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Scheduling irrigation from wetting front depth

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ABSTRACT

Irrigation scheduling is often based around the analogy of a 'tipping bucket', and the measurement or prediction of the amount of water stored within the bucket. We compare this conventional approach of scheduling with stopping irrigation when the bucket tips i.e. when infiltrating water moves from an upper to a lower soil layer. Electronic wetting front detectors were used to close a solenoid valve at the time infiltrating water reached a depth of 300 mm, when irrigating a lucerne crop in a rain-out shelter. Four different ways of using information from the position of the wetting front were compared with scheduling irrigation from soil water measurements made by a neutron probe or calculated by a soil-crop model. Automatically closing a solenoid valve at the time the upper bucket tipped was a successful approach, but only when the correct irrigation interval was selected. If the irrigation interval was too short, water draining from the soil layer above the detector resulted in drainage. Scheduling from wetting front detectors placed at 600 mm depth was unsuccessful because of the difficulty in detecting weak wetting fronts at this depth. The commonly accepted method of measuring a soil water deficit and refilling the bucket to field capacity was not without limitation. Since the soil drained for many days after irrigation, and well beyond the 48 h period typically selected to represent the upper drained limit, drainage and evapotranspiration occurred concurrently.

1. Introduction

Improving the water use efficiency of irrigation requires the measurement or prediction of soil water status. Irrigators commonly use the analogy of 'tipping buckets' to describe the soil layers which are sequentially filled with water (Veihmeyer and Hendrickson, 1931; Hillel, 1980). According to this analogy, the first layer of soil or top bucket is filled by irrigation and spills water to the bucket below, after an upper limit (or field capacity) is reached. The bucket is considered empty at permanent wilting point. Between these limits the irrigator sets a refill point, below which a plant is believed to experience water stress. Water is used most efficiently when yield is maximized (one or more buckets maintained above the refill point), with the minimum amount of water applied (the lowest soil bucket containing roots does not tip). Although soil physicists are well aware that the soil water storage does not behave exactly as a bucket, it is a useful analogy that introduces the concept of a finite and measureable storage capacity (Emerman, 1995; Dalgliesh et al., 2009).

The success of irrigation scheduling hinges on our ability to define the upper drained limit and refill point and subsequently to measure or predict the amount of water readily available to plants stored in the bucket. This straightforward approach is widely promoted by science, extension and industry, but not well adopted by irrigators (Stevens et al., 2005; Stirzaker, 2006). An alternative to predicting or measuring the amount of water in each bucket is to apply irrigation and then stop irrigation when the bucket tips, i.e. when water has moved from an upper to a lower soil layer (Zur et al., 1994). The time of 'tipping' can be inexpensively measured using a passive lysimeter such as a wetting front detector (WFD) (Stirzaker, 2003). The method is simple to automate and also allows for routine monitoring of salt and nutrients in the infiltrating water (Tesfamariam et al., 2009; Van der Laan et al., 2010).

Stirzaker and Hutchinson (2005) demonstrated the success of this approach, but their results showed that when controlling irrigation from the depth of a wetting front, the irrigation interval had

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to be adjusted in line with potential evaporation. Irrigation had to be frequent enough during hot weather to ensure that the bucket did not empty below the refill point. However, irrigation could not be too frequent, particularly in cooler weather. This is because wetting fronts move at water contents well above the upper drained limit, and water will redistribute below an irrigation controlling WFD in the days following irrigation. In other words after a bucket 'tips', it continues to 'leak' water into the layer below for a considerable length of time.

When scheduling irrigation by the conventional 'fill the bucket' method, an amount of water (I) would be applied

$$I(\text{mm}) = d(\theta_{\text{udl}} - \theta_{\text{i}}) \tag{1}$$

where θ_{udl} is the upper drained limit (UDL) of the soil, θ_{i} is the soil water content on the day of irrigation and d (mm) is the depth of the root zone.

Consider a root-zone with three layers with the bottom boundaries denoted by d_1, d_2 *and* d_3. If we were to stop irrigation when the first bucket tips, this would result in an irrigation of

$$I(\text{mm}) = d_1(\theta_{\text{wf}} - \theta_{\text{i}}) \tag{2}$$

where θ_{wf} is the volumetric water content at which the wetting front moves during irrigation and d_1 the depth to the controlling WFD. An amount of water equaling $d_1(\theta_{\text{wf}} - \theta_{\text{udl}})$ will redistribute below depth d_1 after irrigation ceases and enters the second bucket. If the next irrigation was scheduled when the top bucket is half depleted but the second is still near to the UDL, irrigation would again be stopped when the top bucket reached θ_{wf}. However, not all water redistributing from bucket one could be stored in bucket two, so it would spill into the third bucket. Thus a second WFD at depth d_2 would alert us that bucket two was near full prior to irrigation, and hence the irrigation interval was too short.

