# MEASUREMENT AND MANAGEMENT OF FURROW IRRIGATION AT THE FIELD SCALE

Malcolm. H. Gillies, Rod. J. Smith and Steven R. Raine

Cooperative Research Centre for Irrigation Futures (CRC IF) and National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland (USQ), Toowoomba Qld, 4350, gilliesm@usq.edu.au

**ABSTRACT**

Generally, the measurement, evaluation and optimisation of furrow irrigation is restricted to a single furrow or small number of adjacent furrows. The measurement process is too intensive to be applied at the full field scale. Consequently it is necessary to assume that the infiltration characteristics and inflow rates of the measured furrow(s) represent the remainder of the field. Many people have observed or speculated upon the significance of spatial variability but few outline potential strategies to deal with the issue. Clearly, a new approach was required. Research conducted by the authors and others at the NCEA has investigated and developed potential tools and techniques to better evaluate surface irrigation accounting for spatial and temporal variability.

A trial was conducted in a typical commercial cotton field to showcase the tools and techniques to evaluate and optimise irrigation performance at the field scale. The resulting data also provided an insight into the nature of spatial variability. Complete inflow, advance and runoff measurements were used to accurately determine soil infiltration rates for a small number of furrows. Single advance points were then used to predict the infiltration characteristics across the remainder of the field. Combined with the whole field simulation model IrriProb this data enabled evaluation of the true irrigation performance taking into account the inter-furrow variability in infiltration and advance rates. The use of the optimisation component of IrriProb demonstrated the ability to identify the optimal field management to maximise irrigation performance. The evaluated field was found to be operating at near optimal conditions however the analysis indentified some further improvements to efficiency and uniformity through the adoption of higher flow rates.

## INTRODUCTION

All irrigation systems should be designed and managed in order to ensure adequate and uniform water application over the field, while minimising the potential losses. For pressurised systems, the uniformity is almost entirely reliant on the characteristics of an engineered artificial system. Pipes and nozzles may be added, removed or exchanged to alter the water distribution and/or maximise irrigation performance. Furrow irrigation differs in that the water distribution is governed by the soil properties. The soil characteristics at any given point will determine the water applied at that point and therefore the volume of water available to be distributed to other points in the field. It is possible to measure the majority of these soil properties at the most smallest scales. However, it is difficult to relate them directly to a hydraulic intake rate. Furthermore many of these techniques cannot be readily applied at larger scales to provide representative estimates at the furrow or field level.

The soil intake rate, *I* ($m^3$/m/min) or infiltrated depth, *Z* ($m^3$/m) is a function of time which is commonly expressed using the Modified Kostiakov equation:

$$I = ak\tau^{a-1} + f_0 \qquad\qquad Z = k\tau^a + f_0\tau \qquad\qquad \text{Eq. 1}$$

Where $\tau$ is the opportunity or ponding time (minutes) and *a*, *k* and $f_0$ are empirical parameters that must be estimated. The parameters have no physical meaning however $f_0$ is strongly related to the final soil intake rate.

The procedures adopted for the evaluation of furrow irrigation such as the Irrimate™ system developed by the NCEA (Dalton 2001) are well refined and have been used extensively throughout the industry. Recent studies (e.g. Smith et al. 2005) have demonstrated the large potential gains in water use efficiency through use of these techniques in conjunction with minimal changes to irrigation management. Most commonly, the analysis is restricted to a single furrow or small number of furrows. This greatly reduces the both the data collection and modelling requirements but as a consequence renders the approach unable to cope with any level of spatial variability. Standard field sampling techniques are generally too intensive to be adapted to increased spatial scales. The evaluation of a single furrow requires measurements of individual inflow and runoff hydrographs, furrow geometries and several (at least 5) water front advance times.

Existing modelling techniques such as SIRMOD (Walker 2003) and SRFR focus on the simulation of water flow within a single furrow and have no capacity to represent variation between adjacent furrows. Those wishing to calculate field uniformities are faced with a manual process to combine results from individual simulation runs.

