Modeling the furrow irrigation infiltration function from a single advance point

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Abstract

Management and control of surface irrigation, in particular furrow irrigation, is limited by spatio-temporal soil infiltration variability as well as the high cost and time for collecting intensive field data for estimation of the infiltration characteristics. Recent work has proposed scaling the commonly used infiltration function using model infiltration curve and a single advance point for every other furrow in an irrigation event. Scaling factors were calculated for a series of furrows at two sites at four points down the length of the field (0.25*L*, 0.5*L*, 0.75*L* and *L*). Differences in the value of the scaling factor with distance were seen to be a function of the shape of the advance curves. Scaling factor was seen to be strongly correlated with the furrow wetted perimeter.

Key words: Evaluation, infiltration function, single advance point, furrow irrigation

Introduction

Surface irrigation, specifically furrow irrigation, is the most widely used method of irrigation in the world despite its low irrigation efficiency attributed mainly to the complexity of the interactions between field design, soil infiltration characteristics and irrigation management practice. Irrigation advance data (solution of the inverse problem) is the preferred method to obtain the infiltration characteristic (most often in the form of the Kostiakov-Lewis equation). Common practice is then to apply the single-furrow, event-specific, infiltration function in a simulation model for performance prediction or optimization for the whole field. However this denies the temporal and spatial infiltration variability, which has a significant impact on irrigation performance (Raine et al. 1997; Mailhol et al. 2005). Temporal infiltration variability may be managed by real time control, that is, in-field data collection, analysis and processing during the irrigation (Camacho et al. 1997). Spatial variability requires that a field representative infiltration function is modified to reflect the variations in hydraulic factors (for example, wetted perimeter and inflow) and soil intake characteristics across the field (Clemmens 2000; Strelkoff et al. 2000; Oyonarte et al. 2002).

Past research has attempted to adjust the infiltration function for different inflow rates (Sepaskhah and Afshar-Chamanabad 2002) or by taking account of wetted perimeter (Strelkoff and Souza 1984). Camacho et al. (1997) applied volume-balance and kinematic models (the IPE model) to compute the spatial and temporal variability in real time. The limitation here has been the quantity of advance data required to characterize the infiltration equations and the time it takes to process the data. In-field management and control during irrigation requires quality estimates of infiltration characteristics sufficiently early to allow timely irrigation decisions to be made. Deriving this infiltration information from minimum data is important in reducing cost and effort (Gillies and Smith 2005) but comes at the risk of increased chance of measurement errors.

Recent research has proposed promising methods of reducing the intensive field data collection required for estimation of the infiltration characteristics and yet still capturing the soil infiltration variability. Rasoulzadeh and Sepaskhah (2003) used dimensional analysis to scale infiltration equation for furrow irrigation. They used wetted perimeter to find a characteristic space scale L_c (scaling factor) that enabled diverse infiltration equations to be merged into a single curve for application to different soils and furrow conditions. However this is a complex adjustment of the infiltration function that most irrigators may find difficult to apply in real time management where data is collected, studied and processed in the field.

The estimation of infiltration parameters using a single advance point and a model infiltration function is a relatively new concept proposed by Khatri and Smith (2006). They formulated a scaling factor to be applied in conjunction with the Kostiakov-Lewis infiltration equation to scale individual infiltration curves within a field. This method is easy to use and operate in the field as it requires only one advance point measurement along the furrow, plus the inflow rate and the cross-sectional area of flow at the furrow inlet. Thus, it offers farmers and advisors considerable savings in the cost and time of field data collection. However, the method as proposed and tested by Khatri and Smith (2006) arbitrarily used a single advance point located at 50% of the furrow length ($0.5L$). This point may be appropriate for long furrows or where long irrigation times are used, but for short furrows requiring short irrigation durations it may be necessary to measure the advance earlier to allow enough time for irrigation decisions to be made during the irrigation. However, there is uncertainty over the effect of the distance at which the advance is measured or the accuracy of the predicted infiltration and subsequent irrigation modelling.

In this paper the work of Khatri and Smith (2006) is taken further by evaluating the affect that the location of the single measured advance point along the furrow has on the estimation of the infiltration. This is of potential importance for in-field irrigation management and control during irrigation particularly where short field lengths are involved. The ability of the scaling process to deal with spatial variability in infiltration, including that resulting from differences in the hydraulic variables such as inflow rate, slope, and wetted perimeter is also assessed.

MATERIALS AND METHOD

Model infiltration function description

The scaling process proposed by Khatri and Smith (2006) is designed to reduce the amount of data required to predict the infiltration characteristics for each furrow and for each irrigation event for a whole field, for the purpose of real-time irrigation management and control. It involves arbitrary selection of a furrow as a model. Extensive advance and run-off data from this furrow is used to determine as accurately as possible its infiltration characteristic as described by the Kostiakov-Lewis equation:

$$Z = k\tau^{a} + f_{o}\tau \qquad (1)$$

where Z is the cumulative infiltration (m^3/m), a, k and f_o are fitted parameters and τ is the infiltration time (min).

