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Irrigation controlled by a wetting front detector: field evaluation under sprinkler irrigation

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Abstract. The accuracy of scheduling irrigation to turf by sprinkler was evaluated using a simple wetting front detector that automatically switched the water off after the wetting front had reached a prescribed depth in the soil. The detector consists of a funnel-shaped container that is buried in the soil. When a wetting front reaches the detector, the unsaturated flow lines are distorted so that the water content at the base of the funnel reaches saturation. The free water produced is detected electronically and this provides the signal to stop irrigation. The performance of the detector was evaluated over 38 consecutive irrigation events to test the theory that the velocity of a wetting front depends on the difference in water content ahead of and behind the front. The experimental data plotting the irrigation amount permitted by the wetting front detectors as a function of the soil water content before and after irrigation yielded a linear relationship with a slope of 0.95 and a correlation coefficient of 0.73. Thus, if the soil is dry before irrigation the front will move slowly and an irrigation of long duration will be permitted, with the converse applying to wet soil. Independent monitoring of soil water content showed that irrigation was, for the most part, scheduled accurately. Irrigation interval was the key variable to control. When the interval was too short then over irrigation occurred.

Additional keywords: irrigation scheduling, soil moisture sensors, irrigation interval, irrigation uniformity, soil water content.

Introduction

Irrigation scheduling by soil water content measurement requires 3 pieces of information; the minimum water content below which there is unacceptable plant stress, an upper drained limit, and the depth of soil that needs to be replenished with water. The changes in soil water content in an irrigated field are mostly within a range of $0.1\,m^3/m^3$, and several commercially available tools can measure to a precision of $0.001\,m^3/m^3$ (Charlesworth 2005), so it would appear easy to monitor the depletion in soil water from the upper drained limit to some threshold lower limit.

Although the precision of many tools for monitoring soil water content is high, poorer accuracy, combined with variability in application uniformity, compromises their ability to provide information for irrigation decisions (Schmitz and Sourell 2000; Connellan 2004). Moreover, standard terminologies such as the upper drained limit and refill point are not intrinsic properties of the soil–plant system, but depend on a complex interplay between the antecedent water content, evapotranspiration rate and crop stage (Ahuja and Nielsen 1990).

This paper tests the hypotheses that scheduling of sprinkler irrigation can be carried out by irrigating at a fixed interval, but turning the water off when a wetting front has reached a set depth in the soil. The method is potentially simple because it only requires one piece of information. This paper evaluates a wetting front detector designed to be more robust than that proposed by Cary and Fisher (1983) yet simpler than that described by Zur *et al*. (1994).

The wetting front detector was a funnel-shaped object designed to distort the downward movement of water, producing free water at its base which was detected electronically. Assessment of the wetting front detector as a practical means for scheduling irrigation requires 2 separate evaluations. Firstly, we must establish that the device itself can accurately and reliably fulfill its purpose of detecting wetting fronts. Secondly, we must demonstrate that knowing the position of a wetting front at one depth is sufficient information to schedule irrigation. Thus, we must individually substantiate both the device and the method.

Theory

Scheduling by position of wetting front is based on the theory of Philip (1957, 1969), which states that the velocity of a wetting front is inversely related to the initial water

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content of the soil. The wetting front detector evaluated in this experiment was a buried funnel-shaped device (Hutchinson and Stirzaker 2000; Stirzaker 2003). Water converges and diverges around the device to produce a zone of high vertical flow velocity that carries water to the base of the funnel. The flow velocity and volume of water reaching the base of the funnel are functions of its geometry, the surrounding soil properties and the strength of the wetting front. If the soil surrounding the detector is sufficiently wet, the soil at the base of the funnel becomes saturated and water flows through a filter into a chamber where it is detected electronically (Fig. 1*a*). The chamber is vented to the surface via a narrow tube so that the pressure inside the chamber remains ambient as water seeps in through the filter. After irrigation is turned off, the water is withdrawn from the chamber by capillary action, and the device is automatically reset.

