Australian Government
Cotton Research and Development Corporation

FINAL REPORT 2015

For Public Release

Part 1 - Summary Details

Please use your TAB key to complete Parts 1 & 2.

CRDC Project Number: **NEC1302**

Project Title: Commercial prototype smart automation system for furrow irrigation

Project Commencement Date: 1/01/2013 **Project Completion Date:** 30/03/2015

CRDC Program: 1 Farmers

Part 2 – Contact Details

Administrator: Mr Erik Schmidt, Deputy Director
Organisation: National Centre for Engineering in Agriculture
Postal Address: University of Southern Queensland, Toowoomba, Q, 4350
Ph: 07 4631 1347 **Fax:** 07 4631 1870 **E-mail:** schmidt@usq.edu.au

Principal Researcher: Prof Rod Smith
Organisation: National Centre for Engineering in Agriculture
Postal Address: University of Southern Queensland, Toowoomba, Q, 4350
Ph: 07 4631 2510 **Fax:** 07 4631 1870 **E-mail:** smithrod@usq.edu.au

Supervisor: Prof Rod Smith
Organisation: as above
Postal Address:
Ph: **Fax:** **E-mail:**

Signature of Research Provider Representative:

Date Submitted: ___1/6/2015_____________

Part 3 – Final Report

(The points below are to be used as a guideline when completing your final report.)

Background

1. Outline the background to the project.

Furrow irrigation remains the dominant method used for irrigation of cotton in Australia due to its inherent advantages of low capital cost, ease of operation, and low energy. However, a major limitation is the often low application efficiency due largely to the inability of farmers to estimate the required irrigation duration accurately before or during the irrigation (Smith et al., 2005). The cost and availability of labour to manage the mostly over-bank siphon fed systems is an ever present issue.

In current practice, farmers typically irrigate their field until the water reaches the end of the field in the hope that the entire field receives the required water depth in the root zone. This has a significant impact on irrigation performance with a substantial amount of water lost as tail-water runoff and deep drainage, resulting in low application efficiencies. For example, irrigation evaluations undertaken in the late 1990's in the Queensland cotton region showed application efficiencies for individual irrigations varied from 17 to 100%, with deep drainage below the root-zone identified as a major loss. Simulations suggested that increasing the furrow inflow rates to 6 L/s and reducing the time to cut-off (*Tco*) commensurately could increase the potential average efficiency across the industry up to above 70%. Improvement of furrow irrigation performance through the process of evaluation, and simulation with the IRRIMATE^{TM} suite of tools developed by NCEA is now an accepted practice in the cotton industry. Through this process of evaluation, average efficiencies across the industry have risen substantially.

Well-designed and managed surface irrigation systems have the potential to deliver application efficiencies in excess of 90%. However, this can only be achieved by the real-time optimisation of individual irrigation events. Previous research at NCEA funded by the CRC for Irrigation Futures and the Cotton CRC established the basis for the practical real-time optimisation of furrow irrigation. This work developed the concept and tested the software required for the real-time optimisation and showed it capable of sensing the inflow and advance, simulating the irrigation, and predicting the optimum time to cut-off without any user intervention. The field testing was limited but sufficient to establish the potential of the system. This work was encapsulated in the software package AutoFurrow which is jointly owned by CRDC and NCEA. The disadvantage of this system from a practical perspective is that it is data and computationally intensive.

Independently, the development of automation systems involving flow control infrastructure, control software and wireless communications had reached commercial application in the form of the Rubicon Water FarmConnect® system for bay irrigation.

The adaptation of the automation to furrow irrigation and combining it with real-time optimisation was the obvious next step in their development. Together they offered the potential for a modern furrow irrigation system that would give optimal irrigation performance and substantial labour savings, equivalent to centre pivot or lateral move machines, but at a lower capital cost and without the on-going energy costs.

Objectives

2. List the project objectives and the extent to which these have been achieved.

The aim of the project was to develop, test and demonstrate a commercial prototype smart automation system for furrow irrigation of cotton. The preliminary trials at two sites (Moree and Goondiwindi) in 2013/2014 and the successful final trials and demonstration of the prototype system (including the real-time optimisation) in 2014/15 at Redmill north of Moree are the evidence that the **aim has been achieved** and that commercial release is the next step.

Specific objectives of the project included:

Objective 1. Development of a self-learning capability in the NCEA real-time optimisation system.

The idea behind this objective was that by developing a self-learning capability in AutoFurrow it would eliminate the need to characterise the field prior to operation of the real-time optimisation and would allow estimation of and progressive refinement of the 'model infiltration curve' by the optimisation software with each subsequent irrigation event, resulting in improved accuracy of optimisation. While this notion is still valid, two factors led to the modification of this objective in the November 2013 progress report.

First, the sensing required for the application of AutoFurrow and particularly the sensing required for any self-learning capability was not considered viable in a commercial automation system, and second was the development of a simpler approach to the real-time optimisation that required far less real-time sensing of data. The success of this alternative approach has meant that **the modified objective has been satisfied in full**.

Objective 2. Development of a practical/commercially viable inflow system for furrow irrigation automation.

A major impediment to the successful automation of furrow irrigation was the difficulty posed by the issues of flow control, flow measurement, and the even distribution of the inflow to the furrows. Pre-existing Rubicon control structures provided effective flow control. Two inflow systems that attempted to provide the even distribution of flows were devised for use with the Rubicon infrastructure and trialled in the successive 2013/14 and 2014/15 seasons. The flexible gated pipe option evaluated in 2013/14 provided controlled and uniform flow to a set of furrows but may not be suitable for those instances where the supply channel has low head or there is a significant trash load in the channel. The use of the flap gate and secondary channel with individual pipes through the bank tested in 2014/15 enabled a single command structure to control a larger section of the field (and therefore with reduced cost) and performed with even greater uniformity than the gated pipe system. With the success of this revised infrastructure used and demonstrated in the 2014/15 trials at Redmill north of Moree, **this objective has been satisfied in full**.

Objective 3. Integration of the NCEA real-time optimisation model with the Rubicon FarmConnect® software.

This objective was abandoned at the request of Rubicon at the start of the project to ensure a clear separation between project IP and Rubicon IP (refer November 2013 progress report). It was agreed by all parties that developing a protocol that allowed AutoFurrow to communicate with the Rubicon system was the preferred approach in the circumstances. However, the development of the simple optimisation approach has since eliminated any need for software integration or communication. The relevant algorithm for the particular field can simply be programmed into the FloodTech sensor software.

Objective 4. Preliminary field testing of the integrated system, and **Objective 5.** Demonstration trials of the prototype system.

Field trials were undertaken over two seasons culminating in the final trials and demonstration of the prototype system over the 2014/15 season. **These objectives have been satisfied in full**.

Methods

3. **Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research.**

This project was by nature more development than research with a large part of the project being the trialling and finally demonstration of the prototype system. The parts that involved some innovation and application of science were: (i) the adaptation and desk-top testing of the simplified system for the real-time prediction of time to cut-off, (ii) evaluation of the performance of the real-time optimisation during the field trials.

The methodology for the desk-top testing of the proposed method for predicting *Tco* was use of the SISCO surface irrigation simulation model to perform extensive simulations/optimisations on data from some of the numerous irrigation evaluations previously undertaken in the cotton industry. The methodology and data used are described in full in the draft paper '*Estimating irrigation duration for high performance furrow irrigation on cracking clay soils*' attached to this report.

Evaluation of the field performance of the real-time control was conducted using measurements independent of the automation system following the procedures of the IRRIMATE evaluation system. Flow rates down selected furrows were monitored continuously throughout each irrigation event and the irrigation advance measured at several points down the field. Simulations using the SISCO model gave the relevant performance parameters for each irrigation. The methodology and data used are described in greater detail in the draft paper '*Smart automated furrow irrigation of cotton*' attached to this report.

Results

4. **Detail and discuss the results for each objective including the statistical analysis of results.**

Objective 1. Development of the real-time optimisation system.

The hypothesis underpinning the method is that the rate of advance of the irrigation flow down a furrow is an integration of all the factors (flow rate, infiltration, soil moisture deficit, slope, surface roughness) that influence irrigation performance for a particular field. Hence it follows that knowledge of the advance rate alone is sufficient to make a real-time decision regarding the optimal time to cut-off. It also follows from the hypothesis that the method will adapt to changes in the flow rate or soil moisture deficit from one irrigation to the next thus ensuring maximum performance for all irrigations.

The simulations showed that optimising irrigations on a given field for a range of flow rates and infiltration magnitudes with the objective to maximise application efficiency at some nominated minimal value of runoff (say 5%) results in a straight line relationship between the advance time to a nominated point down the furrow (e.g. mid-way down the field) and the optimum time to cut-off. This relationship is independent of flow rate, the magnitude of the infiltration characteristic and soil moisture deficit hence the method requires no knowledge of these variables. However, the relationship varies with the shape of the infiltration characteristic and field length, hence it is field specific.

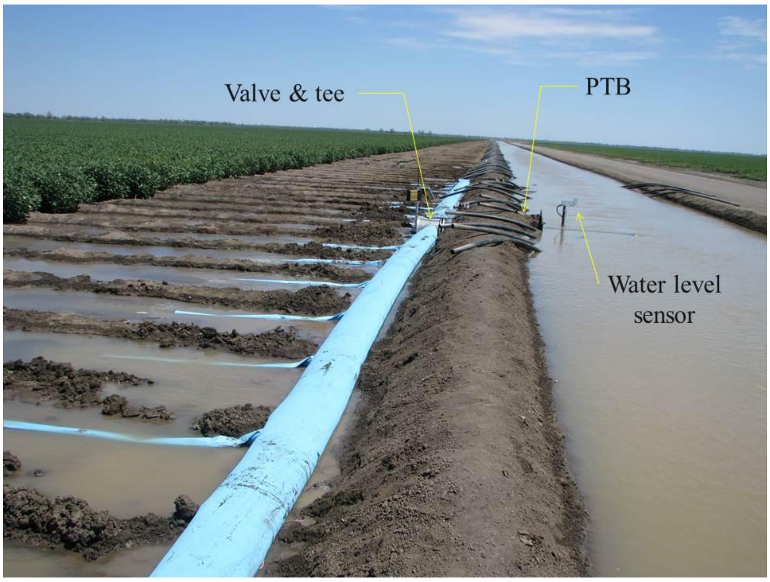
Anecdotal evidence suggests that this approach may not be applicable to all soil types but fortunately it appears to function correctly for typical soils where cotton is grown. This is largely due to the high initial infiltration rate and strong relationship for clay soils which dominate the Australian cotton industry.

