The Effect of Variable Infiltration on Design and Management Guidelines for Surface Irrigation

S. R. Raine, D. J. McClymont and R. J. Smith

National Centre for Engineering in Agriculture, The University of Southern Queensland,
Qld 4350, Australia.

Abstract

The efficiency of surface irrigations is a function of the field design, infiltration characteristics of the soil, and the irrigation management practices. Fourteen commercial surface irrigations on a high infiltration Dermosol and six irrigations on a low infiltration Sodosol in the Burdekin region of Queensland were monitored during 1994-96. Significant ($P<0.05$) spatial and temporal variability in the infiltration characteristics was observed between the sites and throughout the irrigation seasons. This variability was found to significantly affect irrigation performance and the selection of appropriate surface irrigation design and management practices. Simulations of irrigation performance conducted using SIRMOD and the seasonal average infiltration characteristics for the sites indicated that irrigation application efficiencies for the Dermosol site could be increased from the average 41% achieved in the field trials to 71% simply by using a more appropriate rate of water application and time to cut-off. The application of real-time control management practices at this site was also found to potentially increase application efficiency to 93%. Similarly, seasonal application efficiency at the Sodosol site could have been increased from the 22% to 48% by using a more appropriate water application rate and cut-off time, and to 87% by using real time control.

Keywords: Surface irrigation, infiltration, irrigation efficiency, irrigation performance.

Introduction

Surface irrigation (border and furrow) is the dominant method of applying water to pastures and to a wide range of field and row crops. It accounts for in excess of 70% of the irrigation water in Australian and generates more than $4.5Billion in gross products annually. While it is often claimed that the application efficiency of well designed and managed surface irrigated cotton is over 80% (Anthony 1995), there is little published evidence to confirm the widespread existence of these efficiency levels on commercial farms. Smith (1988) suggests that relatively high efficiencies (70-80%) are possible for surface irrigation under experimental conditions where the levels of management and control are high but that efficiencies achieved on-farm under commercial conditions are sometimes low and certainly highly variable. This is supported by Raine and Bakker (1996a) who found that seasonal application efficiencies of surface irrigated sugarcane in the Burdekin region typically ranged between 30 and 60% with the efficiency of individual irrigations ranging between 10% and 90%.

While substantial improvements in application efficiency are possible through the adoption of appropriate surface irrigation design and management practices (Raine and Bakker, 1996a), irrigators often find it difficult to identify best management practices due to variability in irrigation performance across soil types and throughout the irrigation season. The infiltration characteristic of the soil is one of the dominant factors in determining the performance of surface irrigation applications and both spatial and temporal variations in the infiltration characteristic are a major physical constraint to achieving higher irrigation application efficiencies (Shafique and Skogerboe, 1983). The spatial and temporal variation commonly found in infiltration characteristics (Raine *et al.* 1997) also raises concerns regarding the adequacy of generalised design and management guidelines for surface irrigation. Site specific guidelines for surface irrigation are typically based on extensive field experimentation or on irrigation models which rely on a single estimate of the infiltration function. This paper presents data on the variability of infiltration characteristics and surface irrigation performance measured within two Burdekin cane fields, and investigates the effect of this variability on the identification of optimal irrigation design and management practices.

Materials and Methods

Field data used in this study was collected from commercial irrigations conducted on a high infiltration Dermosol (Jarvisfield) and a low infiltration Sodosol (Mulgrave) growing sugar cane in the Burdekin area. Irrigation advance and volume balance parameters were measured on up to four furrows in each irrigation as reported in Raine and Bakker (1996b). Fourteen irrigations were measured at the Jarvisfield site and six irrigations at the Mulgrave site during the 1994 to 1996 growing seasons.

Kostiakov-Lewis infiltration functions in the form: $I = kt^a + f_o t$ where I is the cumulative infiltration, a and k are fitted parameters, f_o is the final infiltration rate, and t is the infiltration opportunity time, were calculated for each irrigation using the McClymont and Smith (1996) method. Having derived the Kostiakov-Lewis functions, the average infiltration characteristic for each site was calculated using the method outlined in Raine *et al.* (1997). The lowest, highest and average infiltration characteristics measured at each site were used in the surface irrigation model SIRMOD (Walker, 1997) to investigate the interaction of infiltration variability, field length, water application rate and cut-off time on irrigation performance. Irrigation performance was assessed by application efficiency, storage efficiency and distribution uniformity parameters (Walker and Skogerboe 1987). The maximum application efficiency for each combination was then used to develop characteristic curves demonstrating the effect of infiltration variation on irrigation performance.

