THE DEVELOPMENT OF GUIDELINES FOR SURFACE IRRIGATION IN AREAS WITH VARIABLE INFILTRATION

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Abstract

The efficiency of surface irrigations is a function of the field design, infiltration characteristics of the soil, and the irrigation management practices. Seventeen surface irrigations were monitored on a single Burdekin Delta farm throughout the 1994-95 season. Significant ($P<0.05$) spatial and temporal variability in the infiltration functions was observed throughout the season. Simulations of irrigation performance conducted using SIRMOD and the average infiltration characteristic for the site, indicated that application efficiencies 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 was found to potentially increase application efficiency to 93%. However, the variability in infiltration was also found to substantially affect the selection of appropriate surface irrigation design and management guidelines. Charts which illustrate the effect of infiltration variability on irrigation performance are presented and the possible use of these charts as design aids is discussed.

Keywords: Surface, irrigation, efficiency, design, guidelines, modelling.

Introduction

In excess of 30% of the Australian sugar crop is produced using furrow irrigation. However, recent research (Raine and Bakker, 1996a) has found that seasonal application efficiencies of surface irrigated cane typically range between 30 and 60% with the efficiency of some individual irrigations falling as low as 10%. During the 1993-1995 irrigation seasons, between 25 and 35 ML/ha/annum of irrigation water was applied to some commercial canefields in the Burdekin Delta area (Raine and Bakker, 1996b). Not only are these volumes higher than would be expected in average rainfall years, they are also far in excess of the plant water requirements and are indicative of the low water application efficiencies of irrigations over much of this area. It is conservatively estimated that over one-third of the Burdekin Delta area has water application efficiencies of less than 30% (Shannon and Raine, 1996). This represents a considerable cost on the production of sugarcane in these areas and arguably raises significant environmental and sustainability concerns.

Substantial improvements in application efficiency are possible through the identification and adoption of appropriate surface irrigation design and management practices (Raine and Bakker, 1996a). However, recommendations have typically been based on extensive field experimentation or on irrigation models such as SIRMOD (Walker, 1993) which rely on a single estimate of the infiltration function. Spatial and temporal variations in the infiltration behaviour of surface irrigated soils is the major physical constraint to achieving higher irrigation application efficiencies (Shafique and Skogerboe, 1983). The substantial spatial and temporal variability observed within field soils also raises concerns regarding the errors associated with the recommendation of generalised design and management guidelines. A further difficulty in providing design and management guidelines under variable infiltration arises due to the interaction of the various irrigation parameters. In excess of seven variables affect irrigation performance and the interaction of these parameters is multi-dimensional, hence irrigation guidelines also need to be multi-dimensional.

SIRMOD has been used to evaluate alternative field designs and management practices (Raine and Bakker, 1996b). However, its use in selecting optimal values of these parameters is limited by the need to apply a trial and error approach. In a comparison of a variety of surface irrigation models, Maheshwari and McMahon (1993a & 1993b) concluded that the SIRMOD hydrodynamic and zero inertia solutions gave slight underpredictions of the advance times but an acceptable overall prediction of irrigation performance. However, where the performance of SIRMOD was assessed for furrow irrigation of sugarcane (McClymont et al., 1996), it was found to consistently underpredict the measured advance times by an average of 22% and the measured infiltrated volumes by an average of 16.9%. This underprediction was attributed to either uncertainties in the infiltration parameters (Maheshwari and McMahon 1993b) or a systematic error within the model (McClymont et al., 1996) which might be able to be removed by an appropriate calibration procedure.

This paper presents data on the seasonal and spatial variability of infiltration functions measured within a Burdekin cane field, and investigates the effect of this variability on the identification of optimal irrigation management and design practices using SIRMOD. The potential to 'calibrate' SIRMOD by adjusting the hydraulic resistance parameter is investigated as well as the potential benefits associated with the real-time control of surface irrigation practices. Design and management guidelines for the field investigated are also presented.

Materials and Methods

Field data

Field data used in this study was collected from commercial irrigations conducted at the Jarvisfield site as reported in Raine and Bakker (1996a) during the 1994-95 irrigation season. Seventeen irrigations were measured at the site with an average root zone soil moisture deficit of 0.6 ML/ha and average volume applied of 1.4 ML/ha. The application efficiency of each irrigation was calculated as the ratio of the average root zone soil water deficit throughout the season and the total volume applied, expressed as a percentage. Where possible, irrigation advance and volume balance parameters were measured on two furrows in each irrigation. However, only furrows where at least four advance points and all of the volume balance parameters were successfully recorded were used in the subsequent analysis.

