Simulation of performance for a simple real time control system of furrow irrigation

K. L. Khatri & R. J. Smith
Cooperative Research Centre for Irrigation Futures and National Centre for Engineering Agriculture, University of Southern Queensland, Toowoomba, Queensland, Australia

Abstract

A simple real-time control system for furrow irrigation is proposed that predicts the infiltration characteristic of the soil in real time using data measured during an irrigation event, simulates the irrigation and determines the optimum time to cut-off for that irrigation. The basis of the system is a new method for estimating the soil infiltration characteristic under furrow irrigation, developed previously by the authors, that uses a model infiltration curve, and a scaling process to predict the infiltration characteristic for each furrow and each irrigation event. Using this method, infiltration parameters were calculated for two different fields. The SIRMOD simulation model was then used to simulate irrigation performance under different model strategies, framed to assess the feasibility of the real time control strategy. The simulation results showed that the system is feasible and that the scaled infiltration is suitable for use in real-time control. The results further indicated that under simple real time control the irrigation performance for the two fields could be improved greatly with substantial reductions in the total volume of water applied.
Keywords: surface irrigation, real-time control, simulation, optimisation, application efficiency, infiltration scaling.

1 Introduction

The performance of surface irrigation is a function of the field design, infiltration characteristic of the soil, and the irrigation management practice. However, the complexity of the interactions makes it difficult for irrigators to identify optimal design or management practices. The infiltration characteristic of the soil is the

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most crucial factor affecting the performance of surface irrigation (Khatri and Smith [3]) and both spatial and temporal variations in the infiltration characteristic are a major constraint to achieving higher irrigation application efficiencies.

A real-time control system has the potential to overcome these spatial and temporal variations and highly significant improvements in performance are achievable with real-time optimization of individual irrigation events. A study undertaken by Raine et al. [8] showed that when the flow rate and application time were optimized for each irrigation throughout the season to simulate perfect real-time control of individual irrigations, the average application efficiency increased to 93% with a storage efficiency of 90%, without any significant difference in the distribution uniformity.

Extracting the maximum information on soil infiltration from a minimum possible quantity of field advance data is of enormous importance for the automation of surface irrigation using real time control. The greatest limitation of the most of the infiltration estimation methods is that they are data intensive and hence not suitable for use in real-time control (Khatri and Smith [4]).

To over-come this problem a new approach to prediction of infiltration in real-time (REIP) that uses a model infiltration curve and a scaling technique was developed by Khatri and Smith [5]. The method requires minimum field data, inflow and only one advance point measured around the mid length of the furrow. Testing of the method using data from the two fields having very different infiltration characteristics has shown reliable results for prediction of infiltration characteristics. The method has potential for use in real time control.

The work reported in this paper is the second part of a study directed at the development of a simple and practical real-time control system for surface irrigation. The feasibility of the proposed system is assessed through simulation of the irrigation performance, using the scaled infiltration parameters given by the proposed method and those estimated from full advance data. The gains in irrigation performance possible from adoption of the real time control strategy are demonstrated.

2 Description of the proposed system

The proposed real-time control system involves: (i) measurement or estimation of the inflow to each furrow or group of furrows, (ii) measurement of the advance at one point approximately mid way down the furrow, (iii) estimation of the infiltration characteristic for the furrow or group of furrows using the technique of Khatri and Smith [5], and (iv) simulation of the irrigation and optimization to determine the time to cut off the inflow. The actual measurement, simulation and control would preferably be automated but could be undertaken manually with very little capital investment on the part of the farmer.

A necessary precursor to application of the system is the determination of the shape of the infiltration characteristic (model infiltration curve) for the particular field or soil type. This is best done from a comprehensive evaluation of one or more furrows from the field, involving measurements of the inflow, advance and where possible runoff, with the infiltration curve determined using a model such as INFILT (McClymont and Smith [6]). The preferred (constant) furrow inflow rate is also determined at this stage although it may be altered over time as experience with operation of the system is accumulated.

The underlying hypothesis for the method is that the shape of the infiltration characteristic for a particular field or soil is relatively constant despite variations in the magnitudes of the infiltration rate or depth of infiltration. These spatial and temporal variations are accommodated by scaling the infiltration curve, where the scaling is determined from the measured advance point and the volume balance equation. The method of scaling is as described by Khatri and Smith [5] and is summarized below. Any infiltration equation can be used however for consistency with available simulation models the present study employs the Kostiakov–Lewis equation.

