Irrigation Application Efficiency and Deep Drainage Potential under Surface Irrigated Cotton

R.J. Smith, S.R. Raine and J. Minkevich
National Centre for Engineering in Agriculture and Cooperative Research Centre for Irrigation Futures,
University of Southern Queensland, Toowoomba, Queensland, 4350, Australia

Corresponding author:
Prof Rod Smith
Faculty of Engineering & Surveying
University of Southern Queensland, Toowoomba, Queensland, 4350, Australia
smithrod@usq.edu.au
Phone +61 7 46312510
Fax +61 7 46312526

Abstract

Furrow irrigation events conducted under usual farmer management were analysed to determine the irrigation application efficiencies being attained, and the magnitude of the irrigation contribution to deep drainage under surface irrigated cotton in Queensland. Application efficiencies were shown to vary widely from 17 to 100% and on average were a low 48%. Losses to deep drainage were substantial, averaging 42.5 mm per irrigation. This has the potential for significant environmental harm and also represents an annual loss of up to 2500 m^3/ha (2.5 Ml/ha) of water that could be beneficially used to grow more cotton. Simulations of each event using the simulation model SIRMOD illustrated simple 'recipe' strategies that would lead to gains in efficiency and reductions in the deep drainage losses. Additional simulations of selected events showed that further significant improvements in performance can be achieved by the application of more advanced irrigation management practices, involving in-field evaluation and optimisation of the flow rate and irrigation time to suit the individual soil conditions and furrow characteristics. Application efficiencies in the range 85 to 95% are achievable in all but the most adverse conditions. The dependency between deep drainage and irrigation management was demonstrated, confirming that substantial reductions in deep drainage are possible by ensuring that irrigation applications do not exceed the soil moisture deficit.

Keywords: Surface irrigation, application efficiency, requirement efficiency, infiltration, deep drainage, simulation, optimisation.

1. Introduction

Irrigation in the Australian cotton industry is typified by furrow irrigation on cracking clay soils with relatively long furrows, low flow rates, and long irrigation durations. Because of the high clay content of the soils it was long assumed that surface irrigation on these soils was inherently efficient and that deep percolation losses beneath the root zone were small or even negligible (for example, Anthony, 1995). This was comforting for the industry because it meant that: (i) there was little need to consider improvements in irrigation practices; and (ii) the absence of deep drainage meant little risk of developing shallow water-tables and the attendant risk of salinisation.

More recently the industry's assumptions have been shown to be false. Irrigation application efficiencies have now been shown to be highly variable across the industry and are often as low as 50% (Dalton *et al*., 2001). Application efficiency as used here is defined as the depth or volume of water added to the root zone store expressed as a ratio of the depth or volume of water applied to the field. It is also recognised that substantial deep drainage can and does occur on these soils (Moss *et al*., 2001). Consequently, deep drainage under irrigated cotton is now acknowledged by the industry as a significant environmental issue.

Numerous factors are seen or assumed to influence the rate or magnitude of the deep drainage, viz:

- soil hydraulic properties/soil texture/clay content;
- cropping pattern;
- irrigation water quality; and
- annual depth of irrigation and rainfall.

Although the depth of irrigation water applied is acknowledged as a contributing factor, few in the industry fully recognise the link between deep drainage and irrigation efficiency. More particularly they do not recognise the role of irrigation management in determining or controlling the depth of that drainage.

Much of the irrigation work undertaken in the cotton industry has focussed on the estimation of irrigation efficiency (ET as a fraction of water diverted) at a whole farm or regional scale (Gilham *et al.,* 1995; Cameron & Hearn, 1997; Tennakoon & Milroy, 2003). Mean values for the irrigation efficiencies from the three studies were relatively low and fell within the range from 50 to 63 %. Estimates for individual properties and regions ranged from 20 to 85%.

Hearn (1998) proposed an irrigation efficiency target for the cotton industry of 75%. This assumed that: (i) deep drainage was non-existent; and (ii) application efficiencies of 97% were attainable (with tail-water recycling). The implication was that the only significant losses were seepage and evaporation during the on-farm storage and distribution of the irrigation water. Hearn's two assumptions were based on limited evidence from two irrigation water balance studies (Yule & Keefer, 1984; Douglas *et al.*, 1998). Both of these studies were conducted under research conditions in which applications were carefully controlled and did not exceed the soil moisture deficit. Of the two, only Douglas *et al.* (1998) measured deep drainage. Yule and Keefer (1984) assumed no deep drainage even though two irrigations involved applications of 142 mm.

The difference (about 20%) between the actual irrigation efficiencies achieved across the cotton industry and Hearn's target value suggest application efficiencies much less than the near perfect 97% assumed by Hearn. It reflects the losses that occur to deep percolation and runoff during the application of water to a furrow or field.