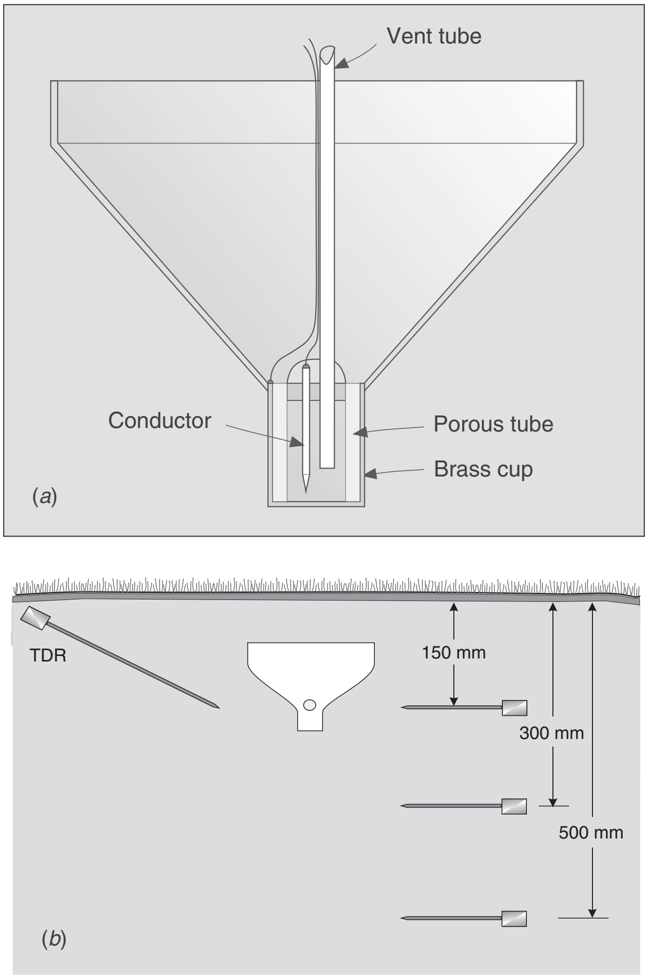

Fig. 1. (*a*) Diagram of the wetting front detector; (*b*) The field layout of the Wetting Front Detector and TDR probes. Detectors were also placed at 300 and 500 mm depths (not shown).

The velocity of a wetting front V is given by Rubin and Steinhardt (1963) as:

$$V = (\mathrm{IR} - K_{\theta_i})/(\theta_{wf} - \theta_i) \qquad (1)$$

where IR is the irrigation rate, K_{θ_i} is the unsaturated conductivity at the initial water content, θ_{wf} is the volumetric water content behind the wetting front, and θ_i the initial volumetric water content or water content ahead of the front. The value of K_{θ_i} is generally 2 or 3 orders of magnitude less than the irrigation rate, so it can be omitted from Eqn 1.

We can determine the time, t, it takes for a wetting front to reach a given depth, d, using $V = d/t$ and combine with Eqn 1 to give:

$$t = d(\theta_{wf} - \theta_i)/\mathrm{IR} \qquad (2)$$

The amount of irrigation in mm, I, is the product of IR and t so:

$$I = d(\theta_{wf} - \theta_i) \qquad (3)$$

If θ_{wf} remains relatively constant for a given soil–irrigation combination, and since d is fixed, then the amount of irrigation applied on any day should be inversely related to the initial water content. Put simply, if the soil is dry before irrigation, then the front will travel slowly and a long irrigation will be permitted before the front reaches the detector. Conversely if the soil is wet before irrigation, the front will move quickly and irrigation would be of short duration.

A wetting front detector that turns irrigation off must be located above the depth we want water to infiltrate because there is an overhead, O, associated with each irrigation event given by:

$$O = d(\theta_{wf} - \theta_{udl}) \qquad (4)$$

where θ_{udl} is the upper drained limit and d the depth to the detector (Zur *et al.* 1994). This water above the upper drained limit moves down through the profile after irrigation ceases. The final depth of the wetting front depends on the ability of the soil below the detector to store the water or $(\theta_{udl} - \theta_i)$. It also depends on the transpiration rate during the redistribution period, since transpiration and redistribution occur simultaneously.

The value of d depends on the rooting depth of the crop, and once d is chosen, a conservative irrigation interval can be calculated. The interval, t, is calculated by estimating the total amount of water that can be added to the soil above the detector and dividing by the maximum expected transpiration rate for any period.

$$t = d(\theta_{wf} - \theta_{rf})/Et \qquad (5)$$

Materials and methods

The field experiment was carried out between 1997 and 1999 in Canberra, Australia (−35.283; 149.217). The soil was alluvial material, uniform with depth, comprising 50% coarse sand, 20% fine sand, 16% silt, and 13% clay, with a pH($CaCl_2$) of 6.2 and organic carbon content of 1.0%. The site was ripped to 200 mm then rotary hoed and PGP Hunter pop-up sprinklers positioned at each corner of a 10 by 10 m square.

Wetting front detectors and time domain reflectometry probes (TDR; Zegelin *et al*. 1989) were installed at each corner of a centrally located 3 by 3 m square. The vertical distance from the rim of the funnel to the conductivity cell of the detector was 150 mm, but the velocity of the front would increase within the funnel as the cross-sectional area decreased. It was assumed that by the time water was detected at the base of the funnel, the front in the surrounding soil would be ~100 mm below the rim of the funnel. Holes were excavated and wetting front detectors positioned to record fronts at depths of 500, 300, and 150 mm below the soil surface as the hole was progressively refilled. TDR probes, with 150-mm-long wave guides, were placed horizontally alongside the detectors at depths of 500, 300, and 150 mm. A TDR probe with 400-mm-long wave guides was installed obliquely to monitor the soil water content from 50 to 150 mm (Fig. 1*b*). The above installation was replicated 4 times.

Roll-on turf (80% fescue and 20% blue grass) was laid over the entire area and a Texas Electronics Model TR-525 M tipping bucket rain gauge (resolution 0.1 mm) placed at the centre of the inner quadrant between the 4 sites (Fig. 2). The wetting front detectors were connected to a data logger, which recorded the exact time water reached the conductivity cell in the neck of the wetting front detector funnel (detector tripped) and the time when water had been withdrawn by capillary action (detector reset). The water content measurements were made at intervals of 10–15 min for the entire duration of the experiment. Approximately 20 mm of soil was attached to the turf, and its water content was assumed to be the same as that in the 50–150 mm depth, as measured by TDR. The grass was mown regularly so that the sward height remained approximately 20–40 mm high.

Thirty-eight consecutive irrigation events were monitored between April 1997 and March 1998. The irrigation rate averaged 14.6 mm/h (range 11.8–17.4) and the 4 sprinklers covered each site. Between 8 October and 25 November, irrigation was carried out on a 7-day interval, starting automatically at 0830 hours and terminating when the third of 4 of the shallowest detectors (150 mm) had tripped. The interval was shortened to 5 days over the summer period (25 November to 18 February.). The irrigation interval before 8 October and after 18 February varied from between 1 day to several weeks, to evaluate the importance of frequency of irrigation on the accuracy of the scheduling method.