## FIELD MEASUREMENTS

The experimental site was situated in the Dawson Valley in Central Queensland. The measurements were collected during the second (first in crop) irrigation in a commercial cotton field. Figure 1 depicts the trial layout showing the relative positions of the advance and runoff measurements. Water front advance times were monitored across a total of 84 wetted furrows (168 m). Full advance data (five points in addition to the starting point) was collected in eight wetted furrows in proximity to each side of the field, as shown in figure 1. A single midpoint advance time (at 460 m) was measured in a further 20 wetted furrows. In the remaining furrows one advance time was measured at a distance of 761m corresponding to the last advance point for the detailed measurements. Internal furrow dimensions were measured at several locations and averaged to yield top, middle and bottom widths of 578, 423 and 263 mm respectively and height of 128 mm.

Total field inflow was measured using a STARFLOW Doppler flow meter mounted within the inlet pipe immediately upstream of the supply channel, recording values of velocity and area of flow at 5 minute intervals. All monitored furrows were situated within a single siphon set and hence have the same irrigation start time (within 15 minutes) and same inflow duration. Furrow inflow rates were measured in three locations using one siphon flow meter (furrow 5) and two flume flow meters (furrows 30 and 67). These furrows correspond to those with runoff measurements (figure 1).

Supply ditch head measurements were collected at several positions across the siphon set approximately 1 hour after commencement of inflow and repeated 12 hours later. Supply channel head measurements being the difference between the supply water level and either (a) the centre of the downstream end of the siphon for free flowing conditions or (b) furrow water level for submerged downstream conditions. The siphons consisted of 3.6 m lengths of 44 mm ID pipe.

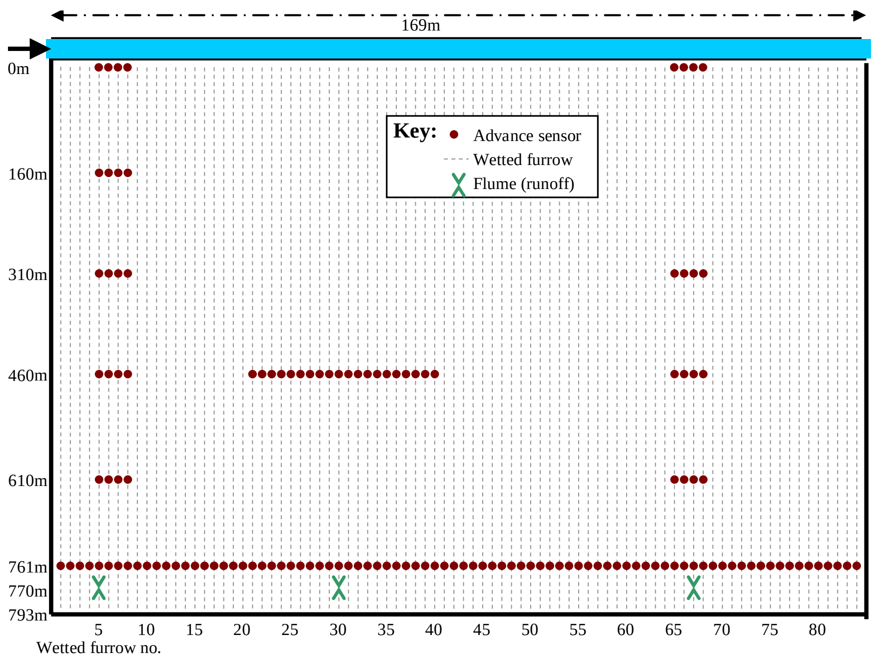


**Figure 1 - Field trial site layout**

Runoff rates were collected using logged flumes for three furrows (no. 5, 30 and 67), two of which coinciding with the detailed advance data. The flumes were positioned at a distance of 770 m, 23 m short of the end of the field to ensure free-flowing conditions. Runoff rates were logged at regular 5 minute intervals for the entire irrigation. Due to difficulties with furrow breakthrough, the flow of one of the adjacent "unwetted" furrows was directed across into the wetted furrow upstream of each flume.