While well designed and managed surface irrigation systems may have application efficiencies of up to 95%, many commercial systems have been found to be operating with efficiencies that are significantly lower and highly variable. Recent measurements by the National Centre for Engineering in Agriculture (NCEA) on irrigation events under commercial conditions in the cotton industry (Dalton *et al.*,

2001) showed application efficiencies for individual irrigations ranging from 35 to 100% and with seasonal efficiencies between 60 and 80%. This supported previous research in the sugar industry (Raine and Bakker, 1996) that found application efficiencies of similar range and magnitude. Deep drainage below the root-zone, (or more particularly a depth of infiltration in excess of the soil moisture deficit), was identified by Dalton *et al.* (2001) as a major contributor to these low efficiencies.

In their review of deep drainage under irrigated cotton, Silburn and Montgomery (2001) reported estimates ranging from 50 to 300 mm/year. These estimates were derived from a number of studies, for a wide scatter of soils and situations, and by a variety of methods. Methods employed in the various studies were: Chloride profiles (Willis & Black, 1996), suction lysimetry (Moss *et al*., 2001), the leaching fraction model (SaLF) of Shaw & Thorburn (1985), irrigation water balance (eg, Douglas *et al*., 1998), and the GLEAMS water balance model (Connolly *et al*., 1998; 1999). While the evidence for the existence of deep drainage is conclusive it should be acknowledged that the estimates of its magnitude vary wildly and all of the methods used display large uncertainties.

The unequivocal conclusions that can be reached from the review and subsequent studies (Hulugalle *et al.*, 2002; Triantafilis *et al.*, 2003) are that:

- deep drainage under irrigated cotton is significant albeit highly variable in its magnitude;
- deep drainage under irrigation is greater than under dryland cropping;
- the magnitude of deep drainage is greater on light textured soils and where the depth of irrigation water applied is high.

The review made no definitive link between deep drainage and irrigation management although the connection was demonstrated in two of the studies reviewed (Douglas *et al*., 1998; Connolly *et al*., 1998; 1999). These suggested that where irrigation applications were substantially in excess of the soil moisture deficit it resulted in a higher level of deep drainage.

Vervoort and Silburn (2002) rightly suggested that some deep drainage from irrigated agriculture is inevitable and further that some is essential to maintain a desirable salt balance in the root zone. They then erroneously put the value of that leaching fraction (or leaching requirement) at 10 to 20% of the applied water, that is, 60 to 120 mm/year. For a relatively salt tolerant crop like cotton, leaching requirements of this magnitude will only be required if the irrigation water quality is very poor. For most cotton areas sufficient leaching will result from the deep drainage resulting from the occasional storm rainfall.

The hypothesis addressed by the present study is that the irrigation component of deep drainage can be controlled and minimised through appropriate irrigation management. In this paper the results from a large number of irrigation events on a range of soils are used to estimate the contribution of irrigation to the annual deep drainage under surface irrigated cotton. The surface irrigation simulation model SIRMOD is then used to show how simple and inexpensive improvements to the management of those irrigations would increase application and water use efficiencies and provide a substantial reduction in the magnitude of the deep drainage. Specific events are analysed to show how further improvements can be achieved through optimisation of the individual events.

2. Methodology

2.1 Irrigation Performance Data

A total of 79 furrow irrigation events conducted by growers using their usual practices were selected for analysis. These were selected from the over 200 individual furrow irrigation events conducted across the cotton growing areas of southern Queensland for which the NCEA has collected irrigation water balance and irrigation advance data. Events for which the data were incomplete or where the irrigation management had been influenced by the research activity or conducted by the researchers were rejected.

Data collected for each event included:

- furrow inflow rate;
- irrigation time (or time to cut-off);
- irrigation advance (advance times for various points along the furrow including the time for the advance to reach the end of the furrow);
- soil moisture deficit; and
- physical characteristics of the furrow (length, slope, cross section shape).

The flow rate and irrigation advance were measured using the IRRIMATE™ suite of tools developed by NCEA (as described by Dalton *et al.*, 2001). The soil moisture deficit was sometimes based on soil moisture measurements and sometimes on the growers' estimate. The range of irrigation management conditions covered by the selected events is illustrated in Table 1.

Table 1 Range of irrigation management conditions covered by the 79 events

Variable	Range
Flow rate	0.83 to 7.9 l/s
Furrow length	250 to 875 m
Advance time	123 to 1550 min
Time to cut-off	200 to 1695 min
Soil moisture deficit	38 to 120 mm
Depth of irrigation applied	19 to 285 mm

2.2 Analysis of Deep Drainage and Application Efficiency

The soil infiltration characteristics for each event were expressed in terms of the modified Kostiakov equation:

$$I = kt^a + f_o t \quad (1)$$

where I is the cumulative depth of infiltration (expressed as a volume per unit length of furrow);
t is the infiltration opportunity time;
f_o is the steady or final infiltration rate for the soil; and
k and a are fitted parameters.

