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Increased Water Savings in Rice Crops Under Aerobic Irrigation Conditions: A Case Study in the Riverina Region, Australia

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Abstract

Rice (Oryza sativa) is a high water-demand crop, with yield strongly dependent on irrigation water availability, particularly in the semi-arid Riverina region of Australia. Enhancing the drought resilience of rice production therefore requires improved water management strategies, such as Aerobic Rice (AR) as an alternative to the traditional Continuous Flooding (CF) strategy. AR is a promising water-saving strategy being promoted in the region, where the crop is grown mostly under non-saturated conditions without continuous ponding. To better characterize AR water-saving potential, the main components of the water balance were measured under these systems. Net irrigation was measured using the Agriflo XCi ultrasonic Doppler sensor, and evapotranspiration (ET) with the LI-710 Eddy Covariance sensor. Three commercial-scale rice farms during the 2024–2025 season in the Riverina region were monitored. The analysis focused on three aspects: (i) rice crop development, (ii) water management and water balance, and (iii) rice performance and water productivity indicators. Water savings associated with AR were estimated at 18.4% in a side-by-side comparison. In addition, final harvested yield increased by 5.5%, resulting in a 29.5% increase in water productivity. ET from the AR paddock was 6.5% higher than under CF. Nevertheless, AR reduced Deep Percolation (DP) by 53.2% compared with CF. Two other CF paddocks were also monitored across the region, and water use from 13.0 to 14.5 ML ha^{-1} has been observed as the baseline irrigation water requirement for permanent ponded rice paddocks in this region. These findings provide evidence that AR can deliver meaningful water savings while improving water productivity in commercial-scale rice paddocks in this semi-arid region of Riverina.

Keywords: water productivity; yield; surface irrigation; deep percolation; evapotranspiration; Aerobic Rice; Delayed Permanent Water; drought resilience

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1. Introduction

Water is essential to food security, and the ongoing global aridification is becoming a central focus amid increasing water scarcity. It is estimated that arid climate dominates 30.2% of the global land area, and specifically accounts for 77.8% of the Australian territory [1]. Inconsistent rainfall and prolonged droughts are more common in arid regions, drastically impacting food production. Reducing water use in irrigated crops is therefore essential since the agricultural sector accounts for almost 70% of global freshwater withdrawals [2]. With water-saving irrigation strategies, FAO [3] projected that a 50% increase in irrigated food production could be achieved by increasing water withdrawals by only 10%. This

increased water-use productivity can be achieved by reducing water use in irrigated crops while increasing yields.

Rice (Oryza sativa) is a high-water-consuming crop worldwide and is particularly vulnerable to the impacts of climate change and increased water scarcity. In Australia, irrigation is the key factor restricting rice production. Even though Australian rice yields have shown a constant increasing trend since 1925, the gross production can be enormously affected by cuts in water allocation, as observed in the 2002–2010 severe drought period [4]. According to [5], an increase in Irrigation Water Productivity (IWP) from 0.34 t ML^{-1} to 0.77 t ML^{-1} occurred between 1980 and 1999 in the MIA region of Riverina, NSW, Australia. This improvement in IWP was mainly driven by the enhancement of crop yields and, to a lesser degree, by better use of irrigation water. As the rate of yield increase declines after this period, little advance was observed in IWP for rice cultivated in Australia in the subsequent 20 years, reaching 0.84 t/ML in the 2020–2021 growing season [6]. This figure is significantly lower than the rice industry goal of reaching 1.5 t ML^{-1} by 2030 [7].

The Riverina is the major rice production hub in Australia, where Griffith, Deniliquin, and the Tocumwal–Finley–Jerilderie axis account for 95.6% of the Australian total rice production [8]. Australian rice is predominantly grown under three Continuous Flooding (CF) systems: (i) Broadcast or Aerial Sown Rice with Early Permanent Water (EPW), with permanent water applied after sowing, (ii) Drill Sown Rice with Permanent Water at Three-Leaf Stage (PW at TLS), and (iii) Drill Sown Rice with Permanent Water at Late-Tillering (PW at LT), also known as Delayed Permanent Water (DPW) [9]. DPW is already recognized as a water-saving practice in the region. The transition from EPW to drill-sown with PW at TLS can increase water productivity by 0.10 t ML^{-1}, and by an additional 0.15 t ML^{-1} if DPW is applied [10]. Although EPW remains widely adopted in Riverina, the two conventional drill-sown techniques with PW at TLS or LT have become standard practice. This strategy accounted for 70% of the irrigated area in the 2024–2025 season. With an average yield of 12.03 t ha^{-1} and a water productivity of 0.92 t ML^{-1} [11], the estimated water use of the season resulted in 13 ML ha^{-1}. The high cost of water threatens rice cropping profit. In this context, further investigations of Water Saving Techniques (WSTs) are essential.

Aerobic Rice (AR) is a promising irrigation strategy for enhancing water savings. Originally derived from upland rice cultivation, AR is characterized by non-puddled soils maintained under non-saturated conditions without standing water [12]. This concept has been adapted to the modern bankless irrigation systems in the lowland rice-growing region of the Riverina. Here, temporary ponding is permitted following irrigation to enhance water infiltration, particularly during fertilizer applications. Nonetheless, the soil is allowed to dry between irrigations within safe limits previously investigated in the Riverina. [13] indicated that extending soil moisture deficits up to −40 kPa delayed panicle initiation and implied severe yield penalties. The study also evidenced −15 kPa as a safe operational limit for AR. Another two-year study on a commercial farm in the Riverina region (Widgelli) investigated differences between aerobic and ponded rice using UAV-based multispectral imagery [14], focusing on canopy reflectance, nitrogen uptake, and grain yield and quality. The study showed that high-yielding aerobic rice can exhibit different canopy reflectance characteristics while achieving yields similar to ponded rice when soil matric potential is kept above −15 kPa. However, to date, no field data have been found on Aerobic Rice (AR) irrigation water requirements in this region.

To ensure sustainable rice production under increasing drought pressure and to improve farm water management to move the industry toward the 1.5 t ML^{-1} benchmark, reduced water use while maintaining high yields is crucial. A review of WSTs worldwide for rice cultivation between 2003 and 2023 highlighted Alternate Wetting and Drying (AWD)

and AR as the two leading strategies for water savings [15], accounting for 43.0% ± 22.2% of registered water savings. Additionally, a yield change ranging from a −52.6% penalty to a 15.4% increase was observed relative to traditional CF approaches, suggesting that, with admissible risk levels of soil drying, it is possible to maintain or even increase yields by non-permanent ponding rice crops [15].

Deeper understanding of paddock-level water dynamics is essential for evaluating how water is conserved, particularly after reducing irrigation volumes in WST practices. Previous research suggests that evapotranspiration (ET) reduction is not the primary driver of water savings in high-yield, competitive production systems [16–18]. Instead, significant reductions in Deep Percolation (DP) have been observed in field trials [15,19–21], emerging as a dominant mechanism for water conservation. Despite existing studies on WSTs and irrigation practices, empirical data quantifying these water-saving mechanisms in commercial AR systems remain scarce, especially in arid regions.

This study aimed to assess water balance parameters across different locations and water management strategies in this semi-arid region, identifying the amount of water that can be saved in a low-risk AR production and how these water savings were achieved. Three commercial rice farms were monitored using on-site sensors to quantify the main components of the water balance under AR, CF with PW-TLS, and CF with PW-LT (DPW). This study investigates ET and DP as potential mechanisms to promote water savings in AR production. The findings document relevant information for the rice industry and growers in the Riverina region by demonstrating how aerobic systems can sustain yields while reducing water losses.

