Cotton Catchment Communities CRC

# FINAL REPORT

*(due on completion of project)*

## *Part 1 - Summary Details*

**Cotton CRC Project Number:** **1.02.21**

**Project Title:** Automation and real time control of furrow irrigation

**Project Commencement Date:** 1/03/2009 **Project Completion Date:** 28/02/2012

**Cotton CRC Program:** Farm

## *Part 2 – Contact Details*


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**Signature of Research Provider Representative:** ______________________________

## *Part 3 – IP and In-kind*

Since the November 2011 6 monthly report, please outline the additional IP and in-kind that has been generated in the project.

1. Intellectual Property developed within the project.
(What Know-How (New Ideas), Confidential Information, Copyright, Patents or Provisional Patents, Registered Design, Trade Secrets or Trademarks have come from this project to date)

No additional IP has been generated in the past 6 months.

2. Project In-kind
(Grower Consultant Ginner or Grower Group In-Kind: Are you conducting part of your project on a cotton farm or in conjunction with an in-kind contribution from a consultant, ginner or Grower Group? Please supply group name - Number of persons involved per week and the number of hours per week involved.)

Field trials for the 2011/12 season are being conducted on the properties of Craig Saunders, St George, and Kim Bremmer, Dalby. In each case the in-kind contribution by the grower was via the provision of group of furrows (8 to 12) where the control of the irrigation was handed over to the research team. The furrows were irrigated with the remainder of each field and there was little or no cost to the grower in terms of water used, labour or crop yield.

## *Part 4 – Final Report Guide (due at end date of project or 31st May 2012)*

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

***Background***

1. Outline the background to the project.

The widely used surface irrigation methods of border check (or bay) and furrow irrigation are variously claimed to be as efficient as any other method or blamed for the perceived low efficiencies of Australian irrigation. However true these opposing claims may be, it is true that there is considerable scope for improvement in both the efficiency and uniformity of surface irrigation applications and that management strategies and technologies are available to start to achieve those improvements. Improvement of furrow irrigation performance through the process of evaluation, and simulation with the IRRIMATE™ suite of tools developed by NCEA is now an accepted practice in the cotton industry. Adaptive real-time control can provide an even higher level of irrigation performance (as demonstrated by Raine *et al.*, 1997, Smith *et al.*, 2005, and Khatri & Smith, 2007) and when coupled with automation can also provide substantial labour savings.

Previous research at NCEA had established the basis for the practical real time control of furrow irrigation. The system involves:

1. automatic commencement of the furrow inflow and automatic measurement of that inflow,
2. measurement of the advance down the furrows mid way through each irrigation,
3. real time estimation of the soil infiltration characteristic and moisture deficit,
4. real time simulation and optimisation of the irrigation for selection of the time to cut-off to give maximum performance for that set of furrows for that irrigation, and
5. automatic cut off of the inflow at the designated time.

All of this is done without user intervention. The system proposed was kept simple, by using a fixed inflow and varying only cut-off time, to encourage implementation of the system. All of the sensing, communication, and software were available but needed to be assembled and a prototype system established for field validation.

Decision support software is an essential part of the system and the software has to perform the following functions:

- continuous inflow measurement through inference from measurement of pressure or head in the supply system,
- characterisation of the field by determining a soil infiltration characteristic from detailed measurements of one irrigation event,
- prediction of the current infiltration parameters from a single observation of the irrigation advance per set of furrows during the irrigation event being controlled,
- simulation of the irrigation and optimisation to determine the preferred time to cut off the inflow to the field, taking into account the current soil moisture deficit and the variation in the infiltration characteristic across the set of furrows.

***Objectives***

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

The aim of the project was to develop, prove and demonstrate an automated furrow irrigation system employing adaptive real-time control. Commercialisation was then assumed to follow after conclusion of the project and if the trials proved successful.

The specific objectives were to:

1. Integrate the modelling software with the sensing, communication and control hardware.
   This objective has been achieved with the successful development of the ‘Autofurrow’ software which completes the above listed functions without user intervention. The software uses the simulation module from the CRCIF developed surface irrigation model SISCO along with unique calibration and optimisation routines, and appropriate communication protocols to allow automatic data input and output.