This paper evaluates three approaches to using the tipping bucket analogy for irrigation of a root zone comprising three layers (or buckets). First, the depletion of water in each layer is measured by neutron probe or predicted using a crop model and then irrigation applied to refill each layer to the UDL. Second, the irrigation is automatically shut off when the first layer tips into the second layer, as determined by a WFD during an irrigation event, with or without feedback from a deeper detector. If the feedback from the deeper detector is positive, an irrigation is skipped. Third, feedback algorithms are evaluated to adjust the next irrigation amount according to whether water has moved from the second layer to the third layer following redistribution after the previous irrigation event. We test the hypothesis that irrigation can be objectively scheduled from information on wetting front depth alone, as opposed to measured or predicted soil water depletion.

2. Materials and methods

The experiments were carried out in a rain-shelter facility at the University of Pretoria research farm (Hatfield Experimental Farm, South Africa; 25°64′S, 28°16′E, altitude 1370 m) on a Hutton soil (Orthic A horizon over red apedal B horizon). The top 300 mm was a sandy loam texture (79% sand, 6% silt and 15% clay) overlying a sandy clay loam (60% sand, 5% silt and 35% clay). A drying soil-water retention curve was produced using the controlled outflow method on disturbed samples packed to the original field bulk density for depths of 300, 600 and 900 mm (Fig. 1). Saturated hydraulic conductivity (K_s) was determined on packed soil cores using a constant-head permeameter (Klute, 1965) and the unsaturated conductivity function was derived using the Van Genuchten (1980) hydraulic model.

Neutron probe access tubes were installed in each plot and the UDL from 0–1200 mm was determined individually for each plot following 48 h of drainage after excess irrigation by sprinkler, using a site calibrated neutron probe. After the experiment when the crop was removed, the change in soil tension at 300, 600 and 900 mm depth was monitored post irrigation for a period of 16 days to evaluate the suitability of using the 48 h time period as the determination for UDL. Tension data from each depth were averaged over 10 plots measured to an accuracy of 1 kPa using a hand held pressure transducer (Soilspec tensiometer, Healesville, Victoria, Australia). The draining profile was also simulated using Hydrus-1D (Šimůnek et al., 2008). A uniform 1.5 m depth profile was set up using the hydraulic properties from the 600 mm depth, and allowed to drain for 16 days from a tension of 1 kPa. Observation nodes were placed at the same depths as the tensiometer measurements so that the measured and simulated results could be compared.

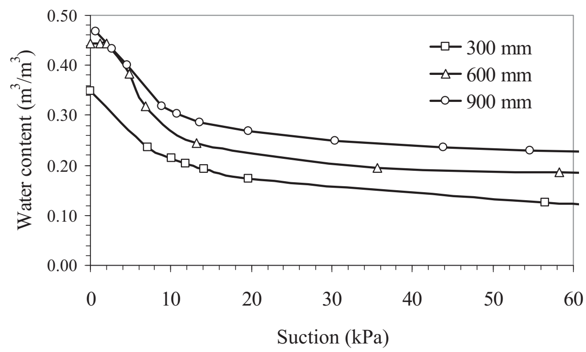

Fig. 1. The draining water release characteristic at 300, 600 and 900 mm depths.

The soil profile was divided into three layers: 0–300 mm, 300–600 mm and 600–1200 mm. WFDs were installed at 300 mm depth at the base of layer 1 in treatments where irrigation was automatically stopped when the infiltrating water passed from layer 1 to layer 2. WFDs were installed at 600 mm depth for treatments that used feedback information to show when infiltrating water had moved from layer 2 to layer 3.

The WFD is comprised of a specially shaped funnel, a filter, and a float mechanism and works on the principle of flow line distortion. Water from rain or irrigation percolates through the soil and is intercepted by the funnel. As the water moves down into the funnel, the soil becomes wetter as the cross-sectional area decreases. The funnel shape has been designed so that the soil at its base reaches saturation when the soil outside the funnel is around 2–3 kPa suction, which corresponds to a relatively 'strong' wetting front (Stirzaker, 2008). Once saturation has occurred at the base of the funnel, free water flows through a filter into a small reservoir and activates either an electrical (treatments 3 and 4) or mechanical float (treatments 5 and 6). WFDs were installed 12 months prior to planting by augering a 200 mm diameter hole to the required depth directly under a dripper.

The rain-shelter contained 60 plots, each 2 m × 2.5 m, that were hydrologically isolated from each other with fibre cement sheets to a depth of 1.2 m. Each plot contained four rows of drip tape 500 mm apart, with an emitter spacing of 300 mm and discharge of 2.7 l h^{-1}, giving an application rate of 18.4 mm/h. Lucerne (*Medicago sativa* var. WL 525 HQ) was sown in rows 25 cm apart four months before the experiment commenced. Six irrigation scheduling treatments were replicated five times and randomly assigned to the 30 inner plots of the rain-shelter, with the remaining 30 outer plots forming a border. Each plot contained a neutron probe access tube located between the irrigation drip lines and within 200 mm of a dripper. Although the six treatments were independent of each other, they are best explained as three groups of two treatments (summarized in Table 1).

Table 1
The treatment summary, showing the measurements taken each 3 or 4 days and the subsequent action.