2. Materials and Methods

2.1. Study Sites

The study experiment was conducted in the Riverina region of New South Wales, Australia. Between October 2024 and April 2025, four commercial-sized paddocks were selected as study sites. Both AR and CF irrigation strategies were implemented side-by-side at the Widgelli (WID) site and compared in terms of crop water use, crop water requirements, and productivity. This assessment between the two blocks represents an observational comparison of two commercial paddocks rather than a replicated field experiment. Additionally, two other sites in Coleambally (COL) and Coree (COR) under the CF strategy were monitored. The description of each trial is given in Table 1.

Three water management strategies were observed. The conventional CF with Permanent Water at Three Leaf Stage (PW-TLS) involves dry seeding with irrigation flushes applied up to the 3–4 leaf stage, followed by a permanent water application until final drainage. Flush irrigation consists of a short-duration irrigation event in which water is applied to uniformly wet the field surface, followed by the rapid drainage of excess water to prevent prolonged ponding. This CF with PW-TLS strategy (CF_a) was monitored in two study sites, WID and COR. The CF with PW-LT strategy (CF_b), also known as Delayed Permanent Water (DPW), extends the flushing irrigation stage from the 3–4 leaf stage to the late-tillering stage or about 2 weeks before panicle initiation [9], and was implemented at the COL study site.

Table 1. Experimental Sites Description.

Farm Trials	Strategy	Paddock Area	Variety	Land Preparation	Crop History	Mean Temperature (°C)	Precipitation (mm)
Widgelli (WID)	AR	5.62 ha	Matilda (V071)	Raised-Bed System	Fourth-year rice following a winter fallow	23.3	205
Widgelli (WID)	CF_a	12.41 ha	Matilda (V071)	Raised-Bed System	Fourth-year rice following a winter fallow	23.3	205
Coleambally (COL)	CF_b	41.40 ha	Matilda (V071)	Raised-Bed System	Fifth-year rice following a winter fallow	22.4	148
Coree (COR)	CF_a	16.79 ha	Illabong	Flat system	Second-year rice following a winter fallow	22.3	155

Note(s): CF: Continuous Flooding (a) PW at TLS and (b) PW at LT./AR: Aerobic Rice. Mean temperature and precipitation refer to in-season averages, from October to April.

In contrast, AR irrigation was implemented in WID, where continuous ponding was avoided throughout the season and the soil was allowed to dry between irrigations. This irrigation strategy is divided into two moments; the first includes a flush irrigation until the three-leaf stage, similar to CF_a. After this stage, short-term ponding was allowed after irrigation to permit water infiltration into the root zone and to enhance fertilizer incorporation, as drainage can cause fertilizer runoff. During this stage, a higher control of soil water status is needed. A targeted limit of −30 cm water depth was followed, monitored through a perforated inspection pipe as the lower threshold for irrigation.

The soil texture at the 30 cm depth in WID was sampled in Oct/2023 on each paddock. The WID CF_a site is classified as a medium clay (Sand—41.5%, Silt—8.5%, and Clay—50.0%), while the WID AR site has a bigger portion of clay content, classified as heavy clay (Sand—32.0%, Silt—7.9%, and Clay—60.1%). The COR site contains medium clay (Sand—40.5%, Silt—11.6%, and Clay—47.8%) [22] and the COL site has a higher percentage of silt compared to the other sites, but is still classified as medium clay (Sand—36%, Silt—13%, and Clay—51%). Soil texture at the Coleambally site has been defined by a weighted average at a 30 cm soil depth (soilgrids.org).

Crop management practices varied across the four study paddocks. Regarding fertilizer application rates and timing, in WID AR and CF, a custom-blend fertilizer (150 kg ha^{-1}; 8% N, 17% P, 7% S, 8% Ca, and 0.6% Zn) was applied at sowing. Subsequent urea applications were conducted on 21 November 2024 (400 kg ha^{-1} in both paddocks) before permanent water in the CF plot and temporary standing water in the AR plot. Another fertilizer application occurred on 28 December 2024 (225 kg ha^{-1} in AR and 125 kg ha^{-1} in CF) at panicle initiation. In COL, Granulock Z (11% N, 21.8% P, 4% S, and 1% Zn) was applied at sowing (200 kg ha^{-1}), followed by urea (460 kg ha^{-1}) and ammonium sulfate (30 kg ha^{-1}) before permanent water on 15 December 2024, and an additional urea application (150 kg ha^{-1}) at panicle initiation on 6 January 2025. In COR, Granulock Z (150 kg ha^{-1}) was applied at sowing, followed by urea applications of 300 kg ha^{-1} before permanent water on 10 December 2024 and 150 kg ha^{-1} at panicle initiation on 1 January 2025. Seeding rates were 142 kg ha^{-1} in CM AR and CM CF, 140 kg ha^{-1} in COL, and 125 kg ha^{-1} in COR. Average

plant establishment densities were 169 plants m^{-2} in both WID paddocks and 152 plants m^{-2} in COL; the established plant density in the COR site is unknown.

2.2. Experimental Design and Instrument Setup

The same experimental setup was applied to each trial. Irrigation and runoff at each site were measured (Figure 1a) using the MACE AgriFlo XCi flow meter (Measuring & Control Equipment Pty Ltd, Dural, NSW, Australia) [23]. Flow velocity was determined with a submerged ultrasonic Doppler sensor, with an accuracy of ±1.0% for velocities below 3.0 m/s, and a measurement range of 0.025 to 8.0 m/s [24]. The sensors were installed at the five o'clock position inside each concrete pipe or above 15 cm from the bottom of the channel, to avoid sediment accumulation over the sensor. The velocity/area sensors were installed at a distance equivalent to two pipe diameters from the pipe exit and oriented upstream. Associated with the velocity sensor, a ceramic pressure transducer measured water level with an accuracy of 0.2–1.0% of full scale (4 m), depending on the temperature range [24,25]. The water level sensors were calibrated post hoc, accounting for each sensor installation height. Recorded variables included water depth, stream velocity, flow rate, total flow, Doppler index, and time of day. Net irrigation for each paddock was calculated by subtracting the runoff (or drainage) from the total irrigation input. Drainage is used as irrigation for the downstream paddocks or recycled; therefore, it cannot be considered a loss. Isotonic regressions were adopted to estimate the effective water volume applied through irrigation per day.