In this method a scaling factor (F_s) is determined for each furrow or event from a re-arrangement of the volume balance model (as used by Elliot and Walker [2]):

$$F_s = \frac{Q_o t - \sigma_y A_o x}{\sigma_z k t^a x + \dfrac{f_o t x}{1 + r}} \tag{1}$$

where Q_o is the inflow rate for the corresponding furrow (m^3/min), A_o is the cross-sectional area of the flow at U/S end of furrow (m^2) (determined by any appropriate method), a, k, f_o are the modified Kostiakov infiltration parameters for the model furrow, σ_y is a surface shape factor taken to be a constant (0.77), σ_z is the sub-surface shape factor for the model furrow, defined as:

$$\sigma_z = \frac{a + r(1 - a) + 1}{(1 + a)(1 + r)} \tag{2}$$

r is the exponent from power curve advance function for the model curve, and t (min) is the time for the advance to reach the distance x (m) for the corresponding furrow.

This scaling factor (F_s) is then applied in conjunction with the Kostiakov–Lewis infiltration model to scale the infiltration parameters for each furrow:

$$a_s = a_m \qquad k_s = F_s k_m \qquad f_{os} = F_s f_{om} \tag{3}$$

where a_s, k_s, f_{os} are the scaled infiltration parameters for a furrow, F_s is the scaling factor for the corresponding furrow, and a_m, k_m, f_{om} are the infiltration parameters for the model furrow.

For the proposed real time control the infiltration estimates are required in sufficient time to allow selection and application of optimum times to cut-off while the irrigation event is under way. To achieve this, the advance times ($t_{0.5}$) taken at or near the mid-point down the furrow/field ($x_{0.5}$) are used in equation (1).

3 Analysis

3.1 Irrigation performance and infiltration data

Two very different fields with a total of 44 furrow irrigation events conducted by growers using their usual practices were selected for analysis, 27 furrow irrigation events for field T and 17 furrow irrigation events for field C. These fields were selected from the different farms across the cotton growing areas of southern Queensland for which irrigation water balance and irrigation advance data have been collected. The basis for selection was the relatively large number of events for each field.

Data collected for each event included: (i) furrow inflow and outflow rates; (ii) irrigation advance (advance times for various points along the furrow including the time for the advance to reach the end of the furrow); and (iii) physical characteristics of the furrow (length, slope, cross section shape).

The flow rate and irrigation advance were measured using the IRRIMATETM suite of tools developed by the National Centre for Irrigation in Agriculture (NCEA), as described by Dalton et al. [1]. The data sets are summarized in Khatri and Smith [5].

The actual infiltration parameters and the scaled parameters for each furrow/event from the two fields, given by the INFILT software (McClymont and Smith [6]) and the method of Khatri and Smith [5]), respectively, have been taken from the previous paper (Khatri and Smith [5]).

3.2 Simulation methodology (using surface irrigation model SIRMOD)

To test the proposed real-time control system, simulations were performed for the two fields using the actual (INFILT) and the scaled infiltration parameters in the simulation model SIRMOD (Walker [9]). These SIRMOD simulations were used to compare the irrigation performance (application efficiency E_a, requirement or storage efficiency E_r, and distribution uniformity DU) of the actual irrigations, recipe approaches to irrigation performance improvement, and the simple real time control strategy.

SIRMOD is a software package designed to simulate the hydraulics of surface irrigation at the furrow scale, and to optimize the irrigation system parameters to maximize application efficiency. The ability of the SIRMOD to evaluate the irrigation performance of furrows and borders has been well documented (for example, McClymont et al. [7]).

3.3 Model strategies

To perform the simulations, six (6) irrigation strategies were framed to test the proposed system and to demonstrate the achievable gains in irrigation performance. The model strategies adopted are:

Strategy 1. Is the actual irrigation simulated using the actual infiltration parameters (INFILT a, k, f_o), actual inflow (Q_o) and actual cut-off time (t_{co}) as recorded under usual farm practices.

Strategy 2. Prediction of the actual irrigation simulated using the scaled infiltration parameters, actual inflow and actual cut-off time.

Strategy 3. Optimisation of the actual irrigation. In this case each irrigation event was optimized by using the INFILT parameters and varying the inflow and cut-off time to obtain maximum application efficiency (E_a). This strategy also indicates the best over all flow rate.

Strategy 4a. A simple recipe for performance improvement, simulated using the INFILT parameters, actual inflow but with the cut-off time fixed equal to 90% of the advance time.

Strategy 4b. An alternative recipe, simulated using the INFILT parameters, a fixed inflow as selected from strategy 3 and cut-off time equal to 90% of the advance time.