SIRMOD simulations were also conducted to identify the potential to improve irrigation performance where either the average infiltration characteristic is known or real-time control strategies are adopted. SIRMOD was used to identify the management practices (water application rate and period of application) required to maximise application efficiency for the field length and average seasonal infiltration characteristic at each site. These management practices were then applied in subsequent simulations conducted using the measured infiltration characteristics for each irrigation. However, where the recommended period of watering was inadequate to enable watering of the entire field length in the simulation, the period was extended until the water reached the end of the field as would occur under commercial conditions. To simulate the potential benefits associated with real-time control management of irrigation practices, SIRMOD was also used to identify the application rate and period of application required to maximise application efficiency for individual irrigations based on individual event infiltration characteristics.

Results and Discussion

Commercial irrigation management

Substantial differences in irrigation management practices were observed between the sites (Table 1). Shorter furrow lengths and higher water application rates were used on the high infiltration Jarvisfield site in an attempt to reduce deep drainage losses. However, a substantially longer field length and lower application rates were used on the low infiltration Mulgrave site to increase the infiltration opportunity time. Water application rate was varied at both sites throughout the season in response to water supply constraints, alternative water application requirements, and farmer perceptions of the changes in infiltration and the benefits associated with various application rates. For both sites, the irrigation application was typically stopped at a convenient period after the water had reached the end of the field. Hence, while the average volume of water applied at the Mulgrave site was lower than the Jarvisfield site, the volume applied in individual irrigations at each site is highly variable (Table 1). The seasonal application efficiency for the Jarvisfield site was 41% with the efficiency of individual irrigations varying from 27 to 55% throughout the season. Similarly, the seasonal application efficiency of the Mulgrave site was 23% (not including recycling) with the efficiency of individual irrigations ranging up to 54%. In the Jarvisfield case, storage efficiency was generally greater than 95% reflecting the commercial practice of completely refilling the root zone. However, at the Mulgrave site, the storage efficiency was highly variable with an average of 74% due to the lower infiltration rates of the soil.

Table 1. Commercial irrigation practice for two sites in the Burdekin area (1994-96)

Site	Field Length (m)	Water Application Rate[a] (L/s/furrow)	Cut-off Time[a] (min)	Volume applied[a] (ML/ha/irrig)	Average soil water deficit (ML/ha)
Jarvisfield	470	2.6 (2.0-3.4)	644 (453-913)	1.4 (1.1-2.1)	0.60
Mulgrave	1000	0.85 (0.6-1.3)	2846 (1120-4675)	1.1 (0.7-1.9)	0.40

[a] Mean value with the range shown in brackets

Infiltration variation

Twenty two infiltration characteristics were measured for the Jarvisfield site and twelve for the Mulgrave site (Fig. 1). The infiltration characteristics were found to differ significantly between furrows and with time for the same furrows. At both sites, temporal variation was greater than spatial variability (Fig. 2). Using the measured infiltration characteristics, infiltrated volumes at the Jarvisfield site were found to vary from 1.0 to 2.5 ML/ha throughout the season for a nominal opportunity time of 500 min and from 0.2 to 2.0 ML/ha at the Mulgrave site for a nominal opportunity time of 2000 min (Fig. 2). While there was substantial variation in infiltration at both sites throughout the season, it is possible to identify definite trends in the data. For example, the lower infiltration rates experienced at the Jarvisfield site during the March-April period may have been due to the incidence of summer rainfall during these months resulting in higher (15-23%) initial surface soil gravimetric moisture contents for these irrigations than for throughout the rest of the season (10-17%). Similarly, the lodging of cane and increased trash levels late in the season may have increased the resistance to furrow flow resulting in the higher infiltration rates observed during the May-July irrigations. The significantly lower infiltration rates observed later in the season at the Mulgrave site are also indicative of the surface sealing and crusting which occurs at this site due to the sodic properties of the soil.

Fig. 1. Variation in infiltration characteristic at the (a) Jarvisfield and (b) Mulgrave sites.

Fig. 2. Variation in cumulative infiltration for (a) 500 min nominal opportunity time at Jarvisfield and (b) 2000 min nominal opportunity time at Mulgrave. Error bars indicate standard deviation due to spatial variation.