## RESULTS

Inflow head measurements were found to be relatively constant with distance along the supply channel. Whereas one might expect that the level would decrease over a length of channel with side outflow, here the head measurements did not show any declining trend. As siphon dimensions were also constant the inflow rates were assumed to be uniform between furrows. The remaining spatial variation in inflow rates should be minimal and is likely to be random in nature. The STARFLOW measurements remained stable throughout the duration of the event (1410 minutes or 23 ½ hours) indicating a constant discharge. This was confirmed by the data collected from the Irrimate siphon and flume meters installed at the upstream end of the field.

Inflow rates were also estimated from siphon head measurements using the expression introduced by Bos (1979). Here, the discharge ($Q$) is a function of the pipe diameter ($D$), length ($L$), roughness ($f$=0.019), gravity ($g$=9.81) and the pressure difference ($\Delta h$, m of water) between the upstream and downstream ends of the siphon:

$$Q = \frac{\pi D^2}{4}\left(\frac{2g\Delta h}{1.9 + f\dfrac{L}{D}}\right)^{\frac{1}{2}} \qquad \text{Eq. 2}$$

Water head readings varied slightly between furrows with an average of approximately 0.3 m resulting in an estimated discharge of 1.98 L/s. The STARFLOW data when divided by the number of furrows in the set produced a value of 1.9528 L/s with coefficient of variation (CV) over time of less than 4%. As the flow measurements were in close agreement, a discharge of 1.9528 L/s was adopted for this analysis.

Initial observation of the advance times to 761m across all wetted furrows (figure 2) indicates that the furrows with detailed measurement experienced advance rates that were representative of the field. However, they do not span the total range of measured advance times. The spatial distribution of advance rates does not appear to be entirely random. The wetted furrows numbered from 15 to 50 tend to have slower advance rates whilst those between 55 and 65 have higher advance rates. This variability may be caused by changes in siphon pressure head caused by differences in channel or field elevation. Alternatively, large scale spatial trends such as these can be the result of subtle changes in soil composition. This is one feasible explanation as the field has undergone significant laser levelling in the past. Field observations indicated that every second wetted furrow was compacted, corresponding to the odd numbered furrows. As anticipated the wheeled furrows were found to have faster advance rates. Compaction typically causes a decrease in soil intake rate and hence increases the advance speed. Statistical analysis indicated the decrease in advance times between adjacent furrows due to compaction was approximately 42 minutes (paired t-test significant at α=0.05).

