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Evaluating the Performance and Opportunity Cost of a Smart-Sensed Automated Irrigation System for Water-Saving Rice Cultivation in Temperate Australia

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Abstract: Irrigated rice is the largest user of precious global water reserves. Adoption of water-saving irrigation practices is limited by the associated increased labor demand compared to flooded rice cultivation. Automated gravity surface irrigation systems have shown the potential to deliver significant labor savings in traditional flooded rice; however, widespread adoption does not seem apparent. Furthermore, previously designed systems have not been capable of irrigation control during both ponded and non-ponded periods. This study aimed to evaluate the performance of an automated irrigation system for rice with features not previously developed, provide direction for future systems and analyze the opportunity cost (the value of other on- or off-farm activities that could be conducted with that time) of time associated with automated irrigation. The automated irrigation system was found to successfully control 23–31 flush-irrigation events per bay per season in a 9-bay border-check aerobic rice field for 2 seasons. In addition, successful water control was achieved in a traditional drill-sown field with 4 flush irrigations followed by 15 weeks of permanent flooding. Labor savings of 82–88% during the flush-irrigation events and 57% during the ponding period were achieved with automation when compared to manual irrigation. However, the opportunity cost of the saved time was found to comprise the greatest benefit. Changing the analysis from using a flat "cash" cost of time to using opportunity cost of time reduced the payback period from seven to four years at the traditional ponded-rice site. In the more labor-intensive aerobic rice site, the payback period was reduced from three years to one year when accounting for the opportunity cost of time as opposed to only the direct costs. Whilst the payback period is site-dependent and cultivation method-dependent, these case studies demonstrate that automated gravity surface irrigation can enable novel water-saving practices in rice and provide substantial economic benefits.

Keywords: water-saving irrigation; water productivity; *Oryza sativa*; aerobic rice; labor-saving technology

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1. Introduction

Increasing global water scarcity is fostering innovative practices aimed at improving agricultural water productivity, which is the practice of increasing or maintaining the amount of crop produced whilst maintaining or reducing the amount of water used. Rice is a highwater demanding crop, compared to other species [1–4], and is the largest water user, estimated to use between 34 to 43% of global irrigation water and 24–30% of freshwater resources [2]. Therefore, improving rice water productivity presents an opportunity to make a substantial impact on worldwide water use. Whilst moving from a traditional flooded rice system to water-saving irrigation practices, such as alternate wetting and drying or to aerobic rice with no flooding, has been proven to increase water productivity in many parts of the world [5–12], adoption in Australia is limited due to lack of cold tolerant varieties and weed and fertilizer management strategies [3]. Furthermore, a substantial increase in labor is required for the high frequency irrigation necessary in a semi-arid climate. Automated irrigation has been identified as a potential solution to overcome the labor burden and enable greater adoption of water-saving irrigation practices. In a global review of automated gravity surface irrigation in rice since 1999, Ref. [13] found only one system [14] that was tested and deemed adequate for use in a commercial setting. The commercially available automated irrigation used in a flooded rice farm in Italy showed substantial economic labor savings, with a payback period of 14 years, despite no water saving or yield benefits [14]. Whilst the cost for automation was reported within the range Italian farmers are willing to spend, there is little evidence of widespread adoption, potentially due to cost or other technical limitations relating to the technology. Of the systems reviewed by [13], none were found to be appropriate for non-flooded rice systems, with many found to be unsuitable for commercial-scale ponded-rice systems due to technical shortcomings. The main limitations identified include a lack of non-ponded water control, small scale water delivery, unregulated flow control, cumbersome infrastructure, AC power required, cost, limited connectivity range, manual or no water threshold configuration and lack of weather and crop forecasting.

A cost-effective and reliable automated irrigation system consisting of the aforementioned capabilities, when combined with an optimal parameter and threshold to initiate irrigation during the non-ponded aerobic period, should enable precision water delivery when required and in the quantity required. Such capabilities are hypothesized to enable adoption of cost-effective water-saving irrigation strategies. Notably, aerobic rice with no periods of ponding and strategic ponding involving flush irrigation, with ponding only during forecast periods of extreme temperatures during sensitive crop phenological periods (e.g., early pollen microspore until flowering). The purpose of this study is to evaluate the technical performance of an automated irrigation system comprising most of the characteristics previously described and to assess its ability to control water in water-saving rice systems in temperate Australia.

In addition to enabling novel water-saving practices, substantial labor savings are expected with automated irrigation. Water changes (open/close outlets) between bays occur at any time of day or night, with manual water changes causing significant disruption of farm duties and lifestyle interruptions, due to the time required to travel to the paddock, make the change and return [14]. This is particularly so in Australia, given the difficulties of finding on-farm labor and the size and extensive spread of irrigation farms. Accounting only for estimated direct labor savings of 85%, without consideration of water or other savings [15], we estimated the payback of the automated gravity surface irrigation evaluated in this study to be 8–9 years, depending on the irrigation bay size. This is comparatively less than the system reported by [14], due to a lower cost per hectare of automation.

Whilst a cost can easily be applied to the direct cost of time and travel associated with irrigation activities, the non-tangible impacts of irrigation-related disruption to personal and family life are more difficult to quantify, particularly in an economic context, despite their importance to farmer health. Inferior physical and mental health in Australian farmers compared to other rural residents has been reported by [16,17], with [18] finding irrigators to have among the highest levels of physiological distress nationally. Poor farmer health is known to have significant flow-on effects to other family members and the community [19]. Involvement in physical activity and maintaining work–life balance has been cited by Australian farmers to improve health [20]. However, these requires significant time investment in non-farming activities, such as spectating and participating in live sporting events, hobbies and time away from the farm [20]. Therefore, measuring only the direct cost savings of automated irrigation does not capture the true benefit of the technology, nor is it the only driver of adoption. Workforce considerations, reducing farm labor, greater precision of input costs and data collection and monitoring are reasons cited by Australian cotton growers to adopt automated technologies, including automated irrigation [21]. Furthermore, growers who were still considering adoption of automated technologies cited workforce implications as an incentive for adoption. Specifically, reducing workload, labor costs and number of employees on farm were among the social drivers for technology adoption found by [21]. Reducing reliance on low-skilled, seasonal labor contributed to motivation to adopt automation, as this was perceived to enable more effective task performance with lower labor costs and result in growers spending more time on other business-related priorities or time with family [21], a known driver of improving farmer health [20].