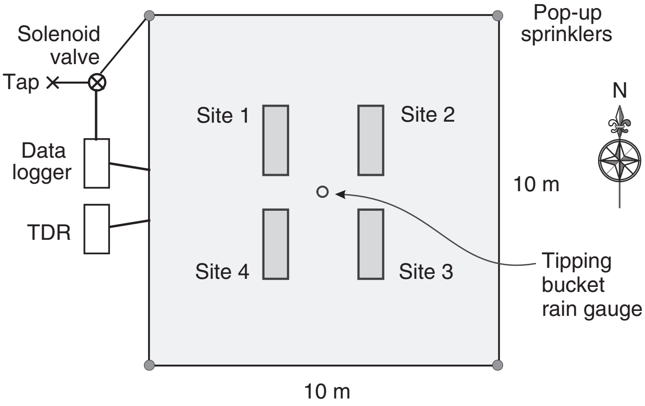

Fig. 2. A plan layout of the site showing the location of sprinklers, rain gauge, and measurement sites.

If sufficient rain fell to trip 3 detectors then the irrigation interval was automatically reset. On 6 occasions the irrigation uniformity was measured by placing 6 catch cups, 73 mm diameter, over each of the sites and comparing the depth of water against that measured by the tipping bucket rain gauge.

Results

Detection of a wetting front

An example illustrates the change in water content with time at a depth of 150 mm from a single irrigation event (Fig. 3). The irrigation event started at 0830 hours and was terminated after 56 min when the third of 4 detectors at 150 mm depth had tripped. The first 3 detectors tripped within 3 min of each other and the fourth (site 2) within 12 min from the

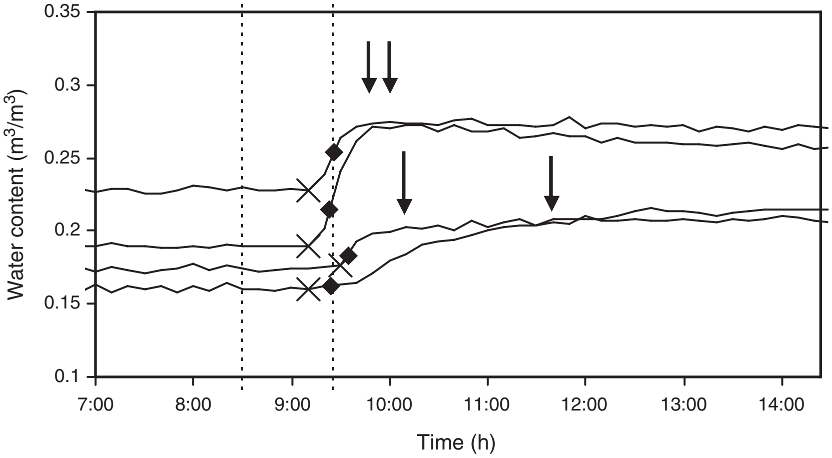

Fig. 3. TDR data of a single irrigation event at the 4 sites. The vertical dotted lines denote the start and end time of the irrigation. The filled diamonds denote the time that the detector tripped. The × marks the last TDR reading before the front arrived. The down arrow marks the time when the water content was no longer on a continuously rising trend.

first (trip time denoted by filled diamonds in Fig. 3). Despite this uniformity in trip time among detectors, there were substantial differences in the water content measured by TDR before and after the front among the 4 measurement sites. Since the soil was uniform and the sites in close proximity, we assume this was due to soil disturbance adjacent to the probes.

Figure 3 shows that a front is not always a sharp divide between wet and dry soil, but rather moves through the soil as a wave. The event shown in Fig. 3 was summarised for 38 consecutive irrigation events in Fig. 4 by plotting the initial and final water contents (joined by a dotted line) and the time between these 2 points. For each irrigation event, the initial water content was taken as the last reading before the TDR recorded the approaching front (denoted by an X in Fig. 3), and this value is plotted at $t = 0$. The time delay until maximum water content was reached, and the maximum water content value, is also plotted (denoted by a down arrow in Fig. 3). These 2 points are joined by a dotted line, and show the maximum change in water content and the time it took from the reading before the front was detected by TDR to the time maximum water content was reached.

At the 4 sites it took an average of 47–81 min from just before the front was detected by TDR to the time maximum water content was reached. The average time each detector tripped is marked by an X ± 1 standard deviation. The detectors always tripped well before the maximum water content was reached and the trip time relative to TDR was remarkably consistent at each site throughout the season (Fig. 4).

Relationship between irrigation applied and soil water content

The relationship between water applied and the change in soil water content was calculated for all irrigation events, where θ_i was the average water content at all sites over the 50–150 mm depth just before irrigation, θ_{wf} the average of the 3 highest water content readings over the same depth just after irrigation and d the depth to the detector. If Eqn 3 is true, then the slope of the regression line between irrigation permitted by the detectors at 150 mm depth and change in water content above the detectors should be 1 with an intercept of zero. The relationship is highly significant ($P < 0.001$), with a correlation coefficient (r^2) of 0.73 (Fig. 5*a*). The slope of the regression line was 0.95 ± 0.096 with an intercept of 5.9 ± 1.4.