Modelling

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 modified two-point method (Elliott and Walker, 1982). Cumulative infiltration volumes were calculated at 50 minute intervals for each infiltration function and averaged to provide data for the determination of the average infiltration function.

The calculated average infiltration function was used in SIRMOD to identify the management practices (water application rate and period of application) required to maximise the application efficiency for the 470 m field length. This application rate and period of application were then used in SIRMOD simulations conducted using the actual infiltration function of each irrigation throughout the season. This enabled identification of the potential to improve irrigation performance through management practices where the field length is pre-determined and an historical average infiltration function for the site is available.

To identify the potential improvement in irrigation performance achievable through real-time control strategies, the flow rate and period of application required to maximise the application efficiency was also calculated for each individual irrigation throughout the season. These management variables were then used in simulations of the individual irrigations. Irrigation performance was assessed in each case by the application efficiency, the storage efficiency (ratio of the water stored in the root zone by the irrigation and the initial root zone soil moisture deficit, expressed as a percentage) and the distribution uniformity (ratio of the average depth of water applied to the last one quarter of the field and the average depth of water applied to the whole field length, expressed as a percentage). The application and storage efficiencies were calculated using the average measured root zone soil moisture deficit of 0.6 ML/ha.

The lowest, highest and average infiltration functions for the season were used to investigate the effect of field length on application efficiency where the rate of water application was fixed at either 0.6, 1.6, 2.6, 3.6 or 4.6 L/s and the simulations were conducted for a range of periods up to 900 min. The maximum application efficiency for each combination was then used to develop design characteristic curves for the site demonstrating the interactions between the infiltration functions, field length, application rate, period of application, application efficiency and storage efficiency.

Results

Field data

The average water application rate measured at the site throughout the season was 2.6 L/s with a range from 2.0-3.4 L/s while the irrigation time to cut-off varied from 453-913 min with an average of 644 min. The actual application efficiencies for the irrigations conducted at the site varied from 27-55% throughout the season with a mean of 41% (Table I). The average recharge of the root zone moisture deficit (storage efficiency) was 98% which is in agreement with the commercial practice of completely refilling the root zone.

Twenty-two infiltration functions were calculated from the seventeen measured irrigations and used in the model simulations (Figure I). The infiltration characteristics were found to differ significantly between furrows and with time for the same furrows. Infiltrated volumes for individual irrigations varied from 1.3-2.4 ML/ha throughout the season for a nominal opportunity time of 500 min (Figure II).

Modelling

The adjustments to the Manning hydraulic resistance parameter needed to improve the accuracy of the SIRMOD predictions were generally found to be small (Table III) indicating that the advance rates predicted by SIRMOD were relatively close to the field measured advance rates for this site. Optimisation of the management practices using the average infiltration function for the 470 m field length indicated that the most efficient irrigation management strategy was to apply the water at 3.7 L/s for a period of 190 mins. Where these management parameters were used for simulations of the individual irrigations throughout the season, the average application efficiency was found to increase significantly ($P<0.05$) from the measured 41% to 71% while storage efficiency decreased significantly to 83% (Table I). Where the management parameters were optimised for each irrigation throughout the season to simulate real-time control of individual irrigations, the average application efficiency increased to 93% with a storage efficiency of 90% (Table I). There were no significant

($P<0.10$) differences between the distribution uniformities for each of the management options.

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 where the water application rate and period of irrigation were fixed (Figure III). 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 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 (Figure IV).

The maximum efficiencies calculated for the seasons lowest, average and highest infiltration functions, range of water application rates and irrigation periods were used to prepare charts (Figure V) showing the effect of variations in infiltration on the interaction of water application rate, period of irrigation and field length. For this site, maximum application efficiencies ranged from 48-70% for the highest infiltration function with storage efficiencies of almost 100%. However, maximum application efficiencies for the lowest infiltration function were almost 100% with storage efficiencies of between 47-60%.

Discussion

Infiltration at the site varied significantly throughout the season (Figures I and II). While there was substantial variation from one irrigation to the next, the general trends (Figure II) indicate that there are some dominant influences affecting seasonal variation. For example, the lower infiltration rates experienced 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.