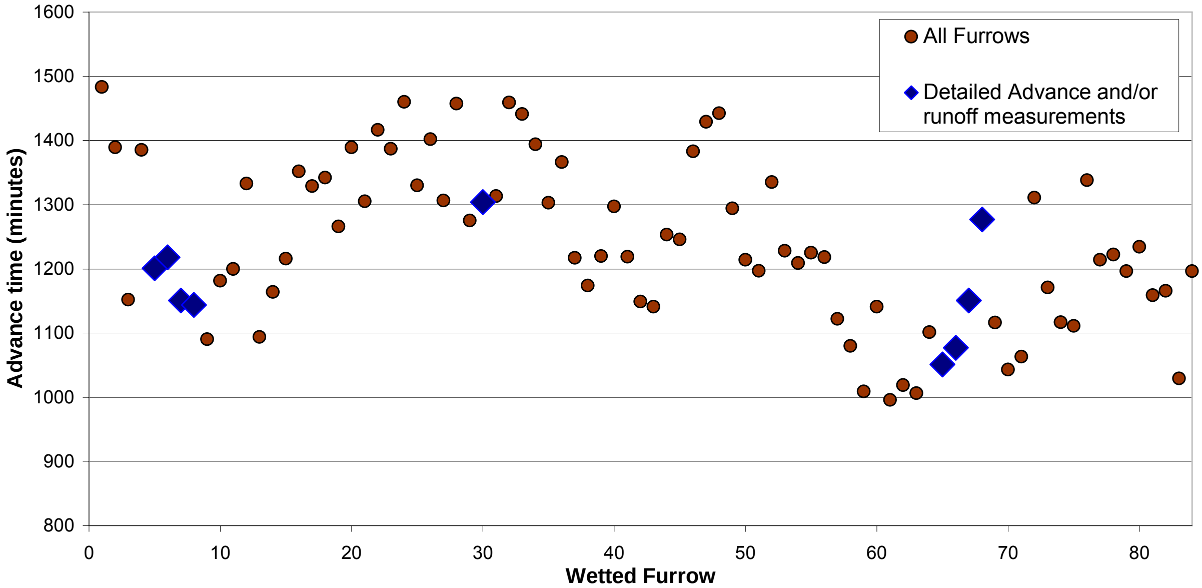


**Figure 2 – Time to reach final advance point**

The runoff volumes measured by the three flumes were equal to 50.7 $m^3$ 41.3$m^3$ and 22.0$m^3$ for furrows 5, 30 and 67. This relates to a percentage of the total inflow volume of 30.7%, 25.0% and 13.3% respectively. The large variation in advance and runoff measurements indicates danger of relying on any one furrow to represent the field application.

## ESTIMATING INFILTRATION

Infiltration parameters were estimated for all individual furrows with complete advance (> 4 advance points) and/or runoff measurements using IPARM (Gillies et al. 2007). IPARM fits the three parameters of the Modified Kostiakov equation (Eq 1) using field measurements and an inverse solution of the volume balance model. IPARM uses the Manning roughness coefficient (*n*) to estimate the volume of water stored in the furrow during the advance and runoff phases. Using the measured upstream water depth of 50 mm results in a Manning roughness of 0.0377 which is typical or smooth clean furrows (*n* = 0.02 for very smooth and 0.06 for rough furrows (ASAE 2003)). In those furrows with measured runoff the parameters were estimated from a combination of advance times and runoff rates with an equal weighting between the two. The use of runoff data appeared to reduce the variance in infiltration rates and standardise the shape of the infiltration curves when compared to advance data alone.

IPARM was also employed to estimate infiltration parameters for those 20 furrows with the mid-point advance measurement. The resulting infiltration curves were found to vary widely in shape indicating a failure to correctly identify the parameters. Hence, the infiltration curves derived from two advance points (excluding furrow 30) were rejected.

## PREDICTING INFILTRATION RATES ACROSS THE WHOLE FIELD

From figure 2 it is evident that the nine furrows with known infiltration functions do not cover the full range of soil behaviour in this field. Therefore any analysis relying on these furrows alone will be unable to predict the full impact of between furrow variability on the irrigation performance.

One possible approach is to estimate the soil intake parameters by scaling the infiltration curve from one of those nine “known” furrows. Khatri et al (2006) describe a technique developed as the basis of a real time control system whereby a “model” infiltration curve (MIC) is scaled according to advance times measured midway down the field length. A scaling factor is estimated from the inflow rate, furrow geometry and single advance point and is then used to adjust the MIC. Khatri et al. (2006) found that the scaling technique performed well over a number of fields and resulted in fair estimates of the irrigation performance. The main problem with the scaling technique is related to its complete dependency on a single MIC, any errors in this curve will be propagated through all the scaled infiltration curves.

A modification to the scaling technique is proposed where the infiltration curves are instead predicted through use of an appropriate statistical probability function. From analysis of data collected from several field sites (not presented here) it was found that the log-normal distribution provided a possible fit to the variation in infiltration curves between furrows and over the season. It was assumed that the infiltration term of the volume balance (at a given advance point and time) follows the same relationship. Using these principles a procedure was developed to predict the infiltration curves across a field using a single advance point and any number of known infiltration curves. Increasing the number of known infiltration curves improves the accuracy and stability of the predicted infiltration curves. Unlike that of Khatri et al. (2006) this technique does not scale the infiltration parameters but instead predicts the form of the infiltration curve and then fits the infiltration parameters via regression.