2. Prove the prototype system through appropriate field trials.
   Trials were held during the 2010/11 season and are continuing through the 2011/12 season. Despite the unusual weather conditions the trials have shown the system (sensing, communication, and software) to be robust and reliable and to give the preferred time to cut-off in adequate time for effective control of the

irrigation events. The system was also successful in delivering irrigation performance significantly better than that achieved by the growers. Improvements to the calibration and optimisation processes identified from the 2010/11 trials have been implemented in the software for the 2011/12 trials. Consequently this objective is considered to be achieved.

3. Evaluate alternative water delivery systems, eg, flexible fluming, bank-less channel, siphon etc.
   This objective was achieved in full with the laboratory trials on gated flexible fluming, participation in the automation demonstration trials conducted by the CRC for Irrigation Futures, and publication of a detailed report on the alternative delivery systems (Koech, RK, Smith, RJ and Gillies, MH (2010) *Furrow irrigation in the Australian cotton industry: alternative water delivery systems and their potential for automation.* Technical Report No. 1002982/1, NCEA).

4. Evaluate the benefits of adoption of the real time system.
   This objective has been partly met. Water savings from use of the system have been demonstrated but the limited (weather disrupted) trials in season 2010/11 were not sufficient to allow these savings to be maximised and the full magnitude of the benefit to be established. This is the main objective of the 2011/12 trials. The decision not to proceed with development of a full scale commercial automation system (see Objective 5 below) has meant that the labour savings were not able to be quantified. However they can be inferred from the labour savings from other more automated irrigation systems such as bankless channel systems or mechanised sprinkler systems. A report based on a desk top study is currently being prepared.

5. Promote adoption of the final system.
   Promotion of the system has taken the form of presentations at five irrigation industry conferences (see publications list) and two farmer extension meetings, one in NSW and one in Qld. Extension officers from the Qld DEEDI have also prepared a video clip for promulgation via Youtube. Promotion has also involved discussions with technology companies that might be interested in commercialising the system. As has been indicated in Section 8 below, NCEA is partnering with the Victorian based company Rubicon Water to develop a commercial prototype system. Funding for this work is currently being sought and is the subject of current proposal to CRDC. This objective has also been satisfied and a viable the pathway has been prepared for commercialisation and adoption of the system.

***Methods***

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

This project was not a typical experimental project and the methodology employed was appropriate for a project involving the development and testing of a piece of technology. It largely followed the objectives outlined above and involved:

1. Development of the system, encompassing:

- Integration of the modelling software with the field specific data and sensing, communication and control hardware to create a system tailored for the particular field, which requires input only of the flow rate and advance time for the current irrigation, and
- Design (as appropriate) and installation of the delivery system and the control and sensing hardware.
- Conduct of field trials of the prototype system(s) over at least one irrigation season to evaluate performance of the system, and
- Evaluation of alternative water delivery systems, using as appropriate, desk top evaluation of system economics, hydraulic modelling, and field trials.

2. Evaluation of the system, which involved the conduct of field trials of the prototype system with the irrigation performance evaluated through standard IRRIMATE™ evaluations.

No new or innovative research methodologies were used or developed during the project.

***Results***

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

Field trials of the automated real-time optimisation system for furrow irrigation were undertaken over the 2010/11 season at a furrow-irrigated commercial cotton property in St George. The property utilised both the siphon and the PTB water application methods almost in equal proportion. Two trial sites, each consisting of 11 furrows, were established, one for each supply method. The trial sites established in the PTB and the siphon-irrigated sections are hereby referred to as Site A and Site B, respectively. Four trials were undertaken at each site during the 2010/11 irrigation season. Each of the four trials at Site A was controlled as per the automated real-time optimisation system as opposed to only one at Site B.