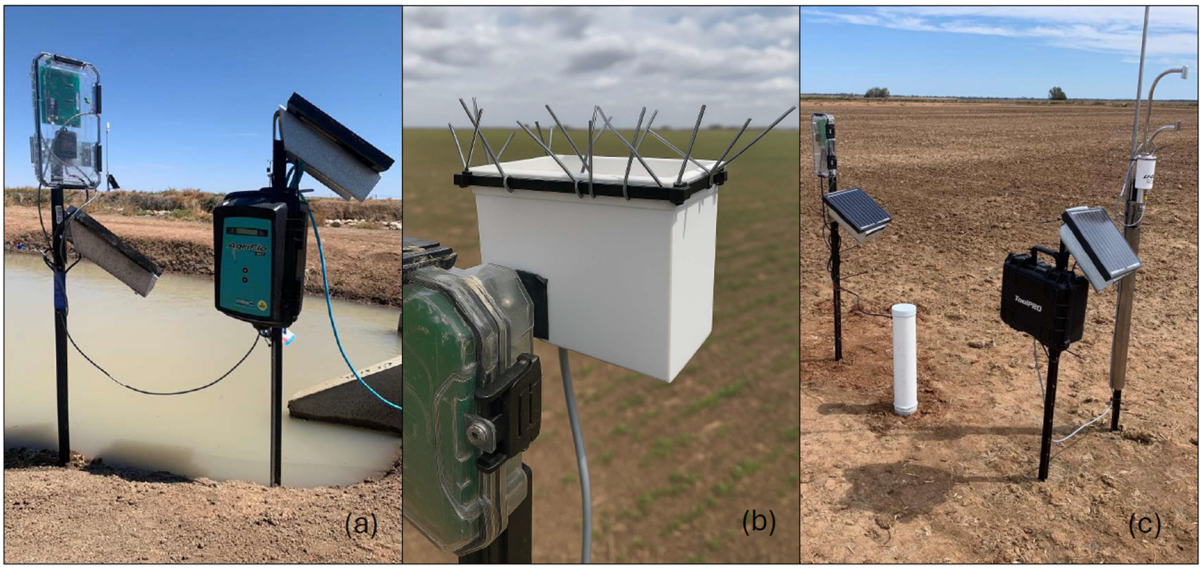


Figure 1. Water Balance monitoring sensors. (**a**) Irrigation: Mace Meter AgriFlo XCi connected to the Arduino-based Integrated circuit. The sensor was positioned at the downstream end of the pipe, oriented upstream. (**b**) Precipitation: tipping-bucket rain gauge with spikes to prevent birds from landing. (**c**) Evapotranspiration: Monitoring station including water depth and the ET LI-710 sensor.

Each paddock included a water status monitoring system positioned at the centre of the monitored area. It included an inspection pipe with a pressure transducer (Model ESMWLPS, Kexlimice, Xi'an ESM Tech Co., Ltd., Xi'an, China) to measure water depth relative to the paddock ground level [26]. The sensor has a measurement range of 0–2 m and a manufacturer-specified accuracy of ±0.15% of full scale (FS), equivalent to ±3 mm of water-level measurement. This instrument was buried in the field at −50 cm; nonetheless, the sensor position inside the pipe only allows accurate observations above −45 cm. Exclusively for the AR paddock, a complementary set of two watermark sensors (Model

200SS, Irrometer Company Inc., Riverside, CA, USA) was placed at 10 cm depth to assess soil matric potential [27]. The sensor has a measurement range of 0–239 kPa. Sensor readings were converted from electrical resistance to soil water tension using the manufacturer's calibration procedure. In addition, a tipping-bucket rain gauge (Small, Model 100.053, PRONAMIC ApS, Skjern, Denmark), was installed at each site and connected to the Arduino-based integrated circuit for field sensing (Figure 1b). This rain bucket sensor has a collection area of 50 cm^2, a measurement resolution of 1 mm, and a manufacturer-specified accuracy of ±5%. The Weather Station (Model WS-2902D, Ambient Weather, Ambient, LLC, Chandler, AZ, USA) was deployed at the WID site for general weather characterization through solar radiation, wind direction and speed, air temperature, humidity, and rainfall. More information about the WS-2902D sensors specifications and accuracy can be found in [28].

Evapotranspiration was measured using an LI-710 eddy covariance evapotranspiration sensor (LI-710, LI-COR Environmental, LI-COR, Inc., Lincoln, NE, USA), which calculates ET from high-frequency vertical wind speed and water vapor concentration measurements. The sensors were deployed at the centre of each field (Figure 1c) as described in Table 1. Data were logged and transmitted using a data logger (Model CR1000, Campbell Scientific, Inc., Logan, UT, USA) connected to an NL241 Wi-Fi WLAN interface, with data recorded at 30-min intervals. Variables include actual evapotranspiration, latent heat, sensible heat, vapor pressure, atmospheric pressure, ambient temperature, and relative humidity. The manufacturer specifies a water vapor mole fraction accuracy of 2% of the reading (above 5 mmol mol^{-1}), an ambient temperature accuracy of ±1.5 °C, and an atmospheric pressure accuracy of ±0.2 kPa. No overall accuracy specification is provided for the final computed ET.

2.3. Water Balance Calculations

A simplified water balance framework was adopted based on practices reported in the literature [29–31]. Lateral subsurface flow into and out of the study paddocks was assumed negligible, consistent with the relatively flat irrigated fields common across major irrigation areas. Capillary rise was also assumed negligible, as expected under a deep-water table and efficient irrigation practices [32]. This study focuses on irrigation water use during the cropping season, with water balance components accumulated from sowing to harvest. No water was applied for tillage operations or prior to sowing.

Equation (1) estimates the water losses through the soil, including DP, variations in Soil Water Storage (ΔSWS), and above-soil Water Storage (ΔWS), especially needed for permanent water conditions. Regarding ΔWS, it is noteworthy that the initial and final season conditions lead to no water accumulation above ground level, resulting in a null difference when a seasonal accumulation is discussed. Equation (1) also includes I = effective Irrigation, P = Precipitation, and ET = Evapotranspiration. Figure 2 illustrates these main components of the water balance applied to rice crops. Since runoff is often recycled to other paddocks or pumped back to the beginning of the system, it has been considered negative irrigation volume and lumped into the I parameter (net irrigation).

$$DP + \Delta SWS + \Delta WS = I + P - ET \quad (1)$$

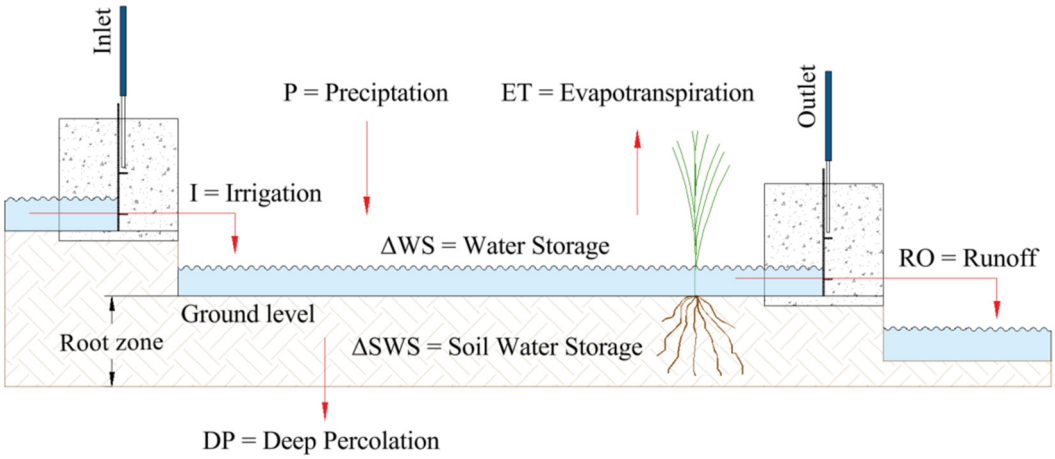


Figure 2. Main water balance components in rice fields. Water is gravitationally conveyed or pumped across the stepped, terraced bays.

