3

Table 6 quantifies the changes in IWP under various sowing schedules for the RCP4.5 scenario, demonstrating significant sensitivity of irrigation needs to planting dates. For the winter-spring crop in the 2041-2070 period, advancing the sowing date by 10 days (to December 5th) reduced IWP from a baseline of 24.8 mm (current practice for that season simulation) to 20.8 mm, a decrease of 15.6%. This reduction is achieved by better aligning early crop growth with residual late-season rainfall and cooler early-season temperatures, thereby enhancing rainwater harvesting. Conversely, delaying the summer-autumn sowing by 15 days (to April 20th) increased IWP from 408.5 mm to 795.1 mm, a substantial rise of 48.6%, as the crop would then face higher evaporative demand and potentially miss early monsoon rains during its initial growth phase, increasing reliance on irrigation. Similar dynamic responses, showcasing opportunities for optimizing rainwater use by minimizing IWP, were observed for the autumn-winter crop and for the later 2071-2099 period. For instance, a December 10th sowing for the winter-spring crop in 2071-2099 still offers a 13.7% IWP reduction compared to the conventional calendar baseline for that future period, underscoring the persistent benefits of calendar adjustment.

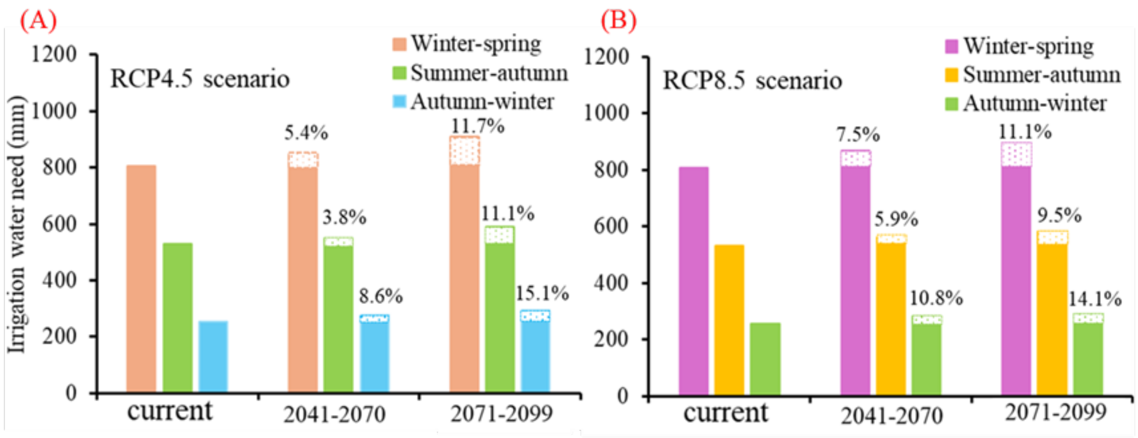

Figure 4. Simulation results of current and future irrigation water need scenarios rice cultivation crops (A) RCP4.5 scenario and (B) RCP8.5 scenario across the study area.

Table 6. Efficient irrigation water potential (IWP) for rice cultivation crops across the study area correspond to time windows 2041-2070 and 2071-2099 for the RCP4.5 scenario.

Sow Times	Winter-Spring Crop		Sow	Summer-Autumn Crop		Sow	Autumn-Winter Crop	
	IWP (mm)	Change (%)		IWP (mm)	Change (%)		IWP (mm)	Change (%)
				For time window 2041-2070				
5-Dec	20.8	-15.6	25-March	441.5	+7.5	01-August	629.7	-8.4
10-Dec	21.3	-13.8	30-March	521.0	+21.6	05-August	680.3	-1.1
Current	24.8	-	Current	408.5	-	Current	688.1	-

Table 6. *Cont*.