For each irrigation event the parameters (a, k and f_o) in this equation were determined from the irrigation advance data using the program INFILT (McClymont & Smith, 1996). These parameters, along with the physical characteristics of the irrigation furrows, were then used in the surface irrigation simulation model SIRMOD (Walker, 1999) to reproduce each irrigation event as measured. Calibration of the model for each event was conducted by adjusting the hydraulic resistance term (Manning *n*) until the simulated advance matched the measured advance for the full furrow length. Once each event was modelled successfully, SIRMOD was used to explore a range of simple strategies (such as varying the flow rate or time to cut-off) aimed at improving the application efficiency and reducing the potential for deep drainage. The strategies evaluated were:

1. Flow rate as measured and time to cut-off equal to the advance time.
2. Flow rate 6 l/s and time to cut-off equal to the advance time.
3. Flow rate 6 l/s and time to cut-off equal to 90% of the advance time.

As indicated in Table 1, most of the irrigations evaluated were continued well beyond the advance time. Hence, Strategy 1 often constituted a substantial reduction in irrigation time. The flow rate of 6 l/s used in the Strategies 2 and 3 is about the maximum usually considered reasonable within the industry for furrow irrigation without inducing erosion. For most furrows, this flow rate represented an increase over the measured flow rate but for some furrows it was a slight decrease.

Performance measures used to evaluate the strategies were the application efficiency (E_a), the depth of deep drainage, and the requirement or storage efficiency (E_s), this latter term defined as the % of the soil moisture deficit that is replenished by the irrigation. E_a and E_s are output measures from the SIRMOD program. The average depth of deep drainage (d_d) over the length of the furrow is calculated from:

$$d_d = \frac{(1 - E_a)V_i - V_o}{LS} \qquad (2)$$

where V_i is the volume of inflow into the furrow;
V_o is the volume of tail-water outflow from the furrow;
L is the length of the furrow; and
S is the furrow spacing.

It should be noted that the deep drainage as calculated by equation 2 is the deep drainage from irrigation only and represents the infiltration in excess of the soil moisture deficit for each event. It does not include any deep drainage from rainfall either within or outside the irrigation season. While this irrigation excess is assumed to move beyond the root zone, there is no guarantee that this is always the case. Hence this deep drainage should be interpreted as the “potential” for deep drainage due to irrigation excess.

2.3 Optimisation of Specific Events

To explore the additional benefits that might be obtained by optimisation of individual irrigation events, 10 events were selected at random from among the poorer performing irrigations and optimised individually by varying the flow rate Q, time to cut-off t_{co} and where necessary the length of the field. The events selected span the range of soil and irrigation management conditions present in the full data set. The objective function employed was to maximise both E_a and E_s simultaneously.

3. Results and Discussion

3.1 Irrigation Performance and Deep Drainage

A summary of the results of the simulations is presented in Table 2, as the means and standard deviations (in brackets) of the three performance measures. Histograms showing the distribution of the performance measures (E_a, d_d, and E_s) for the grower-controlled irrigations and for Strategy 3 are presented in Figures 1, 2 and 3.

Table 2 Summary of the simulations for the 79 irrigation events giving averages (and standard deviations in brackets) for each of the three performance measures

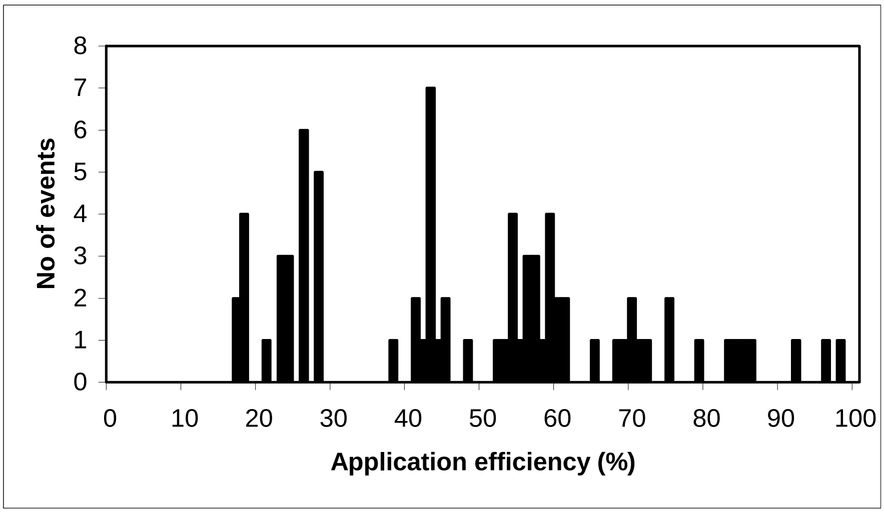
	Application efficiency (%)	Deep drainage (mm)	Requirement efficiency (%)
Farmer managed (as measured)	48.2 (21.2)	42.5 (37.3)	93.6 (16.7)
Strategy 1 (Flow rate as measured, $t_{co} = t_{adv}$)*	72.0 (18.0)	25.8 (29.9)	88.9 (21.1)
Strategy 3 (Flow rate 6 l/s, t_{co} = 90% t_{adv})	73.6 (19.2)	16.0 (23.0)	82.3 (22.7)

* t_{adv} is the time taken for the advance to reach the end of the furrow

Performance of the irrigation events under normal grower control was poor, with the average application efficiency a low 48% and an average deep drainage of 42.5 mm per irrigation (Table 2). However, both measures are also highly variable with E_a ranging from 17 to 100% (Figure 1) and d_d from 0 to >200 mm (Figure 2). These low efficiencies constitute an enormous waste of water and energy. Despite the high deep drainage loss, under grower conditions, tail-water runoff is the greatest contributor to the low efficiencies reflecting the excessive periods of irrigation application. Although most of this tail-water will be recycled and therefore is not a loss to the property, a proportion of this recycled water will be lost to seepage and evaporation during recycling and the pumping costs associated with this volume of recycling will be substantial.