Strategy 5. A simple practical real time control strategy in which the scaled infiltration parameters were used with a fixed inflow while varying/optimizing only the cut-off time to achieve the best irrigation.

Strategy 6. Simulation of the actual result of the real time control strategy (5), using the INFILT parameters and the same inflow and cut-off time as used in strategy 5.

4 Results and discussion

4.1 Advance trajectories

The previous paper (Khatri and Smith [5]) showed that the scaled infiltration was able to reproduce the measured advance curves when applied in the same volume balance model that was used to generate the infiltration parameters. This ability was confirmed by the SIRMOD simulations which showed that the scaled infiltration was able to reproduce the measured advance trajectories (Figure 1). As expected, the advance trajectories pass through the advance point selected for the infiltration scaling, for example, in the case of data sets T1 and T22 as shown in Figure 2, but exhibit some small divergence by the end of the field.

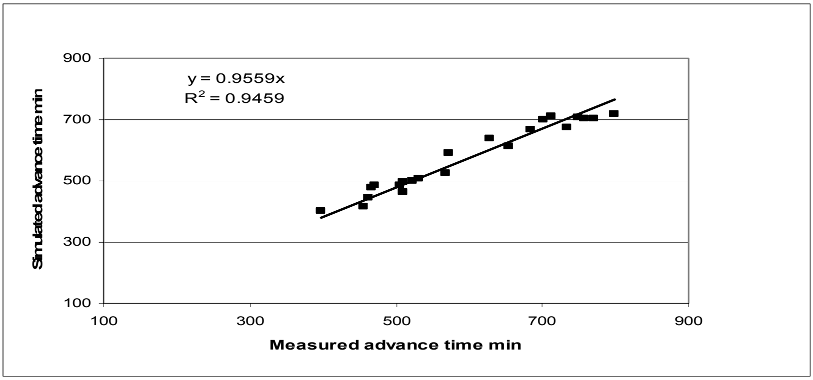


Figure 1: Final advance times for measured and simulated advance trajectories.

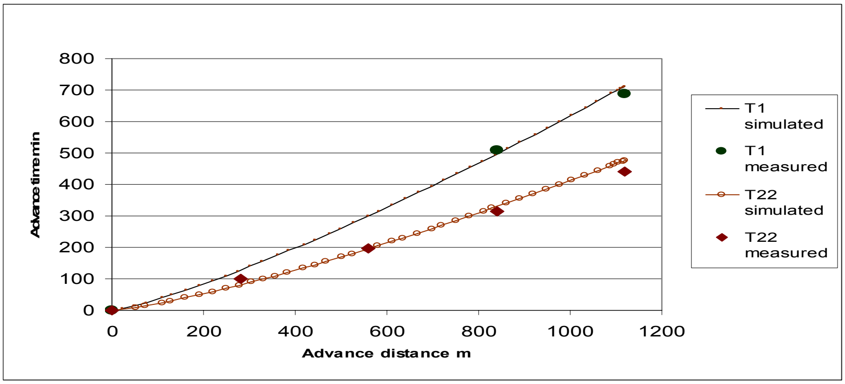


Figure 2: Measured and simulated advance trajectories for selected furrows.

4.2 Irrigation performance

The summary of simulated irrigation performance results obtained for the model strategies are shown in Tables 1 and 2 for fields T and C respectively. The results obtained under each of the model strategies are discussed below.

4.2.1 Strategies 1 and 2 (Actual irrigation - usual farm management)

From the summary of simulation results for field T (Table 1) it is evident that the over all mean irrigation performance (application efficiency and storage efficiency) of the actual irrigations (Strategies 1 and 2) was reasonable, with a mean application efficiency E_a of 77% and storage efficiency E_r 91%. However, application efficiencies were shown to be highly variable from 50 to 95%.

Table 1: Summary of irrigation performance for field T.

Management/Model strategies	E_a (%)	E_r (%)	DU (%)
Strategy 1 Actual irrigation	77.6	91.3	93.4
Strategy 2 Scaled infiltration	77.3	90.6	91.7
Strategy 3 Perfect management	90.2	90.1	94.0
Strategy 4a Simple recipe management **	81.3	86.6	82.2
Strategy 4b Simple recipe management **	80.5	88.6	84.5
Strategy 5 Real-time control (scaled infiltration)	82.1	90.2	92.2
Strategy 5 Real-time control (actual infiltration)	82.7	90.2	92.5

Table 2: Summary of irrigation performance for field C.