There is always a trade-off between surface irrigation practices that maximise application efficiency and those that maximum storage efficiency. Commercial cane growers have typically attempted 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 I). 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 the 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.

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 II) would have reduced seasonal water use at this 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.

Labour is a substantial component of irrigation management. Hence, irrigation blocks are often designed or managed to reduce labour input by producing a particular irrigation period appropriate to the labour schedule (eg 6, 12 or 24 hours). The maximum application efficiency of irrigations with fixed watering periods occurs where the length of the furrow is similar to the advance distance achieved by the irrigation (Figure III). 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 (Figure IV). For example, where water is applied for 100 min at 2.6 L/s, the design length ranged from 150-300 m depending on the variation in infiltration while the design length for a 720 min irrigation ranged from 600-1800 m for the same variation in infiltration characteristic (Figure IV). Hence, it is inadequate to present irrigation design charts without providing some measure of the degree of variation associated with the predictions (Figure V).

Figure V provides the basis for a possible set of design charts and may be used to identify the range of field and management options available to increase irrigation performance. Using these charts it is possible to set either the desired irrigation performance criteria or management practices and determine the range of other parameter variables necessary to meet the requirements. For example, if the desired design criteria is that the irrigations must have on average a 90% application efficiency, a range of field lengths (Figure Vb) from 150 m (0.6 L/s applied for approximately 350 min) to 700 m (4.6 L/s applied for approximately 280 min) could be selected. However, in selecting the appropriate field and management criteria, consideration should also be given to the variability in performance. For example, although the 4.6 L/s, 280 min irrigation of the 700 m furrow has an average application efficiency of 90%, the maximum efficiency for this furrow length possible under high infiltration conditions is only 53% and requires the water to be applied for approximately 450 min (Figure Vc). For the low infiltration condition, the maximum application efficiency would be 100% (but with a storage efficiency of only 50%) when the water was applied for only 150 min but would be substantially less when applied for the recommended 280 min.

The multi-dimensional nature of the interactions between the various irrigation parameters and the need to develop charts for each individual soil, slope and management regime makes the task of developing charts similar to Figure V prohibitive. A further difficulty arises due to the difficulty in interpreting these interactions and the subsequent charts. These problems suggest irrigation guidelines may be best developed using a modelling approach on an as needs basis where at least some of the irrigation parameters (eg. slope, field length, soil characteristics) are defined for the specific investigation.

SIRMOD provides irrigation data that enables quantification of the economic costs and benefits of alternative irrigation designs and management practices. However, due to the large variation in soil infiltration properties both across fields and throughout the season, model predictions are only as accurate as the quality of the input data. For this reason, unless the input data is derived from actual irrigations and includes a measure of field variation, the model should only be used to provide indicative trends. Unfortunately, SIRMOD is not particularly user-friendly in its current form and has no built-in optimisation capability to identify the most appropriate irrigation strategies. These two issues will need to be addressed if SIRMOD is to be widely accepted as a decision support aid in the development of site specific recommendations for improving irrigation efficiency.

Conclusions

The infiltration characteristics of field soils varies substantially throughout the season and across the field and has significant implications for the development of design guidelines for the management of surface irrigation practices. The multi-dimensional effect of various field and management parameters on the performance of surface irrigations requires the development of a design approach which demonstrates the interaction of the various irrigation parameters and includes the effect of infiltration variability. While this could be achieved through the medium of individual design charts, it might well be better done through a much enhanced version of SIRMOD.

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Table I - Irrigation performance of the actual irrigations and simulated irrigations conducted using management parameters optimised according to either the historical average or individual irrigation infiltration functions.

Management practice	Application efficiency [A] (%)	Storage efficiency [A] (%)	Distribution uniformity [A] (%)
Actual	41 (± 2)	98 (± 2)	92 (± 2)
Historical average	71 (± 4)	83 (± 4)	93 (± 1)
Real-time control	93 (± 2)	90 (± 4)	88 (± 3)

[A] Mean (± standard error)

Table II - Adjustments of hydraulic resistance parameter required to 'calibrate' SIRMOD against measured advance data.