The intercept on the *y*-axis means that the TDR measurements do not account for all the water in the soil due to an irrigation event. It is likely that there is a higher water content in the top 50 mm of soil during and immediately after irrigation, a zone not measured by the TDRs. Some water would also be transpired, intercepted by the grass canopy and held up in the thatch layer that typically develops under a vigorous grass sward.

If we assume that θ_{wf} remains relatively constant for a given soil–irrigation combination, and since d remains constant, we can evaluate the relationship between irrigation applied and the initial water content averaged over the 4 sites. This is the key issue for the irrigator—the time the front takes to reach the detector, hence the duration of irrigation, should be negatively correlated with the water content before irrigation. Figure 5*b* shows the significant linear relationship as expected ($P < 0.01$), but the regression coefficient falls from 0.73 to 0.45 when θ_{wf} is removed from the equation.

The scatter in Fig. 5 could be attributed to variability in the TDR measurements or soil, but the major source of variability is most likely to be non-uniformity of irrigation. The average amount of water applied across the 4 sites during six uniformity tests was similar to that measured in the rain

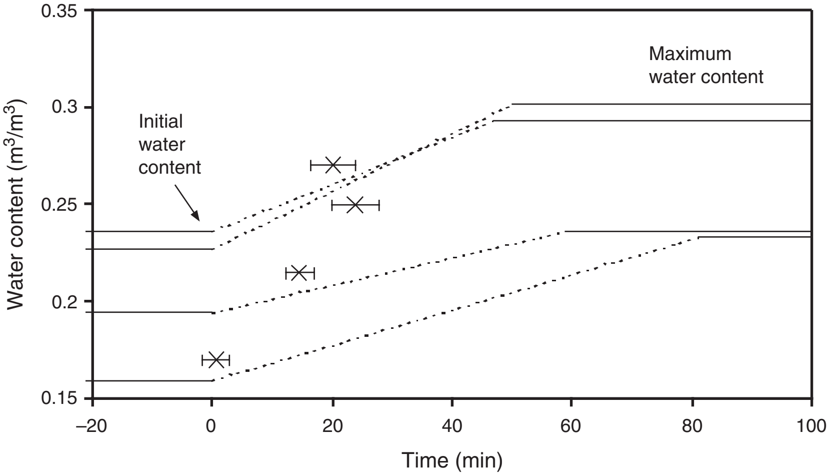

Fig. 4. Average initial and final water contents for all irrigation events at each of the 4 sites. The × denotes the time that the detectors tripped (±1 standard deviation) in minutes after the last TDR reading before there was any rise in soil water content ($t = 0$).

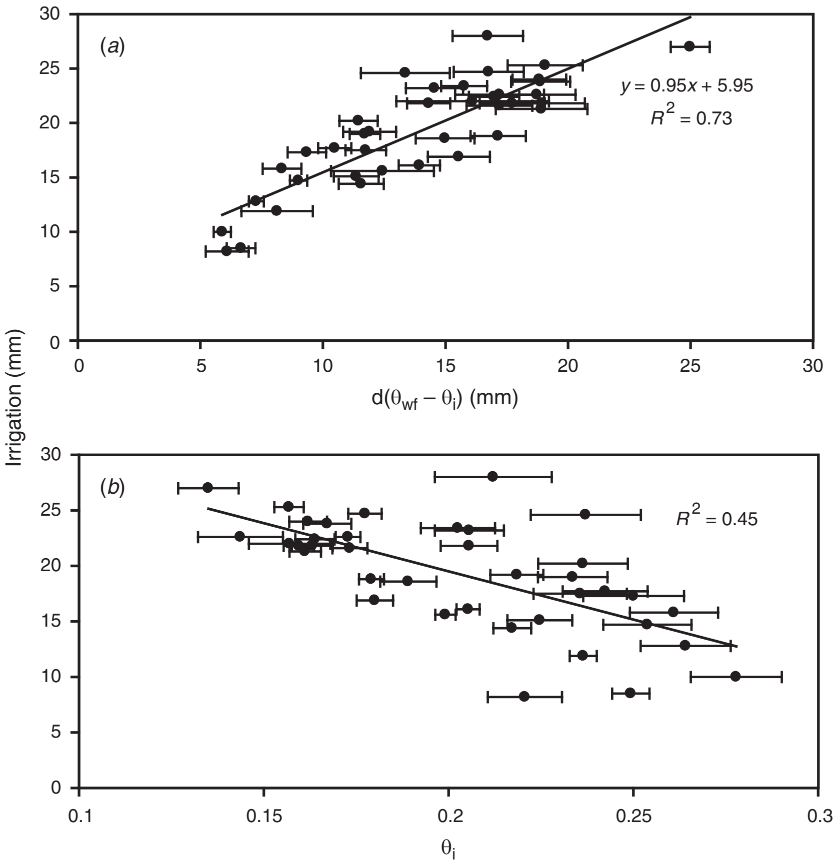

Fig. 5. (*a*) The average difference between the water content ahead of and behind the wetting front multiplied by the depth to the detector (±1 standard deviation) plotted against the amount of irrigation before 3 detectors at 150 mm depth were activated. (*b*) The average water content before irrigation (±1 standard deviation) plotted against the amount of irrigation applied.

gauge. However, whereas the rain gauge data were used for the regression equations, the difference between an individual site and the rain gauge could vary by up to 4 mm (Table 1). The problem was particularly severe on windy days, not reflected in Table 1. On one day with a southerly wind, the sites on the north side recorded the wetting front after an irrigation run time equivalent to 12.1 and 12.2 mm of water, but the third site required a run time equivalent to 28 mm. Since the third detector shut down the irrigation, windy days resulted in higher than normal irrigation amounts. Several of the outliers in Fig. 5 were traced back to windy days.