The basis of the automated real time optimisation system developed in this study is to optimise the time to cut-off in order to improve the irrigation performance. Once the water front reaches the sensor placed approximately midway down the furrow, a signal is relayed to the computer which determines the optimum time to cut off the flow and calculates the expected performance. This time to cut off was used to control the trial set of furrows while the farmer controlled the rest of the furrow sets as per the normal practice. Only the furrow inflows were dictated by the irrigator while the irrigation deficit was determined using the water balance method. The farmer varied the flow rates throughout the season and his time to cut-off based on his experiences.

The predicted performance of the five irrigations controlled using the real-time optimisation system is summarised in Table 1 below. The performance measures are based on data collected from the model furrow in which the system control components were placed. The system allows the user to specify the desired level of performance (optimisation strategy) while the software will then determine the time to cut-off required to achieve these limits. As shown in Table 1 this strategy was adjusted in each irrigation in order to maximise performance.

**Table 1 Performance as predicted by the real-time optimisation system**

| | Site A | | | | Site B |
|---|---|---|---|---|---|
| Trial number | 1A | 2A | 3A | 4A | 2B |
| Time to cut off (min) | 424 | 392 | 456 | 584 | 936 |
| Inflow (l/s) | 6 | 5 | 3.82 | 3.3 | 1.6 |
| Deficit (mm) | 80 | 80 | 82 | 90 | 80 |
| Optimization strategy | | | | | |
| Distribution Uniformity (DU) ≥ | 55 | 95 | 90 | 69 | 30 |
| Requirement Efficiency (RE) ≥ | 90 | 95 | 95 | 90 | 85 |
| Application Efficiency (AE) ≥ | 65 | 57 | 80 | 70 | 58 |
| Predicted Performance (%) | | | | | |
| AE | 67 | 59 | 81 | 73 | 58 |
| AE (with 90% recycling) | 67 | 64 | 81 | 73 | 58 |
| DU | 57 | 95 | 95 | 69 | 30 |
| RE | 91 | 100 | 99 | 93 | 86 |
| Inflow volume ($m^3$) | 105 | 133 | 97 | 111 | 84 |
| Drainage (%) | 32 | 31 | 15 | 27 | 42 |
| Runoff (%) | 0 | 8.98 | 0 | 0 | 0 |

A slight error in the code was discovered after the completion of the field trials. As a result, the optimisation model used the wrong inflow in the simulation process hence leading to a slight over prediction of time to cut-off, and inaccuracies in the predicted performance. However, the model used the correct inflow rates to undertake the infiltration scaling, consequently the errors in the predictions were not signification. The error has since been corrected for the 2011/12 trials.

**Evaluation of the irrigations**

A full evaluation of the irrigation performance (involving flow and advance monitoring) was undertaken for each of the trials at the two trial sites. Conventional furrow irrigation evaluations typically use measurements taken from a single (model) furrow which is deemed representative of the entire set of furrows. However since the Irrimate™ advance meters used in the evaluations have eight sensors each, advance data for a similar number of furrows were obtained. This complete set of data was later used to perform simulations for the entire set of irrigation furrows, hereby referred to as multi-furrow evaluation. The farmer's usual irrigation practice was used to evaluate the performance he would have expected to achieve.

In all cases the evaluation process used the same furrow as used for the real-time optimisation. The evaluations were undertaken using the SISCO model. This involved use of the measured flow rate and advance in the calibration mode of SISCO to determine the soil infiltration characteristic. SISCO in simulation mode was then used to obtain the performance parameters, with the results shown in Table 2.

**Table 2 Actual irrigation performance**

| | **Site A** | | | | **Site B** |
|---|---|---|---|---|---|
| Trial number | 1A | 2A | 3A | 4A | 2B |
| Time to cut off (min) | 424 | 392 | 456 | 584 | 936 |
| Inflow (l/s) | 6.00 | 5.00 | 3.82 | 3.30 | 1.60 |
| Deficit (mm) | 80 | 80 | 82 | 90 | 80 |
| Infiltration parameters | | | | | |
| a | 0 | 1.18E-01 | 6.81E-02 | 0.00E+00 | 3.56E-01 |
| k | 8.15E-02 | 5.76E-02 | 6.08E-02 | 9.01E-02 | 1.16E-02 |
| $f_o$ | 4.16E-05 | 0 | 0 | 0 | 0 |
| Actual Performance (%) | | | | | |
| AE | 51 | 65 | 76 | 76 | 64 |
| AE (with 90% recycling) | 76 | 69 | 87 | 96 | 68 |
| DU | 98 | 95 | 99 | 100 | 81 |
| RE | 100 | 100 | 100 | 100 | 100 |
| Inflow volume ($m^3$) | 153 | 119 | 105 | 116 | 90 |
| Drainage (%) | 12 | 28 | 10 | 0 | 30 |
| Runoff (%) | 37 | 7 | 14 | 24 | 7 |