Water can be lost through excessive storage in the root zone by the end of the season. Equation (2) estimates the SWS volume of water in the root zone on the first and last day [33]. SWS = Soil Water Storage [mm], VWC = Volumetric Water Content [%], SD = Soil depth [mm]. The "i" indicator marks soil depth zones of interest. VWC was measured with a multi-level EnviroPro soil probe (Entelechy Pty Ltd., South Australia) with its sensors positioned every 10 cm below ground level. This analysis has considered SWS for the first 30 cm. Rooting depth varies with irrigation strategy and is generally expected to be greater under Aerobic Rice (AR) than under Continuous Flooding (CF). For practical purposes, an effective root-zone depth of 30 cm was adopted based on previous studies [34,35]. Downward water flux beyond this depth was classified as deep percolation (DP), as it was assumed to be less accessible for crop water uptake.

$$SWS = \sum VWC_i \times SD_i \quad (2)$$

2.4. Water Savings

The WID study site included both AR and CF strategies under side-by-side conditions, allowing water savings to be assessed under comparable field and climatic conditions. Irrigation water savings were calculated relative to the conventional permanently ponded (CF) strategy. As previously described, both strategies received the same initial flush irrigation, with their water management practices diverging from the three-leaf stage onwards. Equation (3) presents the calculation of water savings, considering irrigation water volumes only [15,36].

$$\text{Water Saving } (\%) = {}^{(I_{CF} - I_{AR})}/_{I_{CF}} \times 100 \quad (3)$$

2.5. Metrics for Rice Performance and Water Productivity

Irrigation Water Productivity (IWP) and Water Productivity (WP) were calculated using Equations (4) and (5), respectively [37,38]. The Irrigation-Total Water Input ratio (I/TWI) is shown in Equation (6) and is a relevant parameter to characterize the role of irrigation relative to the available in-season rainfall [15]. Yield (Y) was estimated before harvest (pre-harvest yield) and after harvest (post-harvest truck load yield). The pre-harvest yield was manually sampled and processed when grain moisture content was lower than 23% and normalized to 14% moisture [39].

Three samples (1 m^2 each) were harvested per study site, corresponding to a total sampled area of 3 m^2. Sampling locations were distributed along the paddock to capture

potential spatial variability in crop performance. One quadrat was positioned near the irrigation inlet, another near the outlet, and the third in the paddock center. Inlet and outlet sampling locations were selected away from field boundaries. The average yield from the three samples was used to estimate paddock-level grain yield. The rice samples were mechanically threshed, and moisture content was determined using the Infratec™ NOVA Grain Analyser (FOSS Analytical, Hillerød, Denmark), which employs near-infrared transmittance technology (NIT). Grain quality of each sample was assessed using PaddyVision® (AGS–SunRice Group, Leeton, NSW, Australia, Software Version 2025), which considers cracked and immature grains to estimate potential milling quality.

Final yield was determined after mechanical harvesting using combine harvesters available at each site, when grain moisture content was approximately 18%. The delivered load was similarly standardized to 14% moisture. This yield was used for the IWP and WP calculations because it represents total paddock productivity.

$$\mathrm{IWP} = {}^{\mathrm{Y}}/_{\mathrm{I}} \tag{4}$$

$$\mathrm{WP} = {}^{\mathrm{Y}}/_{(\mathrm{I}+\mathrm{P})} \tag{5}$$

$$(\mathrm{I/TWI})_{\mathrm{ratio}} = {}^{\mathrm{I}}/_{(\mathrm{I}+\mathrm{P})} \tag{6}$$

The crop calendar, including sowing and harvest dates, was recorded for each farm. Additional information, such as PI and flowering dates, was collected using the rice dashboard developed by the Applied Agricultural Remote Sensing Centre (AARSC). The dashboard combines local weather (temperature, solar radiation and growing degree days) and remote sensing inputs such as NDVI (Normalized Difference Vegetation Index), CIRE2 (Chlorophyll Index Red Edge 2), and NDWI (Normalized Difference Water Index) to predict PI and flowering dates. The author indicated an RMSE of 4.91 days for PI and 6.52 days for flowering prediction [40].

Plant height was recorded monthly during the routine inspections of the LI-710 sensor. At each inspection, measurements were taken at 10 sampling points distributed along a transect extending from the paddock border towards its centre. This sampling approach was adopted to capture potential spatial variability in crop development across the field while maintaining a consistent sampling procedure between visits. At each sampling point, the longest leaf was gently extended, and the vertical distance from the soil surface to the leaf tip was measured using a measuring tape. This method is easily replicable and ensures standardized measurements and minimizes the influence of leaf bending, drooping, or differences in leaf orientation on the recorded plant height. In total, 25 visits were made across the four sites with 250 observations. As plant height measurements were collected on different dates, interpolation was applied to estimate intermediate values, allowing the crop growth curve to be characterized and plant height development to be compared across sites. These observations were interpolated using the Gompertz growth function, which is widely applied to describe biological growth exhibiting an S-shaped pattern [41]. NDVI was used to track canopy cover evolution and was collected through the remote sensing platform IrriSAT [32].

2.6. Statistical Analysis

Descriptive statistics were used to summarise yield components, grain quality and dry biomass. For each paddock, the mean and standard deviation (SD) were calculated from three subsamples to describe the central tendency and within-paddock variability of the measured parameters. Results are presented as mean ± SD. No inferential statistical tests were performed to assess differences between irrigation treatments.

3. Results

3.1. Rice Crop Development

The study sites were sown between 4 October 2024 and 8 October 2024, with the first flush around mid-October. Harvest dates ranged between 8 April 2025 and 17 April 2025. PI and Flowering dates diverged by around nine days across the different paddocks. Table 2 shows the complete crop calendar. Plant height measured throughout the season is displayed in Figure 3a. Plants from the AR-treated site reached 101.4 cm at harvest, 1.1 cm shorter than the WID CF_a trial, even though the CF_a paddock presented faster growth in both plant height and NDVI (Figure 3b). The AR trial at WID also produced plants 8.7 cm longer than COL and 6.8 cm shorter than COR. A lower NDVI at early stages indicates the pre-vegetative stage, with an average of 0.15 at the first stage (October included). A peak near 0.8 has been observed in general. The AR (WID) had a similar plant height evolution compared to the CF (WID), but did not reach the same NDVI as the CF practice during the peak of the vegetative stage. This lower greenness factor was observed in the AR practice (WID) and in CF (COR), reflecting a smaller dry biomass in the AR paddock and a smaller plant density associated with a different variety at the COR site. The final NDVI presented similar magnitude across all sites, ranging from 0.46 to 0.51 by early April.