As well as affecting valuable family and social activities, early-season rice irrigation in the Riverina region of temperate Australia coincides with highly time-sensitive on-farm activities: planting, time-critical pre- and post-emergent herbicide application in summer crops and harvesting of winter cereals. Application of permanent water to rice generally occurs once rice reaches the three-leaf stage. This is undertaken to reduce further labor and time pressures associated with more flush-irrigation events as required of delayed permanent water and aerobic rice. In comparison, farmers report that they only check permanently flooded rice once daily on the way to or from other farm activities, and even less so during busy times such as spraying or harvesting. Summer storms are not uncommon in the Riverina and can downgrade harvest-ready winter cereal quality. Delaying or slowing harvest and transport activities to conduct irrigation water changes can lead to substantially delaying harvest completion, increasing exposure to detrimental weather events.

Hence, the value of time saved by irrigation automation may be better represented by the *opportunity cost of time*. Opportunity cost is defined in economic terms, as the opportunities forgone in the choice of one expenditure over others [22]. In this instance, the opportunity cost of time saved by automation is the value of an alternate activity to manually changing water at that time. Whilst the abovementioned alternative social and on-farm costs are challenging to quantify, this manuscript attempts to measure them in terms of economic value on two case-study farms to gain a better insight into the benefits of automated rice irrigation. Whilst the authors acknowledge the subjective nature of valuing time, this analysis has been conducted to highlight that the opportunity cost of time in farming is often greater than the cash cost, considering that most farms are multi-enterprise, farms are rarely overstaffed, and most farmers have family or other social/wellbeing commitments considered essential by today's standards. Therefore, it was hypothesized that the opportunity cost of automated irrigation may well be many multiples of the cash cost of automation and, therefore, greatly increases the assumed internal rate of return and decreases the payback period of automated irrigation investment.

This study had two purposes: (i) to evaluate the performance of an automated gravity surface irrigation system that overcomes many of the technical limitations of previous systems to enable novel water-saving irrigation practice and (ii) to broadly estimate the opportunity cost of time associated with manual and automated irrigation in different rice-growing techniques. In particular, the specific objectives were to:

(i) Analyze sensing and control of water in aerobic and strategically ponded rice systems;
(ii) Critically discuss the real-time water sensing and control of the automation system to provide direction for future automation systems;
(iii) Compare yields of automated and manually irrigated rice and strategic deep-water ponded versus traditional deep-water ponded management;
(iv) Describe the labor and travel associated with automated and manual irrigation across the two sites and cultivation techniques;
(v) Broadly evaluate the opportunity cost of the investment in automated irrigation and highlight other potential benefits of automated irrigation in rice.

2. Materials and Methods

2.1. Experimental Site and Instrumentation

The study was conducted across two commercial rice farms, both near Griffith, NSW, Australia. This temperate rice-growing region typically has hot, dry summers and cool winters, with average in season (October–April) rainfall of 150 mm and evapotranspiration of 1150 mm [3].

Site A:

Site A was used in 2020–2021 (Year 1) and 2021–2022 (Year 2) to evaluate the performance of automated irrigation in aerobic rice, *c.v. Viand* (130 and 120 kg/ha, respectively). The site was a 34 ha, 9-bay border-check field. Each bay was connected to a water supply channel with drainage collected at the opposite end and pumped into a recycle dam. An amount of 220 kg N/ha was applied as urea as thrice split in Year 1 and thrice split or as basal application prior to planting in Year 2. In Year 1, the first three irrigation events were conducted manually before installation of automated gravity surface irrigation technology to enable aerobic rice cultivation. This involved intermittent "flush irrigation" events without any period of permanent flooding. Water management varied between bays and was scheduled based on soil moisture tension (how tightly water holds to the soil, measured in units of pressure (kPa), with saturated soil measuring 0 to −10 kPa and more negative numbers indicating greater tension). Various soil moisture thresholds were investigated during the vegetative period—after establishment until panicle initiation. During the reproductive period, all bays were irrigated every 2–3 days to avoid moisture deficit. Throughout grain ripening, all treatments were irrigated based on soil moisture tension. Greater detail of the irrigation thresholds, agronomic management and yield and water productivity results are provided in [23].

Soil moisture tension was monitored throughout the growing season by two watermark sensors (Model 200SS, Irrometer Company inc., Riverside, CA, USA). In Year 1, these were installed in the middle of bays and connected to low-cost, low-power WiField loggers [24]. Data were collected and stored on the logger, with hourly uploads via an on-farm WiFi network to the Google cloud platform for near real-time monitoring. IoT communication towers—*SensorPro's* (Padman Automation, Strathmerton, VIC, Australia)—were located in the supply channel and ~100 m from the end of every bay and communicated via LoRaWAN. The solar-powered IoT communication devices contained a calibrated pressure transducer to measure water height and were used to sense when irrigation of that bay was completed. In the second year, the IoT communication towers were used to read the watermark sensors and included a capacitance sensor. This enabled monitoring of water down the bay and measurement of water height via the Padman Automation web/phone app.

Existing concrete outlets were retrofitted with rubber lay-flat inserts that could be controlled manually by winch cable. Installation of solar-powered portable outlet controllers—*AutowinchPro's* (Padman Automation, Strathmerton, VIC, Australia)—enabled automated irrigation control via the web/phoneapp. A graphical user interface could also be used for programming outlet controllers, with communication via the LoRaWAN gateway. Images of the automation infrastructure used at Site A are provided in Figure 1.

(**A**) (**B**)

Figure 1. Automation infrastructure used at Site A. (**A**) Padman Automation *SensorPro* IoT communication towers used to sense soil moisture tension and water height. (**B**) Padman Automation *AutowinchPro* portable automated outlet controller used to control Padman rubber lay-flat inserts installed to existing concrete structures (outlet currently closing as water threshold surpassed at IoT sensor).