Strategy	Treatment	Measurement	Action
Refilling the bucket	*Measurement of deficit*	Measure deficit to UDL over 0–1200 mm depth before each irrigation with a neutron probe	Calculate average deficit across 5 replicates, irrigate twice weekly
	Prediction of deficit	Download weather data and input into SWB model	Compute ET from model, irrigate twice weekly
Automatic control at layer 1/2 boundary	*WFD Control*	Depth of wetting	Nil (automatic cut off within 3 h irrigation window)
	WFD Control+feedback	Depth of wetting	If WFD at 600 mm activated, omit the replicate(s) from next irrigation
Iterative feedback from layer 2/3 boundary	*Adjust-coefficient*	Count the number of detectors that responded at 600 mm depth to the previous irrigation	Adjust previous crop coefficient based on WFD response to last irrigation
	Adjust-amount	Count the number of detectors that responded at 600 mm depth to the previous irrigation	Adjust previous irrigation amount based on WFD response to last irrigation

2.1. Refilling the bucket

2.1.1. Measurement of deficit

The amount of water in the soil was measured by a neutron probe, and the soil water deficit to 1200 mm depth was calculated by subtracting this value from the UDL. The average deficit of the five replicates was applied twice per week.

2.1.2. Prediction of deficit

The Soil Water Balance (SWB) model (Annandale et al., 1999) was used to compute the crop water use twice per week, using measured soil parameters, pre-determined growth parameters for lucerne and real-time weather data from an automatic weather station 50 m away from the site.

Table 2
The algorithms used to increase or decrease the irrigation in the Adjust-coefficient and Adjust-amount treatments based on the response of WFDs at 600 mm depth to the previous irrigation.

Deep detectors activated	*Adjust-coefficient* Change crop coefficient by	*Adjust-amount* Change irrigation amount by
0	+ 0.1	+30%
1	+ 0.05	+30%
2	0	0
3	0	0
4	−0.05	−30%
5	−0.1	−30%

2.2. Automatic control at layer 1/2 boundary

2.2.1. WFD control

Electronic WFDs were installed at 300 mm soil depth. When infiltrating water reached the detector and activated the float switch, the power between the solenoid valve and the controller was cut, terminating irrigation.

2.2.2. WFD control + feedback

Same as treatment 3 above, but a second electronic WFD was placed at 600 mm depth to check whether redistributing fronts reached this depth after the irrigation was terminated by the 300 mm detector. If the 600 mm detector was activated in any replicate, that replicate did not receive the next scheduled irrigation event.

2.3. Iterative feedback from layer 2/3 boundary

2.3.1. Adjust-coefficient

Reference evaporation (ET_o) was computed from weather data and multiplied by an estimated initial crop coefficient. This crop coefficient was subsequently adjusted up or down from its previous value, based on the proportion of mechanical detectors at a depth of 600 mm that were activated by the last irrigation (see Table 2).

2.3.2. Adjust-amount

The first irrigation amount was estimated and subsequently adjusted up or down from its previous value, depending on the number of mechanical detectors at a depth of 600 mm that were activated by the last irrigation (see Table 2).

Irrigation of the lucerne was carried out twice per week during each of three growing cycles, at alternating three and four day intervals. Just prior to each irrigation event, neutron probe readings were made to a depth of 1200 mm at 200 mm intervals in the five replicates of each treatment. The weather data was downloaded for calculation of ET_o and as input to the SWB model. Irrigation run times were calculated for each treatment according to Tables 1 and 2 and fed into an irrigation controller. In the case of the automatically controlled treatments, a three-hour run time was entered into the controller and the float switch overrode the controller when the wetting front reached 300 mm depth, by interrupting the circuit to the solenoid valve.

The experiment was repeated over three growth cycles: cycle 1 from 18 January to 14 February when average ET_o was 5–6 mm/day, cycle 2 from 14 March to 11 April when average ET_o was 4–5 mm/day, and cycle 3 from 25 April to 30 May when average ET_o was 3–4 mm/day. The entire experiment was irrigated back to the UDL between harvests to prevent carry over effects between the cycles. The rain-shelter was closed when rain threatened to prevent rain from interfering with irrigation treatments. Errors during treatment implementation resulted in data from the Adjust-coefficient and Adjust-amount treatments being discarded for cycle 1 and data from the Prediction of deficit treatment discarded for cycle 2.

The total volume of water applied to each treatment was measured by water meters. The total water consumed by each treatment, defined as evapotranspiration plus drainage, was calculated as

$$ET + D = I - \Delta S \quad (4)$$

where ET is the evapotranspiration, D is drainage, I is the total irrigation amount required by the treatment and ΔS is the change in soil water storage from the start to the end of the harvest cycle (all in mm), with positive values showing the soil getting wetter. Rain and run-off were zero due to the rain- shelter.

Table 3
Total irrigation, change in soil water storage (ΔS) ± 1 standard deviation over the cycle, evapotranspiration plus drainage (ET + D) and above ground dry matter of lucerne ± 1 standard deviation for harvest 1 (ET_o 5–6 mm/day).