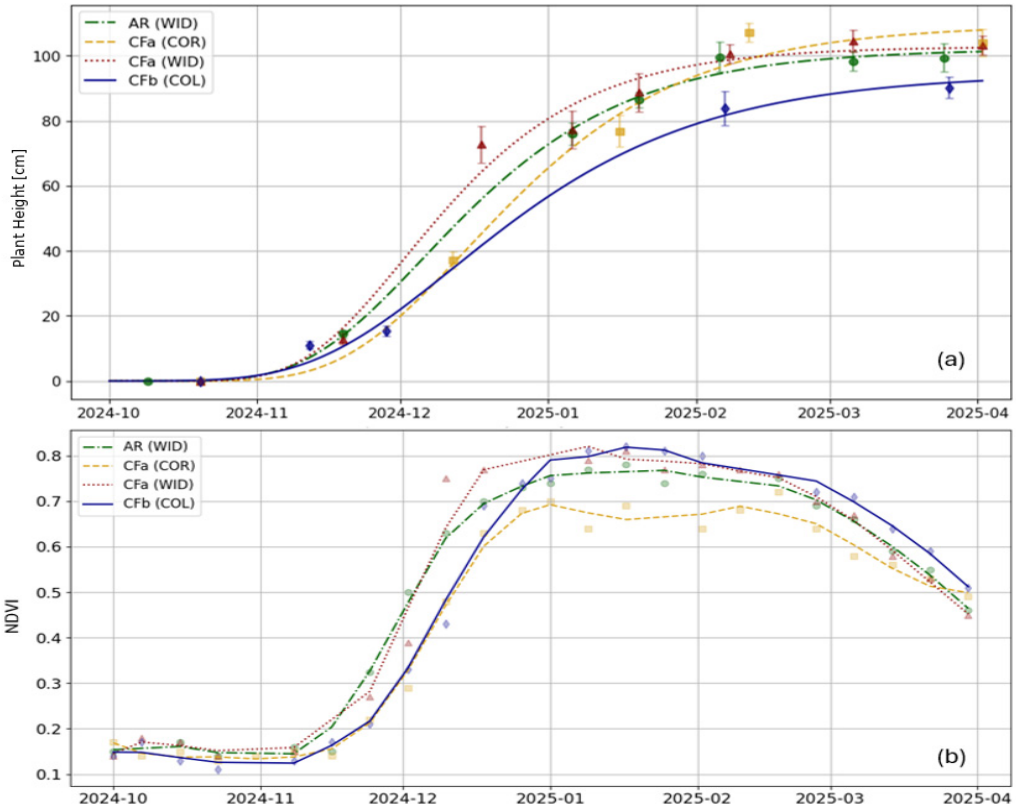


Figure 3. Crop development. (**a**) Plant height measured throughout the season. Dots mark the mean, while the bars indicate the standard deviation of the 10 plant height measurements collected in each visit. (**b**) NDVI measurements for the study sites, as provided by IrriSAT.

Table 2. Crop Calendar.

Trial	Sowing Date	First Flush	PI	Flowering	Final Drainage	Harvest
AR (WID)	5/10/24	12/10/24	28/12/24	28/01/25	14/03/25	8/04/25
CF_a (WID)	5/10/24	12/10/24	29/12/24	29/01/25	19/03/25	8/04/25
CF_b (COL)	8/10/24	14/10/24	6/01/25	5/02/25	14/03/25	12/04/25
CF_a (COR)	4/10/24	18/10/24	1/01/25	27/01/25	25/03/25	17/04/25

3.2. Characterization of Water Management and Water Balance

The characterization of water management was done primarily through water level sensors and soil matric potential sensors. Water depth was monitored using test wells (Figure 1c), with results shown in Figure 4. Specific land-forming practices were adopted at WID and COL, consisting of furrows spaced 1.4 m apart, with a width of 40 cm and a depth of 10 cm. The black dashed line in Figure 4 indicates the furrow bottom elevation (−10 cm). As the water-level sensor was installed within the furrow, readings between 0 and −10 cm represent shallow surface water temporarily stored within the furrow. Early flush irrigations are generally less frequent because a greater degree of soil drying is toler-ated during crop establishment. Consequently, the water level typically remains below the soil surface during the first 40–60 days after sowing. The water level instruments shown in Figure 1 have a blind zone below −45 cm.

The AR practice started with three flushes between October and November, and was followed by 14 aerobic irrigations with a standing water period of 82.2 ± 46.5 h. A lower limit of −29.6 ± 7.5 cm was observed during December to March. Regarding the tensiometer readings, a soil matric potential threshold of −15 kPa at 10 cm depth was observed throughout this aerobic irrigation stage. A similar three-flush approach was applied to the CF_a practice at WID, followed by a total of 110 ponding days. COR and COL had 88 and 57 days of ponded conditions, respectively. A 25 cm water depth was observed at the COR site from mid-January, which rapidly increased water losses, as evidenced in Figure 5.

Net irrigation, precipitation, and evapotranspiration accumulation across the season are shown in Figure 5. The total irrigation applied to AR and CF (WID) can be directly compared to estimate water savings. In total, 1057 mm (10.57 ML ha^{-1}) of water was applied to the AR paddock, while the traditional CF area accumulated 1296 mm (12.96 ML ha^{-1}) over the season, resulting in an 18.4% decrease in irrigation volume between the practices. The difference between I + P and ET is highlighted in Figure 5, representing the water losses by DP, Water Storage above the soil surface (ΔWS), and Soil Water Stored in the root zone (ΔSWS). For the seasonal analysis, total water stored above the soil surface is zero, since the crop began and finished under non-ponded conditions. This, however, does not apply to ΔSWS. Compared with the initial moisture condition (mostly residual moisture), the final soil moisture (after harvest) is significantly higher, resulting in a volume of water stored in the root zone that is not used for rice production. Water loss due to ΔSWS at the WID site was estimated as displayed in Table 3.