**Expected performance as per the farmer management practices**

Table 3 summarises the performance the irrigator would have achieved using his own time to cut off. The inflows as well as the irrigation deficit are the same as those used by the real-time optimisation system. The infiltration parameters used in the evaluations were obtained using the irrigation performance evaluations during the same irrigation and relate to the same trial or model furrow used above in the real-time optimisation process. The data was again determined using the SISCO model.

The farmer's times to cut off inflow (Table 3) were higher than those predicted by the real-time optimisation system (Table 1), with the exception of Trial 4A. As a consequence, the farmer would have obtained a lower AE and deep drainage losses but higher DU, RE and runoff. In addition the farmer would have applied more water than would have occurred under the control system. This is consistent with anecdotal evidence which suggest that farmers generally choose to have longer irrigation runs to guarantee that water reaches the end of the field.

**Table 3 Performance expected as per farmer time to cut off**

| | Site A | | | | Site B |
|---|---|---|---|---|---|
| Trial number | 1A | 2A | 3A | 4A | 2B |
| Farmer's time to cut off (min) | 565 | 489 | 484 | 480 | 936 |
| Inflow (l/s) | 6 | 5 | 3.82 | 3.3 | 1.6 |
| Deficit (mm) | 80 | 80 | 82 | 90 | 80 |
| Actual infiltration parameters | | | | | |
| a | 0 | 0.117676 | 0.068059 | 0 | 0.35624 |
| k | 8.15E-02 | 0.057629 | 0.060834 | 0.09014 | 0.011571 |
| $f_o$ | 4.16E-05 | 0 | 0 | 0 | 0 |
| Expected Performance (%) | | | | | |
| AE | 38 | 53 | 71 | 92 | 64 |
| AE (with 90% recycling) | 81 | 66 | 86 | 99 | 68 |
| DU | 100 | 97 | 99 | 100 | 81 |
| RE | 100 | 100 | 100 | 100 | 100 |
| Inflow volume ($m^3$) | 203 | 147 | 112 | 95 | 90 |
| Drainage (%) | 3 | 25 | 9 | 0 | 30 |
| Runoff (%) | 58.68 | 21.77 | 19.57 | 7.75 | 6.55 |

It is clear from Table 3 that the farmer was utilising the knowledge gained from preceding irrigations to modify his current irrigation. The farmer progressively reduced both the inflow and the irrigation times throughout the season resulting in increased efficiency as the season progressed. This also benefitted the control system which also gave an upward trend in efficiency over the five irrigations controlled by the automated system. It is also the reason why the final irrigation of the season (Trial 4A) had a shorter cut off time than that predicted by the real time control system.

**Discussion**

Table 4 presents a summary of the irrigation performance over the trials. Although the system gave better performance than the grower achieved, the table shows that the actual performance was on average slightly less than that predicted by the real-time optimisation but very much less than suggested by than a post irrigation optimisation undertaken using the full measured data from each irrigation. This indicated that the performance of the real-time optimisation could and should be improved. Factors investigated for their possible contribution to performance of the real time optimisation were the flow rate, the objective function, the selection of the model infiltration curve, and the infiltration scaling process. This investigation involved an exhaustive series of simulations using the SISCO model, varying each of these factors in turn.