The deep drainage is a real and significant loss of water to the grower. For a typical Queensland cotton grower applying 4 to 6 irrigations annually (Potter, 1999), the deep drainage loss would be between 160 and 250 mm/year, which is equivalent to 1600 to 2500 m^3/ha (1.6 to 2.5 Ml/ha). For the Queensland cotton industry as a whole this represents a loss of approximately 200 to 300 GL/annum of irrigation water and a loss of potential cotton production to the value of about US$ 140 million.

On the credit side, the high requirement efficiencies (Figure 3a) reflect that the inadvertent over-irrigation of crops is at least ensuring that soil moisture deficits are replenished fully. Even so, in about 20% of instances the irrigation fails to fill the root zone store, that is, E_s is less than 100% (Figure 3a). These would typically be among the more efficient irrigations with the least deep drainage. One consequence of a low E_s is that the next irrigation might be required sooner and one more irrigation application might be required later in the season. However, reducing the E_s may also provide greater opportunity for capture and utilisation of in-season rainfall.



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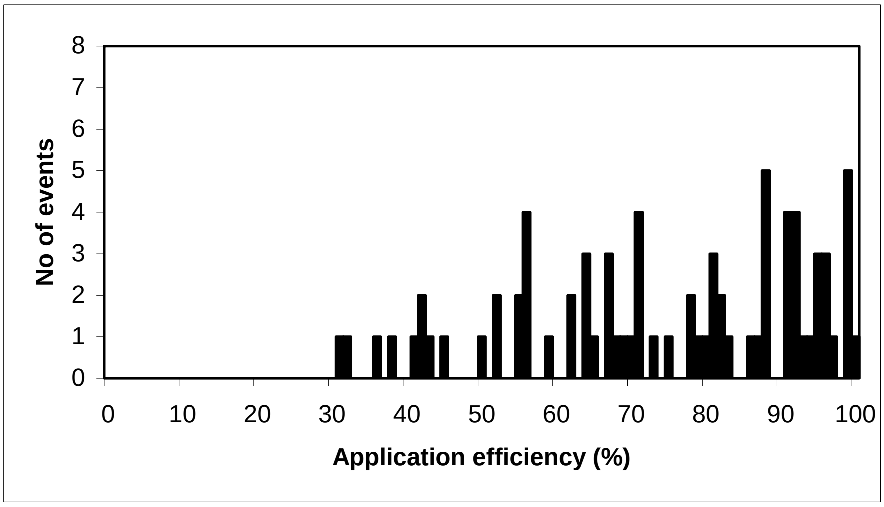

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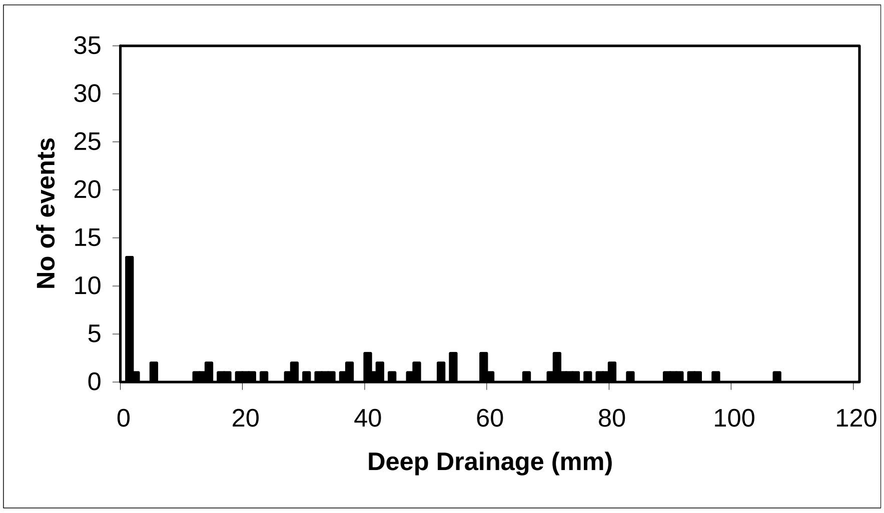
Figure 1 Application efficiencies - where (a) is farmer managed and (b) is Strategy 3 (flow rate 6 l/s and time to cut-off equal to 90% of the advance time)

Applying a simple decision rule (Strategy 1), to stop all irrigations when the advance reaches the end of the furrow results in vastly improved performance (Table 2). Mean application efficiency increases to 72%, with a large number of irrigations better than 90% efficient. However the range of efficiencies remains too wide (from 30 to 100%). More than half the irrigations are still sub-standard (ie, $E_a < 75\%$) indicating that there is further scope for improvement. Average deep drainage is reduced to 25.8 mm per irrigation.