Site B:

In Year 2, 2 adjacent 20 ha bankless channel fields each, with 4 bays (~5 ha, flat with 150 mm step in between) were used to compare automated versus manual irrigation. Furthermore, the site was used to investigate the practicality of strategic deep-water ponding. This involved application of deep water during the cold-sensitive early pollen microspore period only in the event of forecast cold weather (<15 °C). Management was traditional drill-sown rice cultivation (c.v. V071, 130 kg/ha), the common irrigation strategy in temperate Australia [25]. Drill sowing irrigation management in Australia involves dry seeding followed by 3–4 flush-irrigation events prior to the application of shallow permanent water (30–50 mm) after the 3-leaf stage, followed by deep water (>250 mm) after panicle initiation, during the cold-sensitive early pollen microspore period, and then reduced depth with water coverage maintained until drainage at physiological maturity [26,27].

The western field was manually irrigated using pre-existing winch cable-controlled rubber lay-flat stops. Automated outlet controllers—*AutowinchSense* (Padman Automation, Strathmerton, VIC, Australia)—were installed to the winch cable-controlled rubber flaps and undershot sluice gate outlets on the eastern field. The *AutowinchSense* devices operated as per the *AutowinchPro's*; however, they communicated via CAT-M1 and also measured water height using a calibrated pressure transducer. Images of the automation infrastructure used at Site B are provided in Figure 2.

(**A**) (**B**) (**C**)

Figure 2. Automation infrastructure used at Site B. (**A**) Manually controlled pre-existing rubber lay-flat outlet (open). (**B**) *AutowinchSense* installed to pre-existing rubber lay-flat (closed). (**C**) *AutowinchSense* installed on sluice gate to automated field with manual winch on the manually irrigated field (both closed).

In this study, four flush-irrigation events preceded shallow permanent water, which was applied from the three-leaf stage until just after panicle initiation, when deep water (>250 mm) was applied to all bays in the manually irrigated field. Flush irrigation water-height thresholds were set at the time of first irrigation. When water had flooded Bay 1, the outlet between Bay 1 and Bay 2 was opened. In the manually irrigated field, a float was installed near the outlet to easily monitor water height visually, as per standard industry practice. During permanent water, the manual outlets were partially opened to allow water to trickle over the rubber outlets. Similarly, in the automated field, upon completion of irrigation in the first bay, the sensor-measured water height value was recorded and set as the "minimum" threshold on the web app for subsequent flush-irrigation events and during permanent ponding; the "maximum" threshold of 50 mm was used in Bays 2–4 for the first month of permanent flooding from December 5 until January 6. A higher initial maximum water threshold was set in Bay 1 to allow for a buffer whilst the automated irrigation was refined. Substantial rainfall on January 6 increased water height across all bays before deep water (>250 mm) was applied to Bay 4 after panicle initiation, as per the manually irrigated field. At the same time, moderate depth water was applied to Bay

3 (>100 mm) and shallow water maintained in Bay 1 and Bay 2 of the automated field and used to investigate the feasibility of strategic deep-water ponding. Based on forecast nighttime temperatures <15 °C in the proceeding 4 days, strategic deep water (>250 mm) was applied to all bays on January 31. Water levels gradually dropped throughout February once the cold-sensitive early pollen microspore period had passed, with minor top-up irrigation events in March before drainage in the last week of March.

The Padman Automation web/phone app was used to monitor soil moisture tension at Site A, as well as water advancement and height at both sites. Furthermore, thresholds and text message alerts could be configured using the web app, as well as "pairing" outlet controllers to each other and to in-field sensors. Thus, when predetermined thresholds were surpassed, outlet controller commands were initiated to open/close the respective outlet to the desired point. An app-based notification system was used to notify the user of command completion and when thresholds were surpassed, whilst critical text message alerts were sent in the event of command/device failure. Field layouts are provided in Figure 3.

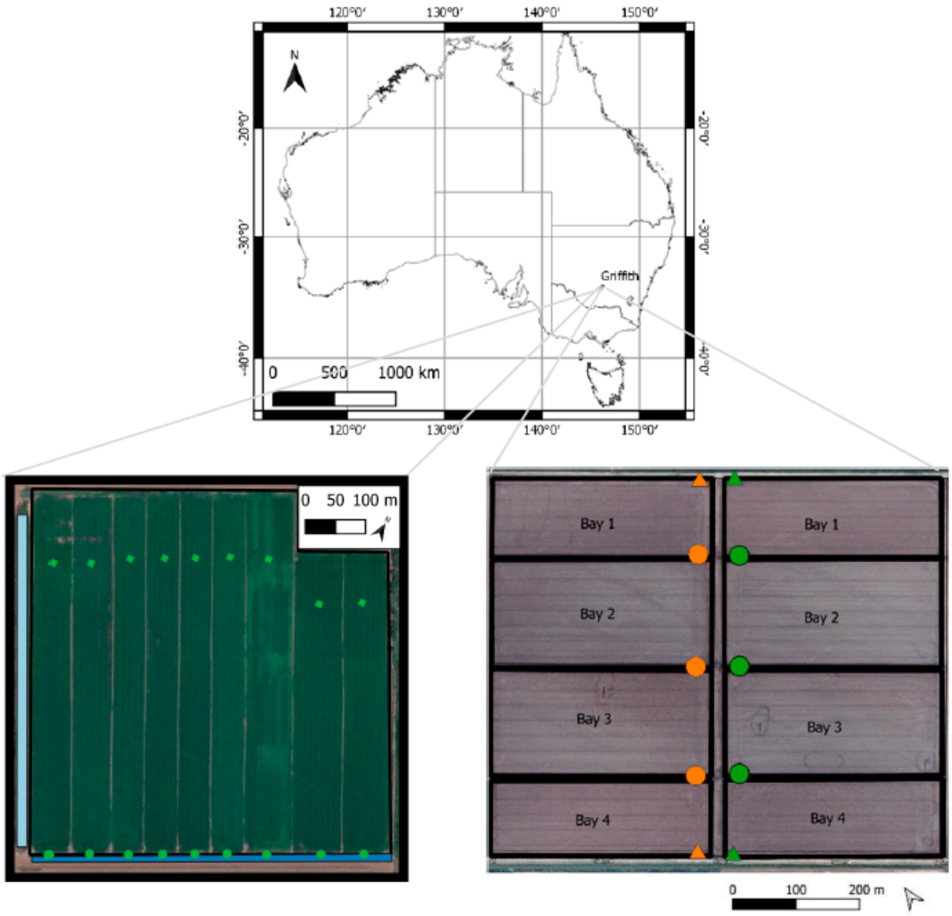


Figure 3. Both field sites were located near Griffith in the NSW Riverina. Site A (**left**) was a nine-bay border check field. Site B (**right**) was two bankless channel fields, each with four bays, with automation installed in the easterly field. Dots identify rubber lay-flat outlets, whilst triangles depict undershot sluice gates and diamonds resemble IoT communication structures. Automated irrigation infrastructure is indicated in green color, whilst manual infrastructure is indicated in orange. Blue is used to show the supply channel and storage dam at Site A. At Site B, Bay 1 was connected to the supply channel and drainage was carried out via Bay 4 outlet.