Infiltration parameters were predicted using this revised approach for all furrows without detailed advance or runoff data (1-4, 9-29, 31-64, and 69-84). The parameters were predicted using the final advance time at 761 m and the known infiltration curves from those furrows with runoff measurements (5, 30 and 67). The resulting IPARM estimated infiltration curves and predicted infiltration curves are shown in figure 3.

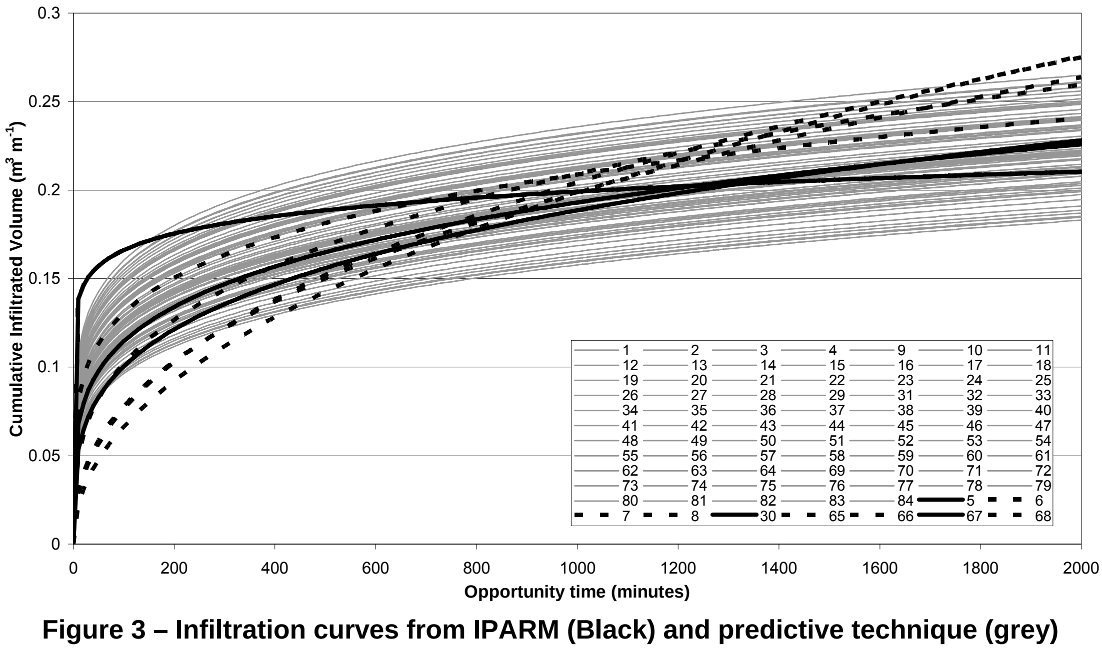


**Figure 3 – Infiltration curves from IPARM (Black) and predictive technique (grey)**

## EVALUATING CURRENT AND POTENTIAL IRRIGATION PERFORMANCE

The computer package IrriProb was developed to extend hydraulic modelling from the single furrow to the whole field scale. IrriProb is built around the FIDO simulation model (McClymont 2007) which applies the full set of hydrodynamic equations to describe the flow of water along a single furrow. The model splits the field into separate furrows, runs multiple simultaneous simulations and combines the results to create a two–dimensional grid of applied depths. IrriProb accommodates in-field variability by allowing each furrow to have individual infiltration characteristics, inflow rates and times and soil moisture deficits.

IrriProb was used to evaluate the irrigation performance under measured field conditions. The simulation was conducted using all 84 infiltration curves as shown in figure 3. The soil moisture deficit was assumed to be equal to 83 mm, based soil probe readings at several locations along the field length. Typically the Manning roughness parameter *n* must be manually adjusted within the simulation model to cause the model to match the advance times. IrriProb predicted the final advance time (at 761 m) with an average deviation of +4.6 minutes without requiring any change in *n*. Improvements to the model fit would require individual values of *n* for each furrow which is beyond the scope of this work. The resulting estimates of irrigation performance indicators are presented in table 1.