**Table 4 Summary of irrigation performance**

| Trial | Control system prediction | | Actual outcome in controlled furrows | Farmer performance | | Post irrigation optimisation | |
|---|---|---|---|---|---|---|---|
| | AE(%) | TCO (min) | AE(%) | AE(%) | TCO (min) | AE(%) | TCO (min) |
| 1A | 67 | 424 | 51 | 38 | 565 | 99 | 190 |
| 2A | 59 | 392 | 65 | 53 | 489 | 72 | 334 |
| 3A | 81 | 456 | 76 | 71 | 484 | 91 | 352 |
| 4A | 73 | 584 | 76 | 92 | 480 | 100 | 406 |
| 2B | 58 | 936 | 64 | 64 | 936 | 77 | 694 |

This investigation showed that:

i. A simpler objective function, that involved maximising the application efficiency while ensuring that the requirement efficiency was maintained above a pre-selected value and that the irrigation reached the end of the field, provided a similar result but greater robustness to the optimisation;

ii. On these particular soils the performance was insensitive to flow rate, although on most other soils, correct choice of flow rate is critical to maximising performance;

iii. Selection of the model infiltration curve for these soils proved to be a significant issue that needed improvement prior to the 2011/12 trials;

iv. The infiltration scaling process was shown to be inaccurate and needed to be modified; and

v. The measured advance curves suggested a change in soil properties about midway down the field that resulted in an advance curve that was difficult for the optimisation system to predict – this appeared to be the major reason for the reduced performance of the system. system and a potential cause of the difference between predictions provided by the control system and those of the actual irrigation.

The latter three points are discussed in greater detail below.

The work required to establish the model infiltration curve for a set of furrows is expensive, time consuming and requires specialized equipment. However, the performance depends on the quality of this curve and the more data that can be used to determine this curve the better. Rather than use data from a single furrow, infiltration curves from multiple furrows can be averaged to give the most reliable estimate of the infiltration characteristic to ensure that its shape is truly representative of the soils in the particular field. To this end, the project team has developed a novel algebraic method for averaging multiple infiltration curves.

The preliminary trials showed that the infiltration scaling using the volume balance model was too dependent on three empirical shape parameters used in the model. Subsequently the optimisation model (based on the SISCO model) which does not use these parameters was modified to undertake this task. It uses the measured inflow and the model infiltration curve in a series of simulations and simply varies the scaling factor until the simulated advance matches the measured value. Again this is done in real time while the irrigation is underway.

Figure 1 below shows an example of the measured and predicted advance curves, in this case for trial 1A. For the first 500 m of the field length the two curves are in reasonable agreement. However at 500 m there is a clear discontinuity in the measured advance as it accelerates rather than the expected reducing advance rate. The simulation model does not predict the advance at all well beyond that 500 m point. The observed discontinuity is strong evidence of a change (reduction) in soil infiltration properties in the lower half of the field, possibly as a result of land forming activities. In this case the simulation of the advance and hence the prediction of the time to cut-off by the real-time optimisation would be improved significantly by the use of different infiltration curves for the two halves of the field. Development of a method of analysis to quantify the varying infiltration for use in the simulation model is in progress.