Sow Times	Winter-Spring Crop		Sow	Summer-Autumn Crop		Sow	Autumn-Winter Crop	
	IWP (mm)	Change (%)		IWP (mm)	Change (%)		IWP (mm)	Change (%)
20-Dec	49.3	+99.5	10-April	690.5	+40.8	15-August	696.9	+1.3
25-Dec	52.9	+114.4	15-April	756.7	+46.0	20-August	651.4	-5.3
30-Dec	36.2	+46.5	20-April	795.1	+48.6	25-August	645.9	-6.1
For time window 2071-2099								
5-Dec	22.6	-15.8	25-March	437.3	+6.6	01-August	647.4	-8.5
10-Dec	23.2	-13.7	30-March	516.1	+20.8	05-August	699.3	-1.1
Current	26.1	-	Current	404.6	-	Current	707.3	-
20-Dec	53.7	+101.7	10-April	683.9	+40.3	15-August	716.4	1.3
25-Dec	57.7	+103.3	15-April	749.5	+45.5	20-August	669.6	-5.3
30-Dec	39.4	+50.9	20-April	787.5	+48.1	25-August	663.9	-6.1

4. Discussion

The robust performance of the FAO-AquaCrop model in simulating rice yields within the Plain of Reeds, evidenced by strong statistical coherence (d-values > 0.82, $R^2 > 0.85$) and low error margins (RMSE < 5% of mean yield) during both validation and calibration, confirms its suitability for this study. These results align with findings from other studies that have successfully employed AquaCrop for predicting crop responses to varying water availability and climatic conditions in similar agricultural systems [17, 22], lending confidence to its application for assessing climate change impacts and adaptation strategies in this region.

The projected increases in irrigation water need (IWN or IWP) under both RCP 4.5 and RCP 8.5 scenarios are primarily driven by rising temperatures, which lead to higher atmospheric evaporative demand. For the 2041-2070 period under RCP4.5, IWN is expected to increase by 3.8-8.6%, and for 2071-2099, by 11.1-15.1% compared to the baseline. This is consistent with regional climate change impact assessments in the VMD, which also predict increased irrigation requirements due to warming[8, 12]. The winter-spring crop, cultivated during the driest part of the year, consistently shows the highest IWN, making it particularly vulnerable to future water scarcity. The autumn-winter crop, conversely, has the lowest IWN due to its alignment with the peak monsoonal rainfall period, highlighting the existing natural rainwater harvesting during that season.

The core of this study lies in demonstrating the potential for optimizing rainwater use and reducing irrigation dependency through strategic adjustments to crop cultivation calendars. The simulations clearly show that shifts in sowing dates can significantly alter IWP. For example, advancing the winter-spring sowing by 5-10 days consistently reduced IWP by approximately 13-16% in both future periods under RCP4.5. This benefit arises because earlier sowing allows the crop to better utilize residual late-season rains and establish during cooler temperatures, completing critical growth stages before the onset of the harshest dry conditions and highest evaporative demand. This is a direct enhancement of in-situ rainwater harvesting. Conversely, delaying the summer-autumn sowing significantly increased IWP, as the crop would then increasingly rely on irrigation during its initial growth phase if early monsoonal rainfall are missed or are more erratic, a plausible scenario under climate variability.

These results underscore the importance of aligning crop phenology with rainfall patterns as a key low-cost adaptation strategy, with significant potential to reduce irrigation dependency[10, 16]. The magnitude of IWP changes observed (e.g., a 48.6% increase in IWP for a 15-day delay in summer-autumn sowing in 2041-2070) highlights the critical sensitivity of agricultural water demand to planting times, especially as rainfall becomes more variable. Such findings provide actionable insights for local agricultural planning, enabling farmers and water managers to make informed decisions that can enhance water use efficiency and build resilience against climate variability. The ability to reduce IWP, particularly for the water-intensive winter-spring crop, is crucial for sustainable water resource management and for maintaining rice productivity in the

Plain of Reeds. The economic implications, while not quantified in detail, are clear: reduced irrigation needs translate to lower pumping costs, less strain on water resources, and potentially more stable yields, benefiting smallholder farmers.

5. Conclusions

This study effectively demonstrates that the FAO-AquaCrop model can reliably predict future irrigation water needs for rice cultivation in the Plain of Reeds under projected climate change scenarios (RCP4.5 and RCP8.5). The model's robust performance during calibration and validation instills confidence in its application for assessing climate change impacts and evaluating adaptation solutions in this vital agricultural region.