**Table 1 – Irrigation performance under measured field conditions estimated by IrriProb**

| | Application Eff. (%) | Requirement Eff. (%) | Distribution Unif. (%) | Absolute Dist. Unif. (%) | Root zone Dist Unif. (%) | Ave. Infiltration (mm) | Deep Drainage (mm) | Runoff (%) |
|---|---|---|---|---|---|---|---|---|
| Whole field | 78.2 | 98.9 | 83.6 | 0.0 | 96.6 | 95.9 | 13.8 | 8.9% |
| Min furrow | 74.4 | 93.7 | 65.7 | 0.0 | 80.0 | 79.9 | 0.4 | 0.0% |
| Max furrow | 79.3 | 100.0 | 94.4 | 90.32 | 100.0 | 105.2 | 26.8 | 23.9% |

The high requirement efficiency (RE) of 98.9% indicates that the irrigation almost completely satisfied the soil moisture deficit of 83 mm. The values of application efficiency (AE) at 78.2% and distribution uniformity (DU) at 83.6% infer that only minimal gains are possible through optimisation. A zero value for the absolute distribution uniformity is a sign that parts of the field receive zero application. Importantly, the values of the performance parameters vary considerably between separate furrows as the Min and Max furrows deviate considerably from the field based estimate. For example, whereas the field runoff is equal to 8.9% of the total inflow the individual furrow inflows vary anywhere between 0% and 23.9%. Hence, evaluation based on any single furrow or small number of furrows may fail to provide an accurate estimate of the field performance.

Apart from the whole-field simulation, the main value of IrriProb is the included optimisation tool. Once the appropriate bounds for the inflow rate and TCO have been selected IrriProb simulates all possible combinations of these two variables to create a database of potential performance results. The optimisation tool encompasses a novel approach engaging the user to customise the objective function. In the example illustrated in figure 4 the user has specified to identify those inflow rates and TCO that will satisfy a RE > 99%, root zone distribution uniformity (DURZ) of at least 90% and AE greater than 70%. The chart also allows the user to visualise the interaction between the selected parameters outside the “Optimal” range (not visible in this greyscale printout).

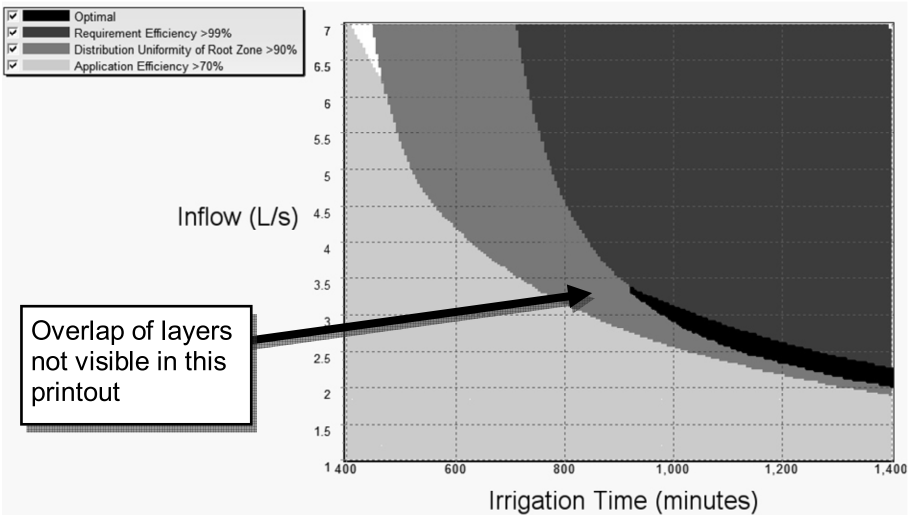


**Figure 4 – Infiltration curves from IPARM (Black) and predictive technique (grey)**

Several strategies were investigated to optimise the entire set of 84 furrows using a single combination of inflow rate and TCO. Considering changes to the TCO (i.e. using the measured inflow rate) only small gains in performance were possible. In reality these small changes (e.g. increasing the TCO by 10 minutes) are probably not warranted as they may be less than the uncertainty in the optimal TCO introduced by errors in field measurements. Considering changes to both inflow rate and TCO slight increases in irrigation performance could be achieved through the use of higher flow rates (table 2). For example, an inflow of 5.82 L/s for 480 minutes (8 hours) maintained a RE > 95% but reduced the depth of deep drainage from 13.8 mm to 3.4 mm.