Altering the furrow flow rate to 6 L/s and cutting it off before the advance reaches the end of the field (Strategy 3) provides a further reduction in the deep drainage to 16 mm per irrigation (Table 2). This represents a saving of water on a seasonal basis (ie, 6 irrigations) of 160 mm or about 1600 m^3/ha. The additional gain in application efficiency is relatively small (1.6%) because the reduction in deep drainage is offset to some degree by an increase in tail-water runoff. With this strategy, the requirement efficiency drops to 82%. As can be seen from Figure 3(b), many events would now have an unacceptably low E_s (say < 80%). For some of those irrigations with a very low E_s the advance did not reach the end of the field. In those cases, Strategy 3 is unsuitable.



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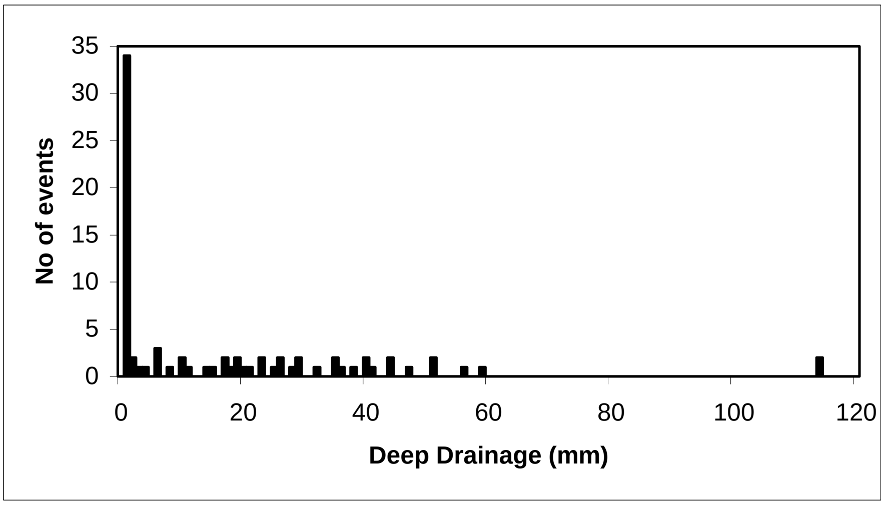
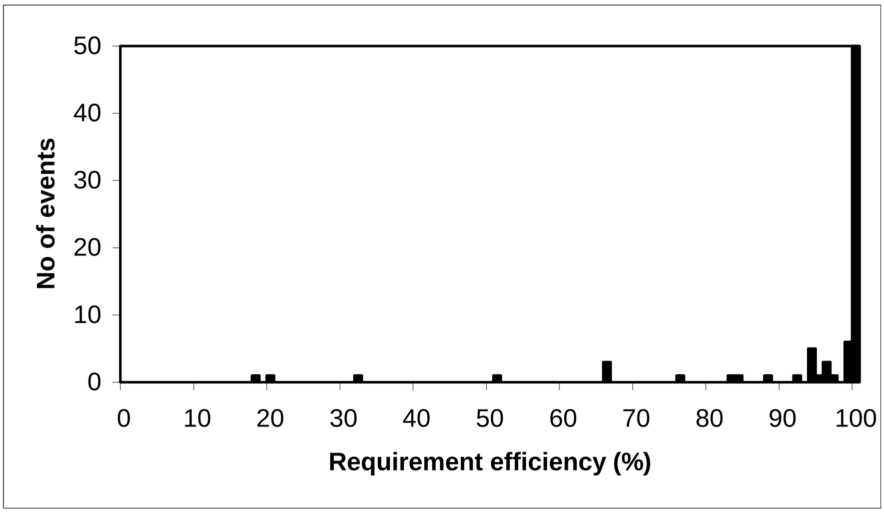


(b)

Figure 2 Deep drainage - where (a) is farmer managed (two extreme points > 200 mm deep drainage have been omitted from this plot), and (b) is Strategy 3 (flow rate 6 l/s and time to cut-off equal to 90% of the advance time)

In summary, application of simple irrigation management strategies involving reduction of the irrigation time or time to cut-off t_{co} and/or increasing the flow rate results in significant improvements in performance as reflected by increased application efficiency and reduced deep drainage losses. However, the detailed results shown in Figures 1 to 3 show that even with the improved management, a large number of irrigations still have low E_a, high d_d, or low E_s. This suggests that there will be a significant number of irrigation events for which adequate performance will not be achieved by "recipe" solutions alone and that adequate performance on these sites will only be obtained by optimising individual irrigations. This supports the results found for the sugar industry by Raine *et al.* (1997).