Management/Model strategies	E_a (%)	E_r (%)	DU (%)
Strategy 1 Actual irrigation	38.0	97.9	80.2
Strategy 2 Scaled infiltration	38.2	96.9	83.9
Strategy 3 Perfect management	72.1	95.9	92.5
Strategy 4a Simple recipe management **	68.5	79.5	72.2
Strategy 4b Simple recipe management	34.4	88.6	86.6
Strategy 5 Real-time control (scaled infiltration)	70.3	82.7	88.5
Strategy 5 Real-time control (actual infiltration)	70.2	82.2	90.7

**Denotes advance failed to reach the end of the field.

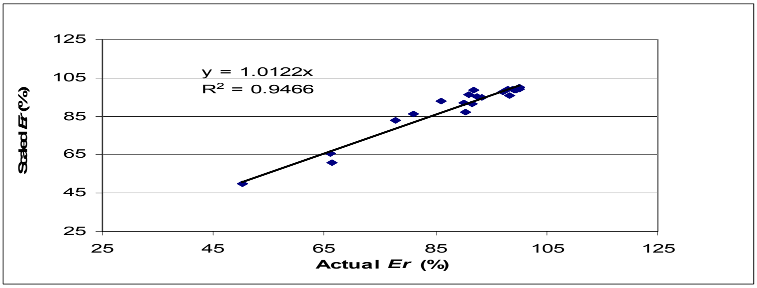
Similarly in case of field C the application efficiencies showed considerable variation from 16 to 57%, but this field showed a poorer performance (Table 2) with an over all mean application efficiency of 38% and storage efficiency of 97%.

For all of the irrigation events, the simulated performance using the scaled infiltration (Strategy 2) was similar statistically to the actual performance (Strategy 1) for each field as shown for field T in Figures 3 a and b, respectively. The results summarized in Tables 1 and 2 also confirm that the overall mean performance obtained for each field under strategies 1 and 2 is almost identical, reflecting the ability of the scaled infiltration parameters to reproduce the actual irrigations.

4.2.2 Strategy 3 (perfect control and management)

In this case the INFILT parameters were used and each irrigation event was optimized by varying inflow (Q_o) and cut-off time (t_{co}) to suit individual soil conditions and furrow characteristics. As expected an excellent performance was obtained for most events. The mean over all irrigation performance (E_a and E_r) obtained for all of the irrigation events for field T was above 90% and for field C the E_a was above 72% and E_r 95% as shown in Tables 1 and 2. This strategy involves the application of advanced irrigation management practices that may not be possible to practically implement in field. The overall best flow rate of 6.5 l/s as observed under this strategy was selected for use in strategies 4, 5 and 6.

(a) Application efficiency



(b) Requirement efficiency

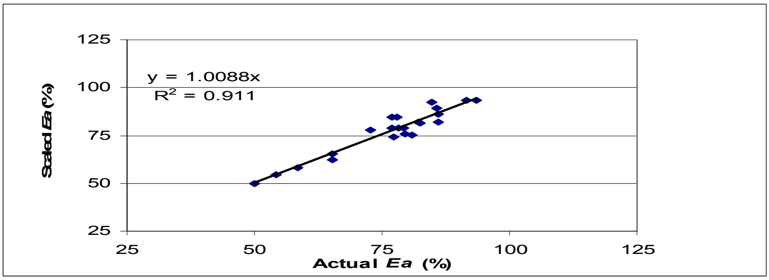


Figure 3: Irrigation performance results for model strategies 1 and 2 for field T.

4.2.3 Strategy 4 a and b (simple recipe management)

Under Strategy 4a a simple recipe management was applied where the cut-off time was fixed equal to 90% of the advance time. The performance was improved but in many events the advance did not reach the end of the field. To overcome this, strategy 4b was applied, using all the same parameters as in Strategy 4a except that the inflow rate was increased to 6.5 l/s.

The simulation results (Table 1) revealed that performance was raised for field T, the application efficiency was improved in most events but showed great variation from 50% to 100% with a mean of 80%. Some furrows still faced an incomplete advance. The simple recipe management showed poorer results in case of field C, under both strategies 4a and 4b. The advance was unable reach the end of the field for many of the furrows and yet the field was shown to have low application efficiencies, varying from 15% to 47% with an overall mean of 34% (Table 2). Field C poses substantial problems for the irrigation manager because of the extreme variation in the infiltration characteristic across the field, hence its poor response to recipe management.