Hydraulic resistance	Mean	Range
Field measured values	0.113	0.7-0.15
Adjusted values	0.133	0.6-0.33

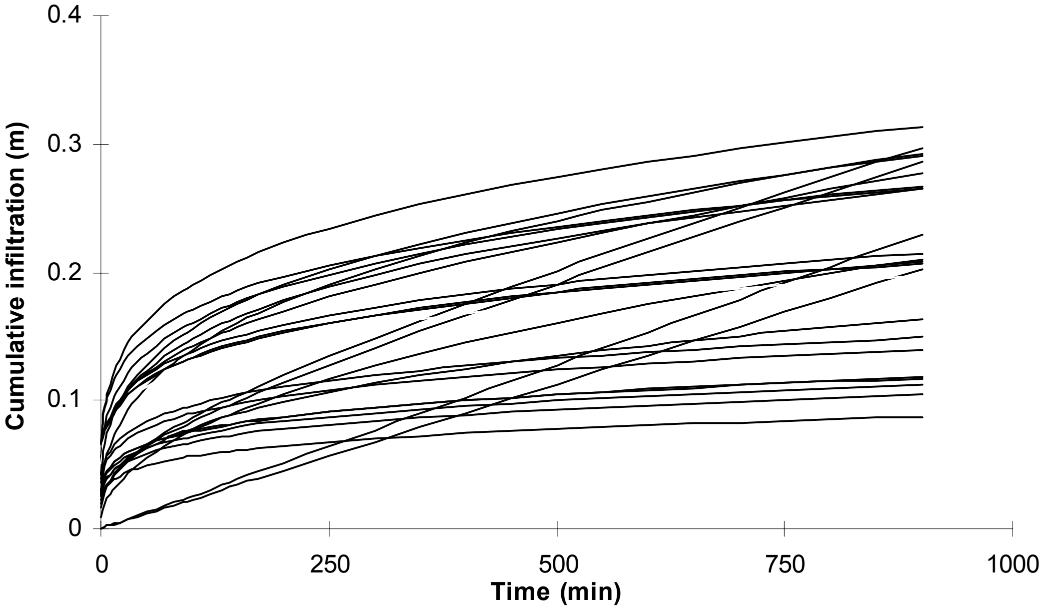

Figure I - Infiltration functions obtained for the Jarvisfield site throughout the 1994/5 irrigation season.

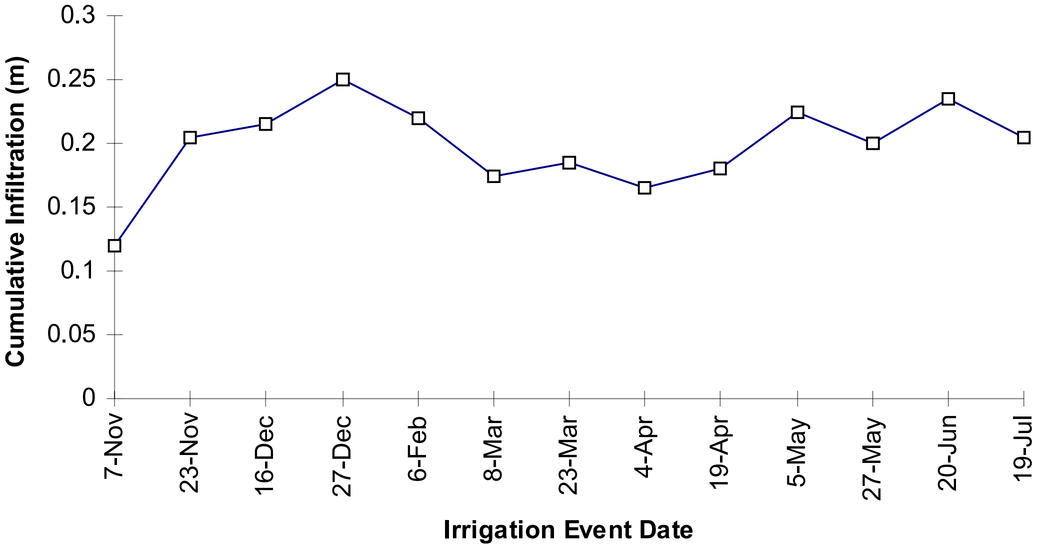

Figure II - Comparison of cumulative infiltration results at the Jarvisfield site throughout the season for a nominal opportunity time of 500 mins.

