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Estimating irrigation duration for high performance furrow irrigation on cracking clay soils

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ABSTRACT

Selection of an appropriate combination of flow rate and time to cut-off is critical to the achievement of high performance furrow irrigation. For the cotton growing regions of Australia the ready availability of land and the relative scarcity of water impose a constraint not present in all surface irrigation areas. In this situation the objective is to improve water use efficiency by maximising application efficiency. In this paper, simulations employing this strategy and historical furrow irrigation data have shown that application efficiency increases with flow rate up to a point where no further increase in efficiency is possible. They have also shown that for any field there is a simple linear relationship between time to cut-off and the time for the advance to reach mid-way down the field. This relationship provides a simple and robust guide for the selection of time to cut-off that requires no knowledge of the flow rate or soil moisture deficit. Application of the relationship delivers a significant increase in efficiency over that resulting from usual grower practice.

1. Introduction

Furrow irrigation is the one of the most widely used methods of irrigation in the world despite its often low irrigation efficiency and high labour requirements. In Australia it is the predominant method for irrigation of cotton (up to 500,000 ha annually) a large proportion of which is grown on heavy cracking clay soils (Koech et al., 2010).

A decade ago Smith et al. (2005) showed that irrigation application efficiencies in the Australian cotton industry were previously a low 48% on average but varied widely from 17 to 100%. Deep drainage below the root-zone (that is, a depth of infiltration in excess of the soil moisture deficit) was identified as a major contributor to these low efficiencies, averaging 42.5 mm per irrigation. In traditional practice, growers have tended to run their irrigation until the advance down the majority of furrows has reached the end of the field. This ensures that the entire field receives the depth of water required to fully replenish the root zone soil moisture deficit (that is, the requirement efficiency was at or near 100%). However, the effect is a significant loss of water to runoff and deep drainage and hence relatively low application efficiencies and low water use efficiencies. The data presented by Smith et al. (2005) also show that by increasing the furrow inflow rates to 6 L/s and reducing the time to cut-off (*Tco*) commensurately, the average application efficiency across the industry could be increased up to about 75% (by decreasing both the runoff and deep drainage), although the range of application efficiency values would still be excessive.

Industry wide adoption of improved practices (higher flow rates and shorter durations) has been estimated (BDA Group, 2007) to have saved the cotton industry 400 GL over a 16 year period or 28.5 GL/annum and has contributed to industry improvement in WUE of 10%, with anticipation of another 10% improvement in WUE by 2014. The gains in performance have been substantiated by more recent evaluations of furrow irrigation performance by Montgomery and Wigginton (2008) that have shown average application efficiencies in the cotton industry currently exceeding 70%.

Raising efficiency further can only come about by managing each individual irrigation (by varying flow rate and *Tco*) to give optimum performance for the prevailing conditions. Simulations performed using historical data (Smith et al., 2005; Khatri and Smith, 2007) have shown that application efficiencies in excess of 85% are possible by this means.

Traditionally, inflow rates are set at the start of the season by selection of the size of the over-bank siphons used to supply each furrow. Optimum cut-off times often occur before the advance has reached the end of the field making them difficult to estimate by growers who typically judge cut-off from experience with previous irrigations. Few if any growers use objective methods of estimating the preferred *Tco*. The challenge in providing guidance to growers is accommodating all the different combinations of the variables that control irrigation performance, namely: field length and slope, flow rate, infiltration, surface roughness and soil moisture deficit.

Various means for estimating optimal or preferred times to cut-off

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Table 1
Summary of field data.

Field	No of irrigations	No of furrows	Length (m)	Slope (%)	Inflow rate (L/s)	Duration (min)	Soil moisture deficit (mm)
T17	5	4	1160	0.14	5.4–7.1	380–837	54–80
D	2	4	565	0.10	2.9–3.7	602–879	100
various	1	10	240–1150	0.05–0.15	1.2–6.8	230–1695	55–130

have been developed, including hydrodynamic simulation modelling such as SIRMOD (Walker, 2003), WinSRFR (Bautista et al., 2009) and SISCO (Gillies and Smith, 2015) or design charts of varying complexity (e.g. Elliott et al., 1983; Strelkoff, 1985; Raine et al., 1998). All tend to be data intensive and require skill in the operation of software or the ability to undertake complex calculations, each of which makes them unattractive to farmers.

A method for the real-time selection of *Tco* has been developed and tested (Khatri and Smith, 2007; Smith et al., 2013; Koech et al., 2014a,b), that requires measurements only of the inflow rate and advance to a single point. The main features of this optimization process are: the use of a model infiltration curve and a scaling process to describe the current soil infiltration characteristic; measurement of the inflow rate to the furrows; measurement of the water advance at a point approximately midway down the furrow; and a hydraulic simulation program based on the full hydrodynamic model to predict the optimum time to cut-off. This method has been shown to give substantially improved irrigation performance. However, because of the computations required it is suitable only for automated systems.