2.2. Opportunity Cost Analysis

Travel time and cost dedicated to irrigation activities were recorded, collected during various irrigation events throughout the irrigation season and reported in AUD. Travel costs were calculated at AUD 0.78/km [28]. Cash cost of labor was calculated at AUD 40/hr as per the estimated cost of farm labor used in the economic analysis previously conducted by [15]. The upfront cost of automation used in the analysis was AUD 576 and AUD 700/ha at Site A and Site B respectively, as calculated previously by [15]. Opportunity cost of time was segmented into low (AUD 40/h), medium (AUD 150/h) and high (AUD 500/h) and it was calculated based on time of day, unless other high-value on- and off-farm duties were undertaken (Table 1). The value of labor during the day was estimated based on the perceived nuisance to farmers. The value of reference farm duties was conservatively estimated based on industry contract rates provided in Appendix A [29–32].

Table 1. Value of time used in the opportunity cost analysis. Costs were based on the perceived nuisance to farmers and conservative industry contract rates provided in Appendix A [29–32].

	Cash Cost		**Opportunity Cost**		
	Labor	**Travel**	**Low**	**Med**	**High**
Price	AUD 40	AUD 0.78/km	AUD 40	AUD 150	AUD 500
Hours			7 am–5 pm	5 pm–12 am	12 am–7 am
Reference points	Standard farm laborer		Standard farm laborer	Skilled farm service provider	Farm machinery contractor
Alternate activities	Standard farm laborer		Standard farm activities	Machinery maintenance, scheduled exercise	Seeding, harvest, spraying, school holidays

2.3. Rice Yield Analysis

The rice yields reported from Site A in Year 1 were calculated from an area of 1 to 1.8 ha (harvested with a commercial combine harvester) and in Year 2 from an area of 28 m^2 (harvested with a plot harvester) and reported at 14% moisture. Water productivity calculations are reported in [23]. Crop yields from Site B were estimated using yield monitor data from a harvester and reported at 14% moisture. Yield monitor data was processed in QGIS (Version 3.10) with polygons created for each replicate. The zonal statistics tool available in QGIS was used to obtain the mean and standard deviation data for yield. Lack of blocking limited the use of statistical analysis at Site B.

3. Results and Discussion

3.1. Performance of Automation System to Manage Irrigation Water

Soil moisture data was successfully collected using data loggers which enabled scheduling of irrigation during the vegetative period. The IoT communication towers and outlet controllers successfully connected to the LoRaWAN gateway located 2 km away at Site A and good CAT-M1 connectivity was achieved at Site B. Successful pairing of devices ensured the outlet controllers open and closed when thresholds were surpassed. Integration of soil moisture monitoring by the IoT communication towers and the addition of capacitance sensors as wet/dry sensors were found to greatly enhance usability in Year 2 as all data could be monitored on the one platform. CAT-M1 devices were considered more appropriate at Site B due to the small number of devices. The increased number of devices at Site A was considered too costly for individual connectivity, with the LoRaWAN gateway preferred by the growers as they wanted to invest in a larger number of devices in the future. Across the 9-bay field at Site A, a total of 264 flush-irrigation events were conducted in Year 1, and 207 flush-irrigation events carried out in Year 2. The number of irrigation events conducted per bay at each site is presented in Table 2. It must be noted that neither the layout nor cultivation strategy implemented at Site A was standard for rice in the region. Nevertheless, such high-frequency irrigation as required in aerobic rice cultivation would not have been feasible without automation.

Table 2. Total number and type of irrigation events conducted across both sites.

Site	Year	Flush-Irrigation Events	Weeks of Ponding
Site A	Year 1	30–34 *	-
	Year 2	23	-
Site B	Year 2	4	15

* The first three irrigation events were conducted manually, with the total number of irrigation events varying due to irrigation treatments, as outlined [23].

Overall, the automation system was found to control outlets and maintain water height within desired parameters, with outlets opening and closing as programmed when desired water height thresholds were met. Outlet controllers were fully opened (100%) at the commencement of an irrigation event at Site A, and fully closed (0%) to reset the encoder counter before unwinding to 40%. This ensured the supply channel did not overflow in the event of a subsequent outlet failing to open. At Site B, upon reaching the maximum threshold during a flush irrigation, the outlet of the first bay was opened 100% to drain the upper bay and irrigate the lower bay. Whilst the farm manager reported a preference for gradually opening the outlets to avoid downstream washouts, this practice was not always undertaken by hired labor in the manually irrigated field. To align with grower preference, the automated outlets were successfully programmed to open to 50% for 3 min, then 75% for 3 min and, finally, to 100%. This method was found to avoid any downstream washouts due to high flow rates and satisfied the grower requirements, with regulated flow not a feature of previous automation systems [13].