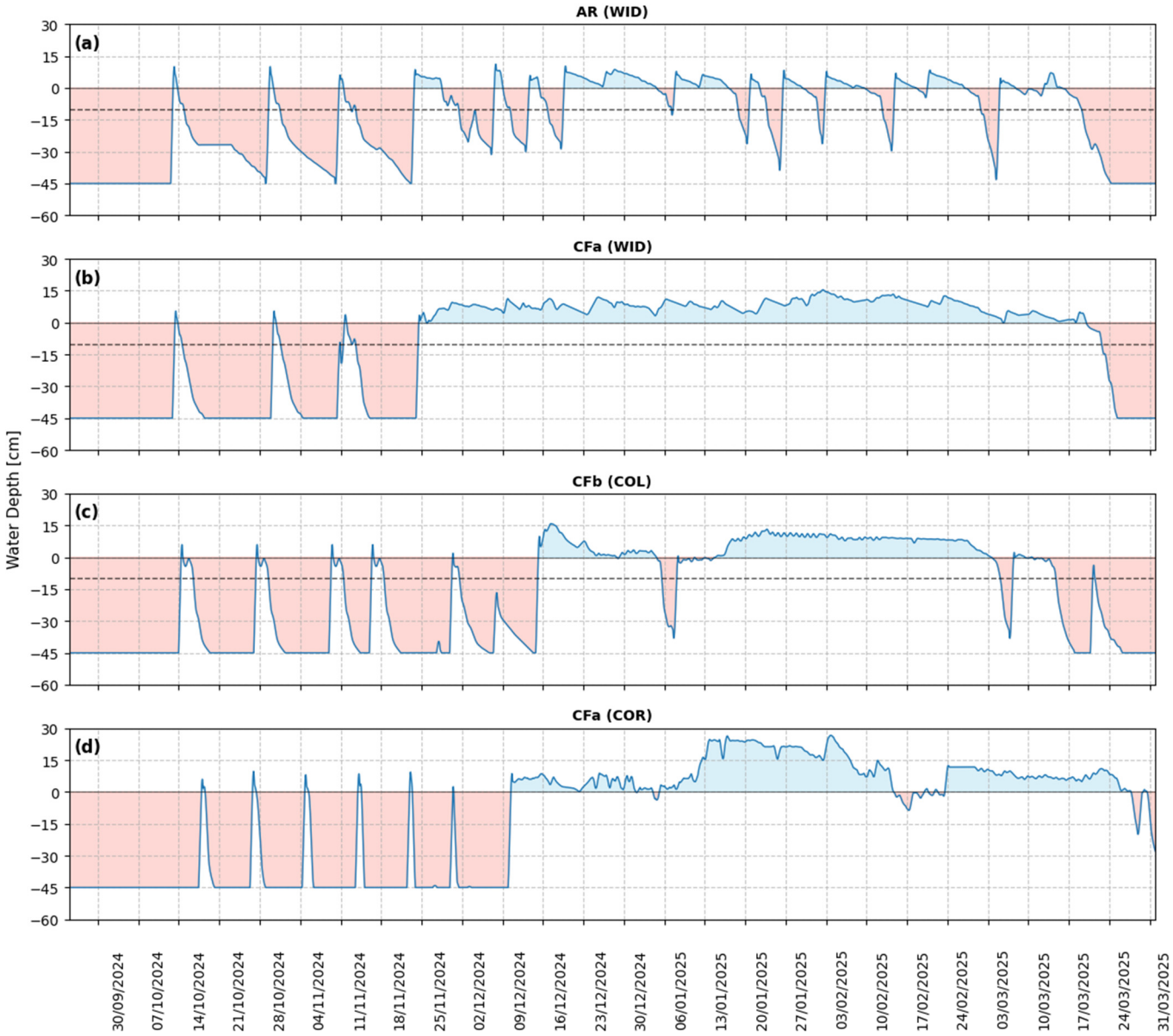


Figure 4. Water depth monitored throughout the season. (**a**) AR paddock in Widgelli. (**b**) CF with PW at TLS in Widgelli. (**c**) CF with PW at LT in Coleambally. (**d**) CF with PW at TLS in Coree. The zero is referenced at the ground level for the flat system in COR and at the top of the bed in WID and COL. The black dashed line represents the furrow level below the bed reference level (−10 cm).

Table 3. DP estimates for AR and CF study sites in Widgelli.

Trial	I	P	ET	ΔSWS	DP
AR (WID)	1057	205	907	85	270
CF_a (WID)	1296	205	852	72	577

DP refers to the volume of water that crosses the root zone (below 30 cm) into deeper soil depths. Using the water balance equation (Equation (1)) DP can be estimated. Table 3 presents the calculation of the seasonal DP, which is estimated at 2.70 ML ha^{-1} for the aerobic strategy and 5.77 ML ha^{-1} for CF_a, representing a 53.2% reduction. In terms of total ponding duration, the AR paddock was ponded for a total of 49 days, accumulated over 17 irrigation events, compared with a continuous 109 ponded days in the CF paddock at Widgelli (WID), representing a 55% reduction in total ponded days.

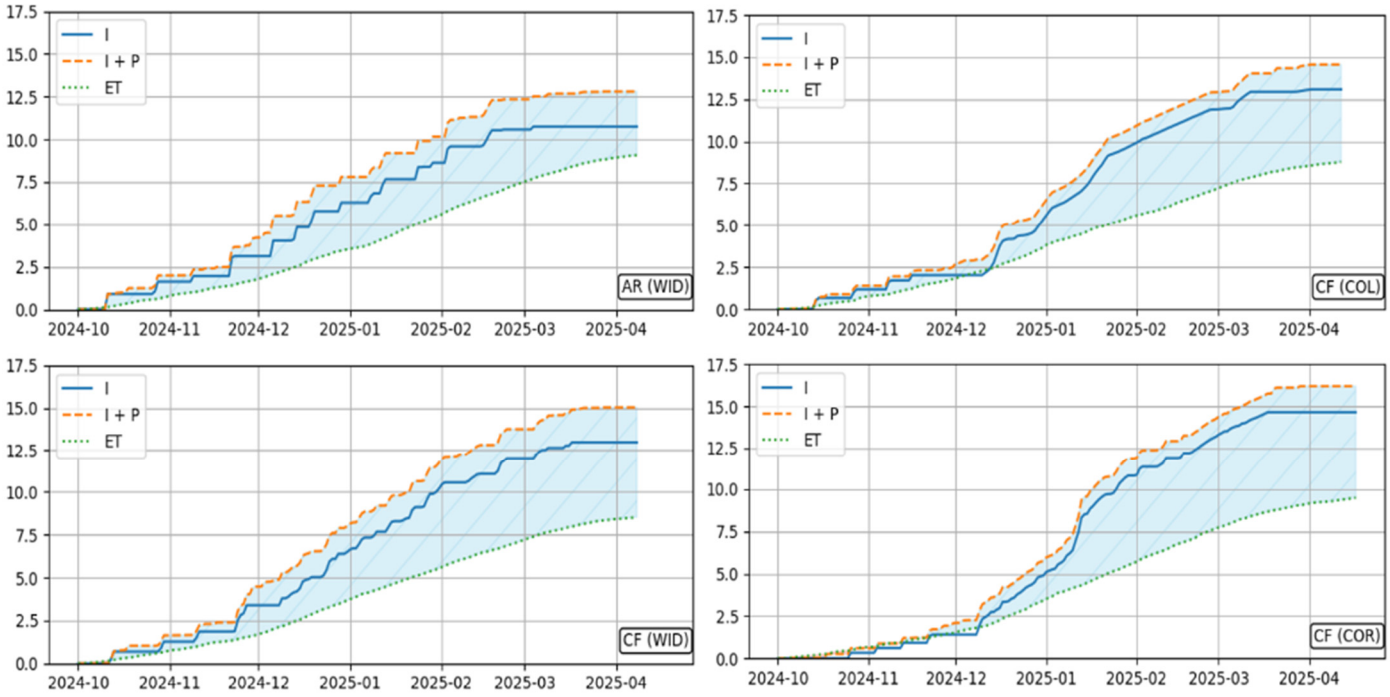


Figure 5. Main water balance component accumulation [ML ha^{-1}]. The blue region marks the difference between I + P and ET (Equation (1)).

Seasonal precipitation was 2.0 ML ha^{-1} mm at WID, compared with 1.5 ML ha^{-1} at COL and 1.6 ML ha^{-1} at COR. COR recorded the highest irrigation water input (14.5 ML ha^{-1}) and total water input (I + P; 16.1 ML ha^{-1}). The largest increase in water loss below the root zone occurred between 10 January 2025 and 10 February 2025 (32 days), when the water level rose to 18.9 ± 5.8 cm, reaching a maximum depth of 25 cm. During this period, irrigation water use increased from 6.4 to 11.9 ML ha^{-1} (+5.5 ML ha^{-1}), accounting for 38% of seasonal irrigation input. A similar pattern occurred at COL, where irrigation and total water inputs reached 13.1 and 14.6 ML ha^{-1}, respectively. The longest permanent ponding period extended from 16/01 to 28/02 (44 days), with an average water layer of 9.2 ± 1.6 cm. Irrigation water use increased from 7.7 to 11.9 ML ha^{-1} (+4.2 ML ha^{-1}), representing 32% of seasonal irrigation input. Under the AR management adopted by the grower, higher water levels were observed from 19 December 2024 to 15 January 2025 (28 days), coinciding with fertilizer application on 28 December 2024. The average water layer over this period was 3.5 ± 4.0 cm, while irrigation water use increased from 5.3 to 7.7 ML ha^{-1} (+2.4 ML ha^{-1}), accounting for 23% of seasonal irrigation input. The highest seasonal irrigation input and below-root-zone water losses were associated with prolonged ponding and increased water levels at COR and COL, whereas AR management at WID exhibited a smaller increase in irrigation demand during the observed period. No effect of irrigation water strategy was observed in the ET observed across sites. AR paddock accumulated 9.1 ML ha^{-1}, while the three other CF practices averaged 8.9 ± 0.4 ML ha^{-1}.

3.3. Rice Performance and Water Productivity Outcomes

Yield performance and water productivity are presented in Table 4 and Table 5, respectively. A yield loss associated with harvesting machinery operations was estimated for both treatments. Following harvest, fallen grains were manually collected using a vacuum device in the WID trial paddocks (CF and AR). The estimated grain losses were 1.21 ± 0.43 t ha^{-1} and 1.11 ± 0.36 t ha^{-1} for CF and AR, respectively. Some discrepancies between these estimates and the actual grain losses between manual sampling yield and delivered

yield presented in Table 4 are expected due to differences in measurement approaches and potential sampling variability.