Applying the method to a selection of historic irrigation evaluation data from the ISID data base suggested that near optimum efficiencies could be routinely achieved through application of the method. The results achieved were equivalent to those that would be given by use of the more complex Autofurrow.

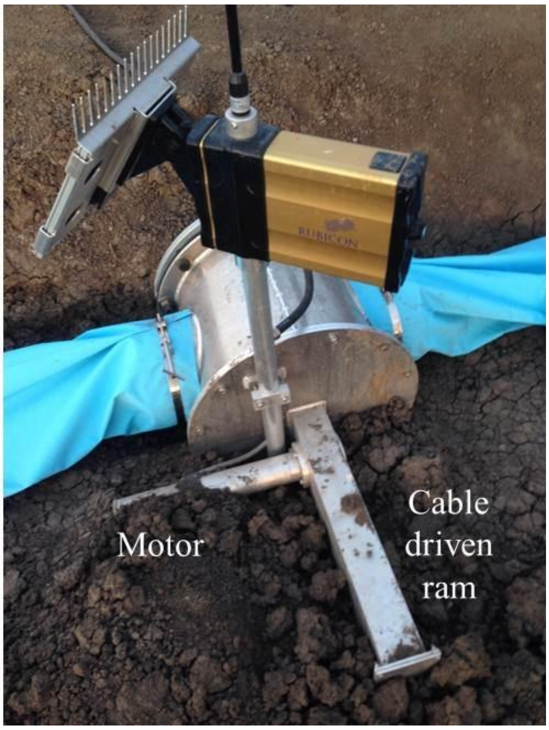
The results of the simulations including comparison with AutoFurrow are described in full in the draft paper '*Estimating irrigation duration for high performance furrow irrigation on cracking clay soils*' attached to this report.

Objective 2. Development of the inflow system for furrow irrigation automation.

The flow control infrastructure used in the 2013/14 trials (at Tallerega near Moree and Fairfield Farming Company at Goondiwindi) consisted of a 450 mm diameter pipe through the bank (PTB) with a Rubicon integrated tee and valve on the field end of the (PTB). Layflat gated fluming of a unique design (manufactured by CE Bartlett of Ballarat) was attached to each arm of the tee, watering 10 furrows (20 metres) on each side of the PTB. The fluming was 350 mm diameter with 75 mm diameter outlets each shrouded by a 2m long 100 mm diameter sleeve to guide the water gently into the furrows. It was located at the toe of the head ditch and occupied about 1 m of the rotabuck area. The tee valves were complete with solar powered, cable driven actuation that opens and closes the valve and with radio telemetry for communication with the other components of the system.



Fluming in operation at the Moree field site



TeeValve and actuator on field end of PTB

The success of the 2013/14 testing was to be measured by the success in achieving uniform flows down the furrows. However the real measure of success is the likelihood of acceptance by growers of the use of gated fluming as the means of supply of water to the furrows, and the absence of any other practical limitations. The outcome of the trials was success on the first point but not as successful on the second.

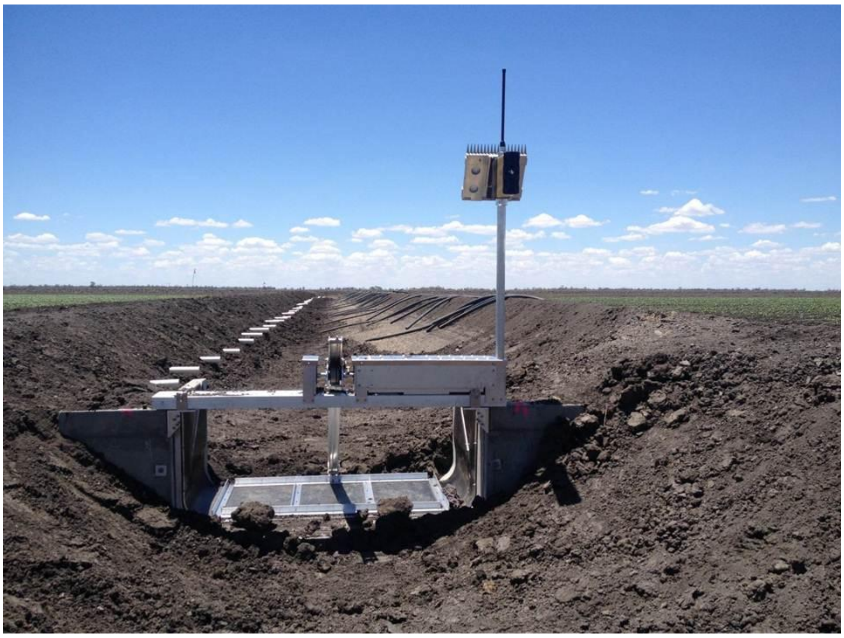
The results demonstrated that when designed correctly the fluming could deliver uniform flows to the furrows and with the TeeValve could give precise and relatively rapid start-up and shutdown of the irrigation. The fluming had the additional advantage of being able to be rolled up and removed if required during the fallow. However there were a number of problems encountered with the chosen configuration, namely:

1. Limitations on the flow rate achieved caused by lower than anticipated heads in the supply channels – flow rate was adequate at only one site (Goondiwindi) and marginally acceptable at another (Moree).
2. Significant head losses through the TeeValve, exacerbating the problem of the low available heads.
3. Difficulties in bedding the layflat fluming.
4. Trash jamming the TeeValve and preventing complete closure at one of the sites.

These problems suggested that: (i) the TeeValve and PTB was not a practical solution, and (ii) the fluming might not be popular amongst growers and that other alternatives needed to be explored.

For the 2014/15 trials at Redmill, a new structure better suited to this application was provided by Rubicon, from its stable of bay irrigation control structures, in the form of the Bay Drive All-in-one, which consists of a BayDrive and flap gate installed in a standard box culvert section (see figures below). Supply to the furrows is via small diameter (80mm) pipes inserted through the bank of a dedicated head-ditch. The small pipes are equivalent hydraulically to the traditional overbank siphons but are laid horizontally at or near furrow level, with one pipe supplying each irrigated furrow. The advantages are relatively uniform furrow flows (uniformity exceeding traditional siphons) and compatibility with the traditional irrigation layout and equipment. The system at Redmill supplied 50 irrigated furrows (~8.5 ha) from the single inlet control structure.

The BayDrive All-in-one in the closed position viewed from downstream

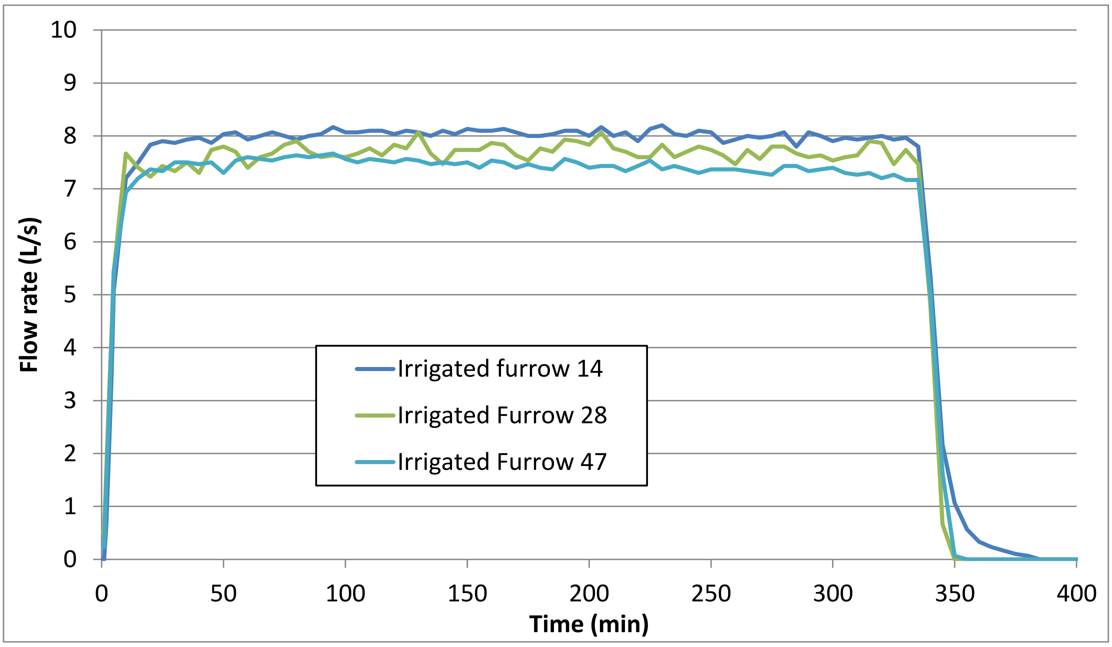


The BayDrive All-in-one in the open position viewed from upstream with the small diameter PTB's through the channel bank on the left

This system gave completely trouble free operation. Flow rates down the furrows were typically about 8 L/s at the normal operating level in the head-ditch. If required, the flow rate could be varied (downward) by varying the rate of supply from the farm storage and the consequent head in the channel. Flow rates were steady throughout each irrigation except for a short (5 min) period of increasing flow rate at the start as the channel filled and a slightly longer period (10-12 minutes) of declining flow rate as the channel drained after closing the gate to end the irrigation. The following figure shows the flow rates measured in three furrows throughout the duration of one irrigation event, where irrigated furrow 50 was be adjacent to the control structure. The heads available at each pipe and hence the flow rates down the individual furrows were identical. The only requirement for this to occur was that the downstream end of each of the PTB's was installed on the same horizontal level along the 100m of channel.

