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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

$$I(\mathrm{mm}) = d(\theta_{\mathrm{udl}} - \theta_{\mathrm{i}}) \quad (1)$$

where $\theta_{\mathrm{udl}}$ is the upper drained limit (UDL) of the soil, $\theta_{\mathrm{i}}$ 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

$$I(\mathrm{mm}) = d_1(\theta_{\mathrm{wf}} - \theta_{\mathrm{i}}) \quad (2)$$

where $\theta_{\mathrm{wf}}$ 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 $d_1(\theta_{\mathrm{wf}} - \theta_{\mathrm{udl}})$ 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 $\theta_{\mathrm{wf}}$. 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.

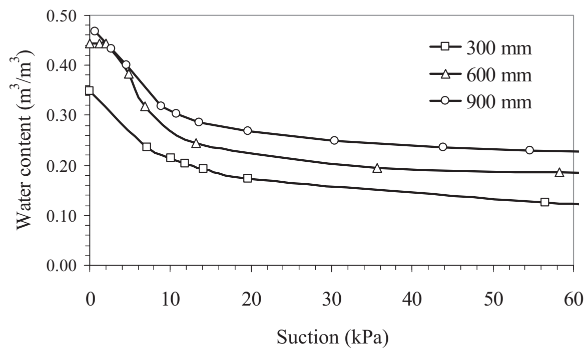


**Fig. 1.** The draining water release characteristic at 300, 600 and 900 mm depths.

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).