Refinements were made throughout the season at Site B to reduce frequency of irrigation events to minimize the risk of device failure or overloading the supervisory system unnecessarily. For example, once the minimum water height threshold was reached in Bay 3, the outlet controller from Bay 2 was initially programmed to gradually open to 100% to fill Bay 3, before closing to 0% when Bay 3 reached the maximum water height threshold. Due to the proximity of the outlets and sensors (100–150 m) in this field layout, this approach was found to immediately drop the water height below Bay 2 minimum, triggering the opening of Bay 1, as programmed. The high-water flow into Bay 3 caused the maximum threshold to be quickly surpassed (within 20 min), triggering the closure of Bay 2 outlet. However, as the water dissipated through Bay 3 within a few minutes of closure, the minimum threshold was again reached, causing another cascade of irrigation events. Whilst there was no technological or systematic limitation to the frequency of irrigation events using the automation infrastructure, such high frequency of commands was considered unnecessary whilst not appropriately irrigating the field. To overcome this identified issue, programming the outlet controllers to open between 60–70% (standard practice in the manually irrigated field) was found to greatly reduce the frequency of commands and ensure effective irrigation as water was able to evenly dissipate throughout the bay before reaching the maximum water height threshold at the downstream sensor. Furthermore, rather than closing to 0% when the maximum threshold was surpassed, upstream outlets were "closed" to 30–45% to enable a trickle of water to flow over the outlet. The amount of trickle-over required to keep up with evapotranspiration was estimated on one of the weekly checks of the automated field. The text message alert functionality of the supervisory system was used to notify the user if too much *trickle-over* caused the water depth to surpass 10 mm over the maximum threshold, at which point a command was sent by the user to close the outlet to 0% and for it to be re-opened when the minimum threshold was reached. This *trickle-over* irrigation approach, to keep up with evaporative demand, is standard practice for manually irrigated rice. Adopting the *trickle-over* approach was found to successfully maintain water height within the desired water depth for each bay whilst minimizing the number of commands. This ability to control flow rate to gradually increase water height is considered necessary in both flooded and non-flooded rice systems. Masseroni et al., (2018) [14] reported the limited functionality (fully open or fully closed) of gates to cause a larger than optimal water height fluctuation when water-height sensors were installed at the far end of the field, with narrowing the range of water height found to be an acceptable workaround. Similarly, fully opened or closed outlets were found to be limiting in this study, highlighting the need for variable flow control. A self-learning process was suggested by [14] to reduce the number of gate openings and closings, a proposal supported by findings presented here. The water heights and outlet position for each bay at Site B can be seen in Figure 4.

The supervisory system successfully captured and displayed data for monitoring or downloading if required, with an intuitive web and smartphone application. Commands could be configured based either on time or when thresholds from other outlets or IoT towers were surpassed. This pairing feature between devices offered much flexibility in how irrigation could be conducted. Furthermore, outlet controllers could be programmed on site using the graphical user interface, a useful backup option in the case of communication network failure or a malfunctioning smart device. In addition, the automated outlet controllers could easily be removed within seconds, providing a fail-safe option in the event of device failure, or if casual farm laborers were unfamiliar with the operation of the automation system. Such functionality has not been incorporated in previous automation systems [13], limiting their use in the event of device or communication failure. As rice is grown in rotation with other crops in Australia, field rotation is a regular occurrence between seasons [3]. The portability of the automated outlets and IoT sensing devices used in the current study is considered an advantage over the equipment previously used in automated rice systems [33].

Positive and negative alerts were found to be a valuable function in alerting the user when thresholds were surpassed, or in the rare instances when an irrigation outlet controller failed to execute a command. The negative text alert functionality enabled the user to resend new commands to the device in the rare instance of failure. However, once the automation had been operating for a period of time and trust in the system had been established, the positive text message alert function notifying the user that a specific command had been executed successfully was found to be an annoyance and, therefore, was turned off. The multi-tier alert function enabled critical alerts (device failure) to be sent as a text message, whilst non-critical app-based notifications were used to notify the use of successful command execution. A similar alert function in automated rice irrigation was pioneered [34] in Brazil and used in Italy, as detailed by [33].

3.2. Rice Yield

Aerobic rice yield in the most frequently irrigated treatment exceeded 8.1 t/ha with irrigated water productivity of 1.0 t/ML and total water productive of 0.85 t/ha in Year 1, with greater detail provided in [23]. In Year 2, no difference in yield was observed between the broadcast or basal application of nitrogen, achieving 10.0 t/ha with irrigated water productivity of 2.1 t/ML and total water productivity of 1.2t/ML in Year 2. Comparatively, no previous aerobic rice research in this environment has achieved total water productivity above 0.8 t/ha [35–38], with aerobic rice production at commercial scale previously considered unviable due to the relatively high labor demands compared to permanent flooding and risk of detrimental drought stress.

Harvest monitor rice yields from Site B are presented in Table 3. Whilst the automated irrigation field yielded 8% higher than the manual field, it is unlikely that this was due to irrigation management but rather to pre-existing soil constraints from previous land leveling. In the automated field, no yield implications resulting from strategic deep-water ponding are evident. Results from this trial demonstrate the opportunity for deep water to be applied strategically to fields using automated irrigation in the event of forecast cold temperatures during sensitive periods, provided that adequate flow rate is available to deliver sufficient water depth in time.

