How could sensor networks help with agricultural water management issues?

Optimizing irrigation scheduling through networked soil-moisture sensors

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***Abstract*—Irrigated agriculture provides 40% of the World's food from 20% of the agricultural land but uses 70% of all global freshwater withdrawals. However, even supposedly efficient and well-managed irrigation systems waste up to 50% of the water applied to the crops under them. Meeting the food needs of an increasing world population from a static or even decreasing land base will, therefore require improved efficiencies in irrigated agriculture and better use of these finite water resources. The first part of this paper reports on a field-based research project which examined a suite of conventional and alternative irrigation systems which were installed at a farm in south west Australia and assessed and compared in terms of their Water Use Efficiency. All "alternative" systems outperformed the conventional surface (flood) irrigation systems with comparative water savings of around 50%. The second part of the paper assesses the potential Water Use Efficiency improvements at farm and system-scales which could be achieved through linking these irrigation systems to wireless soil-moisture sensor networks which are being developed by the authors and which are reported in detail in associate papers. Improving irrigation scheduling and management by better (and, where appropriate, automatic) links to near real-time soil moisture data is shown to produce water savings of up to 30 GL per year at the irrigation system scale.**

Keywords—Agriculture, irrigation, Water Use Efficicnecy, wireless sensor networks.

I. INTRODUCTION

Irrigated agriculture provides 40% of the World's food from 20% of the agricultural land with yields 2-4 times higher than those from rain-fed agriculture. However, the cost in terms of water use is high, with agriculture accounting for 70% of all global freshwater withdrawals and even supposedly efficient and well-managed irrigation systems wasting up to 50% of the water applied to the crops under them [1]. Although Australia is the world's driest inhabited continent and might, therefore, be expected to be a leader in water management, Australians are one of the highest water users per capita in the world [2] with the agricultural sector (largely irrigation) accounting for about 70% of total water use [3, 4]

In the state of Western Australia (WA) which occupies the western third of the continent, the irrigation industry is the single largest water use group accounting for about 40% (940 GL year^{-1}) of all licensed surface water and groundwater allocations. The Australian average of about 70% of water resources diverted for irrigation indicates considerably greater water use and agricultural production in the eastern states of the country. Despite the relatively small scale in WA, irrigation is a high value industry. From a total area of about 83,000 ha, or 3% of the total WA land area, returns to WA are more than $800 - 900 million per annum. This value when assessed per hectare of land equates to more than three times the national average [4].

Licensed groundwater allocations for irrigation in WA total about 490 GL year^{-1} and are used to irrigate about 61,000 ha [5]. This represents approximately 55% of the total water licensed for irrigation use. In comparison, about 450 GL year^{-1} are diverted from surface water resources and used to irrigate approximately 22,000 ha. About 90% of the surface water used is supplied through four main irrigation schemes – the Ord, Carnarvon, Preston Valley and Harvey schemes.

The Harvey Irrigation Area (HIA) is WA's prime irrigated dairying area supplying the state capital Perth and the south west of WA with more than 40 percent of its milk. Irrigated agriculture commenced in Harvey with the establishment of a weir in 1916 and since that time pastures have been irrigated predominantly through surface (flood) irrigation of paddocks, which over time have been leveled and divided into individual irrigation bays. The HIA currently has around 10,000 ha of land under permanent irrigation for dairy farming, beef grazing and horticulture, with a total irrigable area of approximately 30,000 ha. The region is presently experiencing soil salinity problems common to other areas subject to irrigation, as well as producing nutrient-enriched drainage water that runs to environmentally sensitive estuarine receiving bodies including Ramsar-listed wetlands, some of which have a long history of eutrophication and subsequent algal blooms.

Increasing scarcity of water resources to support irrigation and other uses, particularly in the current environment of below average long-term rainfall in the South West of WA, has been a strong catalyst for a number of water use efficiency initiatives. As competition intensifies with escalating demand for multiple uses of WA's limited potable water resources, the necessity to actively demonstrate a sustainable irrigation industry is becoming increasingly essential for growth.

Demand for irrigation water is expected to increase more rapidly than in any other industry [6] making it essential that further water efficiency improvements and savings in the industry are made.