More recently, Smith et al. (2013) proposed relatively simple guidelines for bay irrigated crops and pasture, developed from full hydrodynamic simulations, in the form of plots of advance rate versus *Tco* for various soil types, flow rates, bay lengths and crop densities.

Both of the above approaches rely on the notion that the irrigation advance trajectory integrates the effect of all of the controlling variables. It is therefore hypothesized that some knowledge of this trajectory gained during an irrigation event should be able to be used by growers to estimate with sufficient accuracy the preferred time to cut-off for that irrigation. Hence the objective of the paper is to investigate the relationship between advance rate and the preferred *Tco* for furrow irrigation on cracking clay soils and to compare the performance of alternative methods for estimating *Tco*.

2. Methodology

2.1. Field data

Data used in this study were selected from the many individual furrow irrigation evaluations that have been conducted by the NCEA since 1998 in the cotton growing areas of southern Queensland and northern NSW and which are available from the ISID database (Roth et al., 2014). All irrigations were performed under normal commercial conditions with inflow rates and cut-off times as normally used by the farmer. Measurements were conducted using the Irrimate™ surface irrigation evaluation system developed by the NCEA, as described by Dalton et al. (2001) and Raine et al. (2005). The data that were recorded typically included inflow hydrographs, furrow dimensions and advance times for up to six locations along the furrow length. In some cases runoff hydrographs were also measured.

Field T17 is situated close to Goondiwindi in Southern Queensland, Australia, on a Grey Vertisol (cracking clay) soil. In this case the data used cover a total of five irrigation events with the advance down four furrows observed during each event. The inflow rates varied from irrigation to irrigation (5.4–7.1 L/s) and were constant throughout each event.

Field D is situated on a cracking clay soil (Black Vertisol) on the Darling Downs of southern Queensland. Measurements were available from four furrows over five consecutive irrigation events although data from only two events are used in this paper. Inflow hydrographs were available for all furrows but showed no significant temporal variation during the irrigations. Inflow rates were also similar between furrows and between irrigations. Runoff hydrographs from every furrow were measured close to the end of the field using trapezoidal flumes. However, the short storage phase prevented the onset of steady runoff rates and hence, did not permit direct identification of the steady or final infiltration rate.

For both fields T17 and D the crop row spacing was 1 m and irrigated furrow spacing 2 m. They were selected because the evaluations covered multiple irrigations and multiple furrows. Field T17 data were used to establish the relationship between advance time and *Tco*. Data from both fields were used to compare the performance of the alternative methods for selecting *Tco*.

To further explore the performance of the simpler methods for selecting *Tco*, evaluation data from single irrigations in a number of individual furrows from across the cotton growing region were also used. Table 1 summarises the data for each field, showing the range of lengths and slopes, along with the flow rates, soil moisture deficits and times to cut-off employed by the growers. Some of these data were also used in previous studies by Smith et al. (2005), Khatri and Smith (2006) and Gillies et al. (2011).

2.2. Data analysis

The data analysis in this paper was conducted in five stages:

(i) Determination of the spatially averaged infiltration parameters for each irrigation of each furrow,
(ii) Simulation of each irrigation to determine the actual performance (application efficiency) obtained during the evaluation, that is, under usual farmer management,
(iii) Optimisation of each irrigation at various flow rates to ascertain the maximum efficiency attainable and how performance varies with inflow rate,
(iv) Investigation of the relationship between advance time to a set point in the field and the preferred time to cut-off (*Tco*) for the various flow rates, and
(v) Comparison of alternative methods that could be used for estimating *Tco*.

The detailed methodology for each stage and the results obtained are presented in the following sections.

The modelling tool used in stages (i)–(iv) was the Surface Irrigation Simulation Calibration and Optimisation (SISCO) model of Gillies and Smith (2015). SISCO is a numerical solution of the full hydrodynamic equations for spatially varied unsteady channel flow. The model is capable of performing three different functions.

Firstly it can simulate the irrigation advance down an irrigation furrow or bay. For this it requires the flow rate (steady or variable) into the furrow, the soil infiltration characteristic and the resistance provided to the flow by the bed of the furrow. This resistance is indicated by the Manning n, the roughness term in the widely used Manning equation. From the simulation the model can calculate the usual array of performance parameters (application efficiency (*Ea*), requirement efficiency (*Er*), uniformity (DU), runoff volume, deep percolation). For