Treatment	Irrigation (mm)	ΔS (mm)	ET + D (mm)	Dry Matter (t ha^{-1})
Measurement of deficit	196	20 ± 6.7	176	3.99 ± 0.35
Prediction of deficit	154	21 ± 6.8	133	4.16 ± 0.35
WFD Control	159 (144)[a]	16 ± 9.3	143	4.18 ± 0.35
WFD Control + feedback	148 (142)[a]	−3 ± 22.9	151	3.70 ± 0.35
				n.s. (P < 0.05)

[a] Actual water required by treatment. Additional irrigation was received when detectors reset before the run-time on the controller had elapsed. See text for details.

Table 4
Total irrigation, change in soil water storage (ΔS) ± 1 standard deviation over the cycle, evapotranspiration plus drainage (ET + D) and above ground dry matter of lucerne ± 1 standard deviation for harvest 2 (ET_o 4–5 mm/day).

Treatment	Irrigation (mm)	ΔS (mm)	ET + D (mm)	Dry matter (t ha^{-1})
Measurement of deficit	149	4 ± 2.8	145	2.82 ± 0.48
WFD Control	183 (173)[a]	2 ± 8.0	181	2.81 ± 0.51
WFD Control+feedback	142 (139)[a]	−14 ± 14.3	156	2.77 ± 0.68
Adjust-coefficient	143	−10 ± 19.7	153	3.14 ± 0.86
Adjust-amount	255	21 ± 5.6	234	2.78 ± 0.73
				n.s. P < 0.05

[a] Actual water required by treatment. Additional irrigation was received when detectors reset. See text for details.

3. Results

3.1. Irrigation cycle 1

The WFDs successfully terminated every irrigation event when the fronts reached 300 mm depth in both the automated control treatments. Assuming the soil was at a tension of about 2 kPa at the time the control WFD was activated, and the UDL was around 10 kPa, then the corresponding water content values from Fig. 1 suggests that 300 mm × (0.32 − 0.22) or 30 mm of water would be available for redistribution from layer 1 to layer 2. On no occasion did redistributing water activate the layer 2 detector at 600 mm depth, so the two WFD control treatments were essentially the same, and allowed similar amounts of irrigation. A soil water deficit >50 mm was maintained throughout, largely in layer 3 (600–1200 mm), demonstrating negligible drainage from the bottom of the profile. The treatment involving prediction of soil water deficit by crop model (Treatment 2) required a similar amount of water to the WFD control treatments. The measurement of soil water deficit treatment by neutron probe required substantially more water than the other treatments, probably because the profile was not full of water at the start of the cycle (Table 3).

Table 3 gives a value for the water applied to the WFD control treatments and a second lower number in parenthesis, which is what the treatment actually required. The difference is due to the fact that the electronic WFDs “reset” before the 3 h run-time on the controller had elapsed. Irrigation was shut down when the wetting front first activated the float switch, but the soil surrounding the WFD was able to ‘wick’ water out of the detector funnel by capillary action before the 3 h run-time on the controller had expired. The electronic float in the WFD returned to the rest position, thus reactivating the circuit between the controller and the solenoid. Irrigation recommenced until it was either shut down by the detector again or after the 3 h run-time elapsed. The end result was that the two WFD control treatments received slightly more water than was intended.

3.2. Irrigation cycle 2

Lucerne cycle 2 coincided with slightly cooler conditions and unlike cycle 1 started on a fully wet profile. The layer 1 WFDs terminated each irrigation event in the control treatments, but this time the layer 2 detectors at 600 mm in the control + feedback treatment were activated 11 times out of a potential 40 (8 irrigation events and 5 replicates). This means that the redistributing water from layer 1 could not be stored in layer 2, and a wetting front was recorded as moving into layer 3 (600–1200 mm depth). When a layer 2 detector was activated in any of the control + feedback replicates, that plot was omitted for the next irrigation. For this reason this treatment received 41 mm less water than the equivalent treatment without feedback (Table 4).

The Adjust-amount treatment required the most irrigation water. The layer 1 detectors responded to every irrigation event in each of the 5 replicate plots, but the control criteria were derived from the layer 2 detectors at 600 mm i.e. water moving to layer 3. Irrigation events 1, 2 and 5 activated the layer 2 detector in only one replicate plot, thus triggering 30% increases in application over the previous amount (Table 2). Only event 4, where 38 mm was applied, caused layer 2 detectors to respond in all replicates and hence the irrigation to be reduced (Fig. 2a). The amount of water applied over the final three irrigation events was greater than the combined soil water deficit in layers 1 and 2, but the required number of detectors did not record water moving into layer 3 and thus irrigation was not reduced (Fig. 2b).

By contrast, the Adjust-coefficient treatment was under-irrigated. There were only two responses from layer 1 detectors and none from the layer 2 detectors over the first four irrigation events of cycle 2 (Fig. 2c). The initial crop coefficient was set at 0.4, and the control criteria in Table 2 allowed for a 0.1 increment after each irrigation event, which was not enough. It took until near the end of the cycle before irrigation matched, and then slightly exceeded crop demand, as shown by the change in soil water storage (Fig. 2d).