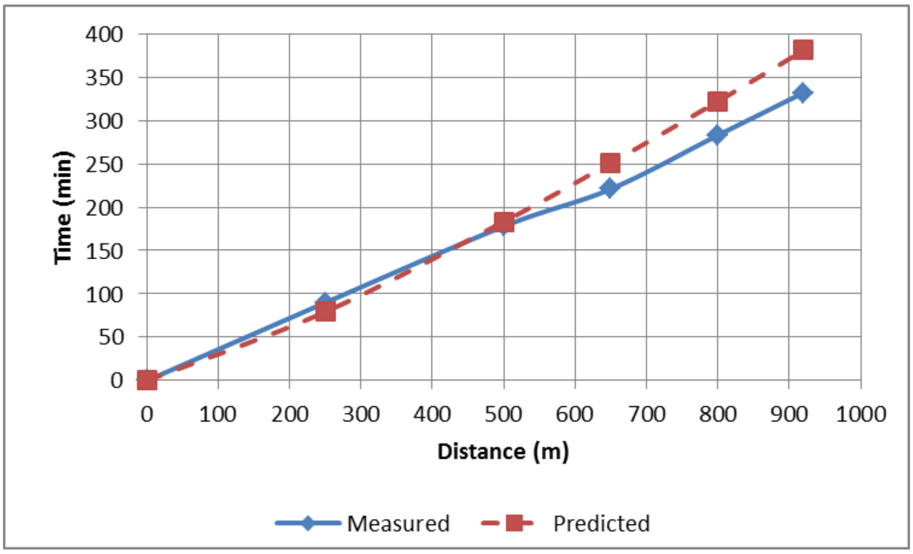


**Figure 1 Comparison of measured and predicted advance curves for Trial 1A**

The 2011/12 trials are still in progress and the results, analyses and conclusions from both the 2010/11 and 2011/12 trials will be reported in detail in the PhD dissertation to be prepared by Richard Koech.

***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.

**Output 1**

The first planned output was a functioning automated real-time control system for furrow irrigation. The actual output is slightly different from that planned and is best described as a functioning real-time optimisation system able to be integrated with any commercial system for automation of surface irrigation, including furrow irrigation. Despite that minor change in emphasis, both of the planned outcomes have been achieved. Unique software has been developed for the simulation, optimisation and control of irrigations in real time. Field testing of the system has shown it to be reliable and robust. It is ready for commercialisation and has attracted the interest of one major manufacturer of irrigation automation equipment, Rubicon Water.

**Output 2**

Output 2 was given as the proof of concept of the system and quantification of improvements in irrigation performance. The field trialling of the system has proven that the concept was valid and that it will deliver substantial improvements in irrigation performance, i.e. savings in water. However as indicated above the field trials have not so far enabled the extent of those improvements to be quantified with any degree of precision or certainty.

**Output 3**

Hydraulic theory, software and procedures for selection, analysis and design of alternative systems constituted output 3. From a science perspective this has been achieved completely. Laboratory and modelling studies have advanced our understanding of the behaviour of: (i) head ditches operating with siphons and with siphon-less systems such as bankless channels, and (ii) gated flexible fluming. Software for the analysis and design of flexible fluming systems has been revised, calibrated and validated. This work has resulted in two journal publications to date, with a possible third paper to follow. Based on these studies it is clear that a furrow automation system will be best served by lengths of fluming supplied by pipes through the bank.

**Output 4**

This was intended to be quantification of savings from application of the system. As indicated above this outcome has not been achieved and will be an objective of the first stage of commercialisation of the system, planned to commence in 2012.

6. Please describe any:-
   a) technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);
   b) other information developed from research (eg discoveries in methodology, equipment design, etc.); and
   c) required changes to the Intellectual Property register.

The significant technical advance and commercially significant development is the software developed for the real-time optimisation and control. Its key features are that it:

i. Is tailored specifically for each individual field through the field specific data such as field lengths and slopes and the model infiltration curve for the field;
ii. Communicates by telemetry with the inflow measurement and advance sensors, and with the control hardware;
iii. Rapidly adjusts (scales) the soil infiltration characteristic to determine the soil conditions prevailing for the particular irrigation;
iv. Contains a proven, robust and accurate simulation of the irrigation advance taken from the CRCIF developed SISCO model;
v. Optimises the current irrigation to satisfy the soil moisture deficit and user specified objectives that can include particular target efficiency, uniformity, runoff and/or deep drainage and determines the time to end the irrigation in sufficient time for effective control of the irrigation.
vi. Will display the predicted performance and the time to cut off required to achieve this level of performance and send shut-down commands to the inflow control system.

***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?

The take home message from the project is that 'smart automation' of furrow irrigation involving adaptive real-time optimisation and control is feasible and can deliver significant improvements in irrigation performance along with the labour saving expected of automation.

The project has proven the concept and established the basis for commercialisation of the system. Development and adoption of a successful commercial system will deliver irrigation performance and labour savings similar to the pressurised systems but at greatly reduced capital and energy costs.