The Redmill field site in operation

The Redmill site viewed from downstream after the flow had been shut off



Variation of furrow inflow rates with time (Irrigation 6)

Objective 5. Demonstration trials of the prototype system.

Nine irrigations at the Redmill trial site were monitored and evaluated of which the first two were under farmer control and the remaining seven were controlled using the simple real-time optimisation. A summary of the results of these trials is presented in the table below. It shows: (i) the application efficiencies measured in the control furrow for each irrigation, (ii) the optimum or maximum application efficiency that could be achieved in that furrow with perfect management, and (iii) the efficiencies that would have been achieved with the use of the improved control algorithm for the trial field. In summary the results suggest that although the efficiencies achieved in the trial were relatively good, they fell short of the maximum possible, in some cases by a considerable margin. Use of an improved relationship between the advance time and the time to cut-off, developed from the trial irrigations 3 to 9, would have resulted in improved performance for all but irrigation 9.

Application efficiencies (%) from the Redmill trial

Irrigation	Measured Ea (%)	Optimum Ea (%)	Improved control algorithm Ea (%)
1	50.7	65.3	
2	83.0	70.7	
3	87.1	87.1	96.0
4	88.6	94.8	93.4
5	71.0	87.6	82.6
6	80.2	80.2	79.1
7	70.2	95.1	90.3
8	69.8	94.6	73.0
9	83.1	86.2	62.4

The complete results and analysis of the performance evaluations are described in the draft paper ‘*Smart automated furrow irrigation of cotton*’ attached to this report.

Outcomes

5. Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.

Three outputs were foreshadowed in the project submission as detailed below.

Output 1. Functioning prototype automated real-time control system for furrow irrigation
This output was achieved and provided the key outcomes, viz:

- the science outcome of the proving of the simple novel method for determining time to cut-off in real time with minimum data (formerly planned as the integration of the simulation, optimisation and control software, and
- the industry outcome of a demonstrated prototype automated real time control system ready for commercialisation/adoption.

Both of these outcomes are encapsulated in the draft papers appended to this report.

Output 2. Proof of concept and quantification of improvements in irrigation performance
This output was achieved through the field trials at Redmill and led directly to the science outcome of improved knowledge of performance and potential of furrow irrigation. The results of these trials and the performance improvements achievable are quantified in the second of the draft papers attached to this report.

Output 3. Quantification of savings
The planned outcome was to be proof of the economic benefits and labour savings from adoption of automation. This output and associated outcome were not achieved. However based on the set-up costs of the Redmill trial an indicative capital costing of less than \$1000/ha for the automation system is available in the following table.

Indicative cost of automation

Item	**Cost**	**Cost/ha**
In-field infrastructure[1]		
BayDrive All-in-one plus FloodTech advance sensor	\$5100	
Pipes through the bank	\$5000	
	\$10100	\$594
Base station[2]	\$4400	\$220
Soil moisture probe[3]	\$3800	\$76
Total cost		\$890

1. Assumes one control structure per 100 irrigated furrows x field length of 850 m.
2. Assumes 200 ha automated serviced by a single base station.
3. Assumes one soil moisture probe per 50 ha.

6. Please describe any:-
a) technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);

The significant technical advance is the application to furrow irrigation of a method for developing field specific algorithms (in the form of equations, charts, or tables) for real-time prediction of time to cut-off (*Tco*) or irrigation duration from a single advance measurement taken about mid-way through the irrigation.

The method involves three steps:

i. Evaluation.

An IRRIMATE or similar evaluation is made of an irrigation on the particular field. The required outcome of this evaluation is an indication of the infiltration characteristic for the field (equivalent to the model curve as required by AutoFurrow). The furrow selected for this evaluation must be representative of the field, e.g. not a wheeled furrow.

ii. Simulations.

Simulations (using SISCO or equivalent) to optimisation irrigations on that field are conducted with the objective to maximise application efficiency at some nominated minimal value of runoff (say 5%). The resulting relationship between the advance time to the nominated point down the furrow (e.g. mid-way down the field) and the optimum time to cut-off can be presented as an equation, a chart or a look-up table.

iii. Application to irrigation control.

During each irrigation, a measurement of the advance time to the specified distance down the field (for which the relationship was developed). Once that advance time is obtained the relationship is applied to give the time to cut-off.

a) other information developed from research (eg discoveries in methodology, equipment design, etc.); and

Nil

b) required changes to the Intellectual Property register.

Nil

Conclusion

7. Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?

Conclusions from the project are:

i. Automation of furrow irrigation in cotton is feasible, practical and able to be implemented immediately using commercially available equipment and innovative in-field design.
ii. Real-time optimisation (or prediction of time to cut-off) using a simple field specific algorithm can deliver improved application efficiencies easily and reliably.
iii. Together they deliver a modern surface irrigation system with water and labour savings equivalent to the pressurised centre pivot and lateral move machines at a lower capital cost and without the on-going energy costs.
iv. The real-time adaptive optimisation is equally applicable to manually controlled systems (siphon or PTB).

The impact for the industry should be:

- a significant and rapid uptake of automation by innovators in the cotton industry, and
- further water savings across the remainder of the industry through dissemination and uptake of the adaptive optimisation system via a re-invigorated IRRIMATE furrow irrigation evaluation system.

Extension Opportunities

8. Detail a plan for the activities or other steps that may be taken:

(a) to further develop or to exploit the project technology.

It is proposed that further testing of the simplified system for real-time optimisation be undertaken over the 2015/16 season to: (i) verify the robustness of the method over a wider range of soil types, (ii) determine if accuracy is gained by moving the measurement point further down the field, and (iii) explore the possibility of generalised relationships with wider applicability than a specific field. This testing could be undertaken at the ambassador sites of the Cotton Info Team thus demonstrating and promoting the method to the industry simultaneous with the additional testing. It would also be appropriate to work with interested parties such as Aquatech during this phase to determine how Steps 1 and 2 might be progressed as a service to growers, for example, under the IRRIMATE name. Finally this further work could also involve development of the 'smartphone' app for irrigators with manually controlled systems. The system envisaged will involve an advance sensor installed in each furrow set, able to transmit the advance time directly to the grower's smartphone, which will then calculate the time to cut-off and alert the grower.

(b) for the future presentation and dissemination of the project outcomes.

The primary vehicle for dissemination of the project outcomes is the commercial release and promotion of the automation system to the industry, which we see as the responsibility primarily of Rubicon Water. NCEA anticipates continuing to work with Rubicon in the initial application of the real-time optimisation method in its commercial systems.

Promotion of the science outcomes will be via the usual journal publications and conference presentations. It is proposed to submit the attached draft papers for publication and to present a paper on the final trials at the 2015 IAL conference.

(c) for future research.

Future research is to move from the automation and control of individual irrigation events to the development of an autonomous surface irrigation system capable of managing the entire irrigation process including: the integration with VARIwise for the scheduling of irrigations, sequencing the irrigation of the whole farm, and allocating water between fields when supply is limiting. This is the subject of a research submission from NCEA to CRDC and elements of this work are included in the recently successful application for funding to DAFF.

9. A. List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)

Note: Publications include those arising directly from the project and those by the project team on related work not funded by CRDC.

Journal Papers

Smith, RJ, Uddin, MJ and Gillies, MH (2015) *Estimating irrigation duration for high performance furrow irrigation on cracking clay soils.* Irrigation Science, (draft submitted for CRDC approval).

Uddin, MJ, Smith, RJ, Gillies, MH, Moller, P and Robson, D (2015) *Smart automated furrow irrigation of cotton.* Irrigation Science, (preliminary draft submitted for CRDC approval).

Gillies, MH and Smith, RJ (2015) SISCO – surface irrigation simulation, calibration and optimisation. Irrigation Science, (in press).

Koech, RK, Mossad, R, Smith, RJ and Gillies, MH (2015) *CFD study of the hydraulic performance large diameter gated fluming*. ASCE Journal of Irrigation & Drainage Engineering, 141: 04014052-1.

Koech, RK, Smith, RJ and Gillies, MH (2014) *Evaluating the performance of a real-time optimisation system for furrow irrigation.* Agricultural Water Management, 142: 77-87.

Koech, RK, Smith, RJ and Gillies, MH (2014) *A real-time optimisation system for automation of furrow irrigation*. Irrigation Science, 32(4): 319-327.

Koech, RK, Smith, RJ and Gillies, MH (2013) *Hydraulics of large diameter gated flexible fluming*. Biosystems Engineering, 114: 170-177.

Conference papers:

Smith, RJ (2012) *Precision irrigation – a uniquely Australian perspective.* SPAA, 15th precision Agriculture Symposium in Australia, Mildura, 5-6 September.

Smith, RJ (2013) *Automation and real-time optimisation: Managing time to cut-off*. Irrigation Australia's Regional Conference 2013, Griffith, NSW, 28-30 May.

Smith, RJ, Uddin, MJ, Gillies, MH and Morris, M (2013) *Selection of flow rate and irrigation duration for high performance bay irrigation*. SEAg Conference on Engineering in Agriculture, Mandurah, WA, Oct 2013.

Smith, RJ, Uddin, MJ and Gillies, MH (2014) *Estimating irrigation duration for high performance furrow irrigation on cracking clay soils.* Irrigation Australia Conference, Gold Coast, 3-5 June 2014.

Smith, RJ, Uddin, MJ, Moller, P, Clurey, K and Gillies, MH (2014) *Evaluation of the performance of automated bay irrigation: Preliminary results.* Irrigation Australia Conference, Gold Coast, 3-5 June 2014.