3.3. Irrigation cycle 3

The third cycle was carried out when the ET_o was about half that of the first cycle. These conditions produced the largest range in irrigation applications across treatments, although there was still no significant difference in lucerne yield (Table 5). The Adjust-coefficient treatment received just 92 mm, whereas the Adjust-amount treatment received 260 mm. Using feedback from a layer 2 detector gave a difference of 57 mm between the two automatic control treatments.

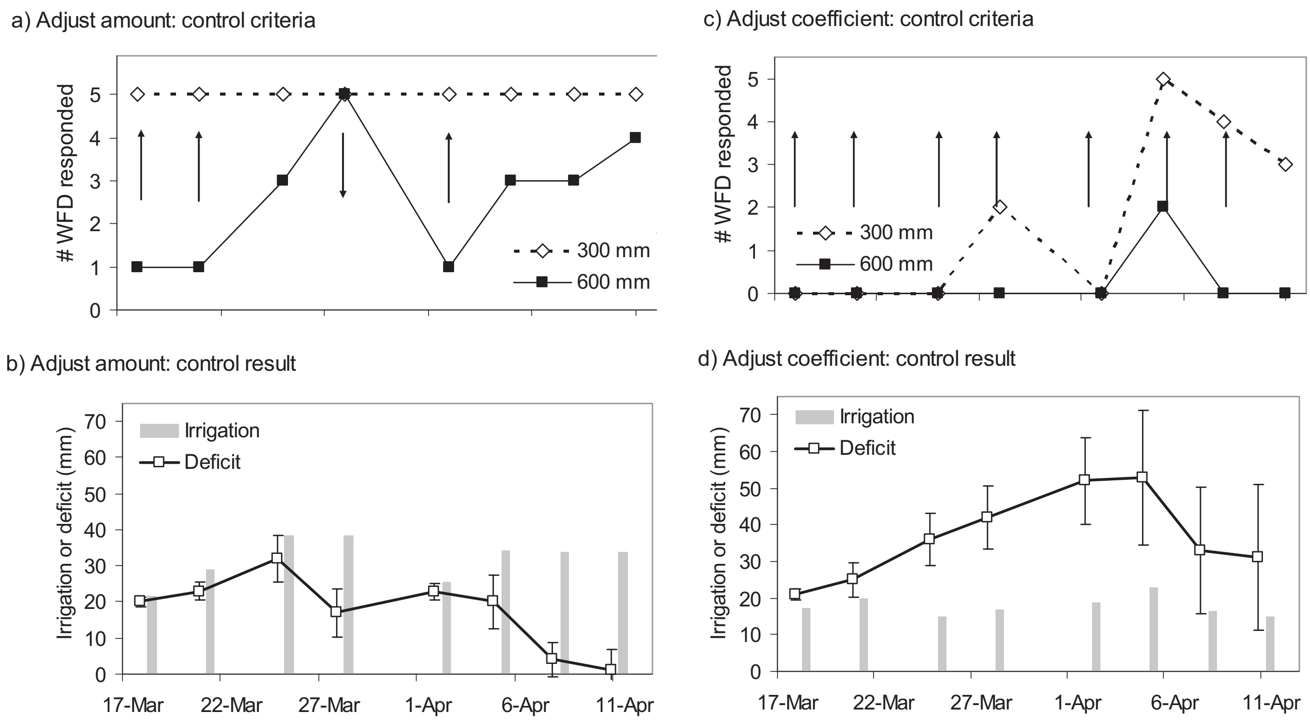

Fig. 2. The number of WFDs that responded to each irrigation event at 300 and 600 mm depths for cycle 2. The up and down arrows show whether the control criteria required the amount of irrigation to be increased or decreased for a) the Adjust-amount treatment and c) the Adjust coefficient treatment. The amount of irrigation applied as a result of the control criteria, and the soil water deficit to 600 mm is shown for b) the Adjust-amount treatment and d) the Adjust coefficient treatment. Error bars show one standard deviation of the soil water deficit measured by neutron probe across the five replicates.

Table 5
Total irrigation, change in soil water storage (ΔS) ± 1 standard deviation over the cycle, evapotranspiration plus drainage (ET + D) and above ground dry matter of lucerne ± 1 standard deviation for harvest 3 (ET_o 3–4 mm/day).

Treatment	Irrigation (mm)	ΔS (mm)	ET + D (mm)	Dry matter (t ha^{-1})
Measurement of deficit	196	18 ± 6.7	178	2.44 ± 0.12
Prediction of deficit	113	6 ± 7.4	107	2.66 ± 0.27
WFD Control	230 (196)[a]	17 ± 10.1	213	2.54 ± 0.07
WFD Control + feedback	173 (157)[a]	19 ± 13.5	154	2.54 ± 0.20
Adjust-coefficient	92	−20 ± 15.9	112	2.64 ± 0.13
Adjust-amount	260	23 ± 8.3	237	2.53 ± 0.25
				n.s. $P < 0.05$

[a] Actual water required by treatment. Additional irrigation was received when detectors reset. See text for details.

The starting estimate of 47 mm for the first irrigation event in the Adjust-amount treatment proved too high, and substantial over-irrigation occurred before the control criteria could reduce the irrigation quantity to a more realistic value (Fig. 3a, b). The Adjust-coefficient treatment was under-irrigated despite the fact that the crop coefficient was increased from 0.4 to 1.2. The soil water storage was on a falling trend and no WFDs responded to irrigation (Fig. 3c, d).