Effects on irrigation design

The lowest and highest measured infiltration functions, and the calculated average infiltration function, were used to determine the effect of field length on irrigation performance at the Jarvisfield site where the water application rate and period of irrigation were fixed (Fig. 3). In each case, application efficiency increased with increasing field length due to a reduction in tailwater losses. For each period of irrigation, the maximum irrigated field length was a function of the application rate and the infiltration characteristic. The maximum application efficiencies and corresponding field lengths were determined for each of the infiltration characteristics and plotted to provide an indication of the effect of infiltration on efficiency and optimum field length (Fig. 4).

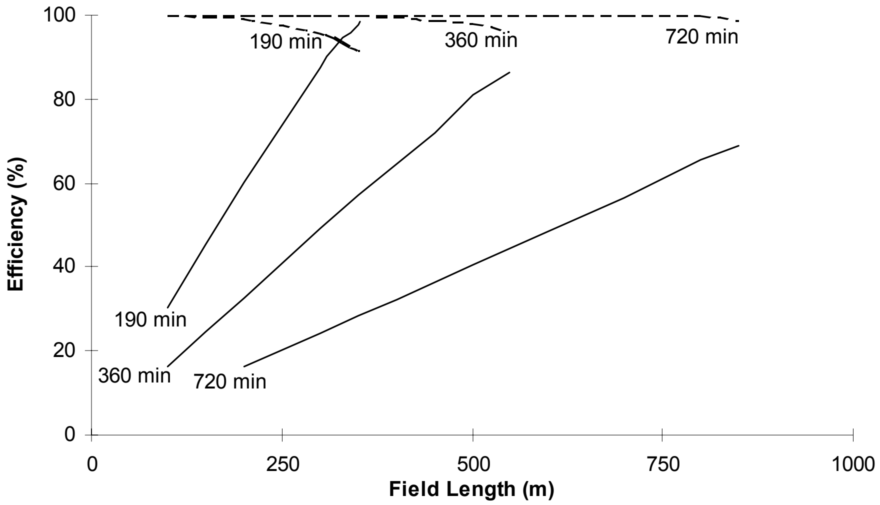

Fig 3. Application (—) and storage (- -) efficiencies for the Jarvisfield site calculated using the seasonal average infiltration function, a water application rate of 2.6 L/s and a range of irrigation periods from 190-720 min.

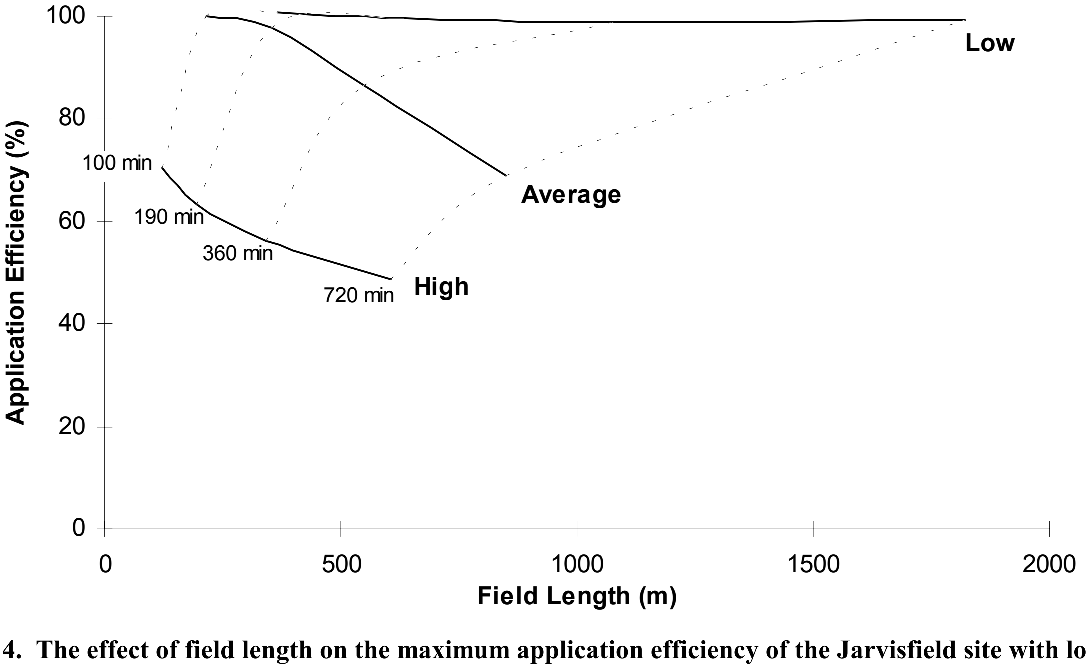

Fig 4. The effect of field length on the maximum application efficiency of the Jarvisfield site with low, average and high infiltration characteristics when water is applied at 2.6 L/s for a range of irrigation periods.