Uddin, MJ, Smith, RJ, Gillies, MH, Moller, P and Robson, D (2015) *Smart automated furrow irrigation of cotton.* Irrigation Australia Conference, Penrith, 26-28 May 2015.

B. Have you developed any online resources and what is the website address?

Nil

Part 4 – Final Report Executive Summary

Provide a one page Summary of your research that is not commercial in confidence, and that can be published on the World Wide Web. Explain the main outcomes of the research and provide contact details for more information. It is important that the Executive Summary highlights concisely the key outputs from the project and, when they are adopted, what this will mean to the cotton industry.

Development and demonstration of a practical and commercially viable 'smart' automation system for furrow irrigation was the aim and key outcome of this project. The system consists of three major component parts.

The core component is automation hardware and software initially developed for bay irrigation and which is available commercially from Rubicon Water under the FarmConnect® name. This provides:

- precise, automated control of flows throughout the farm open channel delivery system from the source (river, channel or on-farm storage) to the field, and
- sequencing of the irrigation of fields and sets of furrows according to pre-programmed schedules.

The second component is specifically designed in-field flow control infrastructure that gives automated control of flows into the furrows. The recommended configuration is a Rubicon Bay Drive All-in-one structure, which consists of a BayDrive and flap gate installed in a standard box culvert section, supplying small diameter (50 to 80 mm) pipes inserted through the bank of a dedicated head-ditch. These small pipes are equivalent hydraulically to the traditional overbank siphons but are laid horizontally at or near furrow level, with one pipe supplying each irrigated furrow. The BayDrive provides positive drive in both the raise and lower directions, enabling the gate to open and close in high flow, high head environments.

The final component is the sensing and simulation required for the real-time selection of time to cut-off for individual furrow sets to maximise application efficiency. Two options are available. The first is the program AutoFurrow, which was developed by CRC Cotton, the disadvantage of which is that it is both data and computationally intensive. Under the current project a simpler approach was trialled which hypothesises that the rate of advance of the irrigation flow down a furrow is an integration of all the factors (flow rate, infiltration, soil moisture deficit, slope, surface roughness) that are needed to be known by AutoFurrow. Simulations showed that, for a given field, there is a straight line relationship between the advance time to a nominated point down the furrow (e.g. mid-way down the field) and the optimum time to cut-off. This relationship is independent of flow rate, the magnitude of the infiltration characteristic and soil moisture deficit hence the method requires no knowledge of these variables, making it a preferred method for practical control.

Trials of the system at Redmill, near Moree, have demonstrated the efficacy of the flow control infrastructure and have shown how near optimum efficiencies can be obtained from the real-time selection of time to cut-off. The system is practical and, perhaps more importantly, is commercially viable at a capital cost less than $1000/ha.

Attachment 1 Draft Paper

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

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

RJ Smith, MJ Uddin* and MH Gillies

National Centre for Engineering in Agriculture, University of Southern Queensland,
Toowoomba, Qld, Australia

* Corresponding author mdjasimu@usq.edu.au

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.

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 potential average efficiency would be increased up to about 75% (by decreasing both the runoff and deep drainage), although the range of efficiencies 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 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.,* 2012; Koech *et al*., 2014 a & 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^{TM} 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 to 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, 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).

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 to 7.1	380 to 837	54 to 80
D	2	4	565	0.10	2.9 to 3.7	602 to 879	100
various	1	10	240 to 1150	0.05 to 0.15	1.2 to 6.8	230 to 1695	55 to 130

2.2 Data analysis

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

(i) Determination of the infiltration parameters for each furrow,

(ii) Simulation of each irrigation to determine the actual performance 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.

3. FURROW INFILTRATION PARAMETERS AND SIMULATION OF ACTUAL IRRIGATIONS

The soil infiltration characteristic for each furrow and each irrigation was described by the Kostiakov-Lewis equation:

$$I = kt^a + f_o\tau \tag{1}$$

where I is the cumulative depth of infiltration (m^3/m length), a and k are fitted parameters, f_o is the final or steady infiltration rate (m^2/min/m length) and τ is the infiltration time (min).

The infiltration parameters of equation 1 were evaluated for every furrow/irrigation using the calibration function in the Surface Irrigation Simulation Calibration and Optimisation (SISCO) model of Gillies and Smith (2015). SISCO is self-calibrating and in addition to the inflow data can use any or all of advance, runoff, recession and flow depth data in the furrow to estimate the Manning roughness coefficient *n* and the parameters in the Kostiakov-Lewis infiltration equation.

For field T17 the infiltration parameters were estimated using only advance data while for field D, advance data and runoff hydrographs were available.

In all cases the Manning roughness coefficient *n* was assumed to be 0.04 as there was insufficient data available from each event to allow reliable estimation of *n* during the calibration. This is the value that most often results from the SISCO calibration for bare furrows. It is also recommended by the US Soil Conservation Service for smooth bare soil (Clemmens, 2003) and also suggested by ASAE (2003). It is worth noting that the furrow hydraulics behaviour is insensitive to small changes in the Manning *n* (McClymont *et al*., 1996).

Examples of the resulting cumulative infiltration curves for field T17 are presented in Figures 1 and 2. They show characteristics typical of cracking clay soils with a significant rapid initial depth of infiltration followed by a relatively low steady infiltration rate. The differences in magnitude between furrows (Figure 1) are typical of the spatial variability experienced in any irrigated field while the differences between irrigations for a given furrow (Figure 2) are largely a reflection of the variation in soil moisture deficits. The slight differences in the shape of the infiltration functions might be real but could also be an artefact of the calibration process. The infiltration curves also suggest that the deficits vary more than indicated by the growers' estimates. For example, the assumed deficit for irrigation 5 at field T 17 was 64 mm, however, based on the initial rapid infiltration at this site a deficit of less than 40 mm is indicated.

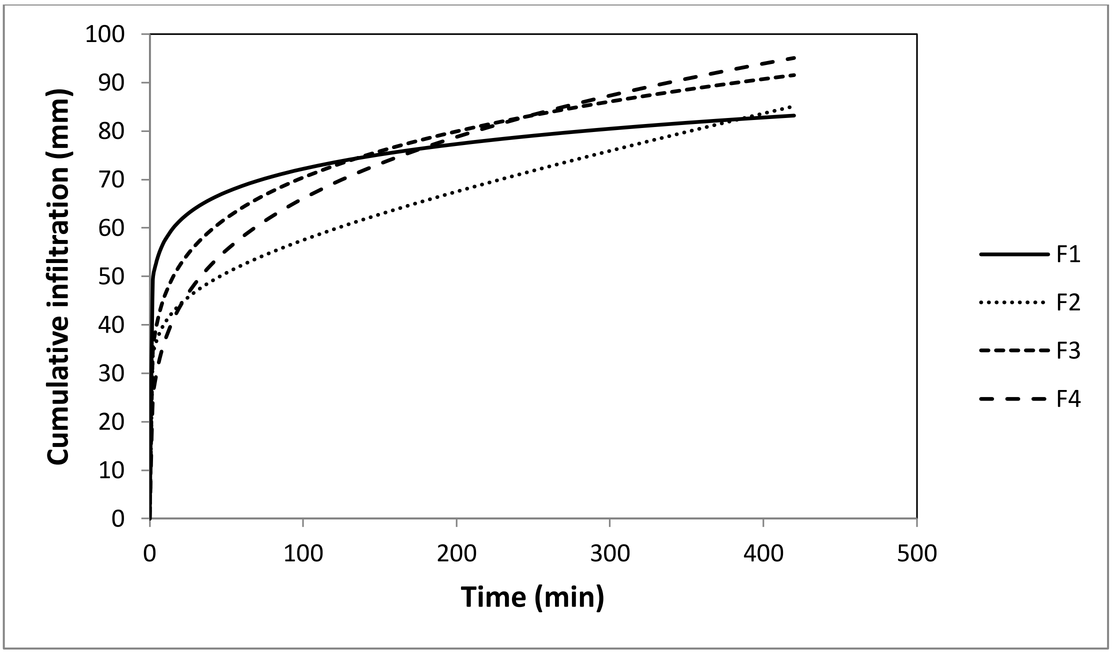


Figure 1 Cumulative infiltration curves for irrigation 2 field T17 (furrows 1 to 4)

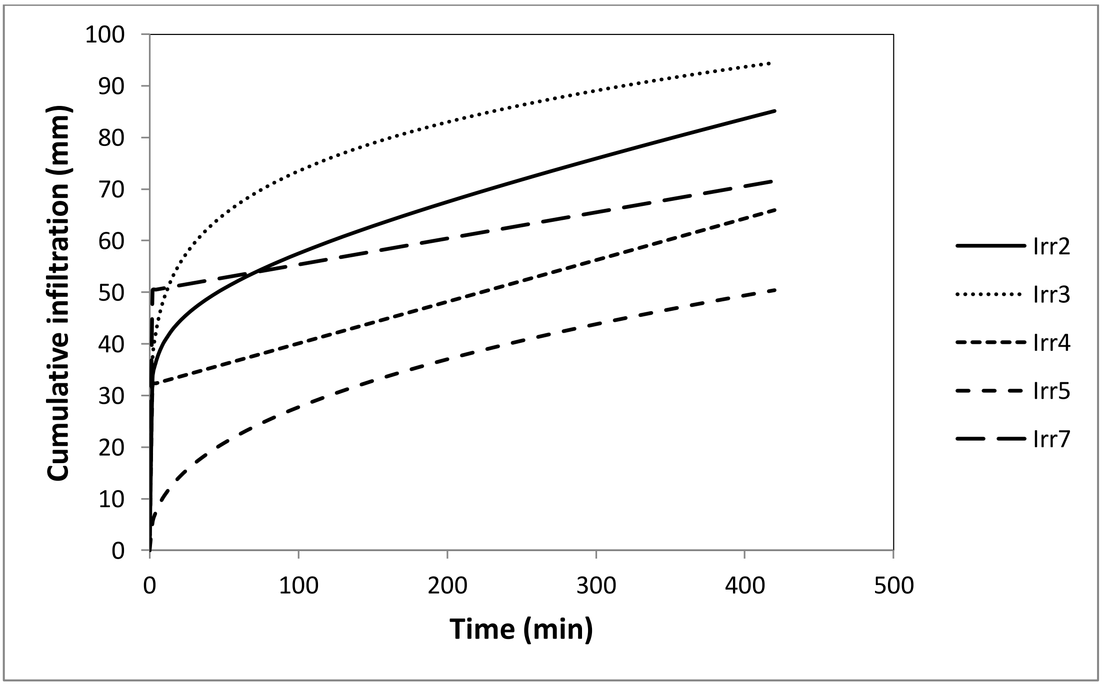


Figure 2 Cumulative infiltration curves for field T17 furrow 2 (irrigations 2, 3, 4, 5, 7)

Although the soil at field D was described as a cracking clay, the infiltration characteristics estimated from the irrigation advance show no evidence of cracking behaviour and are indicative of a permeable clay soil (Figure 3). Curves for the individual irrigations and individual furrows mostly showed a similar shape (as with field T17), and again the magnitudes differed substantially.