Seasonal performance

The average water deficit in 3 soil layers throughout the season (0–150, 150–300, and 300–500 mm) is shown in Fig. 6 together with the irrigation and rainfall record. The irrigation season has been divided into 3 periods. The first period, 8 October to 9 January, was dry (45 mm

Table 1. Amount of water (mm) recorded at each site (±1 s.e.) and that recorded in the tipping bucket rain gauge positioned equidistant from the 4 sites

Test no.	Site 1	Site 2	Site 3	Site 4	Average	Rain gauge
1	14.6 ± 0.8	16.7 ± 0.3	12.6 ± 0.5	13.7 ± 0.6	14.4	14.6
2	22.0 ± 0.3	20.5 ± 0.8	18.0 ± 0.4	17.4 ± 0.5	19.5	18.0
3	18.6 ± 0.2	18.8 ± 0.4	16.5 ± 0.3	15.3 ± 0.2	17.3	16.1
4	19.5 ± 0.4	19.6 ± 0.3	20.4 ± 0.2	21.7 ± 0.9	20.3	19.7
5	18.9 ± 0.3	18.1 ± 0.4	18.7 ± 0.4	17.8 ± 0.3	18.4	19.8
6	18.6 ± 0.3	18.3 ± 0.2	16.6 ± 0.4	15.8 ± 0.2	17.3	20.5
Average	18.7	18.7	17.1	17.0		

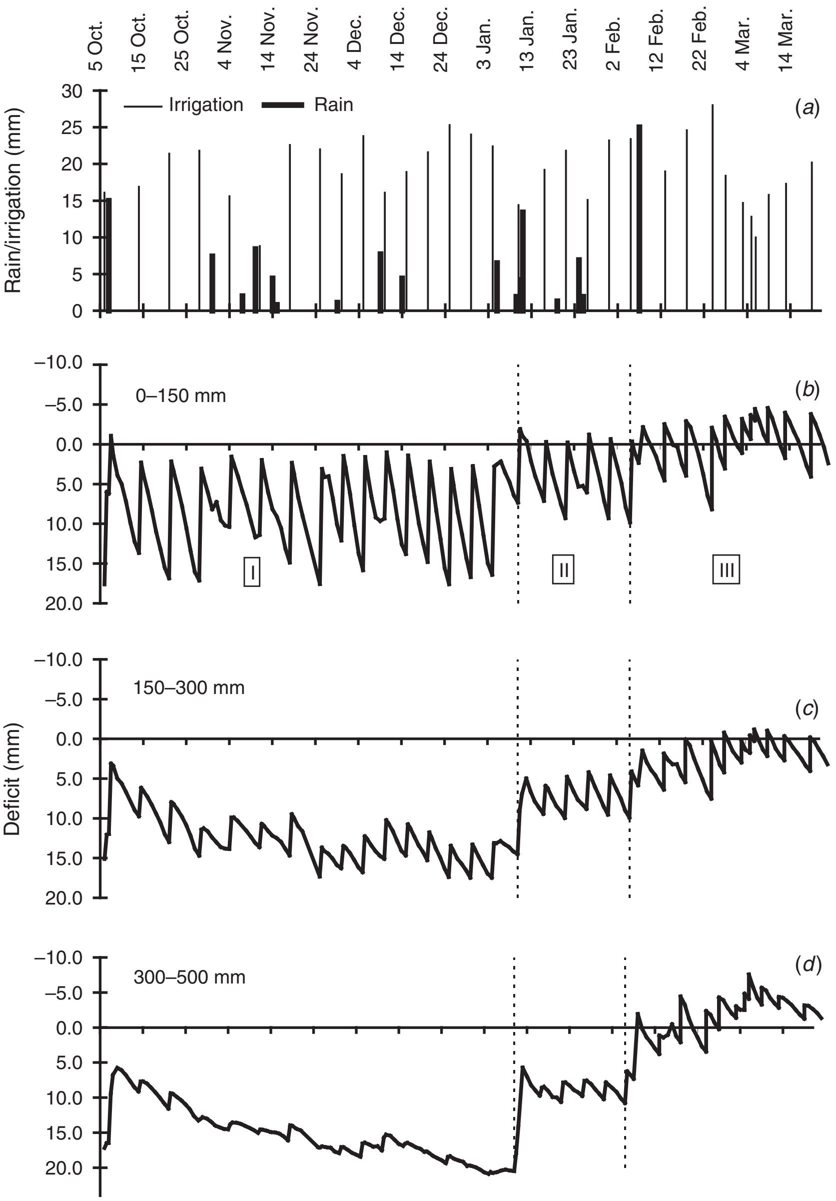

Fig. 6. (*a*) The amounts of irrigation and rainfall during the irrigation season, (*b*) the deficit in the 0–150 mm layer, (*c*) deficit in the 150–300 mm layer, and (*d*) deficit in the 300–500 mm layer. The vertical dotted lines denote time periods discussed in the text. During stage I the irrigation interval was at first 7 days then 5 days. During stage II the irrigation interval was 5 days, and during stage III the interval was varied between 1 and 6 days.

rainfall) and 300 mm of water was applied in 15 irrigation events. Maximum soil water deficits of 9–18 mm were reached in the 0–150 mm layer (Fig. 6*b*). Over the 93-day period, the deficits increased from 1.4 to 12.5 mm in the second layer (Fig. 6*c*) and 2.8–16.5 mm in the third layer (Fig. 6*d*). Each irrigation event filled the topsoil layer, while the lower layers were slowly dried at a combined net rate of about 0.25 mm/day.