The cumulative infiltration curve for this furrow becomes the model infiltration function whose infiltration parameters are then used to estimate (by scaling) cumulative infiltration functions, for the whole field or other irrigation events, using only one advance point for each of the remaining furrows or for each subsequent irrigation event. In this scaling process a scaling factor F is formulated for each furrow or event from volume balance model as:

$$F = \frac{Q_o t - \sigma_y A_o x}{\sigma_z k t^{a} x + \frac{f_o t x}{1+r}} \qquad (2)$$

where Q_o is the inflow rate for the target infiltration function (m^3/min), σ_y is a surface shape factor usually taken to be constant at 0.77, a, k, and f_0 are infiltration parameters for the model infiltration function, t is the advance time (min) for a known advance distance x (m) in the target furrow, r is the exponent from the power curve advance function for the model furrow:

$$x = pt^{r} \quad (3)$$

and σ_z is the sub-surface shape factor for the model infiltration function and calculated as:

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \quad (4)$$

The scaling factor F was defined by Khatri and Smith (2006) as the ratio between the infiltrated volume as calculated by the volume balance in the trial furrow at a particular advance time and the infiltrated volume as calculated by the parameters of the model furrow. It is applied in conjunction with equation 1 to produce scaled infiltration curves for each furrow as follows:

$$Z_{target} = F\left\{k(\tau)^{a} + f_0(\tau)\right\} \quad (5)$$

where Z_{target} is the cumulative infiltration (m^3/m) for the target furrow.

Field data

The data considered in this study were from published field evaluations in two cotton growing areas, the Bura Irrigation Scheme in Kenya and the Darling Downs in Queensland, Australia.

Bura Scheme data

Furrow irrigation advance data were collected from the Bura Irrigation Scheme Settlement Project in Kenya by Mwatha and Gichuki (2000). The soils of the project area are sandy clay loams and cracking clays with shallowly overlying (about 20 cm) a saline and alkaline subsoil of low permeability. The evaluation data were collected from four fields of the same soil and average slopes of 0.09%, 0.13%, 0.25% and 0.31%, denoted in this paper as 9S, 13S, 25S and 31S, respectively. The discharge treatments for each field were 1.5 ls^{-1}, 2.0 ls^{-1} and

3.0 ls^{-1}. Furrow spacing was 0.9 m. Parshall flumes placed at 50 m intervals were used to measure inflow and out flow for each 50 m furrow section. Data only for the fifth irrigation were used in this study.

The data published included furrow characteristics (Table 1), furrow inflow rates and irrigation advance parameters for two irrigation events in each of the four fields. The advance parameters for the power advance curve (Table 2) were calculated by Mwatha and Gichuki (2000) from the measured advance data.

Insert Tables 1 & 2 about here

Australian cotton field data

These data, taken from Khatri and Smith (2006), are from four furrow irrigation events from a single field (field C) in the Darling Downs region of Southern Queensland, Australia. All irrigations were conducted by the farm staff using their usual practices. Data collected for each event included:

- furrow inflow,
- the irrigation advance (advance times for various points along the furrow including the time for the advance to reach the end of the furrow), and
- the physical characteristics of the furrow (length, slope and cross-sectional area of flow).

The flow rate and irrigation advance were measured using the IRRIMATE^{TM} suite of tools developed be NCEA, as described by Dalton et al. (2001). The data are summarized in Table 4.

Calculation of infiltration parameters

Infiltration parameters from advance data were obtained for each furrow/event using the INFILTv5 program (McClymont and Smith 1996). INFILTv5 is a computer software package for determination of the Kostiakov-Lewis equation soil infiltration parameters using inflow rate and irrigation advance data as the only input. It also determines the average cross-section area of flow $\sigma_y A_o$ if this term is not known. However, use of cross-section area, if known, as an input parameter results in better estimates of the infiltration parameters. INFILTv5 was preferred method in this study because of its proven performance over time and over a range of soils and situations in Australia (Bakker et al. 2006; Khatri and Smith 2005; Smith et al. 2005) and also because it was appropriate for the available data. The infiltration curves calculated by the INFILT program are hereafter referred to as actual to distinguish them from scaled curves.

Actual measured advance data was used to obtain the infiltration parameters for field C. For the Bura site advance curves were generated from the power curve parameters published by Mwatha and Gichuki (2000).