Inefficient, open-channel water distribution networks have until very recently delivered most irrigation scheme water within the HIA, but significant efforts have recently been undertaken to improve water delivery systems and the majority of irrigators in the HIA are now supplied by a highly-efficient pipe scheme. Surface (or flood) irrigation however, which is more common to farms that are part of an irrigation scheme, can be an inefficient method of water application and this remains the most popular form of irrigation in the HIA. This disconnect between on and off-farm water management is an important issue as highly-efficient water distribution schemes providing water to inefficient on-farm systems can still result in significant water wastage. Better surface irrigation scheduling combined with the use of more efficient on-farm application methods such as spray irrigation or drippers provides a significant opportunity to improve Water Use Efficiency (WUE) within the industry. Water savings of 2 ML ha^{-1} yr^{-1} (around 20%) are achievable using spray irrigation in comparison to flood irrigation [7, 8]. The first component of this paper reports on a research study undertaken in the HIA which assessed a number of alternative irrigation systems in terms of their WUE.

Experience has shown, however, that improved irrigation scheduling for either low-efficiency irrigation systems (such as surface irrigation) or high-efficiency systems (such as sprinkler systems) or as a motivation to switch to more efficient systems does not tend to be either adopted widely or implemented well. This is because it is necessarily based on the measurement or monitoring of parameters such as soil moisture and this increases the demands placed on land managers in terms of both time and workload [9]. Furthermore, current soil moisture monitoring systems are expensive, unreliable and provide only limited representation of both spatial and temporal variations in soil moisture.

Recent work undertaken by some of the authors of this paper [10, 11, 12, 13] has demonstrated the potential for the use of sensor networks to reduce this load on land managers by providing both a high frequency sensor network for the monitoring of important soil parameters, and the consequent decision support and irrigation control systems which allow the implementation of improved irrigation scheduling. The second component of this paper, assesses the likely improvements in WUE which might be achieved through the use of sensed networks as a driver to switch to more efficient irrigation systems and to control the alternative irrigation systems discussed in the first component of the paper.

II. Methods

A. *Alternative Irrigation Systems Trial*

The field research site for this work is the Harvey Campus of the WA College of Agriculture which is located in the southern portion of the HIA. The HIA is located on the southern portion of the Swan Coastal Plain, around 100 km south of Perth the state capital (Figure 1). The site includes five distinct irrigation areas: surface irrigation (3 ha); centre pivot (15 ha); sub-surface drip irrigation (1 ha) divided into three equal areas with drip lines spaced at 0.8 m, 1.0 m and

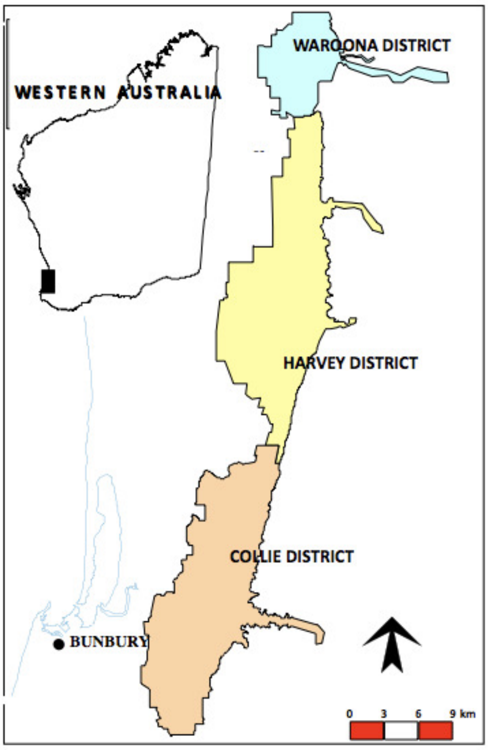

Figure 1: Location of Harvey Irrigation Area

1.15 m; solid set sprinklers (0.5 ha), and; floppy sprinklers (2 ha) (Figure 2).

Surface irrigation is the simplest and most commonly used irrigation method in the HIA. It consists simply of a water distribution transfer channel (head ditch) which carries water along the top of an irrigated field (or bay). The fields are generally very flat with a slight slope away from the head ditch. During irrigation events, the land manager manually opens a series of gates along the head ditch to allow water to flow onto and down the bay overland under the influence of gravity. The most common management practice in terms of planning the duration of an individual irrigation event is to simply close the gates when the water flow appears to have reached 60% of the length of the bay. Excess water flows off the bottom of the bay into a "tail drain".