Although the irrigation was terminated when the wetting front was detected at a depth of 150 mm, water percolated to the second and even third layer (below 300 mm). There are 2 reasons for this: firstly, the data is a composite of 4 sites, and 2 sites always received more water than they needed, until irrigation was terminated by the third site; and secondly, the soil water redistributed after irrigation, so water almost always moved below 150 mm.

During the second period, 10 January–5 February, the deficit in the 150–500 mm soil layers was reduced. This occurred principally because rain followed irrigation on 11 January. Over the following 24 days, 103 mm of irrigation was applied in 5 events. We observed additions and depletions of water in the lower 2 layers (150–500 mm), but no net change.

Irrigation interval

The irrigation interval was varied between 1 and 6 days during the third period shown in Fig. 6, and the turf was over-irrigated. The amount of water used by the turf could not be calculated from TDR measurements during the third period because transpiration and drainage were occurring simultaneously. Instead a crop factor was calculated by dividing the total water used in each irrigation cycle in period 1 by the pan evaporation for Canberra over the same period. Figure 7 presents a ratio of the water applied and water used by the turf plotted against the irrigation interval. The turf water use is therefore only an estimate, but provides clear evidence that irrigation interval is a critical variable. Excess water is applied if the interval is too short, whereas the profile will steadily be depleted if the interval is too long.

Compensation for rain

There were 17 rainfall events during the summer period and on 3 occasions rainfall was sufficient to trip 3 detectors and therefore delay the next irrigation event by one full cycle. When the rainfall was not sufficient to delay the irrigation cycle, the duration of the subsequent irrigation was shortened. For example the irrigation events on 21 and 28 October required 21.3 and 21.8 mm, respectively. Three days after the irrigation on 28 October there was 7.4 mm of rain. This was not sufficient to activate 3 detectors and restart the irrigation interval, so when irrigation commenced 4 days later the initial soil water content was greater than usual. Thus the wetting fronts moved faster in the soil so that irrigation was terminated after just 15.6 mm, giving a total rain plus irrigation of 23 mm (Fig. 8). A further 10.4 mm of rain fell before the next irrigation event scheduled for 7 days later and the detectors recorded the front after just 8.8 mm of irrigation. The total amount of rain plus irrigation remained relatively constant, with the irrigation requirement reduced in proportion to the rain occurring between irrigation events.

Using more than one detector

The control algorithm of 3 detectors at 150 mm depth resulted in 668 mm of water being applied through the season. If irrigation had been controlled by site 1 only, then irrigation would have totalled 547 mm. For sites 2, 3, and 4 the totals would have been 613, 662, and 633 mm, respectively (Fig. 9*a*). If the control algorithm had been to stop irrigation at the first detector to trip, then 530 mm would have been applied. Stopping irrigation after any 2 or 3 detectors tripped would have given a seasonal total of 608 mm and 668 mm, respectively (Fig. 9*b*).

The results also showed that a second, deeper detector would have been valuable in improving irrigation management. During period I in Fig. 6, when irrigation management was near perfect, the detector response rate at 300 mm depth was 10% and the response rate was 2% at 500 mm depth. The detector response rate was calculated as the average number of detectors that were activated at a particular depth divided by the number of irrigation events in the period. During period II when there was more rainfall, the response rate was 67% at 300 mm and 17% at 500 mm depth. During the final period when over-irrigation occurred due to short irrigation intervals, the response rate was 83% at 300 mm and 50% at 500 mm depth, even though the irrigation itself was terminated when the wetting front reached 150 mm (Table 2).

Discussion

In order to assess the practical use of a wetting front detector we must validate both the device and the method of automatically turning off irrigation when water has

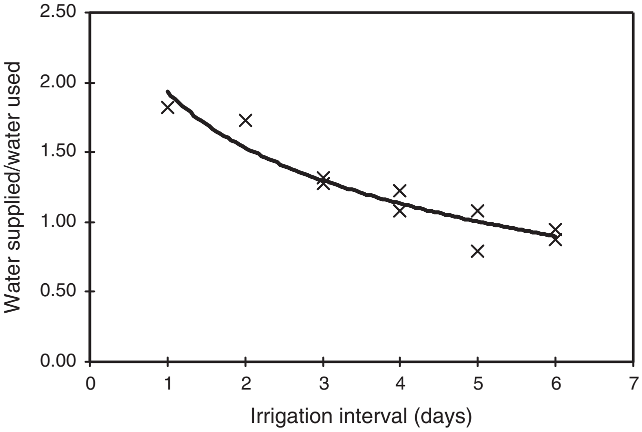

Fig. 7. The water applied before 3 detectors at 150 mm tripped divided by the estimated turf water use as a function of irrigation interval.