Measurement of soil tension made after the experiment showed that the soil continued to drain for many days, long after the 48 h period which is the conventionally accepted time period for setting the UDL (Fig. 4). The simulation using Hydrus-1D followed the measured data, showing a maximum deviation of 2 kPa. The initial tension in the simulations was set a 1 kPa, whereas the actual soil measurement did not reach such a low value following irrigation, particularly at 300 mm depth (Fig. 4a). Changes in tension at 600 and 900 mm reflect drainage alone, as the lucerne crop had been removed by this stage, and the correlation with the simulated data was high (Fig. 4b,c). The drier actual starting condition and soil evaporation contributed to the measured values being slightly above the simulated at 300 mm depth.

4. Discussion

The lucerne crop was effective at creating sufficient soil water deficit to allow the three methods of deploying the tipping bucket analogy to be evaluated. The lucerne yield itself did not discriminate between treatments, since it is a deep rooted crop growing on a profile with a large water holding capacity, and the profile was refilled between cycles. Treatment accuracy was therefore assessed against the following protocol. Soil water content readings were always taken before the bi-weekly irrigation, at the driest point in the cycle, and should reflect three or four days of ET. If the soil water storage was on a generally falling trend, the treatment was considered to have been under-irrigated because the soil store was mined. If the soil water content was fairly constant or rising towards field capacity, the treatment was considered to be satisfactorily irrigated. However, this does not account for drainage past 1200 mm, which cannot be calculated from water content measurements alone. Therefore, the treatments receiving the least water without mining the soil water store were considered to be ‘About right’.

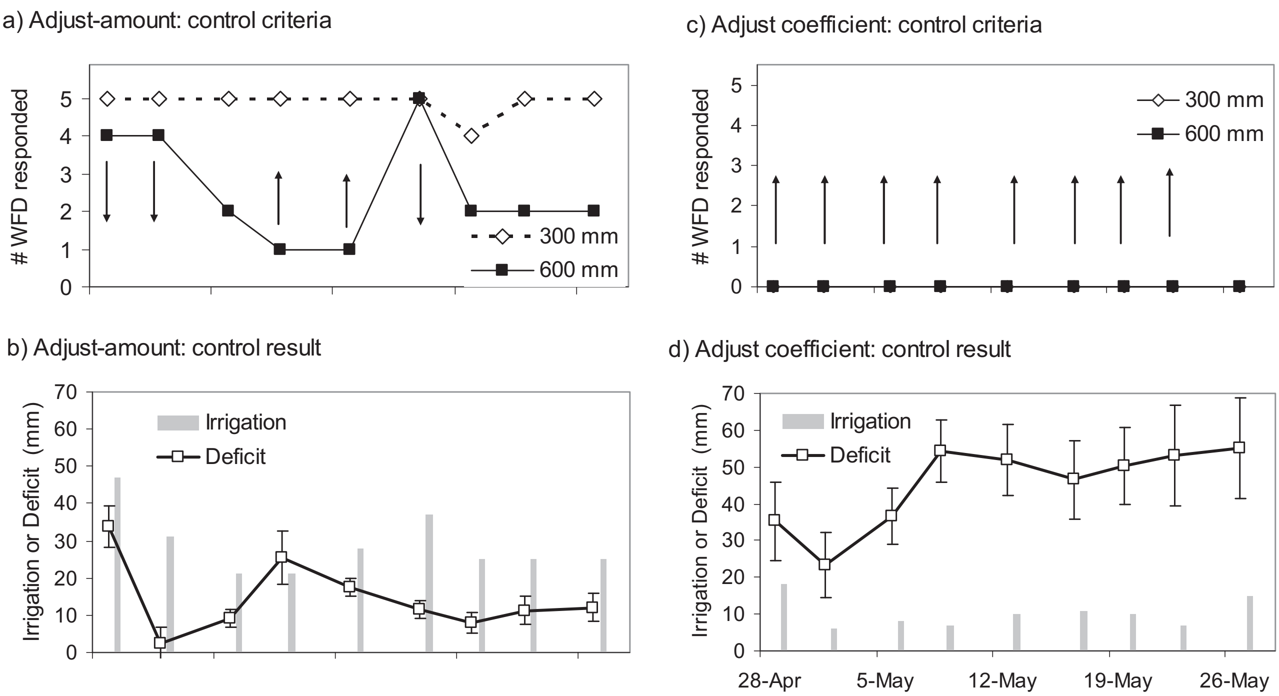

Fig. 3. The number of WFDs that responded to each irrigation event at 300 and 600 mm depths for cycle 3. The up and down arrows show whether the control criteria required the amount of irrigation to be increased or decreased for a) the Adjust-amount treatment and c) the Adjust coefficient treatment. The amount of irrigation applied as a result of the control criteria, and the soil water deficit to 600 mm is shown for b) the Adjust-amount treatment and d) the Adjust-coefficient treatment. Error bars show one standard deviation of the soil water deficit measured by neutron probe across the five replicates.