A centre pivot irrigator is a travelling, sprinkler irrigation line that is fixed at one end and rotates in a circle. It comprises a series of spans and towers (commonly 4 to 12) that support the irrigation pipe and spray outlets. Each tower has a pair of wheels that are driven at a pre-determined speed by electric or hydraulic motors. The size of the sprinkler outlets increases towards the end of the span because the outer sections of the pivot are moving more rapidly than those near the pivot point and are, effectively, covering a larger area than the centre sections. This means that the longer a pivot is, the greater the application rate needed at the end. The major advantages of centre pivots are that their pressure requirement is quite low, and sprinkler packages can be set to deliver very accurate irrigation rates.

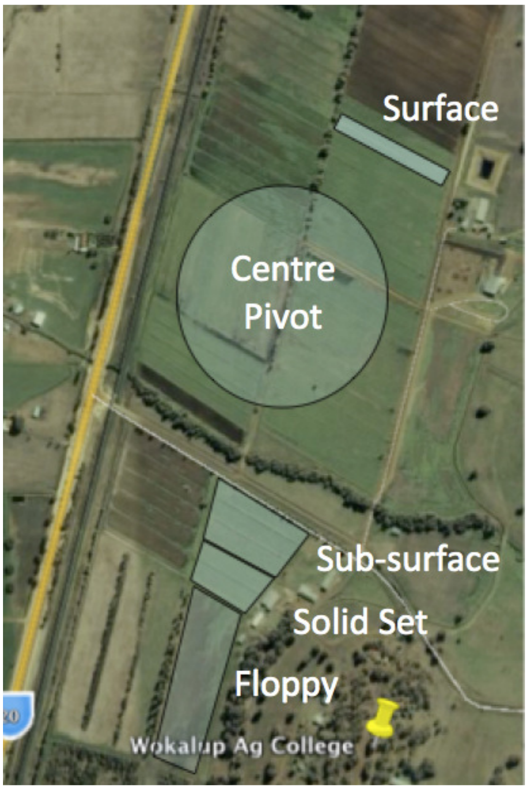

Figure 2: Trial layout

In sub-surface drip irrigation, water is reticulated through flow emitters regularly spaced along a flexible polyethylene drip line which is buried 15 to 20 cm below the soil surface. Water is distributed slowly and uniformly over a large surface area. Sub-surface systems have a number of advantages including uniformity of application over large areas, minimization of evaporative losses and their ability to be used to efficiently deliver nutrients to plants by injection of liquid fertilisers directly into the irrigation lines (fertigation).

Solid set irrigation is a system of irrigation sprinklers and piping placed permanently or semi-permanently in a field. Adjacent pipes and sprinklers are usually spaced a distance of one sprinkler radius apart from each other. This creates a square spacing of sprinklers within the field. The piping may either be buried PVC or steel to create a permanent system or it may be aluminum and portable.

The floppy sprinkler overhead cable system is an innovative irrigation system in which the actual sprinkler consists of a flexible, moulded, silicone tube surrounded by a solid outer casing into which a flow controller is fitted. When water passes through the flow controller and then on through the tube, it causes the tube to oscillate randomly while slowly rotating through 360 degrees. This unique action cuts the stream of water into uniform, medium sized, low energy droplets, similar to raindrops. There is no mist formation, resulting theoretically in very high application efficiencies. The sprinklers and their polyethylene water supply pipes are suspended from a cable held approximately 5 m above ground. The cable is suspended between rows of poles up to 75 m apart and installed across the width of a field at 12 m intervals. As there is no other irrigation equipment in the field, tractors and implements can move unhindered throughout the field.

Water supply volumes to all sites at the trial location were metered over two (annual) growing seasons although the first growing season was shorter than usual due to both unusual seasonal conditions as well as delays in the installation of the irrigation systems. Pasture (millet) growth rates were measured over the growing seasons through the use of randomized and replicated stock-exclusion cages which were manually harvested approximately every 7 to 10 days. To ensure that variations in pasture growth and, therefore, measures of WUE varied only with water supply and utilization, identical fertiliser applications were applied to all sites and stock movements around the sites were also managed to ensure consistent nutrient inputs from animal excretion.

All systems were assessed for Dry Matter Yield (t ha^{-1}), Gross Water Use (ML ha^{-1} day^{-1}) and WUE (in this case expressed as t ha^{-1} ML^{-1}).

B. Potential WUE improvements from the use of sensor networks

The results of the field work described above were used to illustrate the potential water savings and increases in WUE which could be achieved through the use of alternative irrigation systems at the farm scale in the HIA. However, as mentioned above, actual system (or even farm) scale implementation of these improvements is generally poor and sensing, triggering, control and automation are seen as important tools to endure broader implementation.