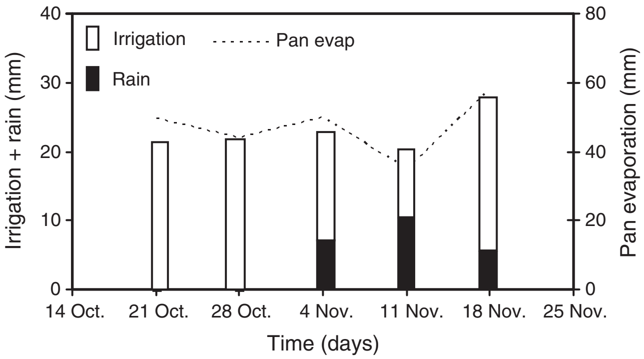

Fig. 8. The amount of irrigation (open bar) plus the rainfall falling since the previous irrigation (filled bar) and the pan evaporation.

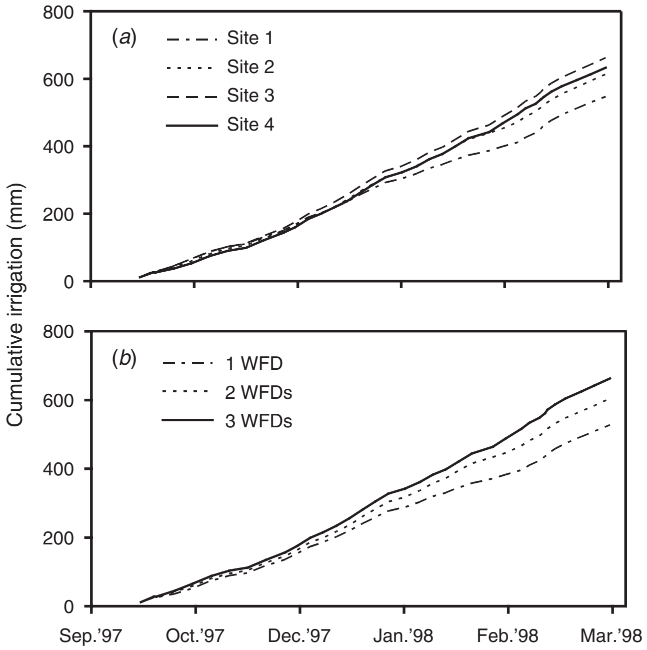

Fig. 9. The cumulative amount of irrigation that would have been applied if irrigation were controlled by (*a*) an individual site and (*b*) if irrigation were controlled by the first, first 2 or first 3 wetting front detectors to trip.

Table 2. Response rate (%) of detectors at 300 and 500 mm depths during periods shown in Fig. 6, calculated as the average number of detectors that responded at each depth after irrigation divided by the number of irrigation events in each period

Period	Date	Detector response rate 300 mm	 500 mm
I	6 Oct.–9 Jan.	10%	2%
II	10 Jan.–5 Feb.	67%	17%
III	5 Feb.–19 Mar.	83%	50%

infiltrated to a prescribed depth. The device itself proved to be adequately sensitive and robust. Every irrigation event was terminated, and the detectors tripped well before maximum water content was reached during the passage of a wetting front. The time water was detected relative to the TDR measurements at each site occurred over a remarkably narrow range throughout the season (Fig. 4), suggesting that the filter was not clogged by soil particles or roots. Many roots were observed within the detectors when they were removed 18 months after installation. Root tips near the base of the funnel had died, so it appears that the periodic waterlogging was an efficient anti-fouling mechanism.

General validation for the method of turning water off when the wetting front reaches a particular depth is provided in Fig. 6. The top 150 mm of soil was refilled at each irrigation event and drainage past 500 mm would have been low up to 5 February, before rainfall and the changed irrigation interval intervened.

An important distinction between the theoretical and practical assessments is that the irrigation events are treated as unrelated in Fig. 5 but occur in a sequence in Fig. 6. Thus there is the opportunity for compensation following slight over or under irrigation, so that errors tend to cancel one another rather than accumulate. As long as the errors are within certain limits, and correction occurs frequently enough, the water content can be kept within acceptable limits.

Irrigation interval is the key variable to control (Fig. 7). The reason for over-irrigation during period III in Fig. 6 was because of the overhead, or water above the control detectors that redistributed below the detectors after irrigation was turned off. For site 4, the overhead, O, was 6.8 mm ($\theta_{wf} = 0.31$ mm, $\theta_{udl} = 0.27$ mm, and $d = 170$ mm, Eqn 4). On average, 4 mm of water was transpired from the top 170 mm over the 24 h period when most of the redistribution was taking place, so about 2.8 mm would move below the detector. The final depth of the wetting front depends on the ability of the soil below the detector to store the water or ($\theta_{udl} - \theta_i$). If $\theta_i = 0.25$ then the wetting front would travel 140 mm below the detector. If $\theta_i = 0.20$ then the wetting front would travel 40 mm below the detector. The problem is much greater during cool weather when transpiration is low and the initial water content below the detector is likely to be wetter.

It is essential to either get the irrigation interval roughly right using Eqn 5, or use deeper detectors to alert that the interval is wrong. The correct interval for this experiment was 3–5 days. Detectors at 300 and 500 mm depths showed when the interval was wrong, because they were hardly ever activated during period I and activated frequently during period III of Fig. 6 (Table 2). A better method of automatic control may be to prevent the control system from turning the irrigation on if the soil is too wet, rather than control the 'off'. Electronic tensiometers were used to schedule sprinkler irrigation to turf in this way with great success by Augustin and Snyder (1984), but 20 years later the method is rarely used. Several newer devices in which tension is inferred by the electrical measurement in a porous ceramic block may provide the necessary accuracy and robustness required for automatic control (e.g. Pathan *et al.* 2003).