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

Adoption of the system depends on development of a viable commercial system and a successful strategy for commercialisation. A recent appearance on the market is a quality sophisticated automation system (Rubicon Water FarmConnect®) for surface irrigation. This system operates to preset triggers and has no optimisation capability. Rubicon Water is a successful technology company with substantial experience in flow control and automation who have only recently expanded their interests from main channel control to control of on-farm operations. Discussions with Rubicon Water have resulted in an agreement to merge our respective systems. This has eliminated the need for USQ to continue the development of automation hardware (flow control structures, sensing and telemetry). The integration, proving and demonstration of the commercial prototype merged system is the subject of current proposal to CRDC. Further work is also proposed, in conjunction with Rubicon Water, to adapt the optimisation system to bay irrigation and to trial the system in Victoria and in the USA. Rubicon Water will take on the manufacture and marketing of the final commercial system (subject to appropriate agreements regarding the intellectual property).

***Publications***

A. Publications relevant to this project.

Peer reviewed articles / books

Smith, RJ and Gillies, MH (2010) *Head ditch hydraulics and the variability of furrow inflows*. Irrigation and Drainage, 59: 442-452 (doi 10.1002/ird.495).

Non-peered reviewed articles

Presentations (conference, field days, workshops etc)

Smith, RJ, Gillies, MH and Koech, RK (2012) *Real time optimisation for smart automation of surface irrigation.* USCID Conference, Austin, Texas, April 3-6.

Koech, RK, Smith, RJ and Gillies, MH (2011) *Design of an automatic furrow irrigation system utilising adaptive real-time control.* Proceedings of the Biennial Conference of the Australian Society for Engineering in Agriculture (SEAg), 29-30 September 2011, Surfers Paradise, Queensland, Australia, 288-297.

Koech, RK, Smith, RJ and Gillies, MH (2011) *Trends in the surface irrigation systems in the Australian irrigated agriculture*. Proceedings of the Biennial Conference of the Australian Society for Engineering in Agriculture (SEAg), 29-30 September 2011, Surfers Paradise, Queensland, Australia, 277-287.

Smith, RJ (2010) *Precision irrigation: the future of irrigation.* FAR International Conference 2010, The Foundation for Arable Research, Ashburton, NZ, 27-29 July.

Koech, RK, Smith, RJ and Gillies, MH (2010) *Simulation modelling in surface irrigation systems.* Southern Region Engineering Conference, USQ, Toowoomba, 11-12 November.

Koech, RK, Smith, RJ and Gillies, MH (2010) *Automation and control in surface irrigation systems: Current status and future trends.* Southern Region Engineering Conference, USQ, Toowoomba, 11-12 November.

Koech, RK, Smith, RJ and Gillies, MH (2010) *Furrow irrigation in the Australian cotton industry: alternative water delivery systems and their potential for automation.* Technical Report No. 1002982/1, National Centre for Engineering in Agriculture, Toowoomba, Australia.

Koech, RK, Smith, RJ and Gillies, MH (2010) *Hydraulic characteristics of large diameter gated flexible fluming.* In: Irrigation Australia Conference and Exhibition 2010: One Water Many Futures, 8-10 June 2010, Sydney, Australia.

B. All other publications by project team during this period.

Peer reviewed articles / books

Gillies, MH, Smith, RJ and Raine, SR (2011) *Evaluating whole field irrigation performance using statistical inference of inter-furrow infiltration variation.* Biosystems Engineering, 110: 134-143.

Smith, RJ, Raine, SR, McCarthy, AC and Hancock, NH (2009) *Managing spatial and temporal variation in irrigated agriculture through adaptive control.* Australian Journal of Multi-disciplinary Engineering, 7(1): 79-90.

Navabian, M, Liaghat, AM, Smith, RJ and Abbasi, F (2009) *Empirical functions for dependent variables in cutback furrow irrigation*. Irrigation Science, 27: 215-222 (doi 10.1007/s00271-008-0138-8).

Non-peered reviewed articles

Ezlit, YD, Smith, RJ and Raine, SR (2011) *Management options to use highly saline-sodic water for irrigation*. The 12th Annual Conference of Thai Society of Agricultural Engineering "International Conference on Agricultural Engineering", Chon-Chan Pattaya Resort, Chonburi, Thailand, 31 March-1 April.