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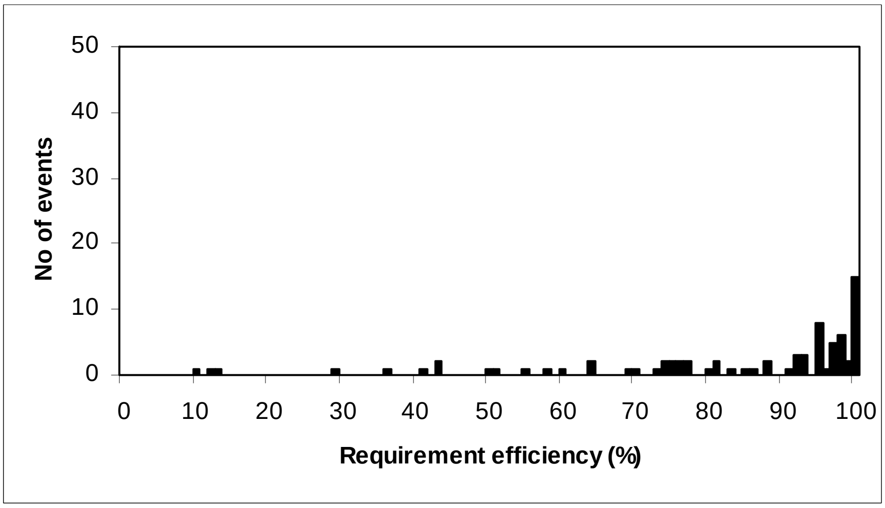
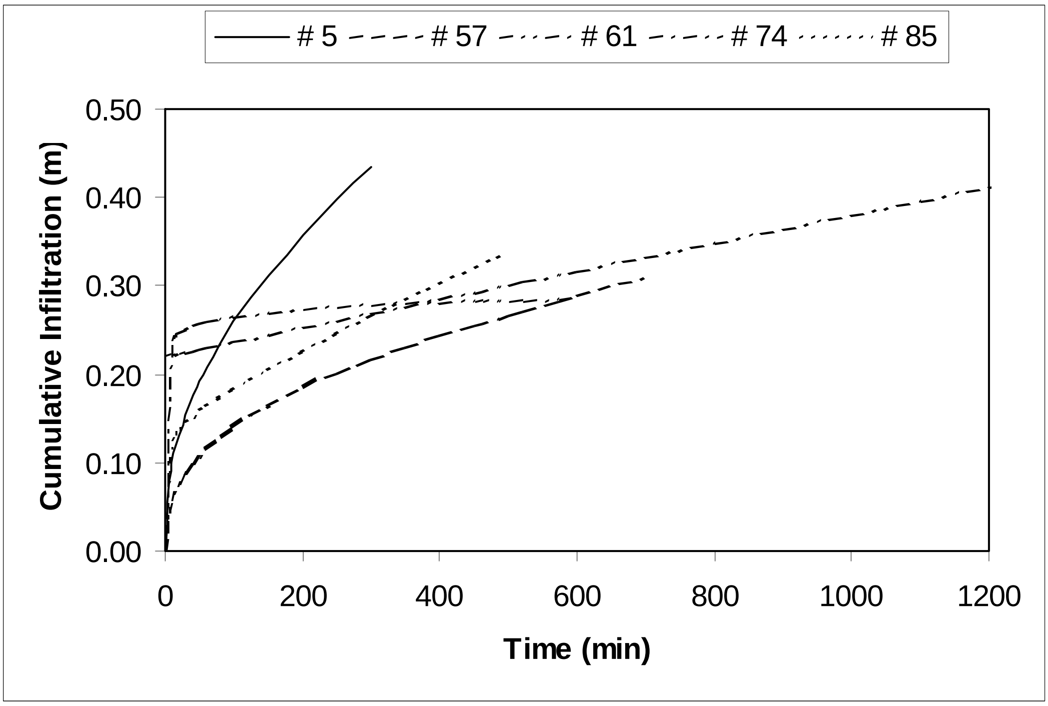


(b)

Figure 3 Requirement efficiencies - where (a) is farmer managed, and (b) is Strategy 3 (flow rate 6 l/s and time to cut-off equal to 90% of the advance time)

3.2 Optimisation of Specific Events

The 10 events evaluated for site specific optimisation strategies were selected from among the poorer performing events, as shown by low efficiency and high losses to deep drainage, and spanned the full range of soils and irrigation management conditions represented by the full set of events. Cumulative infiltration curves from the INFILT analysis (Figure 4) show the extreme variability in soil infiltration characteristics covered by the selected events.