**Table 2 – Optimising whole field performance by changing inflow rate and time to cut off**

| | Objective | Inflow rate ($L\ s^{-1}$) | TCO (min) | AE (%) | RE (%) | DU (%) | DURZ (%) | Inflow ($m^3$) | Runoff ($m^3$) | Infilt. (mm) | Deep Drain. (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Current** | 1.953 | 1410 | 78.21 | 98.87 | 83.57 | 96.57 | 166.4 | 14.75 | 95.9 | 13.8 |
| **Opt 1.a** | RE>95, DURZ>90 Maximise AE | 3.170 | 790 | 83.67 | 96.71 | 84.24 | 91.01 | 152.2 | 14.74 | 86.7 | 6.5 |
| **Opt 1.b** | RE>99, DURZ>90 Maximise AE | 2.150 | 1311 | 76.65 | 99.30 | 85.27 | 97.88 | 170.5 | 19.20 | 95.6 | 13.2 |
| **Opt 2.a** | RE>95, AE>70 Minimise Deep Drainage | 5.820 | 480 | 73.11 | 95.15 | 86.41 | 90.12 | 171.3 | 40.41 | 82.4 | 3.4 |
| **Opt 2.b** | RE>99, AE>70 Minimise Deep Drainage | 3.280 | 933 | 70.36 | 99.04 | 87.03 | 97.09 | 185.3 | 39.13 | 92.1 | 9.9 |

## CONCLUSIONS

This study has provided valuable information capturing the spatial variation in infiltration that occurs within a single irrigation event. Statistical analysis identified the change in infiltration rates due to machinery compaction however this only accounted for a small proportion of the total variability observed. The trial demonstrated how the existing measurement tools can be better used to evaluate spatial variability. The infiltration characteristics estimated via conventional techniques for a small number of furrows were used to derive the infiltration characteristics across a large field area. Simulation of the irrigation under measured conditions indicated that the field is already being managed at a near optimum combination of inflow rate and time. However, further improvements are possible and can be identified using the optimisation techniques employed here.

## REFERENCES

ASAE (2003). "*Evaluation of Irrigated Furrows*" ASAE EP419.1 FEB03, American Society of Agricultural Engineers

Bos, M.G. (1979). "*Discharge measurement structures*", Third edition, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Clemmens, A. J., and Strelkoff, T. (1999). "*SRFR - A Surface Irrigation Simulation Model*." U.S. Water Conservation Laboratory, Agricultural Research Service, Phoenix.

Dalton, P., Raine, S. R. and Bradfoot, K. (2001). "*Best management practices for maximising whole farm irrigation efficiency in the Australian cotton industry*", USQ, Toowoomba.

Gillies, M.H., Smith, R.J. and Raine S.R. (2007). "*Accounting for temporal inflow variation in the inverse solution for infiltration in surface irrigation*" Irrigation Science, 25(2), 87-97.

Khatri, K and Smith, R.J. (2006) "*Real-time prediction of soil infiltration characteristics for the management of furrow irrigation*", Irrigation Science, 25(1), 33-43

McClymont, D.J. (2007) "*Development of a decision support system for furrow and border irrigation*", PhD Dissertation, University of Southern Queensland, Toowoomba.

Smith, R.J., Raine, S.R. and Minkevich, J. (2005). "*Irrigation application efficiency and deep drainage potential under surface irrigated cotton*." Agricultural Water Management, 71(2), 117-130.

Walker, W.R (2003) "*Surface irrigation simulation evaluation and design - User Guide and Technical Documentation*" Utah State University, Logan, Utah.