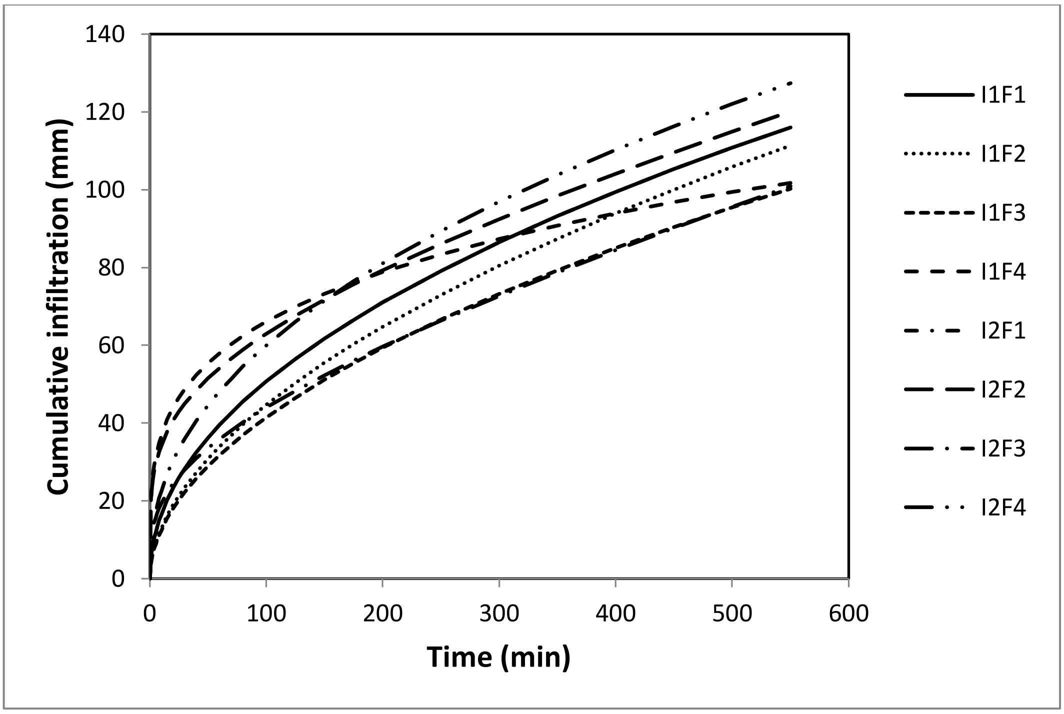


Figure 3 Cumulative infiltration curves for field D (irrigation 1 & 2, furrows 1 to 4)

Although much of the cotton in Australia is grown on ‘cracking’ clay soils the infiltration curves for field D suggest that not all will display the expected cracking type infiltration characteristic. This has significant implications for irrigation management, as will be demonstrated in the later sections of this paper.

Once the soil infiltration parameters had been estimated, the SISCO model was then used to simulate the actual irrigations (using the measured flow rate and the farmer’s *Tco*) and to calculate the performance parameters (application efficiency (*Ea*), requirement efficiency (*Er*), uniformity (DU), runoff volume, deep percolation) for the actual irrigations. These were taken to represent the results for the farmers’ usual management. The results of these simulations for field T17 are presented later in Tables 2 to 4. They show that the actual performance achieved under farmer management is typified by relatively low and highly variable application efficiencies.

4. OPTIMISATION

Each irrigation event in each individual furrow was simulated for a range of flow rates in order to determine the optimal *Tco* for each flow rate. The optimisation strategy chosen for this analysis was to select the *Tco* that gave maximum application efficiency for the given flow rate and a runoff volume equal to 5% of the inflow volume. The purpose of this target runoff volume was to provide a small margin of safety to ensure the advance would always reach the end of the field.

The optimisation objective used in studies such as this is always subjective. Individual researchers and growers place different values on the key performance parameters depending on their particular circumstances. It is not uncommon, for example, for the requirement efficiency to be set at 100%, meaning complete replenishment of the soil moisture deficit over the entire length of the field (e.g. Feyen and Zerihun, 1999). Such a strategy inevitably results in substantial runoff volumes, deep percolation losses and reduced application efficiency, and arguably is not a valid strategy when water is limiting. As well as reduced application efficiency it also leads to reduced water use efficiency (WUE). This was well illustrated by Uniwater (2008) who showed substantial increases in WUE on irrigated lucerne by reducing cut-off times below those required for an *Er* of 100%. The only consequence of this strategy is that the next irrigation might need to be sooner than would otherwise be required. An alternative strategy sometimes used is to maximise uniformity (e.g. Finger and Morris, 2012). This is only valid if *Er* is substantially less than 100%. If *Er* is close to 100% then the uniformity of moisture added to storage in the root zone is by definition at or very near 100%. In this situation the uniformity of infiltration is irrelevant.

Examples of the results of the optimisations undertaken for the present study are presented in Figures 5 and 6, as plots of the key performance measures *Ea*, *Er* and *Tco* versus flow rate for one irrigation event in one furrow from each of fields T17 and D, respectively. They show, as in all irrigations simulated, that the application efficiencies initially rise with increasing flow rate until reaching a plateau at some particular flow rate. The magnitude of this flow rate where the plateau commences is a function of the soil type, surface roughness, field length and deficit, being higher for the more permeable soils, denser crops, longer fields and higher deficits (Smith *et al.*, 2013). It is worth noting here that a different optimisation strategy, such as used by Feyen and Zerihun (1999), will lead to a different relationship between *Ea* and flow rate. In their case efficiency reached a peak at a relatively low flow rate and declined with increasing flow rate. Figures 5 and 6 also shows the times to cut-off (*Tco*), the times for the advance to reach the mid-point of the field (T_{50}) and the advance distances

(*Xco*) corresponding to the time to cut-off for each flow rate. There was one very significant difference between the optimisation results for field D (Figure 6) and those for field T17 (Figure 5). For field D the optimum *Tco* exceeded the advance time to the end of the field for all irrigations.

The effect of flow rate on application efficiency is sufficiently clear to suggest preferred flow rates in the vicinity of 6 L/s for the 1160 m long furrows of field T17 and 4 L/s for the shorter furrows of field D. At these flow rates the irrigation durations (*Tco*) were typically between 7 to 10 hours for field T17, 6 to 8 h for field D. Because runoff was set to 5% (to ensure the advance reached the end of the field) the maximum application efficiency possible was 95%. At or just before the point of maximum *Ea*, the requirement efficiency *Er* was generally adequate (> 95%), although it was substantially lower for at least one irrigation (which will be shown later to be caused by a substantial overestimate of the soil moisture deficit for that irrigation).

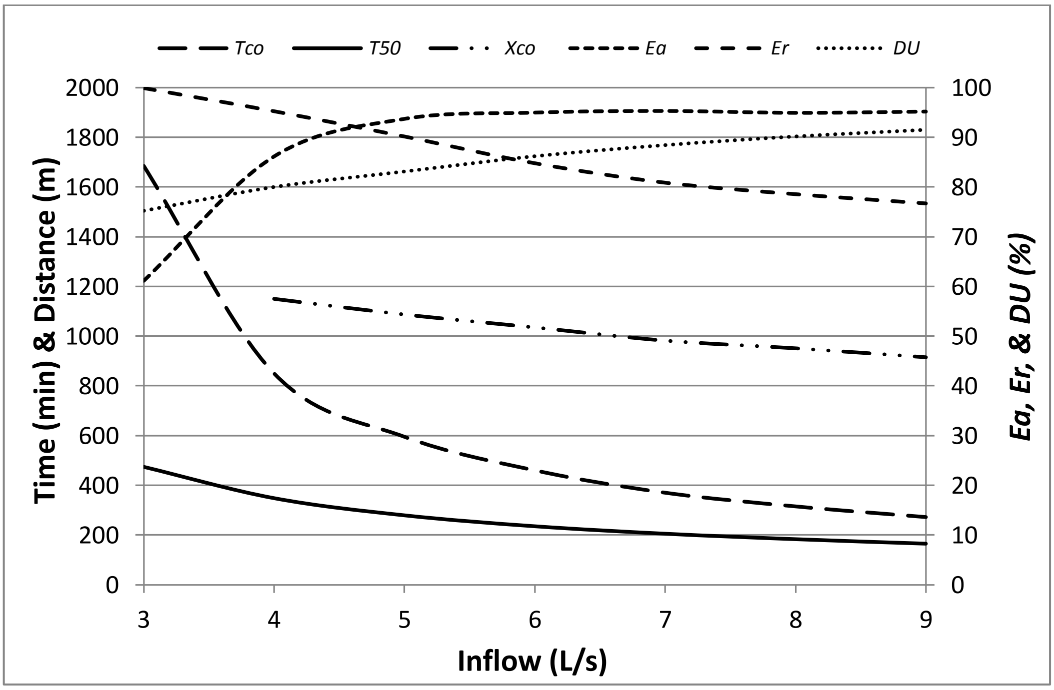


Figure 5 Optimisation results for irrigation 7 furrow 1 field T17 (field length 1160 m, deficit 80 mm)