Table 4. Rice performance indicators.

Irrigation Strategy, Site and Variety	Manual Sampling Yield [t/ha]	Harvested Delivered Yield [t/ha]	Panicles/m^2	Grains/Panicle	Weight 1000 Grains [g]	Grain Quality	Dry Straw Biomass [t/ha]	Total Dry Biomass [t/ha]
AR (WID) Matilda	17.1 ± 0.4	15.3	878 ± 166	121.9 ± 13.0	29.7 ± 0.1	8.7 ± 0.1	12.5 ± 2.7	27.3 ± 2.6
CF_a (WID) Matilda	15.2 ± 2.6	14.5	863 ± 62	105.6 ± 8.1	27.6 ± 0.4	8.9 ± 0.2	16.0 ± 0.9	29.1 ± 1.7
CF_b (COL) Matilda	13.8 ± 0.6	12.3	703 ± 56	114.4 ± 3.4	30.6 ± 0.7	7.3 ± 1.1	12.2 ± 2.1	24.0 ± 2.3
CF_a (COR) Illabong	16.0 ± 1.5	11.3	626 ± 65	127.7 ± 20.2	35.7 ± 0.6	8.3 ± 0.6	11.2 ± 0.5	25.0 ± 1.6

Note(s): Yield was determined through pre-harvest manual sampling and post-harvest truck-delivered grain weighing, with both measurements standardized to 14% grain moisture content. Values are expressed as mean ± standard deviation. "Dry Straw Biomass" represents the above-ground biomass with grain weight excluded. "Total Dry Biomass" includes above-ground biomass including the grains at 0% moisture.

Table 5. Water use productivity at different locations and water management strategies.

Irrigation Strategy and Site	Variety	Irrigation I (ML/ha)	Total Water Input I + P (ML/ha)	IWP [t/ML]	WP [t/ML]	I/TWI Ratio
AR (WID)	Matilda	10.6	12.6	1.45	1.21	0.84
CF_a (WID)	Matilda	13.0	15.0	1.12	0.97	0.86
CF_b (COL)	Matilda	13.1	14.6	0.94	0.84	0.90
CF_a (COR)	Illabong	14.5	16.1	0.78	0.70	0.90

Note(s): IWP = Irrigation Water Productivity, WP = Water Productivity (based on total water input I + P).

Regarding water use in WID, a significant decrease in irrigation was observed in the AR strategy, resulting in a 2.4 ML ha^{-1} (−18.4%) decrease. The CF strategies adopted in different farms across the Riverina region presented a total irrigation water use from 13.0–14.5 ML ha^{-1}, while the AR study site used 10.6 ML ha^{-1}. With a slight yield increase (5.5%) and higher water savings, AR irrigation water productivity (IWP) reached 1.45 t ML^{-1}, while the other trials ranged from 0.78 to 1.12 t ML^{-1}.

4. Discussion

Adopting AR with drying limits of −15 kPa, or −30 cm water depth, saved 18.4% of water, relative to the CF at TLS in WID. A slight yield increase of 5.5% led the IWP to increase from 1.12 t.ML^{-1} to 1.45 t.ML^{-1} (+29.5%). Evidence of yield increases (up to 15%) in the literature induced by a reduction in irrigation is found, although yield penalties are more frequently reported [15,42]. The yield increase observed in WID may have been attributable to the AR practice, but other factors may also have contributed, such as fertilizer applications. As previously stated, the AR paddock received an additional 100 kg ha^{-1} of urea on 28 December 2024 to compensate for potential nitrogen losses through runoff associated with the continuous drainage of the paddock. However, the exact amount of residual nitrogen fertilizer remaining in the soil is unknown and warrants further investigation in future studies. Nonetheless, this documented result indicates that this low-risk AR practice is a suitable strategy to improve water savings.

A similar level of soil dryness, kept above −10 kPa at 10 cm depth, was adopted by [43], with a range of 15–18% water savings found in trials in China (Temperate) and the Philippines (Tropical), without affecting yield components and biomass. This alternately submerged-nonsubmerged system (ASNS) adopted allowed the soil to dry for 3–5 days between irrigations, with a maximum allowed water depth of +10 cm; any additional excess rainfall was drained. This practice maintained non-ponded conditions for 40–60% of the cropping period while keeping the silty clay loam soil close to saturation [43]. Nonetheless, larger water savings have been reported in the literature: [44] reported that changing the condition from a 5 cm permanent standing water to −10 kPa in a sandy clay loam soil in India (Tropical) reduced the irrigation water requirement by 40–43% respectively in two consecutive years, saving around 950–965 mm of irrigation with only a 5.3% yield penalty registered. Comparatively, [45] reported a +43.9% and +50.0% increase in IWP when 30 mm of irrigation was applied every time the soil matric potential reached −30 kPa and −60 kPa, respectively, in the "Hot and Dry Season" of a large-scale trial in the semi-arid climate of Pakistan. These findings suggest that greater water savings might be achievable if higher soil water depletion levels are taken. Nonetheless, more studies are necessary to set those boundaries.

Delivered yields at WID were higher than at the other two farms, COL and COR, regardless of the water strategy employed. The measured yield components indicated that higher panicle density per unit area was the main factor driving the increased yields, even though grain weight was lower than at COL and COR farms. AR surpassed the CF yield in WID primarily due to the higher number of grains (+15.4%) per panicle and grain weight (+7.6%). Nonetheless, aboveground straw dry biomass for AR decreased by 21.9% compared with CF in WID and showed the highest standard deviation (±2.7 ton/ha). This lower biomass associated with higher grain yield observed in the AR paddock may explain lodging in part of the paddock at the end of the season. Higher grain yields can shift the centre of gravity of the crop canopy further from the ground, and when combined with a lighter plant with similar height, as measured, the risk of lodging is expected to increase [46,47]. Nonetheless, no evidence of a yield penalty in manual samples or the machine-harvested yield in WID was observed.

ET totals on AR were not smaller than CF, suggesting that the water savings observed were not generated by ET reduction. The AR paddock had a total ET sum of 907.5 mm, while ponded environments at WID, COL, and COR farms accumulated 852.0, 878.2, and 948.6 mm, respectively. A similar understanding was reported by [19] where only a parcel of 74 mm of ET reduction was found between Alternate Wetting and Drying with drying limits of −10 kPa and CF. Here, the water savings were primarily attributed to reduction in drainage beyond the root zone (or DP).

Differences between I + P and ET provide evidence that water losses through the root zone start as soon as the permanent water condition starts, as highlighted in Figure 5. Conventional CF with permanent water resulted in total differences between I + P and ET of 648.5, 577.4 and 659.0 mm for the sites in WID, COL and COR, respectively. By contrast, the non-permanent ponded conditions in the AR system resulted in a residual water balance difference of only 354.7 mm. This difference is mainly related to water losses due to deep percolation and the excess of water stored in the soil by the end of the season (DP + ΔSWS). By estimating seasonal water storage in the root zone (ΔSWS) in WID, effective DP could be calculated as 2.70 ML ha^{-1} for the AR strategy and 5.77 ML ha^{-1} for CF_a, representing a 53.2% reduction. This reduction is primarily due to a 55% reduction in cumulative ponding days, from 109 to 49. Nonetheless, the higher clay content in the AR plot (60.1%) compared with the CF_a paddock (50.0%) may have influenced this reduction in deep percolation (DP)

by affecting soil hydraulic properties and downward water movement. This observational comparison cannot separate the effects of both factors on DP reduction in the AR paddock.