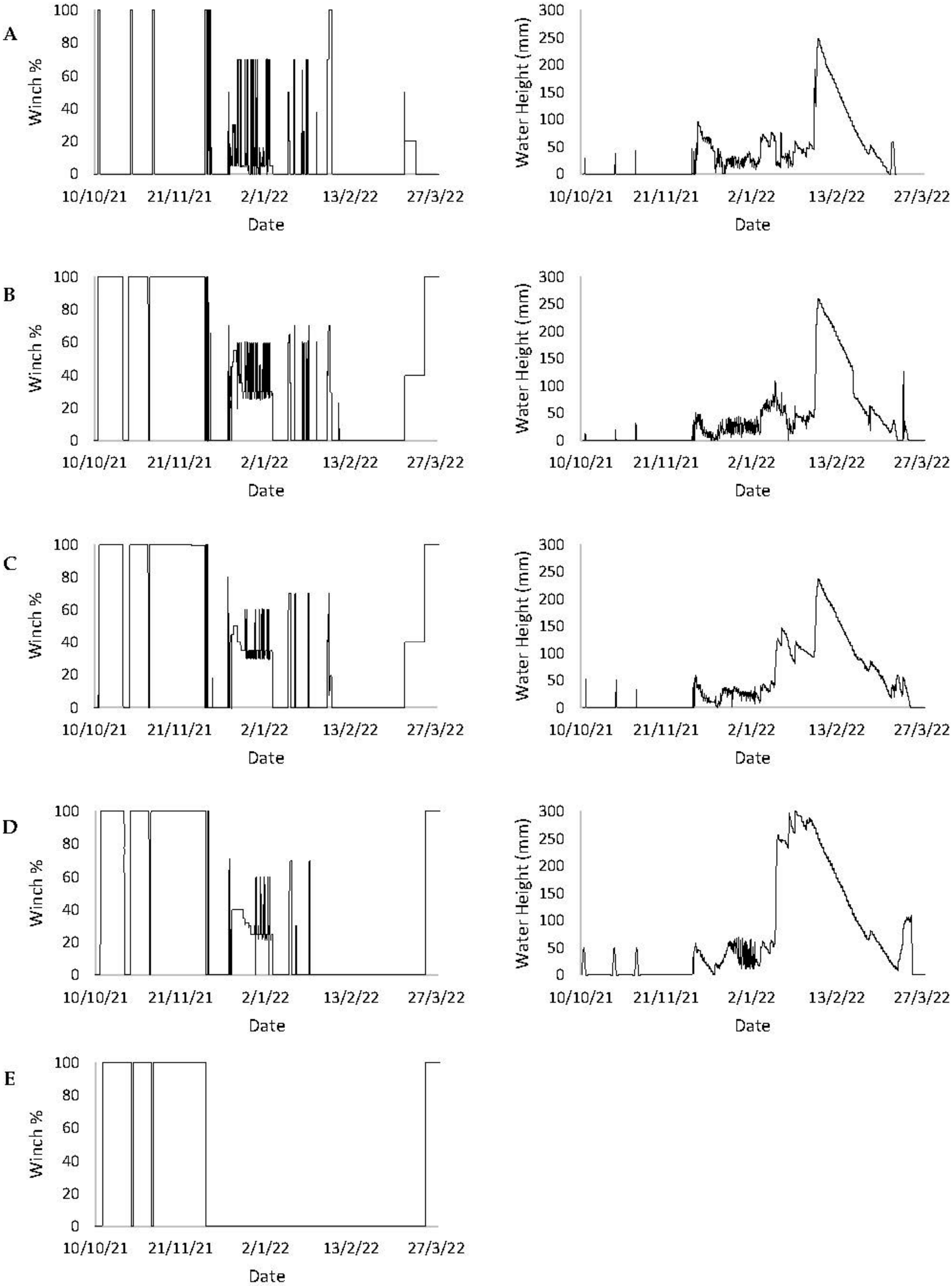


Figure 4. Seasonal outlet position (%) and water height (mm) for each bay at Site B. (**A**–**D**) Bay 1–4, respectively, and (**E**) drain.

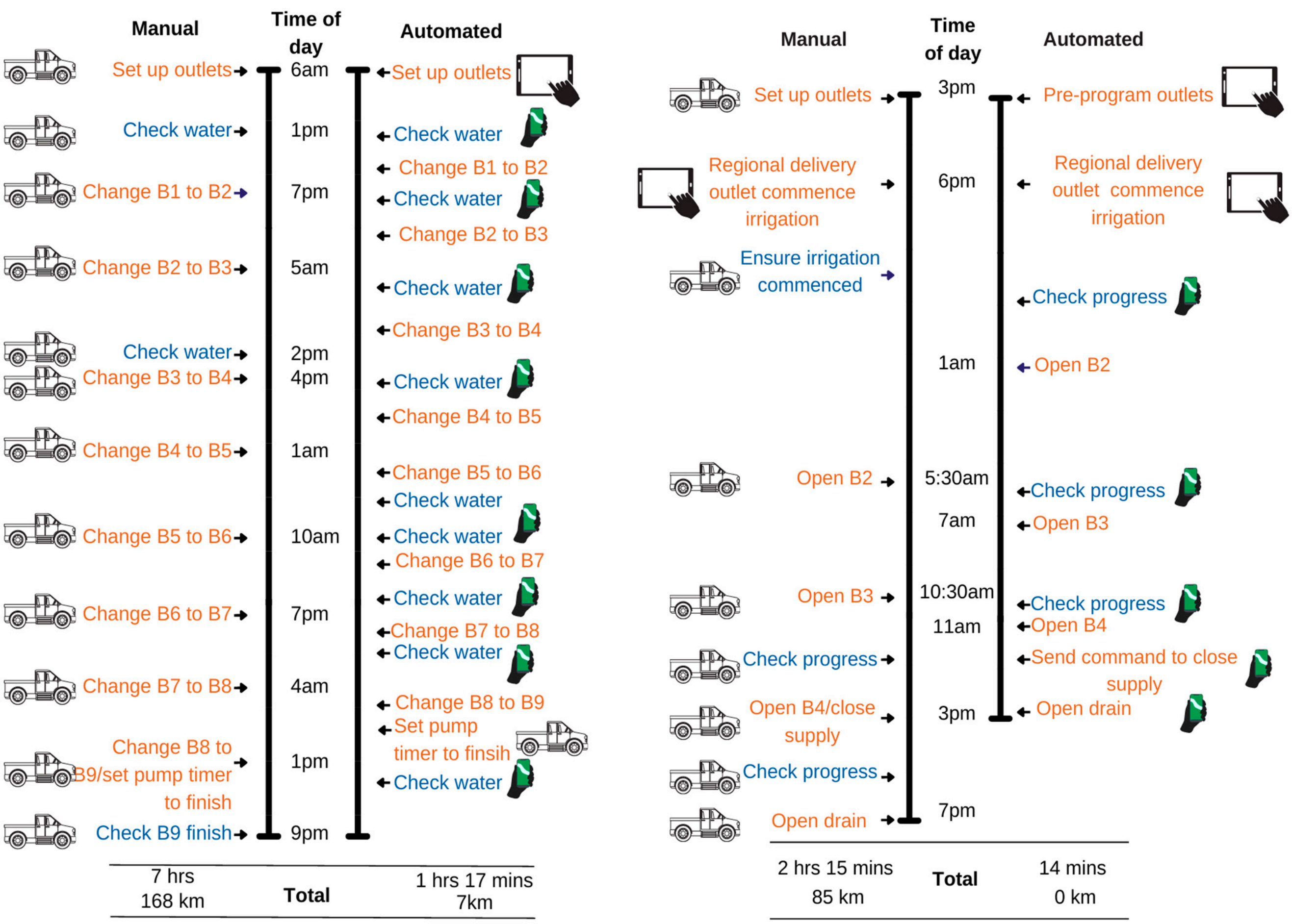
Table 3. Yield monitor results (t/ha) from Site B. Mean values ± standard deviation.