Foley, JP and Smith, RJ (2011) *Performance evaluation of commercial CP&LM machines.* Proceedings of the Biennial Conference of the Australian Society for Engineering in Agriculture (SEAg), 29-30 September 2011, Surfers Paradise, Queensland, Australia, 169-178.

Uddin, J, Smith, RJ, Hancock, NH and Foley, JP (2011) *Eddy covariance measurements of the total evaporation during sprinkler irrigation – preliminary results.* Proceedings of the Biennial Conference of the Australian Society for Engineering in Agriculture (SEAg), 29-30 September 2011, Surfers Paradise, Queensland, Australia, 506-515.

Uddin, J, Smith, RJ, Hancock, NH and Foley, JP (2011) *Evaluation of sap flow sensors to measure the transpiration rate of plants during sprinkler irrigation.* Proceedings of the Biennial Conference of the Australian Society for Engineering in Agriculture (SEAg), 29-30 September 2011, Surfers Paradise, Queensland, Australia, 516-525.

Khatri, KL and Smith, RJ (2011) *Surface irrigation for energy and water use efficiency.* Irrigation Australia, 2011 Irrigation & Drainage Conference, Launceston, Tasmania, 27-28 September.

Raine, SR, Smith, RJ, McCarthy, A, Gillies, MH, Hancock, NH (2011) *Precision Irrigation – Its more than just technology*. LandWISE Annual Conference, 11-12 May 2011, Havelock North, New Zealand.
Gillies, MH, Smith, RJ, Williamson, B and Shanahan, M (2010) *Improving performance of bay irrigation through higher flow rates.* Australian Irrigation Conference and Exhibition, Sydney, 8-10 June 2010.
Koech, RK and Raine, Steven R (2010) *The effect of irrigation non-uniformity on carrot production.* In: Irrigation Australia Conference and Exhibition 2010: One Water Many Futures, 8-10 June 2010, Sydney, Australia.

(NB: Where possible, please provide a copy of any publication/s)

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

## *Part 5 – 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.

Furrow irrigation remains one of the most commonly used methods for irrigating crops in Australia and around the world due to the low cost and low energy requirements. While well designed and managed surface irrigation systems may have high application efficiencies, many commercial systems have been found to be operating with significantly lower and highly variable efficiencies. Previous research in Australia in the sugar and cotton industries found application efficiencies for individual furrow irrigations ranging from 10 to 90%.

Real-time optimization of individual irrigations has the potential to provide a significant improvement in irrigation performance. Coupling this real-time optimisation with automation gives a 'smart automation' system where the time to cut-off (and possibly flow rate) are varied automatically in response to the behaviour of an irrigation to give the maximum performance for that irrigation. A number of simulation studies have quantified the potential improvement in irrigation performance achievable through real-time optimization and control. When the management parameters were optimized to simulate perfect real-time control of individual irrigations, average application efficiencies in excess of 90% resulted.

A system for the real-time optimization of furrow irrigation has been developed and tested. The system estimates the soil infiltration characteristics in real-time and utilizes the data to control the same irrigation event to give optimum performance for the current soil conditions. The main features of the system 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; transfer of the flow rate and advance data by telemetry; and a microcomputer running a hydraulic simulation program based on the full hydrodynamic equations to predict the optimum time to cut-off.

The system was trialled on a furrow-irrigated commercial cotton property, at St George in south western Queensland, utilizing pipes through the bank (PTBs) to supply groups of furrows.

A significant outcome from the trials was that the real-time optimization model (sensing, infiltration scaling, simulation and optimization) performed robustly and reliably without user intervention. Results from the trials showed that, with the one exception, the irrigation times predicted were shorter than those used by the farmer in irrigating the remainder of the field. This translated to reduced runoff and deep percolation, higher application efficiencies, and hence higher water use efficiency as a direct result of the real-time optimization.

While the real-time optimization can be operated as a manual system the greatest benefits (labour and water savings) occur when it is integrated with automation. The future development of the system will be to integrate it with commercially available automation hardware and software.

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