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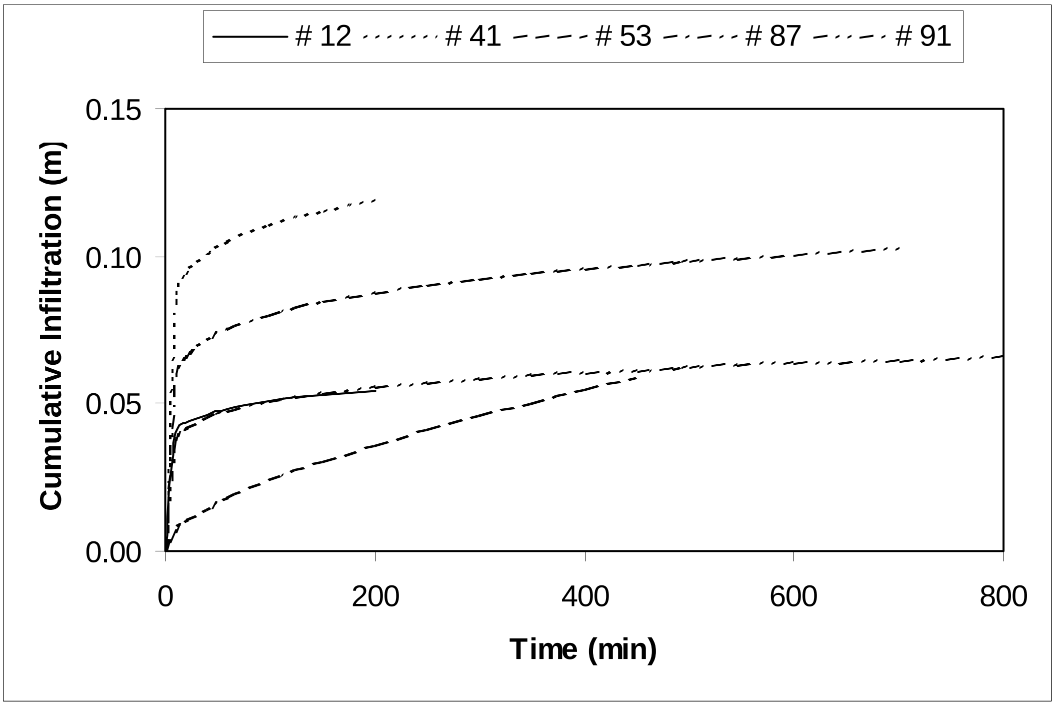

(b)

Figure 4 Cumulative infiltration curves for selected irrigations, grouped by permeability where (a) are more permeable soils, and (b) less permeable.

The results of the basic optimisations (using Q and t_{co} only) for these selected irrigations are presented in Table 3. For the selected events, application of Strategy 3 improved performance over the farmer-controlled irrigation management for all but irrigation # 53 (the improvements for irrigations # 74 and # 91 were marginal). Optimising each event individually by varying only Q and t_{co} resulted in further significant improvements in the performance of all but two of the irrigations, # 41 and 74 where the optimum Q and t_{co} were those of Strategy 3.

Table 3 Results of optimisations of selected events using only Q and t_{co}

			Farmer managed			Strategy 3			Optimised (varying Q & t_{co} only)		
Irrigation	Deficit (mm)	Length (m)	E_a (%)	*dd* (mm)	E_s (%)	E_a (%)	*dd* (mm)	E_s (%)	E_a (%)	*dd* (mm)	E_s (%)
# 5	60	250	17	204	100	31	113	100	43	72	99
# 12	60	250	28	89	100	56	40	100	100	0	90
# 41	38	450	18	27	100	68	17	100	68	17	100
# 53	60	735	75	0	67	59	0	42	91	3	92
# 57	100	675	42	79	100	67	34	98	70	29	99
# 61	100	882	55	78	100	71	43	100	72	40	99
# 74	80	750	59	53	100	63	50	99	63	50	99
# 85	120	804	69	41	99	77	22	74	74	35	97
# 87	80	752	26	58	100	73	18	100	87	11	99
# 91	38	750	53	31	100	50	20	100	71	15	99
Means			44	66	97	61	36	91	74	27	97

The events fall into three groups, viz:

(a) Events # 12, 53 and 87.
For these events optimisation using Q and t_{co} alone was sufficient to obtain excellent performance (Table 3). For example, for event # 12 the simple Strategy 3 gave an application efficiency of 56% and 40 mm deep drainage. Optimisation of that event increased the application efficiency to 100% with no deep drainage. However, Es was reduced to approximately 90% for two of the three events.

(b) Events # 5, 57 and 85.
For this group, substantial improvements in performance are only possible if the lengths of the furrows are reduced to half their actual length. These are all permeable soils with high final or steady infiltration rates. Halving the length of furrow gave increased efficiencies of 65.6, 85.5 and 91.5% for the respective events (Table 4). The performance of irrigation # 5 is still relatively poor but the soil at this site is so permeable that even the very short half furrow length of 125 m is too long for efficient surface irrigation. It is debatable whether surface irrigation is appropriate for this soil. This event was responsible for the highest

deep drainage of any event in the data set used for this paper.