The maximum application efficiency of irrigations occurs where the length of the furrow is similar to the advance distance achieved by the irrigation (Fig. 3). Using furrow lengths shorter than this maximum advance distance results in tailwater losses and a reduced application efficiency while longer furrow lengths aren't fully irrigated due to insufficient advance. However, it should also be noted that as the design irrigation period increases from 190 to

720 min, the maximum achievable application efficiency decreases from almost 100% to approximately 70% due to increasing deep drainage losses. Similarly, as the design irrigation period increased, the degree of uncertainty in the prediction of the optimum design field length also increased (Fig. 4).

It is possible to use figures similar to Fig. 4 as aids in decision making during irrigation field design. In this case, the approximate rate of water application is normally known. For example, given an objective function of designing a field with a minimum seasonal application efficiency of 85% and a minimum event application efficiency of 50%, it is possible to identify that the maximum appropriate field length when applying 2.6 L/s/furrow at this site is approximately 500 m (Fig. 4). However, it is important to note that to achieve these efficiencies the irrigation cut-off time will need to be varied from approximately 190 min under low infiltration conditions to approximately 600 min under high infiltration conditions. Using periods of watering different to those specified will result in either inadequate watering along the field length or lower application efficiencies through excessive deep drainage and tailwater.

Effects on irrigation management

After the field has been designed, irrigation performance is primarily affected by application rate and period of application. However, in many cases (ie. where siphon pipes are used) there is only limited potential to change the water application rate. Hence, period of watering is often a primary determinant of efficiency. Where the field length is known and the water application rate fixed, it is possible to identify the effect of irrigation cut-off time on irrigation performance. Figure 5 shows the effect of cut-off time on application and storage efficiency for the Jarvisfield site where the field length is 500 m and the water is applied at 2.6 L/s/furrow. This figure can be used as a decision support aid to demonstrate the trade-off between application efficiency and storage efficiency in irrigation management as well as the effect of cut-off time on irrigation performance under the various infiltration conditions. For example, irrigation periods of less than 190 min produce inadequate water advance (and hence, inadequate watering of the bottom of the field) under all infiltration conditions. However, irrigating for less than approximately 300 min will also result in inadequate advance under average infiltration conditions and 600 min of application is required for complete advance under high infiltration conditions. Under the low infiltration conditions, increasing irrigation periods beyond 190 min results in only a marginal improvement in storage efficiency and substantial decreases in application efficiency due to excessive tailwater loss. However, under both the average and high infiltration conditions, 100% storage efficiency is achieved soon after the water has reached the end of the field. Where a fixed watering period is adopted for all irrigations (say 600 min) then application efficiencies of between 30% and 50% and storage efficiencies of between 75% and 100% would be achieved. This

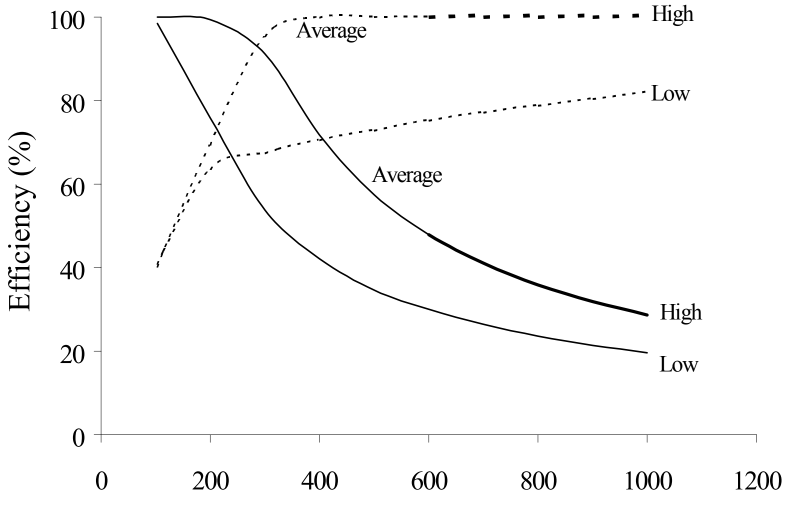

Fig 5. Effect of irrigation cut-off time on application (—) and storage (- -) efficiencies with variable infiltration for a 500 m field length and water application rate of 2.6 L/s at the Jarvisfield site.

is similar to the results obtained for current commercial practice and highlights the importance of altering irrigation management (both water application and irrigation schedule) in response to infiltration conditions.