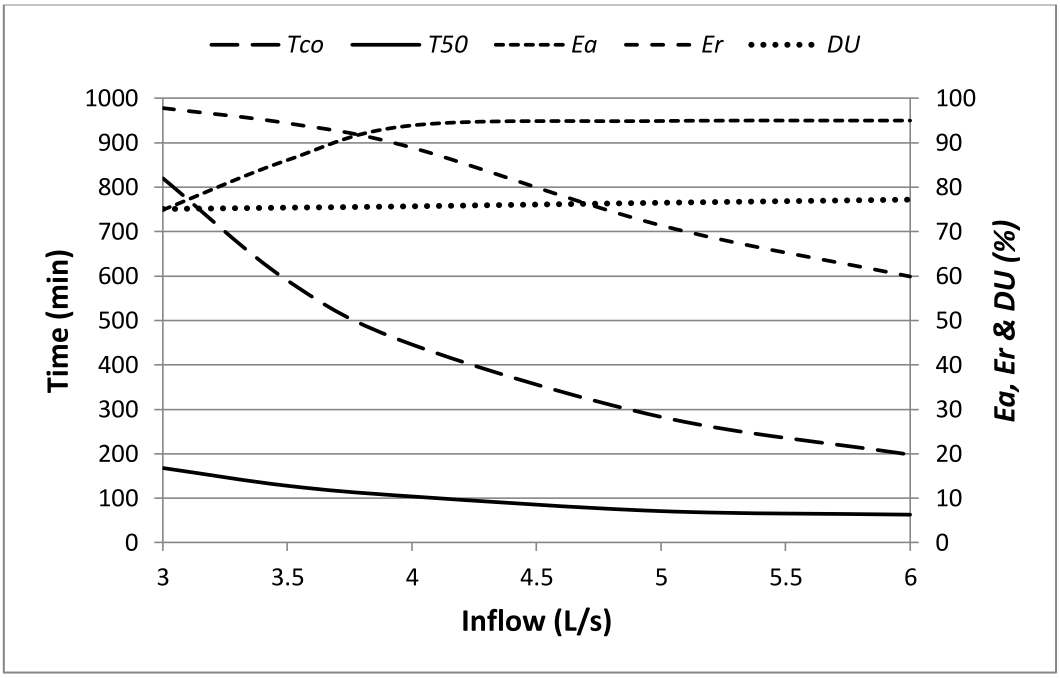


Figure 6 Optimisation results for irrigation 1 furrow 1 field D (field length 565 m, deficit 100 mm)

On both soils the uniformity of infiltration represented by *DU* was relatively insensitive to changes in flow rate. Moreover at the higher flow rates required to maximise application efficiency, *DU* was also tending toward a maximum. There is little that can be done to improve *DU*. However the effective uniformity of the moisture added to the root zone can be increased by over-irrigating, but this comes at substantial cost to the application efficiency through the generation of substantial deep percolation losses. This is not a valid strategy in a water scarce environment. For this reason *DU* will not be considered any further in this paper.

5. RELATIONSHIP BETWEEN ADVANCE TIME AND TIME TO CUT-OFF

To be effective, procedures or guidelines for selection of *Tco* need to be simple to apply, involve the minimum of measurement and calculation on the part of farmers, but at the same time be adaptive to changes in the key variables of flow rate, infiltration and soil moisture deficit. The advance rate tends to integrate the effects of these variables. It is something that irrigators can measure relatively simply. It is also assumed that irrigators will at least be able to estimate the inflow rate into their furrows.

From the above optimisations for field T17, plots of advance time to the half distance along the furrow (T_{50}) versus the optimal time to cut-off (*Tco*) were prepared for one furrow (irrigation 3 furrow 2) for flow rates and infiltration magnitudes (Figures 7) and various furrow lengths (Figure 8).

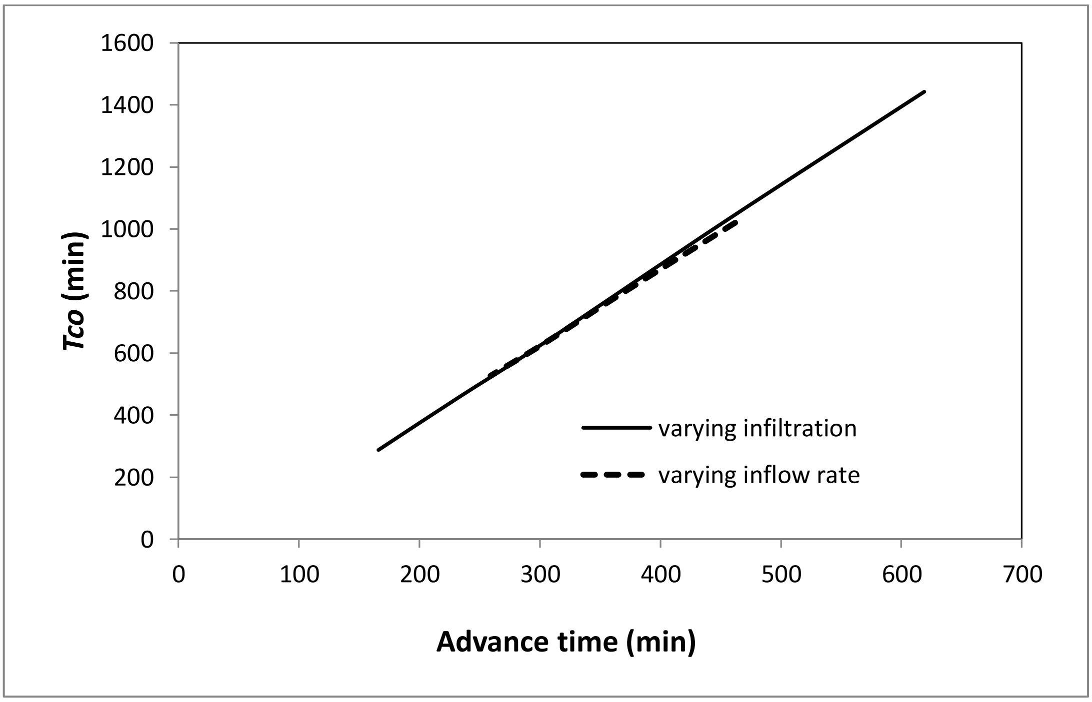


Figure 7 Relationship between advance time and *Tco* for a single furrow for various inflow rates (4 to 7 L/s) and infiltration magnitudes (*k* and f_o scaled by factors from 0.5 to 2)

Figure 7 shows that for this particular furrow and the previously defined optimisation strategy, there is a linear relationship between the advance time and the *Tco* that will result in maximum application efficiency across a wide range of flow rates (4 to 7 L/s) and infiltration magnitudes (*k* and f_o scaled by factors from 0.5 to 2). In this latter case the shape of the cumulative infiltration curve is maintained and only the magnitude is varied. This is in effect equivalent to varying the soil moisture deficit which for a cracking clay soil is assumed to be a multiple of the crack volume (and which in this case is approximated by the *k* parameter in equation 1). The distance used for the advance time was selected arbitrarily but in all cases T_{50} is much less than the *Tco* hence giving time for the farmer to make the necessary control decision. The results suggest that the relationship between advance and *Tco* is independent of the deficit and the infiltration characteristic which means that an irrigator on these soils does not need to know the value of either variable to apply the relationship. It is worth noting here that the relationship is independent of the deficit simply because the requirement efficiency *Er* is not considered in the optimisation strategy. Use of a different optimisation strategy might also result in a non-linear relationship between T_{50} and *Tco*. However, the relationship between T_{50} and *Tco* does change for different length furrows (Figure 8).

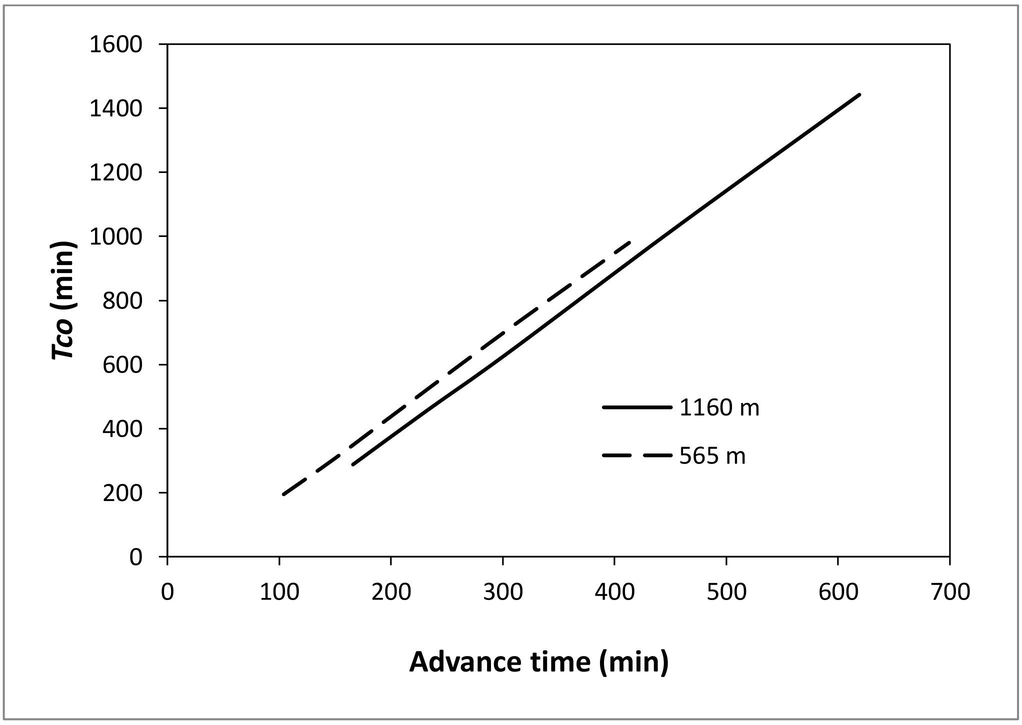


Figure 8 Relationship between advance time and *Tco* for different length furrows (flow rate and infiltration constant)

When data from all furrows and all irrigations from field T17 are used, substantial scatter occurs around the line of best fit (Figure 9). This is assumed to be due to variations in the shape of the cumulative infiltration curves between furrows and between irrigations, some of which may be real and some an artefact of the SISCO calibration process. This scatter adds an element of uncertainty and will result in a loss of efficiency if the relationship is used as intended to control irrigations in large groups of furrows. However the 5% runoff used in the simulations leading to this relationship provides some margin of safety and should ensure that the irrigation replenishes the soil moisture deficit adequately. If this is not sufficient the margin could be increased, thus increasing *Tco* by a similar proportion. The penalty is a reduction in application efficiency.