Work on the development of wireless sensor networks for agricultural uses is being undertaken by some of the authors of this paper and this has been reported in detail previously as well as at this conference. These sensor systems and their associated networks essentially comprise: sensors (in this case soil-moisture sensors although as reported in [13], de-facto data may in fact exist for this parameter); wireless communication, control and data-transfer networks and protocols, and; decision support and equipment control systems including algorithms and models for assessment of the large volumes of sensed data.

In this paper we assess the potential water savings and WUE improvements which could be obtained if alternative irrigation systems were implemented throughout the HIA. The use of sensing systems as decision-support platforms and automated control systems is seen as essential to this adoption.

III. RESULTS

Results for Total Dry Matter Yield (t ha^{-1}), Daily Growth Rate (t ha^{-1} day^{-1}), Gross Water Use (ML) and WUE (t ha^{-1} ML^{-1}) are shown in Table 1.

A. Dry Matter Yield (DMY)

Pasture growth rates in the first year of the trial were all low due to the shortened growing season and system installation issues as discussed previously. The total DMYs for years one and two for the surface irrigation system were

Year	Irrigation System	Total Dry Matter Yield (t ha^{-1}),	Daily Growth Rate (t ha^{-1} day^{-1})	Gross Water Use (ML)	WUE (t ha^{-1} ML^{-1})
1	Surface	3.57	0.04	8.85	0.40
	Centre Pivot	4.73	0.06	5.60	0.84
	Floppy	4.22	0.05	5.60	0.75
	Solid Set	4.79	0.06	6.06	0.79
	Sub-surface (1 m spacing)	3.36	0.04	4.97	0.68
	Sub-surface (0.8 m spacing)	3.68	0.05	4.97	0.74
	Sub-surface (1.15 m spacing)	3.64	0.05	4.97	0.73
2	Surface	38.05	0.29	19.26	1.98
	Centre Pivot	22.96	0.17	9.24	2.48
	Floppy	27.74	0.21	8.65	3.21
	Solid Set	24.46	0.19	11.38	2.15
	Sub-surface (1 m spacing)	24.89	0.19	10.35	2.40
	Sub-surface (0.8 m spacing)	25.78	0.20	10.35	2.49
	Sub-surface (1.15 m spacing)	25.85	0.20	10.35	2.50

Table 1: Trial results

3.57 t ha^{-1} and 38.05 t ha^{-1} respectively, while the mean DMYs for the other irrigation systems for the two years were 4.07 t ha^{-1} and 25.28 t ha^{-1} respectively. These represent an average increase in production in year 1 of 14% and a decrease of 40% in year two when alternative systems are compared with the traditional surface irrigation system. Daily growth rates (t ha^{-1} day^{-1}) were comparable across all systems in year 1 and higher under surface irrigation in year 2.

B. Gross Water Use (GWU)

The total water use for years one and two for the surface irrigation system were 8.85 ML and 19.26 ML respectively, while the mean water volumes used for the other irrigation systems for the two years were 5.36 ML and 10.06 ML respectively. These represent an average decrease in volumetric water consumption in year 1 of 40% and a decrease of 50% in year 2 when alternative systems are compared with the traditional surface irrigation system. Metered water use across the individual alternative irrigation systems were comparable.

C. Water Use Efficiency

Water Use Efficiency (in this case) is a measure of the "productive" use of water and can be described as the amount of pasture production grown per unit of water applied. It represents, therefore, a combination of the gross DMY and the water used to produce that dry matter (DMY and GWU). The calculated WUE for years 1 and 2 for the surface irrigation system were 0.4 t ha^{-1} ML^{-1} and 1.98 t ha^{-1} ML^{-1} respectively, while the mean WUE for the other irrigation systems for the two years were 0.76 t ha^{-1} ML^{-1} and 2.54 t ha^{-1} ML^{-1} respectively. These represent improvements in WUE in year 1 of almost 90% and 30% in year 2 when alternative systems are compared with the traditional surface irrigation system. Although GWU figures for all of the alternative systems were comparable, when both water use and pasture yield are combined into this measure of WUE, there is some separation of the performance of the various systems. In increasing order of WUE: Surface irrigation is the least efficient in terms of WUE; solid set performs similarly to surface irrigation; all variations of the sub-surface systems perform similarly to each other and to the centre pivot (having, on average, WUE improvements of 25% when compared to the surface irrigation system), and; floppy irrigation systems are approximately 60% more efficient than surface irrigation.