The simulation results for irrigation water potential reveal that strategic adjustments to traditional sowing schedules offer a practical and significant pathway for farmers to better utilize available rainwater and reduce their reliance on supplementary irrigation. Specifically: Advancing the winter-spring crop sowing dates (e.g., to early December) can lead to substantial reductions in irrigation water requirements (13-16% under RCP4.5), by leveraging late-season rainfall and cooler establishment periods, thereby enhancing rainwater harvesting.

The timing of summer-autumn and autumn-winter crops also presents opportunities for optimization to minimize irrigation demand, although the responses are more dynamic and season-specific, requiring careful consideration of shifting monsoon patterns.

This study underscores that adjusting cultivation calendars is a viable, low-cost adaptation strategy. It provides a practical approach for farmers in the Plain of Reeds to reduce their dependency on supplementary irrigation, thereby enhancing their resilience to the adverse impacts of climate variability and promoting more sustainable water use. The findings offer valuable guidance for agricultural planners in developing climate-smart agricultural practices tailored to the specific conditions of the Vietnamese Mekong Delta. Future research could expand on these findings by exploring a wider range of global circulation models to better capture uncertainty, refining optimal calendars under RCP8.5, and integrating socio-economic factors to assess the feasibility and adoption potential of these calendar adjustments at the farm level. The innovation of this research lies in its specific application of AquaCrop to identify precise, actionable calendar shifts for enhanced rainwater utilization in a vulnerable, economically important rice-producing region under detailed future climate projections..

Author Contributions

T.D.P., K.T.T.H., and V.T.P., conceptualized the study and performed the simulations. T.A.D. designed the overall research framework, supervised the work, and analyzed the data. T.A.D. wrote the manuscript. All authors reviewed and approved the final manuscript.

Funding

This research is supported by project B2024-SPD-10.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data will be provided upon request to the corresponding author.

Acknowledgments

The author would like to extend sincere gratitude to the Departments of Agriculture and Rural Development of Dong Thap, Long An, and Tien Giang provinces for providing valuable data from the region, which facilitated the completion of this research. The authors would also like to sincerely thank the reviewers as well as the editorial board for reviewing and providing feedback to help improve the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Acharjee, T.K., Halsema, G., Ludwig, F., et al., 2019. Shifting planting date of Boro rice as a climate change adaptation strategy to reduce water use. Agricultural Systems. 168, 131-143.

[2] Akinbile, C.O., 2020. Crop water requirements, biomass and grain yields estimation for upland rice using CROPWAT, AQUACROP and CERES simulation models. Agricultural Engineering International: CIGR Journal. 22(2), 1–20.

[3] Alemayehu, A., Behaylu, A., Agumass, G., et al., 2023. Farmers' traditional knowledge on climate change and weather forecast: The case of Menze Gera Midir district, Ethiopia. Environmental Development. 47, 100908.

[4] Alvar-Beltrán, J., Saturnin, C., Grégoire, B., et al., 2023. Using AquaCrop as a decision-support tool for improved irrigation management in the Sahel region. Agricultural Water Management. 287, 108430.

[5] Apriyana, Y., Surmaini, E., Estiningtyas, W., et al., 2021. The Integrated Cropping Calendar Information System: A coping mechanism to climate variability for sustainable agriculture in Indonesia. Sustainability. 13(11), 6495.

[6] Bagula, E.M., Majaliwa, J.G.M., Mushagalusa, N.G., et al., 2022. Climate Change Effect on Water Use Efficiency under Selected Soil and Water Conservation Practices in the Ruzizi Catchment, Eastern D.R. Congo. Land. 11(9), 1409.

[7] Beetstra, M., Wilson, R., Toman, E., 2022. The influence of the seasons: How the agricultural calendar impacts farmer perceptions of cover crops. Renewable Agriculture and Food Systems. 37(3), 187–197.

[8] Busschaert, L., de Roos, S., Thiery, W., et al., 2022. Net irrigation requirement under different climate scenarios using AquaCrop over Europe. Hydrology and Earth System Sciences. 26, 3731–3752.