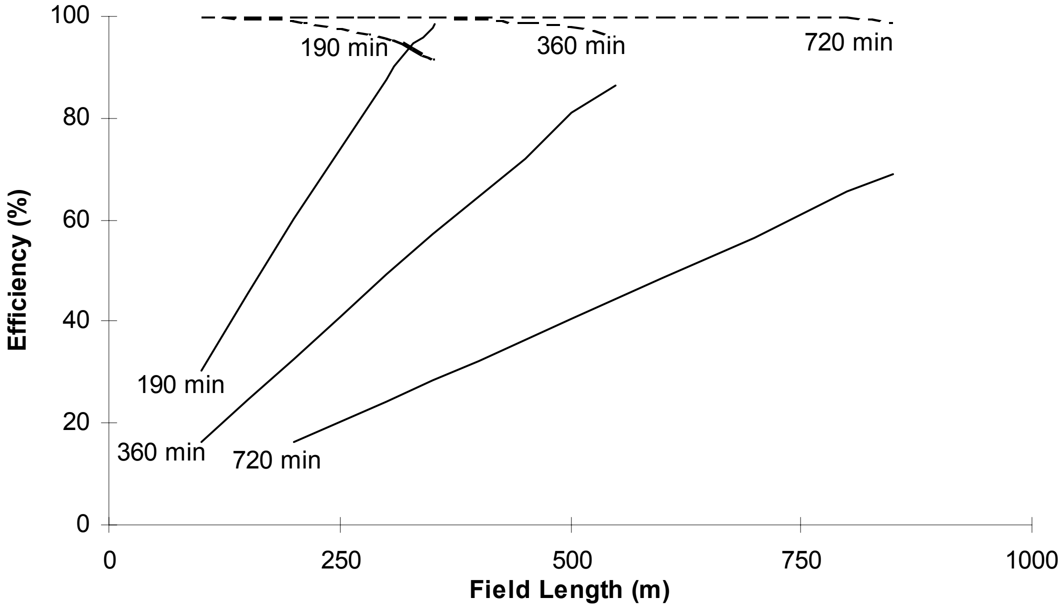

Figure III - Simulated irrigation performance using the seasonal average infiltration function, a fixed water application rate of 2.6 L/s and a range of irrigation periods from 190-720 min.

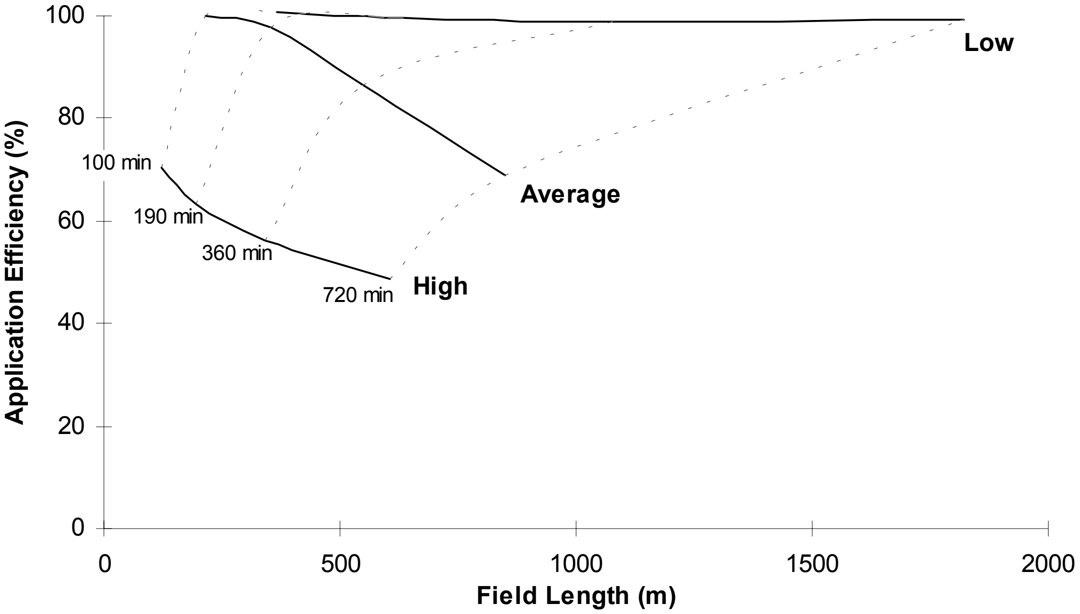

Figure IV - The effect of field length on the maximum application efficiency of the soil with low, average and high infiltration characteristics when water is applied at 2.6 L/s for a range of irrigation periods.