Table 6
Qualitative evaluation of the water applied by the six treatments.

Treatment	Cycle 1	Cycle 2	Cycle 3
Measurement of deficit	Over	About right	Over
Prediction of deficit	About right	–	About right
WFD Control	About right	Over	Excessive
WFD Control + feedback	About right	About right	Over
Adjust-coefficient	–	About right	Under
Adjust-amount	–	Excessive	Excessive

The ‘About right’ terminology reflects the fact that there was large variability in neutron probe readings among replicates (Figs. 2 and 3), so we cannot be definitive about the exact water requirements for each cycle. The ‘Under’ and ‘Over’ ratings were made on the assumption that ET was similar across treatments, with the ‘Excessive’ rating applied when water was clearly well in excess of plant requirements (Table 6).

The best outcome came from prediction of soil water deficit using the crop model. The SWB model required some computer skills, as well as correct crop parameters and access to real-time climatic input data. It was operator error that caused this treatment to fail in cycle 2, so in that sense there is risk if users are not thoroughly trained. The crop model would appear to represent the most reliable way of scheduling irrigation, so the relatively low adoption of models by irrigators (Leib et al., 2002; Stevens et al., 2005) appears to be part of the aversion farmers show to decision support systems in general (McCown, 2002).

Irrigation cycle 1 demonstrated that automatic control by overriding the solenoid valve with an electronic WFD can work well, but the method over-irrigated for cycles 2 and 3. This occurs because automatic control applies an amount of water $d\ (\theta_{wf} - \theta_{udl})$ more than the deficit to the depth of the detector, amounting to 30 mm if we assume θ_{udl} is reached at a tension of 10 kPa. Given that UDL was closer to 5 kPa tension (Fig. 4a) this ‘extra’ water was approximately 15 mm. However when the ET_o over 3 days is also around 15 mm or less, the method is prone to over-irrigate. Either the irrigation interval must be lengthened or the controlling WFD must be closer to the surface.

The control treatment with feedback from the layer 2 detectors managed to fully correct for the declining ET_o in cycle 2, and partially correct in cycle 3. Since some of the water that redistributed below the 300 mm WFD was not transpired in the days following irrigation, the soil between 300 and 600 mm depths became wetter. As layer 2 approached UDL, the redistributing water from layer 1 from the following irrigation event now activated the layer 2 detector. As the next irrigation was skipped for these plots, this effectively lengthened the irrigation interval as the weather cooled.

The two treatments that relied on adjusting the next irrigation based on whether water moved from layer 2 to layer 3 performed poorly. This was partly a fault of the chosen control criteria. For example, the control criteria could only increase the crop coefficient in increments of 0.1 twice per week, and this proved to be too slow an adjustment for a lucerne crop re-growing after cutting. Similarly, the first irrigation applied to the Adjust-amount treatment was too high for cycle 3, and by the time the control criteria had decreased irrigation from 47 to 21 mm, substantial over-irrigation had already occurred.

This iterative method of scheduling where corrections are made based on feedback might have worked if i) the control criteria were improved or ii) if iteration occurred more frequently than twice a week. However, regardless of the control criteria, the version of WFD used was not capable of providing adequate feedback from a depth of 600 mm. Figs. 2 b and 3 b clearly show instances where the irrigation applied was significantly above the deficit to 600 mm, and not all the WFDs were activated.

If we assume that the WFD has a sensitivity limit of 3 kPa (Stirzaker, 2008), then according to the Hydrus simulation, the drainage rate would be about 0.5 mm/h (Fig. 5). Water was entering the soil surface as irrigation at a rate of 18 mm/h, but only for a short period of time. During the slow redistribution phase after