[9] Bwambale, E., Abagale, F.K., Anornu, G.K., 2022. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: a review. Agricultural Water Management. 260, 107324.

[10] CGIAR-Research Program on Climate Change., 2016. Agriculture and food security-Southeast Asia (CCAFS SEA). In assessment report: The drought crisis in the central highlands of Vietnam; CGIAR research program on climate change, agriculture and food security (CCAFS): Hanoi, Vietnam.

[11] Chun, J.A., Li, S., Wang, Q., et al., 2016. Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. Agricultural Systems. 143, 14-21.

[12] Dang, T.A., 2021. Grain yield optimization in the Plain of Reeds in the context of climate variability. Brazilian Journal of Agricultural and Environmental Engineering. 25, 591-596.

[13] Deines, J.M., Schipanski, M.E., Golden, B., et al., 2020. Transitions from irrigated to dryland agriculture in the Ogallala Aquifer: Land use suitability and regional economic impacts. Agricultural Water Management. 233, 106061.

[14] Deb, P., Tran, D.A., Udmale, P.D., 2016. Assessment of the impacts of climate change and brackish irrigation water on rice productivity and evaluation of adaptation measures in Ca Mau province, Vietnam. Theoretical and Applied Climatology. 125(3-4), 641-656.

[15] Dharmarathna, W.R.S.S., Herath, S., Weerakoon, S.B., 2014. Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district, Sri Lanka. Sustainability science. 9(1), 103-111.

[16] Fatichi, S., Paschalis, A., Bonetti, S., et al., 2023. Water use efficiency: A review of spatial and temporal variability. Encyclopedia of Soils in the Environment. 5, 527–542.

[17] Pörtner, H.O., Roberts, D.C., Tignor, M., et al., 2022. IPCC. Climate Change 2022: Impacts, adaptation, and vulnerability. contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK and New York, USA. 3056.

[18] Kamara, A.Y., Friday, E., David, C.,et al., 2009. Planting date and cultivar effects on dryland corn production. Agronomy Journal. 101, 91-98.

[19] Kelly, T.D., Foster, T., Schultz, D.M., 2023. Assessing the value of adapting irrigation strategies within the season. Agricultural Water Management. 275, 107986.

[20] Kontgis, C., Schneider, A., Ozdogan, M., et al., 2019. Climate change impacts on rice productivity in the Mekong River Delta. Applied Geography. 102, 71-83.

[21] Lee, S.K., Dang, T.A., 2019. Spatio-temporal variations in meteorology drought over the Mekong River Delta of Vietnam in the recent decades. Paddy and Water Environment. 17, 35–44.

[22] Mbava, N., Mutema, M., Zengeni, R., et al., 2020. Factors affecting crop water use efficiency: a

worldwide meta-analysis. Agricultural Water Management, 228, 108663.

[23] Li, M., Zhou, S., Shen, S., et al., 2024. Climate-smart irrigation strategy can mitigate agricultural water consumption while ensuring food security under a changing climate. Agricultural Water Management, 292, 108663.

[24] Mondo, J.M., Chuma, G.B., Matiti, H.M., et al., 2024. Crop calendar optimization for climate change adaptation in yam farming in South-Kivu, eastern D.R. Congo. Plos One. 19(9), e0309775.

[25] Raes, D., Waongo, M., Vanuytrecht, E., et al., 2021. Improved management may alleviate some but not all the adverse effects of climate change on crop yields in smallholder farms in West Africa. Agricultural and Forest Meteorology. 308–309, 108563.

[26] Wang, Q.G., Chun, J.A., Lee, W.S., et al., 2017. Shifting planting dates and fertilizer application rates as climate change adaptation strategies for two rice cultivars in Cambodia. Journal of Climate Change Research. 8(3), 187-199.

[27] Wang, X., Folberth, C., Skalsky, R., et al., 2022. Crop calendar optimization for climate change adaptation in rice-based multiple cropping systems of India and Bangladesh. Agricultural and Forest Meteorology. 315, 108830.

[28] Salman, M., García Vila, M., Fereres, E., et al., 2025. AquaCrop on the ground – Model applications for sustainable agricultural water management. FAO Water Reports: Rome. 48.