Bay	Manual	Automated
Bay 1	10.0 ± 1.03	11.7 ± 1.01 *
Bay 2	11.1 ± 1.02	12.4 ± 1.05 *
Bay 3	11.6 ± 1.12	12.0 ± 1.18
Bay 4	11.8 ± 1.18	11.8 ± 1.19

* Denotes bays with strategic deep water applied, as opposed to moderate to deep water applied for the whole duration of early pollen microspore to flowering.

3.3. *Direct Labor and Travel Cost Benefits of Automated Irrigation*

Irrigation was found to cause considerable disruption to both on- and off-farm activities, particularly during a flush-irrigation event, as timely water changes are necessary to avoid over-irrigation and unnecessary tailwater. An example of the travel, labor and daily interruption associated with a single flush-irrigation event at both Site A and B is provided in Figure 5.



(A) (B)

Figure 5. (**A**) Time and travel associated with manual flush irrigation at Site A. (**B**) Time and travel associated with flush irrigation of manual and automated fields at Site B. Essential activities are indicated in orange, whilst non-essential water checks in blue. "Water checks" were often occasions when the farmer went to close the inlet of one bay and open the next inlet, but irrigation was not complete and was required to return later.

Labor and travel across multiple irrigation events are provided in Table 4, where it can be seen after the initial pre-emergent irrigation, a 82–88% reduction in time was associated with automated irrigation, compared to manually irrigated fields when flush irrigating. This is similar to assumed irrigation management-related labor savings of 85% as reported by [15]. Distance and time to complete a water change varied depending on if the farmer was coming from the house/workshop (3.5 km and 5 km each way for Site A and B, respectively), or from farther, as is often the case at other farms. Therefore, the economics of automation will vary between sites. At times, irrigation was not complete upon arrival at the field, with the irrigator having to wait until it was complete or returning later. The labor benefits of automation during permanent flooding were less pronounced (57%) than during a flush irrigation, as daily app checks were combined with weekly physical inspections of the field.

Table 4. Average time taken (minutes) and distance travelled (km) for an individual irrigation event at both sites.

Irrigation Event	Manual		Automated	
Site A	Time	Distance	Time	Distance
Irrigation 1 (set thresholds for season)	180	65	104	35
Irrigation 2–4	115	68	14	0
Permanent water monitoring (1 week)	105	70	45	10
Site B				
Irrigation event	420	167	77	7

3.4. Opportunity Cost Analysis of Automated Irrigation

Whilst the layout and cultivation method (aerobic rice) used at Site A is not standard practice in Australia, the analysis was conducted to explore the benefits of automation over non-automated fields. The authors acknowledge the economic analysis will vary between individual sites, depending on how farmers value time and on cultivation methods. Therefore, the opportunity and cash cost of time and travel cost, under both automated and manual irrigation at both sites, provided in Figure 6, are unique to these individual case studies.

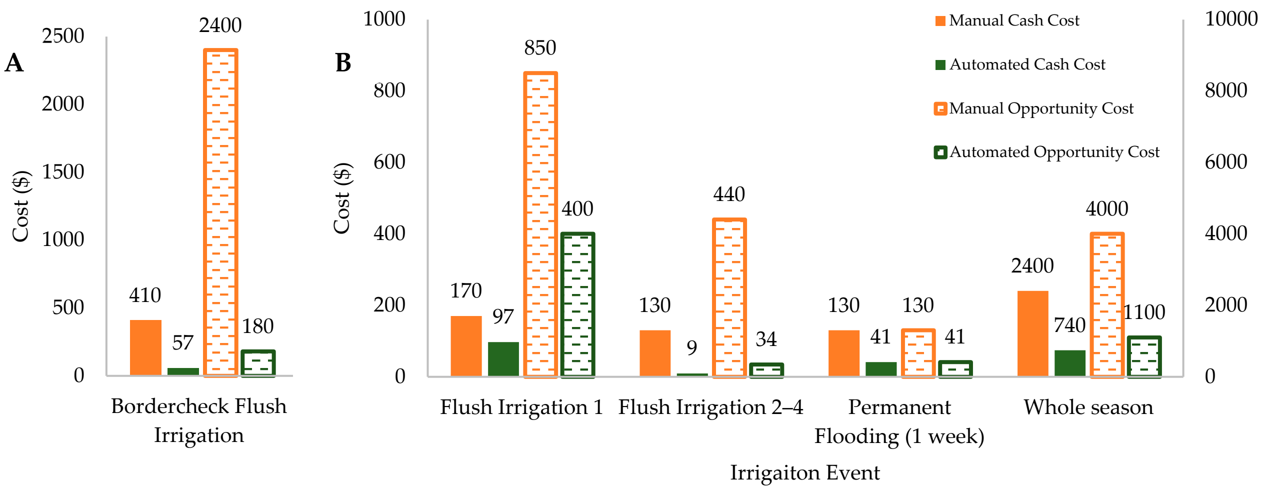


Figure 6. (**A**) Site A: Cash cost and opportunity cost of manual and automated irrigation. A: Site A, for one flush-irrigation event across the nine-bay field on the left axis. (**B**) Site B, flush irrigation 1, flush irrigations 2–4 and 1 week of daily check during permanent flooding on the middle axis; the seasonal data is provided on the far-right axis.

For a single irrigation event at Site A, automation saved AUD 2300 of opportunity cost of time and travel cost over a single manual irrigation event, compared to AUD 350 of cash cost of time saving and travel cost. At Site B, automation saved AUD 406–450 per event of opportunity cost of time and travel cost for flush-irrigation events, compared to AUD 73–AUD 121 per event of cash cost of time plus travel cost. Depending on the number of irrigation events (30 and 23 in Year 1 and 2, respectively), this equated to AUD 53,000–70,000 (AUD 1600–2000/ha) of opportunity cost of time and travel cost benefit over the whole season compared with cash cost savings and travel cost of AUD 8000–11,000 (AUD 240–310/ha). At an initial investment cost of automation of AUD 700/ha [15], the payback period of automation was recouped within 1 year when accounting for the opportunity cost of time, as opposed to 3 years when only the cash cost was included.