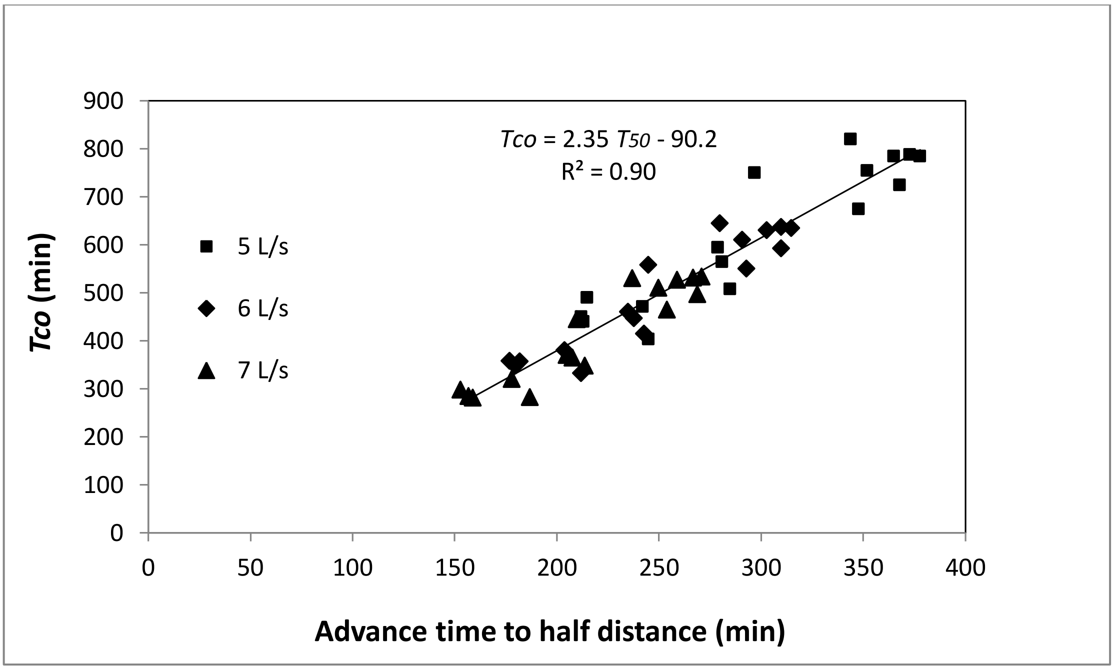


Figure 9 Advance time T_{50} vs *Tco* for field T17 (all furrows/various flow rates)

The data from field T17 suggest a relationship between *Tco* and T_{50} for that field of:

$$Tco = 2.35T_{50} - 90.2 \tag{2}$$

For the same soil in a field of different length a more general relationship that accounts for field length is suggested:

$$Tco = 2.35T_{50} - 0.11L \tag{3}$$

where *L* is the length of the field.

The data for field D (Figure 10) similarly show a straight line relationship *Tco* and T_{50} although the scatter around the line of best fit is substantial at the lower flow rates. In this case the equation of the line of best fit:

$$Tco = 4.11T_{50} - 70.9 \tag{4}$$

gives a much larger *Tco* for any given advance time compared to that for the cracking soil of field T17.

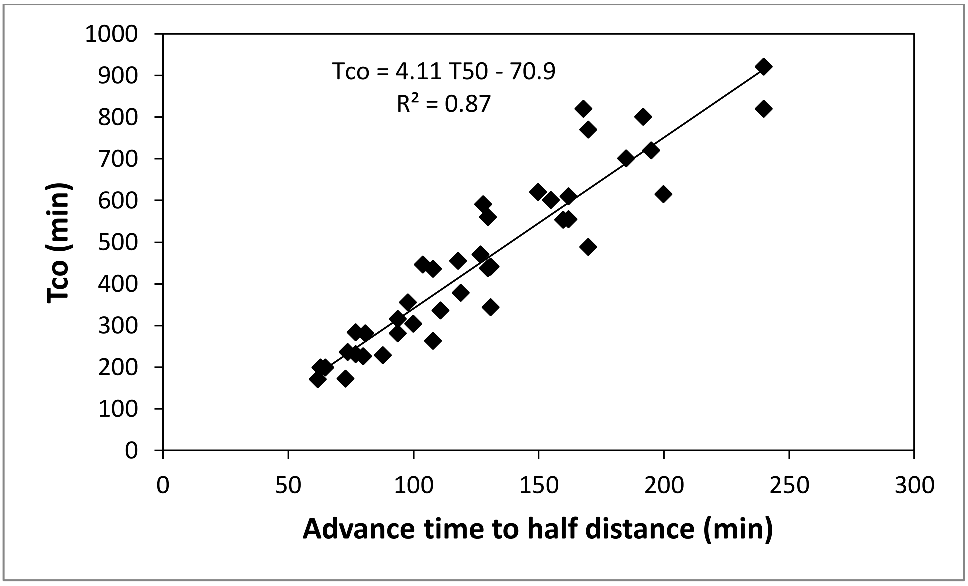


Figure 10 Advance time T_{50} vs *Tco* for field D (all furrows/various flow rates)

6. COMPARISON OF METHODS FOR SELECTING TIME TO CUT-OFF

Three methods for estimating *Tco* were selected for comparison. They are:

a) Cut-off when the advance reaches a set distance along the furrow,

b) Cut-off according to the relationships between *Tco* and T_{50} developed in Section 5, and

c) Cut-off determined by the real-time optimisation of Koech *et al.* (2014) – fields T17 and D only.

For purposes of replicating the working of a practical control system, one furrow at each site was designated as the control furrow, that is, the furrow that would contain the advance sensor (located at the set distance for method (a) or at the mid-point along the furrow for the other two methods). These were selected arbitrarily and for field T17 it was furrow 2 and for field D it was furrow 1. The infiltration characteristic used as the model curve in the real-time optimisation was that for the first irrigation in the nominated control furrow. The optimisation strategy for the real-time optimisation was the same as in the individual optimisations in Section 3, that is, maximisation of *Ea* and with 5% runoff. Based on the simulations for field T17 the set distance was selected as 90% of the length. Flow rates used in the comparison were 6 L/s for field T17 and 4 L/s for field D. For each irrigation and each of the three methods, *Tco* was determined from a single advance measurement in the control furrow. That *Tco* was then used to simulate that irrigation in each of the four furrows in the group. This gave performance that would have been obtained in that particular irrigation in each of the four furrows and also the average performance for the group.

The results for field T17 are presented in Tables 2, 3 and 4, along with the farmer performance and maximum possible performance achievable by optimisation of each furrow individually. These data show that for this field each of the three methods for selecting *Tco* gave very similar performance. In all cases it was better than that achieved under usual farmer management and was very close to the optimum performance for the furrows taken individually. This is not surprising given that the guideline equation and the choice of the 90% set distance were based on the data from this site. The exception was the real-time optimisation for irrigation 5. As indicated earlier the soil moisture deficit provided by the grower (64 mm) was substantially greater than that (40 mm) indicated by the infiltration characteristics for that event. Hence the optimisation resulted in an excessive *Tco* in its attempt to achieve an *Er* of 90% in the control furrow. Changing the optimisation strategy to one of maximising *Ea* and ensuring 5% runoff gave a much improved result, as seen in the final column of Tables 2, 3 and 4.

Table 2 Times to cut-off (min) for field T17 for the various methods of estimating *Tco*

Irrigation	Farmer	Individual Optimum*	Set distance	Eqn 2	Real-time (*Er*>90)	Real time (5% runoff)
2	740	591	516	495	434	555
4	837	624	604	616	614	505
3	650	361	370	386	398	400
5	380	326	272	286	1586	150
7	463	414	460	483	560	420

* Mean of the individual optimum *Tco* values for the four furrows

Table 3 Application efficiencies (%) for field T17 for the various methods of estimating *Tco* (values are averages for four furrows with same *Tco*)

Irrigation	Farmer	Individual Optimum	Set distance	Eqn 2	Real-time (*Er*>90%)	Real time (5% runoff)
2	49.5	58.6	64.2	65.2	66.8	61.5
4	54.5	70.9	73.2	74.1	72.2	77.6
3	70.6	95.0	95.1	86.4	90.0	89.7
5	90.3	95.0	95.0	96.9	26.1	98.8
7	81.8	95.0	86.8	83.8	74.9	92.5
Mean	69.4	82.9	82.9	81.3	66.0	84.0

Table 4 Requirement efficiencies (%) for field T17 for the various methods of estimating *Tco* (values are averages for four furrows with same *Tco*)

Irrigation	Farmer	Individual Optimum	Set distance	Eqn 2	Real-time (*Er*>90%)	Real time (5% runoff)
2	100	100	95.9	93.4	84.0	98.7
4	100	100	100	100	100	88.8
3	97.9	82.1	84.3	86.1	85.7	85.9
5	85.0	75.2	74.3	67.2	100	36.1
7	78.1	76.5	77.2	78.2	82.1	75.6

For field D acceptable performance was given by both the real-time optimisation and the *Tco* / T_{50} relationship (Table 5). The slight difference between the two approaches was due to the different optimisation strategy used, with the real-time optimisation aiming to maintain Er above 90%.