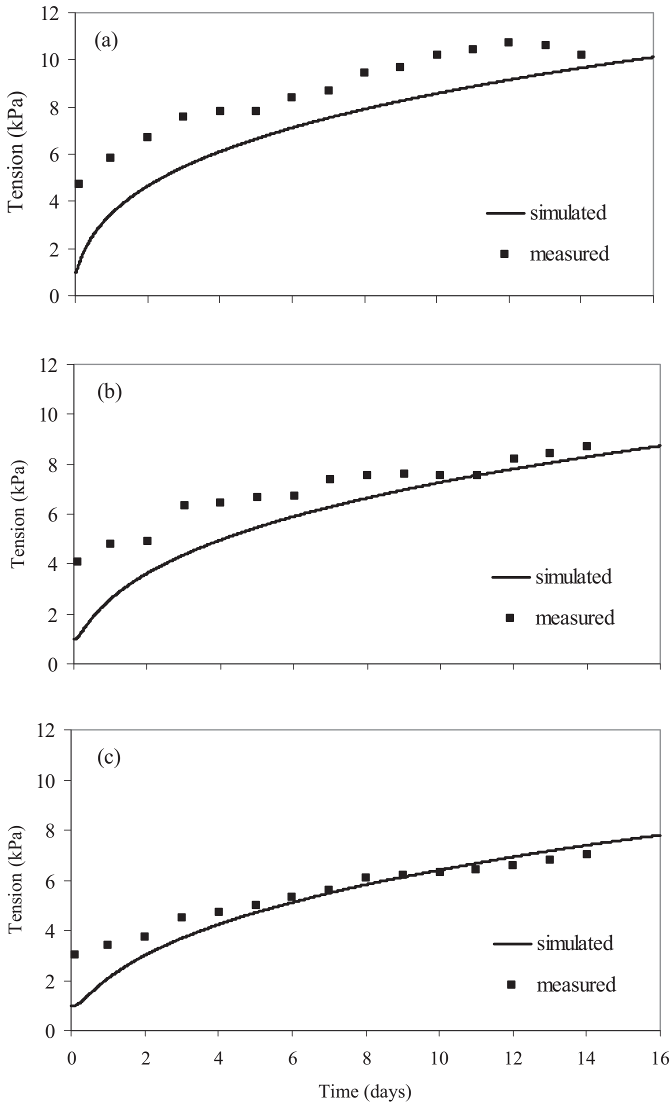

Fig. 4. The change in tension post saturation after the lucerne crop was removed at a) 300 mm b) 600 mm and c) 900 mm depths. The solid lines show the simulations from Hydrus-1D.

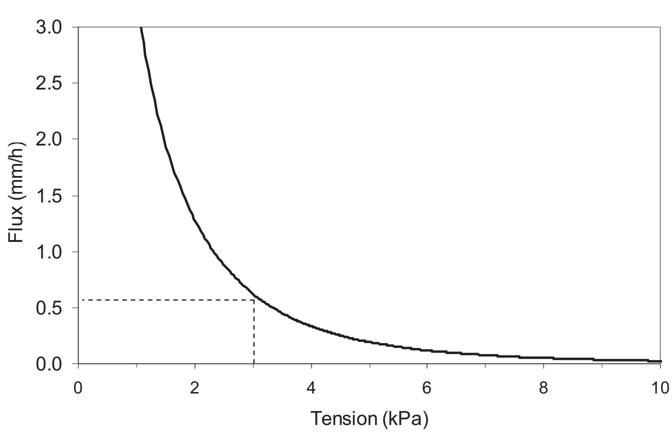

Fig. 5. The flux rate as a function of soil tension at 600 mm depth from the Hydrus simulation of a draining profile. The dotted line represents the sensitivity limit of the WFD.

irrigation has ceased (Fig. 4), the small rates of drainage occurring over several days would account for the substantial drainage that was unrecorded by WFDs in the Adjust-amount treatment.

The treatment relying on neutron probe measurements provided too much water for cycles 3, when ET_o was at its lowest. UDL is not an intrinsic soil property and its calculation is prone to error (Ahuja and Nielsen, 1990; Adhanom et al., 2012). The tipping bucket analogy assumes the bucket is full after 48 h drainage, and that drainage after this time is negligible. However, layers 1 and 2 were at 7 kPa and 5 kPa respectively after 48 h (Fig. 4) and could still be draining at a rate of up to 5 mm per day.

Figs. 2 and 3 show that the sensitivity of a WFD is an important consideration. If deep placements are required or low fluxes need to be detected, WFDs need to be more sensitive (respond to “weaker” wetting fronts). This can be achieved by the inclusion of wicks, which can increase the sensitivity of passive lysimeters (Gee et al., 2002; Zhu et al., 2002; Stirzaker, 2008). The advantage of the funnel shaped detector described here is that it gives a quick response to a strong front, is useful for soil solution monitoring and is easily converted from electronic to mechanical form, but it must be deployed within its limitations. Although the WFD was originally conceived as an irrigation scheduling tool, it is now largely used for nutrient management. The ability to capture and store a water sample from the wetting front at the time the front passes is utilized by scientists and farmers to measure nitrate leaching and salt accumulation (Fessehazion et al., 2011; Stirzaker and Cutting, 2016), in addition to wetting depth.

5. Conclusion

Irrigation can be scheduled objectively by automatic control from a WFD, but this requires us to compute a combination of detector depth and irrigation interval that can provide control within the limits of the technique. The use of a second, deeper detector can help to adjust the irrigation interval without the above information, but is not a complete solution in itself. The control methods that relied on WFD feedback from deep in the soil were inadequate. Control was broadly in the right direction, but too coarse to provide an acceptable result. However the commonly accepted method of filling the bucket based on deficit from a UDL was no better than the two layer WFD method (Table 6). The weakness of the WFD method was its inability to detect weak redistributing fronts. The weakness of the Neutron Probe method was that the bucket analogy can lead to error in slow draining soils—at best it is a leaky bucket.

It is possible to learn from the above experiments and generate rules on how to use the WFD method. For example if few detectors at 300 mm depth respond, the crop will be under-irrigated and if detectors at 600 mm depth are regularly activated, the crop is likely to be over-irrigated. In practice we found that commercial farmers did develop rules of thumb around WFD response rates, based on their past experience and other methods of monitoring (Stirzaker et al., 2010). Our experience shows that a ‘first principles’ approach of irrigation by wetting front depth is problematic, and these heuristics are best developed from experience.

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