The increase in the difference calculated through Equation (1) marks the soil-related water losses that occurred when the permanent water stage started. As indicated in Figure 4, the permanent water application happened on 23 November 2024, 15 December 2024, and 10 December 2024 for WID, COL, and COR, respectively. The CF at LT (or DPW) applied in COL was effective in extending the period during which water losses began. At the COR farm, after flush irrigation, the soil remained saturated without drying for an additional month, and the results are evident in the gradual increase in water losses from 10 December 2024 to 10 January 2025. Nonetheless, deep water increased to 25 cm for the consecutive month, applied mainly for temperature protection [4,48], rapidly increased water losses. The following month led to an increase in irrigation water use of 5.5 ML ha^{-1}, representing 38% of total irrigation input over the 32-day period.

CF study sites at WID, COL, and COR used more irrigation water than the AR, with values of 13.0, 13.1, and 14.5 ML ha^{-1}, respectively, against only 10.6 ML ha^{-1} for the AR paddock. These values for ponded practices were consistent with the irrigation water requirements observed across Riverina in the 2024–2025 season, which averaged 13 ML ha^{-1} including drill, broadcast, and aerial sown rice [11]. CF with Early Permanent Water (EPW) associated with Aerial Sowing or Broadcast Sowing is currently the most water-consuming practice and remains widely adopted in the Riverina. It is inferred that during the 2024–2025 season, around 30% of the rice was aerially or broadcast sown [11]. The full potential water savings for the AR still need to be calculated based on this strategy.

A study by [49] conducted in COL indicated that deep drainage in rice crops corresponds to approximately 75% of the total deep drainage for agriculture in this region. Annual deep drainage for rice crops was higher in TRBE (Transitional Red Brown Earth) soils, ranging from 129 to 547 mm. This soil type represents most of the dedicated rice-growing area in the COL region (57.0%), as reported by [49], followed by Clay (28.8%) and Red Brown Earth-RBE (14.2%). According to [50], non-self-mulching clays and TRBE soils are well suited for rice production, as their high clay content results in low final infiltration rates of 1–10 and 10–30 mm day^{-1}, respectively. However, self-mulching clays, despite their high clay content, can exhibit infiltration rates of 20–80 mm day^{-1} due to the stability of their macropores, potentially increasing water use and DP losses. RBE soils are generally unsuitable for continuously ponded rice due to their high infiltration rates (30–120 mm day^{-1}). Therefore, by eliminating permanent ponding, AR may reduce DP and offer a feasible alternative for expanding rice production into RBE and self-mulching clay areas. Further studies are needed to characterize AR performance and water balance in these soil types.

The I/TWI ratio represents the proportion of irrigation (I) relative to total water input (I + P). The 2024–2025 season was marked by consistent low rainfall available across Riverina, ranging from 1.5 to 2.0 ML ha^{-1}, which increased the dependency on irrigation. The AR paddock presented the lowest I/TWI ratio (84%), compared with the conventional CF_a paddock at WID (86%), indicating that the AR strategy presented a slightly higher relative contribution of rainfall to total water inputs (less irrigation dependent). COL and COR followed, both with an I/TWI ratio of 90%, as rainfall accounted for only 10% of their respective total water inputs. This metric is particularly relevant when comparing water-saving irrigation strategies [15], as seasonal precipitation can influence the proportion of total water inputs supplied by irrigation and, consequently, the estimated magnitude of water savings. Future assessments of alternative irrigation strategies should therefore report the I/TWI ratio alongside water-saving estimates to account for differences in precipitation between seasons and locations.

5. Limitations

These results are limited to the growing seasons and commercial sites investigated in the Riverina region of Australia. The findings are primarily based on an observational comparison between two adjacent paddocks managed under different water management strategies at Widgelli, complemented by observations from two additional sites under continuous flooding (CF). As only one paddock per irrigation strategy was monitored at Widgelli, the study lacks independent field replication, limiting the extent to which the observed differences can be attributed solely to irrigation practice or generalized to other sites. No inferential statistical tests were performed to assess differences between irrigation treatments. Further studies involving multiple independent paddocks per irrigation strategy and across multiple growing seasons are therefore needed to validate and generalize the findings presented in this study.

Additionally, continuous flooding with permanent water established after sowing remains a common practice for aerially sown or broadcast rice (around 30% of the rice grown in Riverina). As this is among the most water-intensive irrigation strategies, the full potential for water savings under AR conditions remains to be quantified through direct comparisons with this conventional practice.

6. Conclusions

AR is a promising strategy for advancing the Australian rice industry towards a more sustainable and resilient future. The Drill Sown AR system at Widgelli resulted in 18.4% water savings and a 5.5% increase in yield, leading to a 29.5% increase in IWP. These results evidenced that this AR practice could improve water-use efficiency without compromising yield, supporting its wider adoption, particularly during periods of water scarcity or in regions with limited water availability. Notably, this AR strategy allowed soil water depth to decline to approximately −30 cm, corresponding to −15 kPa at 10 cm soil depth as measured by the watermark sensors. By contrast, the CF study sites at WID, COL, and COR used more irrigation water than the AR system, with values of 13.0, 13.1, and 14.5 ML ha^{-1}, respectively. These values are consistent with the irrigation water requirements typically observed for conventional CF rice systems across the Riverina, in which permanent water is established at either the Three-Leaf Stage (CF_a) or Late Tillering (CF_b) [11].

Water savings observed at Widgelli were not associated with reduced ET, which was slightly increased by 6.5% in the AR paddock. Instead, the water balance analysis indicated that reduced DP primarily drove water savings under AR. Water losses rapidly increased after the application of permanent ponding, suggesting that minimizing the duration of continuous ponding can reduce irrigation requirements. Reducing accumulated ponded days from 109 to 49 was associated with an approximately 53.2% reduction in DP.

Further studies are needed to investigate how aerobic rice and its reduction in DP perform across different soil types. Soils such as TRBE and RBE have a higher potential for deep percolation than clay soils. Therefore, applying AR to those soil types may achieve greater water savings and enable more area for rice production.

Drill-sown CF rice with permanent water established at the three-leaf stage or during late tillering was selected as the reference system in this study, as it represents the predominant cultivation method in the region (approximately 70%) and provides a more practical pathway for growers to transition between irrigation strategies while maintaining the same sowing method. The results demonstrate the potential of AR to increase water savings through changes in irrigation management, while maintaining yield. Furthermore, the field dataset generated provides an important regional reference and baseline for future research, supporting the further development, evaluation, and optimization of aerobic irrigation strategies to improve water-use efficiency in rice production across the Riverina region.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Aerobic Rice
AWD	Alternate Wetting and Drying
CF	Continuous Flooding
COL	Coleambally (Farm Location)
COR	Coree (Farm Location)
DP	Deep Percolation
DPW	Delayed Permanent Water
DSR	Drill-Sown Rice
EC	Eddy Covariance
EPW	Early Permanent Water
ET	Evapotranspiration
FAO	Food and Agriculture Organization
IWP	Irrigation Water Productivity
NDVI	Normalized Difference Vegetation Index
PW-LT	Permanent Water at Late Tillering
PW-TLS	Permanent Water at Three Leaf Stage
WP	Water Productivity
WID	Widgelli (Farm Location)
WST	Water-Saving Technique

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