D. Potential System-Scale Water Savings from Sensor-Driven Water Management.

The results of analyses of DMY, GWU and WUE shown above indicate, essentially, that surface irrigation can produce substantial amounts of pasture, but that this is achieved through the use of significantly more water than would occur if other systems were used.

The use of networked soil moisture sensors has been shown to allow optimal control over water and land management systems such as those which are the subject of this paper [13]. We therefore utilize this optimization potential to calculate the paddock and system-scale water savings which might occur if sensor networks were introduced into the HIA and were used to change to and manage automated irrigation systems. This is already occurring to some extent, but is not yet being widely adopted.

The GWU for the surface irrigation system at the research trial site in the second year of the trial represents a more typical GWU figure than year one and was 19.26 ML over the entire (132 day) growing season. The use of alternative irrigation systems over an (average) 180 day growing season for this property presents an opportunity to save approximately 12.5 ML per ha per year. At the current value of water (approximately AU$50 ML^{-1}) this represents an annual saving to the property manager of AU$625 ha^{-1}. For an average property with 50 ha of irrigated pasture, this represents an annual saving of AU$31,250.

There are currently approximately 2,500 ha of land under irrigation for milk production within the HIA. The application of improved irrigation systems to this land would save approximately 30 GL of water per year at a value of approximately AU$1.5 million. Alternatively, at an average application rate of 9 ML ha^{-1}, this water could be used to irrigate an extra 3,372 ha of land; more than doubling the current area of land used by dairy farmers for milk production.

IV. Discussion and Conclusions

A. Benefits of alternative irrigation systems

Optimization of irrigation systems through improved scheduling, better monitoring and measurement of soil and crop water balances, optimization and synchronization of irrigation equipment and transitions to more water use efficient technologies is the focus of much work in Australia and the rest of the world. Our continued reliance on inherently inefficient water and irrigation management systems to produce food for a growing world population means that improvements in WUE are of paramount importance if we expect to be able to feed the world in a sustainable manner.

The water use and, therefore, WUE of the surface irrigation system used in the trials reported in this paper was very poor (19.26 ML over a 132 day growing season) and there may be some argument that, because of particular farm management issues at the time of the research, that this does not represent "average" water use under surface irrigation systems. However, similar water use figures have been obtained from comparable sites in similar studies to the one reported here [8]. In these other studies, WUE of surface irrigation systems was improved markedly by managing the irrigation system very closely (much more closely than would be expected from a typical land manager with many other responsibilities to deal with around the property) but these efficiencies still did not approach those obtained by the alternative irrigations systems tested in this trial.

The use of a near real-time data suite obtained by networked sensors collecting information regarding soil moisture content and which could be used to both monitor soil condition and, more importantly, autonomously start and stop irrigation events presents a unique opportunity to move towards truly "efficient" irrigation practices. This may be either through the optimization of traditional surface irrigation systems or, more ideally, by using easily-captured sensed data to facilitate a shift to more efficient irrigation technologies and to then automate these systems based on the information provided by the sensor network.

B. Water Savings or Additional Irrigation Areas?

Water savings calculated in this research for one relatively typical property indicate that approximately 625 ML of water worth approximately AU$31,000 per year could be saved on a typical property irrigating 50 ha of land if efficient irrigation systems were used. Importantly, the implementation of new irrigation technologies is not what drives more efficient water use. The critical issue in delivery of more efficient water use is the correct and appropriate use of that technology and this tends to only be achieved when systems are linked to relevant parameters, such as soil moisture data, and then automated. Traditional soil moisture probes are expensive, unreliable and do not represent spatial variations across irrigation bays or farms. Soil moisture "sensing" rather than "monitoring" is the only realistic option to ensure that adequate data are captured to enable appropriate irrigation activities.

At the irrigation system scale, the implementation of sensed and automated irrigation systems could potentially yield annual water savings of 30 GL for the HIA if only one land use (dairying) adopted the technology. The potential water savings are even higher if other land uses such as horticulture and broadacre grazing adopted the technology but, even if only 50% of dairy farmers chose to use sensor networks, then water savings of 15 GL per year, with a value of around AU$750,000 are achievable.

This is a considerable water saving but, rather than conserving this water or using it for other applications, another option would be to use this saved water to expand the irrigation area, thereby increasing the overall productivity of the HIA. At an average application rate of 9 ML ha^{-1} this represents more than 3,000 ha of additional irrigable land, or a doubling of the current dairy land. Even more land than this could be utilised for irrigated agriculture if more water use efficient land uses than dairy (such as horticulture) were to be considered as part of an expansion programme.

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