A potential drawback of the wetting front detector is disturbance during installation. Even if soil is repacked to similar bulk density, disturbance changes the connectivity of soil pores, which impacts on the saturated hydraulic conductivity. However when water is applied at rates less than the infiltration rate, as is typical for drip or sprinkler systems, the soil surface remains below saturation and the large pores do not conduct water (White *et al.* 1979). The dominant factor impacting the movement of the wetting front is therefore the initial water content, not the saturated hydraulic conductivity.

Moreover, many soil water content tools require soil disturbance during installation and their sensitivity to changes in water content is greatest in the disturbed zone (Evett *et al*. 2002). McKenzie *et al*. (2002) warn that the size of the specimen measured has a major impact on the result, since much of the short range variation occurs because of measurement at inappropriate scales. The concept of 'representative elementary volume' means that a sample containing up to 20 elementary units (peds) may be required for measuring a soil property that is influenced by structure. In this sense the large measurement volume of the detector is an advantage. Variability caused by soil disturbance must be viewed together with the other sources of variation that are difficult to control, in particular the irrigation application uniformity (Table 1). It is instructive to note that site to site variability in the TDR measurements was large, despite the widely held view that it is the most accurate method of continuously measuring soil water content.

Conclusion

We accept the hypothesis that irrigation can be accurately scheduled by turning the water off when the front reaches a specified depth. However we reject the hypothesis that irrigation can be carried out at a fixed interval. There is a certain minimum amount of water that must be applied to propagate a front of sufficient strength to activate the detector. The irrigation interval must be sufficiently long so that crop water use exceeds this minimum amount, or the crop will be over-irrigated. In practice a second deeper detector would provide the necessary feedback that water was infiltrating too deep and that the irrigation interval was too short.

Variability remains the greatest enemy of automated scheduling by soil water status. If only one location had been monitored in the above experiment and site 3 was chosen, then 21% more water would have been applied than if site 1 had been chosen (Fig. 9). If the control algorithm had been that the first detector to be activated would shut off irrigation rather than the third, then 26% less water would have been used. Thus, there is a case for distributing inexpensive devices in the crop to capture this variability, rather than taking very accurate measurements at several depths in one location.

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References

Ahuja LR, Nielsen DR (1990) Field soil-water relations. In 'Irrigation of agricultural crops'. Agronomy Monograph No. 30. (Eds BA Stewart, DR Nielsen) pp. 144–190. (ASA-CSSA-SSSA: Madison, WI)

Augustin BJ, Snyder GH (1984) Moisture sensor controlled irrigation for maintaining bermudagrass turf. *Agronomy Journal* **76**, 848–850.

Cary JW, Fisher HD (1983) Irrigation decisions simplified with electronics and soil water sensors. *Soil Science Society of America Journal* **47**, 1219–1223.

Charlesworth PB (2005) 'Irrigation insights No. 1—Soil water monitoring.' 2nd edn. National Program for Irrigation Research and Development. (CSIRO Publishing: Melbourne)

Connellan G (2004) Performance benchmarking of turf and landscape irrigation systems. In 'Irrigation Australia 2004 Conference'. 11–13 May 2004, Adelaide. (The Irrigation Association of Australia Ltd)

Evett S, Laurent J-P, Cepuder P, Hignett C (2002) Neutron scattering, capacitance, and TDR soil water content measurements compared on four continents. In '17th World Congress of Soil Science'. 14–21 August 2002, Bangkok. Transactions, pp. 1021-1–1021-10. (IUSS: Bangkok)

Hutchinson PA, Stirzaker RJ (2000) A new method and device for scheduling irrigation. In 'Irrigation Association of Australia 2000 National Conference'. 23–25 May 2000. pp. 584–592. (The Irrigation Association of Australia Ltd)

McKenzie N, Henderson B, McDonald W (2002) Monitoring soil change. Principles and practices for Australian conditions. CSIRO Land and Water Technical Report 18/02.

Pathan SM, Barton L, Colmer TD (2003) Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turf. Final Report to Horticulture Australia. http://www.fnas.uwa.edu.au/_data/page/17750/Final_report_for_HAL_project_TU02006.pdf

Philip JR (1957) The theory of infiltration. 2. The profile at infinity. *Soil Science* **83**, 435–448.

Philip JR (1969) Theory of infiltration. *Advances in Hydroscience* **5**, 215–296.

Rubin J, Steinhardt R (1963) Soil water relations during infiltration. I. Theory. *Soil Science Society of America Proceedings* **27**, 246–251.

Schmitz M, Sourell H (2000) Variability in soil moisture measurements. *Irrigation Science* **19**, 147–151. doi: 10.1007/s002710000015

Stirzaker RJ (2003) When to turn the water off: scheduling micro-irrigation with a wetting front detector. *Irrigation Science* **22**, 177–185. doi: 10.1007/s00271-003-0083-5

White I, Smiles DE, Perroux KM (1979) Absorption of water by soil: The constant flux boundary condition. *Soil Science Society of America Journal* **43**, 659–664.

Zegelin SJ, White I, Jenkins DR (1989) Improved field probes for soil water content and electrical conductivity using time domain reflectometry. *Water Resources Research* **25**, 2367–2376.

Zur B, Ben-Hanan U, Rimmer A, Yardeni A (1994) Control of irrigation amounts using the velocity and position of wetting front. *Irrigation Science* **14**, 207–212. doi: 10.1007/BF00190192

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