Effect of management practices on irrigation performance
Optimisation of the management practices using the average infiltration function for the two sites indicated that the most efficient irrigation management strategy was to apply the water at 3.7 L/s for a minimum period of 190 mins at the Jarvisfield site and at 0.8 L/s for a minimum period of 1400 mins at the Mulgrave site. Where these management parameters were used in simulations of the individual irrigations throughout the season, the average application efficiency was found to increase significantly ($P<0.05$) at the Jarvisfield site from the measured 41% to 71% and at the Mulgrave site from 23% to 48% (Table 2). However, in both cases the storage efficiency decreased significantly. Where the management parameters were optimised for each irrigation throughout the season to simulate real-time control of individual irrigations, the average application efficiency at both sites was increased to in excess of 85% with storage efficiencies comparable to the current farm practices. No significant ($P<0.10$) differences between the distribution uniformities for each of the management options were observed at the Jarvisfield site but differences were found for the Mulgrave site (Table 2). These results highlight the trade-off between application efficiency and storage efficiency in irrigation management. Commercial cane growers currently attempt to maximise storage efficiency in an attempt to minimise crop stress between irrigations. However, by maximising storage efficiency, these irrigators have been operating with substantially reduced application efficiencies (Table 2). One benefit of not completely refilling the root zone, is that the crop is able to make more opportunistic use of rainfall events. For example, where a crop has been irrigated with 100% storage efficiency immediately prior to a rainfall event, none of the rainfall water benefits the crop. However, where a crop is watered at 80% storage efficiency immediately prior to rainfall, the soil is able to store up to an additional 20% of water from the rainfall event resulting in irrigation water savings. With the increasing direct and indirect costs of high water usage, growers may need to re-assess their management strategies to adopt a more balanced approach to irrigation management.

Table 2. The effect of management practice on irrigation performance

Site	Management practice	Application efficiency [a] (%)	Storage efficiency [a] (%)	Distribution uniformity [a] (%)
Jarvisfield	Current farm practice	41 (± 2)	98 (± 2)	92 (± 2)
	Using average infiltration	71 (± 4)	83 (± 4)	93 (± 1)
	Using real time control	93 (± 2)	90 (± 4)	88 (± 3)
Mulgrave	Current farm practice	23 (± 4)	74 (± 10)	90 (± 3)
	Using average infiltration	48 (± 7)	53 (± 8)	82 (± 8)
	Using real time control	87 (± 6)	71 (± 9)	82 (± 3)

[a] Mean (± standard error)

Reducing the storage efficiency of individual irrigations does not reduce crop yield where the irrigations are scheduled according to the soil moisture availability. Thus, where irrigations result in lower storage efficiencies, irrigations need to be scheduled more frequently to ensure that the crop is not stressed. Increasing the application efficiency by optimising the management practices based on the average infiltration characteristic (Table 2) would have reduced seasonal water use at the Jarvisfield site by approximately 11 ML/ha if additional irrigations were not scheduled. However, as the average storage efficiency would have decreased by 15% for each irrigation, up to three additional irrigations throughout the season would have been needed to maintain crop yield. Hence, 8.5 ML/ha or 32% of the actual seasonal water use could have been saved even with the additional irrigations. If real-time control management practices were used, the water saving would have been 14.2 ML/ha or 51% of the seasonal water usage. As the current cost of water in this area is $16.12/ML (Raine and Shannon, 1996), this would represent a direct saving of $229/ha/yr or $11445/yr for a 50 ha farm.

Conclusions

The infiltration characteristics of field soils varies substantially throughout the season and across the field and has significant implications for the design and management of surface irrigation. Current commercial surface irrigation practices at the sites investigated resulted in relatively low and highly variable application efficiencies. By quantifying the nature of infiltration variation at particular sites, it is possible to develop decision support aids to improve irrigation performance through the adoption of more appropriate irrigation design and management practices. The optimisation of irrigation management practices for average infiltration conditions would have produced improvements of between 25% and 30% in seasonal application efficiency for the sites investigated. The use of real-time control to optimise irrigation management practices due to variations in infiltration would have increased seasonal application efficiencies to more than 85%.

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