In the traditional rice system, Site B, automation saved AUD 3300 (AUD 160/ha) of manually irrigated opportunity cost of time and travel cost, compared to a cash cost of time and travel cost saving of AUD 1700 (AUD 85/ha) for the season. Thus, the payback period on capital investment of AUD 580/ha is reduced from 7 to 4 years.

3.5. Potential Further Benefits of Automated Irrigation

In this analysis, no opportunity cost benefits of automation were observed during permanent flooding at Site B, as the time of day of daily water checks was not critical, with daily checks occurring on the way to or from other farm tasks, with opportunity cost of time deemed *low.* However, this analysis was limited to a single field, which required only 15 min to travel to and check. It is conceivable that the time to check multiple fields (conducted on this farm by another family member) may increase the commitment of high opportunity cost time. Furthermore, consideration of automation to enable farmers to leave the farm for an extended time was not included in this analysis. Permanent flooding of rice occurs over the summer festival season, with farm staff generally provided annual leave, whilst the manager generally cannot leave the farm despite family holiday pressures. Automation could enable irrigators to leave the farm, providing considerable mental relief and precious time with family. Holidays, hobbies and involvement with groups and teams were reported as self-management strategies to assist in the improvement of Australian farmers' physiological wellbeing [20]. Extended periods off farm may be considered very valuable by some irrigators, depending on individual prioritization of activities.

One of the manual water change events documented in Figure 5A took almost 2 hours and involved travelling 70 km, as the farmer was applying a critical post-emergent herbicide to another summer crop on a distant farm. After making the water change and returning to the prior task, weather conditions had changed, with the task not able to be completed for several more days. For this analysis, time was valued at AUD 500/hr, the estimated cost of spraying. However, the true value of the reduction in yield, as reported by the farmer, due to reduced herbicide efficacy from delayed application, was likely far greater than AUD 500/hr. Accounting for such instances or for wheat quality downgrades due to delayed harvest, could easily justify a valuation much higher than the opportunity cost used in this analysis. In addition to the drivers to adopt technology on farm outlined by [21], both farmers involved in the current study cited the opportunity for automation to prolong their farming career, due to the lifestyle benefits they experienced, as a reason to invest in automated irrigation.

In addition to the potential lifestyle and labor benefits already outlined, water savings as a result of automation are possible, although not measured in the current study. It can be seen in Figure 5B that during the first four flush-irrigation events at Site B, the automated field finished irrigation, on average, four hours earlier than the manually irrigated field. Whilst this study did not measure water use between fields, or bays, at a flow rate of 25 ML/day and average water cost in excess of AUD 130/ML [39], a four-hour reduction in time required to irrigate due to timely irrigation changes associated with automation would likely reduce water use and provide further economic benefits. Percolation loss reduction is another potential benefit resulting from the flexibility of water management enabled by automated irrigation. Percolation losses (the vertical movement of water beyond the root zone to the water table [40]) are related to soil type, with higher percolation losses on coarser textured (sandy) soils compared to heavier, clay/loam soils [41]. Percolation losses are increased with increasing depth of water [42]. Therefore, both aerobic rice, strategic ponding (aerobic rice with deep water applied only if deemed necessary), and strategic deep-water ponding (shallow ponding with deep water applied only if deemed necessary) in traditional flooded rice systems, as opposed to applying deep water regardless of forecast conditions, offers the potential to reduce percolation losses, another potential benefit enabled by automated irrigation. Nevertheless, adequate flow rates are required to ensure that enough water can be applied across the field before the onset of cold conditions, with incorporation of weather forecasting, similar to [43], a likely benefit to the system.

These outlined water-saving opportunities enabled by automated irrigation are most likely to provide the greatest benefit to farms with coarser soil types and deep groundwater tables where percolation and water use is highest; northern Coleambally, NSW, is an example [44]. Here, farms are increasingly growing other crops, such as cotton, due to reduced water use providing higher returns per megaliter of water [45]. However, reintroducing water-saving rice in rotation may offer substantial agronomic advantages, such as weed and disease prevention and reduced reliance on herbicides [46].

4. Conclusions

This study evaluated the performance of automated gravity surface irrigation used for the first time for aerobic rice cultivation and to enable strategic deep-water ponding in a traditional rice system. The automated irrigation and sensing system built upon previous schemes to successfully manage water in both irrigation systems within the desired parameters. Notable characteristics not incorporated in previous systems include: (i) the ability to control water in non-ponded periods due to water advance and soil moisture sensing, (ii) portability of self-powered sensing and outlet controllers and (iii) outlet controllers capable of regulating commercial scale flow rates. This system controlled over 470 flush-irrigation events in aerobic rice across 2 seasons. Such high-frequency flush irrigation is not viable without automation. Further, the system was able to dynamically control water in ponded-rice fields, with the ability to apply strategic deep-water during cold sensitive periods demonstrated for the first time. Incorporation of weather forecasting and a self-learning approach to the degree of opening of outlet controllers may further enhance system functionality. Labor savings of 82–88% were found during flush-irrigation events, with a 57% reduction in labor achieved during permanent flooding. Considering the opportunity cost of time saved—the value of other on- or off-farm activities possible during that time—as opposed to cash costs, reduced the payback period from seven to four years in the tradition ponded-rice system. At the aerobic rice site, the payback period was reduced from three to less than one year when considering the opportunity cost of time. Although the economic will vary with sites and cultivation strategy, this research demonstrates the ability of gravity surface irrigation to enable novel water-saving rice practices which result in substantial economic labor savings and likely water-saving benefits.

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Appendix A

Seeding summer crops = AUD 400–500/h (AUD 40–50/ha at 10 km/h × 10 m) [5].

Harvest of winter cereals = AUD 600–750/rotor h exc. diesel [4,6,7].

Spraying summer crops = AUD 330–640/h (AUD 11–16/ha @ 30–40 ha/h exc. diesel, chemistry) [4,5].

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