(c) Events # 41, 61, 74 and 91.
While optimisation was able to improve the performance of these events, the soil infiltration characteristics and the simulation modelling indicate errors in the estimates of the soil moisture deficits. These are all soils that exhibit cracking and the estimates of the deficit are not consistent with the volume of the cracks (as indicated by the 'apparent' intercept on the relevant cumulative infiltration curve in Figure 4). Bridge and Ross (1984) showed the magnitude of shrinkage and cracking to be directly related to the soil moisture content, and suggested that the crack volume would typically be equal to about two thirds of the soil moisture deficit. This was supported by Robertson *et al.* (2004) who developed an empirical relationship between crack fill volume and soil moisture depletion under irrigated pasture in southern Australia. For the present study, increasing the deficit to a value consistent with the crack volume results in greatly improved efficiencies and reduced estimates of the deep drainage for each of these events (Table 5).

Table 4 Optimised results for different furrow lengths

	Full length furrow				Half length furrow			
Irrigation	Length (m)	E_a (%)	*dd* (mm)	E_s (%)	Length (m)	E_a (%)	*dd* (mm)	E_s (%)
# 5	250	43.2	72	98.7	125	65.6	29	100
# 57	675	69.7	29	99.1	335	85.5	8	97
# 85	804	73.8	35	97.1	400	91.5	9	100

Table 5 Optimised results accounting for errors in the estimates of the soil moisture deficit

	Original estimated deficit				Revised Deficit			
Irrigation	Deficit (mm)	E_a (%)	*dd* (mm)	E_s (%)	Deficit (mm)	E_a (%)	*dd* (mm)	E_s (%)
# 41	38	68.0	17	100	55	94.2	1	99.1
# 61	100	72.0	40	98.9	120	81.6	27	99.9
# 74	80	62.9	50	99.1	130	93.5	9	100
# 91	38	71.2	15	98.9	55	90.6	1	98.8

It should be noted here that any error in the estimate of the soil moisture deficit (Z_{req}) has no impact on the actual depth of irrigation water applied or on the simulation of the advance or depth of infiltration. The sole effect is an error in the estimates of the performance measures, that is, E_a, d_d, and E_s. Hence the specific and average values for these parameters determined by this study (Table 2 and Figures 1 to 3) should be seen as estimates only. It is possible that in a proportion of the events analysed, E_a may be underestimated and d_d overestimated. However, the improvements in performance and the reductions in deep drainage indicated by the various strategies will be unaffected by any errors in the deficit.

From a practical point of view, certainty in irrigation management requires accurate estimates of Z_{req}. Regular monitoring of soil moisture should be seen as a necessity, not for the purpose of scheduling irrigations, but to inform irrigators of what depth (or volume) of irrigation is required.

In summary, it has been shown how a group of poorly performing irrigations can be improved dramatically through a process of optimisation. The average application efficiency of this group of events rose from an initial 44% under farmer management to:

- 61.2% using the rule-of-thumb of Strategy 3;
- 73.9% by individual optimisation varying Q and t_{co} only; and
- 87.8% if the furrow length is varied as well as Q and t_{co}.

As well, deep drainage was reduced substantially, from an initial 66 mm per irrigation to 11 mm.

In practice, many of these gains would be realisable with current technology. The gains obtainable using the simple rule-of-thumb strategy of increasing flow rates and reducing times can be achieved immediately by most growers with little cost or effort. Selection of preferred and site specific Q and t_{co} based on previous irrigations requires an in-field evaluation of present practices and the associated optimisation. This can be implemented reasonably inexpensively using one of the commercial evaluation services that now operate in the cotton industry. However, the full gains that can be achieved through an optimisation that takes into account the temporal variability in the soil infiltration characteristic may only be attainable through the implementation of some form of real-time control.

4. Conclusions

This study analysed the results from 79 furrow irrigation events on a range of soils and all under usual farmer management to: (i) determine the irrigation application efficiencies being attained, (ii) determine the magnitude of the irrigation contribution to deep drainage, and (iii) demonstrate strategies that would lead to gains in efficiency and reductions in the deep drainage losses.

Application efficiencies were shown to vary widely and on average to be much lower than is desirable, with a mean of 48% and range from 17 to 100%. Losses to deep drainage are substantial under present management practices, averaging 42.5 mm per irrigation. For the cotton industry this represents an annual loss of up to 2500 m^3/ha (2.5 Ml/ha) of water that could be beneficially used to grow more cotton. It also represents a considerable environmental demerit for the industry.

Simulations were undertaken for each irrigation event using the surface irrigation model SIRMOD. These showed that application efficiencies can be increased substantially and deep drainage losses reduced equally substantially by the application of simple inexpensive irrigation management practices involving increased furrow flow rates and reduced irrigation times.

Further significant improvements in performance can be achieved by the application of more advanced irrigation management practices involving in-field evaluation and optimisation of the flow rate and irrigation time to suit the individual soil conditions and furrow characteristics. Application efficiencies in the range 85 to 95% are achievable in all but the most adverse conditions.

The study has shown conclusively the dependency between deep drainage and irrigation management. Unlike the rainfall component of deep drainage, the irrigation component is controllable and is able to be minimised by responsible irrigation management. Substantial reductions in deep drainage are possible by ensuring that irrigation applications do not exceed the soil moisture deficit. However, if maximum irrigation performance and minimal deep drainage are to be attained, then an accurate measure of the soil moisture deficit is required.

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