Table 5 Application and requirement efficiencies (%) for field D for two methods of estimating *Tco* (values are averages for four furrows with same *Tco*)

Irrigation	*Tco* / T_{50} relationship (Eqn 4)		Real time	
	Ea	Er	Ea	Er
1	98.4	74.6	89.1	87.8
2	91.5	87.8	78.3	97.1

From section 5 it appears that the main determinant of the relationship between *Tco* and T_{50} is the shape of the infiltration characteristic. Hence, if it can be assumed for example that all of the cracking soil types have infiltration curves of similar shape then the relationship developed for field T17 might be applicable for all cracking soils. To test this notion, data from single irrigation events in individual furrows from 10 farms across the cotton growing region that had infiltration characteristics which displayed a cracking behaviour were used. In each case the irrigations were controlled using times to cut-off based on the set distance (L_{90}) and the relationship between *Tco* and T_{50} (equation 2) with the results presented in Table 6. For purposes of comparison, the actual measured (farmer managed) performance and the optimum performance for that furrow/irrigation determined using the previously define optimisation strategy are also presented.

The results in Table 6 show a wide spread of farmer performance with application efficiencies from a very poor 25% up to very good performance with efficiencies between 80 and 90%. In all cases both the set distance and *Tco* / T_{50} relationship options typically outperformed the grower although the performance was sometimes well below optimum and in some cases the advance failed to reach the end of the field. Taken over all furrows, performance of the two methods was generally similar. However in the individual cases one method often outperformed the other although neither was consistently better. This suggests that the two methods react differently to the slight differences in the shape of the infiltration characteristic for the different furrows.

Table 6 Application and requirement efficiencies (%) for individual furrows on cracking clay soils

Furrow	Farmer		Optimum		Set distance		*Tco* / T_{50} *(Eqn 2)*	
	Ea	Er	Ea	Er	Ea	Er	Ea	Er
#12	52.1	94.3	92.2	88.4	79.3	89.9	71.7	90.9
#41	27.9	100	94.8	92.4	95.3	92.3	96.9	91.9
#61	63.6	100	75.4	100	82.8*	98.6	74.0	100
#74	87.8	100	87.8	100	93.7*	98.2	79.6	100
#87	25.7	100	83.4	99.9	72.7	100	71.6	100
#91	75.9	99.9	93.2	97.7	69.9	100	86.0	99.1
Ba	85.8*	90.8	79.9	99.8	87.1*	86.7	77.7	99.9
By	56.7	100	93.4	94.6	94.0	93.4	99.5	91.4
F	86.5	99.2	89.8	93.7	87.5	98.9	85.9	98.6
K	66.3	99.6	92.8	62.7	94.6	61.3	99.8*	56.4

* advance did not reach end of field

6. DISCUSSION

The methods available to predict *Tco* vary substantially in the degree of sophistication or ‘smarts’, that is, in the extent of the sensing and computation required. Unexpectedly the accuracy of the estimate and the subsequent irrigation performance achieved was not directly related to the level of sophistication. The determining factor was how well the particular system adapted to the prevailing conditions, for example:

- to changes in the soil infiltration characteristic between irrigations as a result of changes in the soil moisture deficit, or
- to changes in the flow rate between irrigations.

For bay irrigation of pasture or fodder crops the method has also to adapt to changes in the vegetation density (surface resistance to the flow), however, this is relatively unimportant in furrow irrigation where the surface condition does not change materially with time.

One control strategy commonly used in currently available automation systems is where the irrigation is shut off at a pre-set time, irrespective of conditions. In this case selection of the time to cut-off depends entirely on the skill and experience of the grower. It is non-adaptive and consequently would be expected to give highly variable performance. However the grower can provide some level of adaptation by altering the set times after observing the irrigation behaviour (i.e. advance rate) on the first set to be irrigated. This approach was not considered in the present study.

Of the alternatives considered in this study, the simplest is to cut off when the advance reaches a pre-set distance down the furrow – for field T17 at 90% of the field length. The speed of advance, and hence the time for the advance to reach the set cut-off distance, is a function of the flow rate, soil infiltration properties, soil moisture deficit and to a lesser degree field slope and surface roughness. Consequently, this approach is crudely adaptive and this is demonstrated in the good performance it delivered for the heavy cracking soils of field T17 and the various individual furrows. While it performed well in these situations it is not known how universally applicable the 90% distance is, and what factors other than shape of the infiltration curve might cause that optimal cut-off distance to vary. The failure of the advance to reach the end of the field in furrows #61, #74 and Ba, suggests that some fields will require a different set distance for optimal performance. However no common cause is evident. On the permeable (non-cracking) soil of site D the optimum time to cut-off occurred after the advance had reached the end of the field hence the set distance approach was not applicable. It also suggests that the set distance might not be an option for other non-cracking soils.

Unlike other approaches the use of the set distance does not allow the system to predict the cut-off time in advance. In many instances it is beneficial to have advance knowledge of the cut-off time so that changes can be made to the distribution system upstream or the field or in the case of manually controlled irrigations the farmer has sufficient time to get to the field in time to shut it off.

One factor that affects the choice of the set distance is the surface roughness as described by the Manning n (Smith *et al*., 2013). Consequently this approach is likely to be less effective in situations where there is considerable variation in n such as in bay irrigation, or furrows with high trash loads, because of the difficulty in separating the opposing effects of changes in infiltration and crop density. For example, an increased infiltration rate (as a result of a drier soil profile) slows the advance to the cut-off point thus allowing greater infiltration to occur to satisfy the greater deficit, that is, the system is adapting in the correct direction. However, a higher surface resistance (i.e., trash or thick pasture) also slows the advance causing more water to infiltrate resulting in over-irrigation, and also causing more water to be on the bay when cut-off occurs resulting in a greater volume of runoff. In this case the method is adapting in the wrong direction.

The simple relationships between Tco and T_{50} observed in this study and the optimisation using hydrodynamic simulation can both be considered as methods of real-time prediction of Tco. Both use data collected during an irrigation to control that irrigation. Both require some prior knowledge of the infiltration behaviour of the soil (e.g. from a single evaluation of a previous irrigation at the site). Both also require (at the very least) measurement of the rate of advance during the irrigation that is being managed. Real-time optimisation using the hydrodynamic simulation also requires measurement of the inflow rate and knowledge of the soil moisture deficit. Both of these methods adapt to changes in flow rate, soil properties, and soil moisture deficit and would be expected to give consistently good irrigation performance.

As seen from the results above, the real-time optimisation delivered excellent irrigation performance for both fields T17 and D, supporting the conclusions of Koech *et al.* (2014a & b). The exception was irrigation 5 on field T17 where a substantial error in estimation of the deficit caused significant error in calculation of Tco by the real-time optimisation. This indicates that the increased sophistication and greater data requirements of the real-time optimisation makes it susceptible to significant errors in the data. The positive for this method was that it worked well for both the cracking (T17) and non-cracking (D) infiltration characteristics.

The robustness and simplicity of a relationship between Tco and T_{50} is a distinct advantage. Once the relationship is established for a field the grower (or automation system) only has to monitor the advance to the half-way point of the field. No knowledge of the flow rate and soil moisture deficit is required. However a disadvantage of this approach is that a constant inflow rate is assumed, whereas hydrodynamic simulation can readily accommodate inflows that (all too often) vary with time. Further testing is required to determine if the approach can accommodate variable inflow rates and if performance can be improved by moving the control point further down the field.

The simple relationship between Tco and T_{50} will change and likely no longer be linear for different optimisation strategies. For example, inclusion of Er in the optimisation will cause the relationship to be sensitive to the soil moisture deficit. Fortunately the optimisation strategy adopted here neglecting *Er* should be suitable for most cracking clay soils as the deficit is typically mostly replenished in a short period after wetting.

The choice of 5% runoff in this study is based on previous experience by the authors, it would be important to investigate whether this 5% limit is satisfactory to account for the range of variability of furrow behaviour expected in a typical irrigation.

Further work is also required to determine whether these simple relationships between *Tco* and T_{50} are field specific or can be applied more generally. For example, the results for the individual furrows on the cracking clay soils suggest that the relationship developed for field T17 works reasonably across other cracking clay soils and might form the basis for a general relationship. The greater variety of infiltration characteristics found in the non-cracking soils poses a more difficult task to develop any generalised approach for these soils.

7. CONCLUSIONS

Optimisations were performed on historical data from a number of individual furrows with the objective of maximising application efficiency whilst ensuring water reaches the end of the field. They showed that the application efficiency increases with flow rate until it reaches a plateau beyond which increases in flow rate result in no further increase in efficiency. Further increases in flow rate only serve to reduce the requirement or storage efficiency to undesirable levels. The point where maximum application efficiency first occurs defines the preferred flow rate for a field.

The optimisations performed using the adopted strategy also showed that for any field there appears to be a linear relationship between time to cut-off and the time of advance to the mid-way point down the field, thus providing a simple guideline for selection of time to cut-off. Evaluation of one irrigation event on the particular field is all that is required to establish this relationship. Once established its application requires measurement only of the T_{50} advance time. Knowledge of the flow rate or soil moisture deficit is not required. Differences in the relationship for cracking and non-cracking soils suggest that the shape of the infiltration characteristic is the main factor in determining the relationship. Crucially, this prediction of time to cut-off can be performed well in advance of when the control decision must be implemented.

Simulations that replicated the control of groups of furrows showed that use of the simple relationship between *Tco* and T_{50} would deliver performance well in excess of that from current grower practice. Performance achieved was equivalent to that delivered by the more data and computationally intensive, hydrodynamic based, real-time optimisation.

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