4.2.4 Strategies 5 and 6 (real-time control)

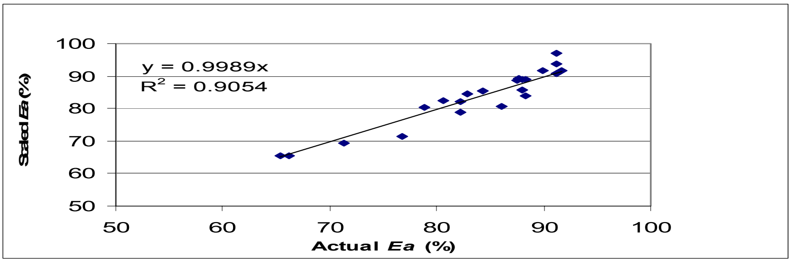
From Tables 1 and 2 it is evident that the simple real time control strategy (5) predicts improved performance (E_a and E_r) for both fields. For field T the means of the performance measures are E_a 82.1% and E_r 90.2%, with mean E_a of 70.3% and E_r 82.7% for field C.

The actual outcomes from the real time control strategy predicted using the actual infiltration parameters (strategy 6) are comparable to those above, with mean E_a 82.7%, E_r 90.2% and E_a 70.2, E_r 82.2% for fields T and C, respectively. This indicates that the mean performance predicted by the real time control system based on the scaled infiltration is very close to the actual outcomes. The predictions obtained under both strategies for the 44 individual irrigation events are also almost identical to each other, providing further evidence of the equivalence between the scaled and actual infiltration parameters. This is illustrated in the comparison of the requirement and application efficiencies predicted under both strategies for individual irrigation events as shown for field T in Figure 4. The volume of water infiltrated under both strategies is also similar. The results for these strategies show that real-time control using the scaled infiltration parameters is feasible and that significant gains in irrigation performance are possible from this system.

4.3 Water savings from real-time control

The performance simulation results (Tables 1 and 2) show there is considerable opportunity to improve the irrigation performance obtained under usual farm practices (Strategy 1). The recipe management strategies (4a & b) were shown to raise the performance for field T but for some furrows the advance failed to reach the end of the field. However, the recipe management could not bring a simultaneous improvement in the three irrigation performance measures for field C.

(a) Application efficiency



(b) Requirement efficiency

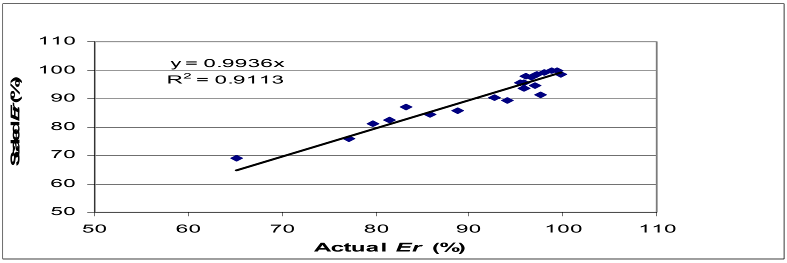


Figure 4: Irrigation performance results for model strategies 5 and 6 for field T.

When the real time control (strategy 5) was applied the overall mean irrigation performance was improved for both fields. A highly significant improvement in irrigation performance was noted in case of field C, with application efficiency increasing from 38% to 70% as shown in Table 2, along with acceptable uniformity and storage efficiency. It is evident from these results that the simple real-time control system does have potential to bring significant gains in irrigation performance, with the additional benefit of reducing the volume of water applied per irrigation and deep drainage volumes, thus reducing the potential for environmental harm.

The volume of water applied to the 44 furrows at fields T and C was reduced from 7341 m^3 under usual farm management to 5071 m^3 under real-time control. This indicates the substantial potential savings of 2270 m^3 (2.270 Ml) of volume of water per irrigation, which is a significant loss of water to the grower. For Queensland cotton growers applying 4 to 6 irrigations annually this represents an annual water saving of 1.283 to 1.924 Ml/ha that can be used beneficially to grow more crop, indicating the substantial benefits that are achievable in the industry by implementing simple real time control.

5 Conclusions

A simple practical system for real-time control of furrow irrigation that varies only the time to cut-off is proposed. To evaluate the method, the SIRMOD model was used to simulate the irrigation performance for two fields, for a range of irrigation strategies using both the scaled and the actual infiltration parameters. One of the strategies included in the simulations was the proposed real-time control strategy.

It is concluded that the measured advance curves and measured irrigation performance were able to be reproduced with sufficient accuracy using the scaled infiltration parameters. Consequently, the simple real-time control strategy is feasible and has the potential to bring significant improvements in irrigation performance over that achieved under simple recipe management or current farmer management. Substantial reductions in the total volume of water applied per irrigation are achievable, that could be used beneficially to grow a greater area of crop.

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