The cross-sectional area of flow (A_o) at the furrow inlet was calculated for each event at the Bura site using the furrow geometry measurements provided by Mwatha and Gichuki (2000) and by assuming a Manning *n* of 0.04 (ASAE, 2003;Walker, 2001) in the Manning equation:

$$A_o = \left\{ \frac{Q_o n}{S_o p_1} \right\}^{\frac{1}{p_2}} \qquad (6)$$

where S_o is the slope of the furrow and p_1 and p_2 are furrow geometry parameters estimated as:

$$p_2 = 3.333 - 1.33\frac{c_2}{\sigma_2} \quad \text{and} \quad p_1 = \frac{\sigma_1^{(3.333-p_2)}}{c_1^{1.333}} \qquad (7,8)$$

The parameters c_1 and c_2 express wetted perimeter WP as a simple power function of flow depth y by:

$$WP = c_1 y^{c_2} \qquad (9)$$

Similarly, σ_1 and σ_2 give the cross-section area A_o as a power function of flow depth y:

$$A_o = \sigma_1 y^{\sigma_2} \qquad (10)$$

Model infiltration function and scaling factor

A model infiltration function for each site was arbitrarily selected from the set of actual cumulative infiltration curves. Scaling factors F (eqn 2) were then calculated for each furrow (including the model furrow) using advance points at 25% (*0.25L*), 50% (*0.5L*), 75% (*0.75L*) sections of the furrow length and the end of the furrow (*L*). Furrow length was taken to be 300m for Bura site and 240 m for field C.

Results and discussion

Effect of advance distance on scaling factor

The scaling factors F for calculated for each furrow at the different advance points along the furrow are presented in Table 3 for the Bura site and Table 4 for field C.

Insert Table 3 & 4 about here

Scaling factors varied considerably between furrows reflecting the expected variability (spatial, temporal and hydraulic) in the infiltration characteristic at the two sites. Differences are also evident between the scaling factors at the various advance distances. These differences are illustrated in Figures 1 and 2 for the Bura site and field C, respectively, presented as plots of the scaling factor at each distance versus the values at the full advance distance L. The assumption implicit in these plots is that the scaling factor at length L is the best estimate of the correct value of the scaling factor for the particular furrow.

Insert figures 1 & 2 about here

For each site the values of F at $0.75L$ and at L are almost identical. At $0.5L$ the values follow the 1:1 line but exhibit some small scatter about the line. By $0.25L$ the scaling factor values are showing considerable variation from the values at L. They no longer follow the 1:1 line and the scatter about the regression line is substantial. In the case of field C particularly, some values of the scaling factor at $0.25L$ are much lower than expected. This is due to an apparently very rapid initial advance in some furrows giving an advance time to that point being much less than that predicted by the fitted power curve. This may be attributed to an initial unsteadiness in the furrow inflow, the effect of which diminishes for longer advance distances (Bautista and Wallender 1993). This cannot be confirmed because full inflow hydrographs were not available for this site.

If the scaling process is to be used in a real time control system there is an obvious tension between the desire to use an early advance point (to give adequate time for the subsequent analyses) and the loss of accuracy in the scaled infiltration characteristics caused by the use of that early advance point. The significant conclusion that can be drawn from these data is that use of the mid-point (0.5*L*) is a reasonable compromise. Use of the point at 0.25*L* results in too great a loss of accuracy and should be avoided.

The nature of the variation of *F* with advance distance is determined entirely by the shape of the advance curve, as reflected in the value of the exponent *r* in the fitted power curve. When *r* for a furrow is less than that for the model curve, that is, the advance exhibits lesser curvature than that for the model furrow, *F* increases with distance. This is seen, for example, at the Bura site (Table 3) for the furrows 13S 3 and 25S 2, and furrows C10 and C11 (Table 4). When *r* is greater than that for the model furrow, *F* decreases with distance (furrows 9S 2, 31S 3, C12 and C15). This decreasing trend with distance is not as clear as the previous increasing trend because, as has been seen earlier in Figures 1 and 2, the values at 0.25*L* tend to always be lower than the values at *L*. Trends with distance are also clearer for Bura where *F* was calculated from the fitted power curve compared to field C where the actual measured advance points were used. For those furrows where the *r* value is the same as or similar in magnitude to that for the model furrow, there is little or no change in *F* with distance (furrows 9S 3, 25S 1.5, C8 and C17). Any variation seen in these furrows is caused by the extent of any deviation of the advance points from the smoothed advance curve.

Figures 3 and 4 for furrows C1 and C12, respectively, provide an explanation for the above behaviour. These plots show advance curves for these furrows calculated using the volume balance equation and the scaled infiltration characteristic for the advance points at 0.25*L*, 0.5*L*, 0.75*L* and *L*. The measured advance points and the fitted power curve are also shown. In both cases the calculated advance curves are of slightly different shape from the actual advance curve and intersect the actual advance curve at the advance point used to calculate the scaling factor. Where *r* is lower than that for the model curve (furrow C1) the calculated advance curves lay mostly below the actual advance curve. The reverse applies when *r* is greater than that for the model curve. In both cases the curves predicted using F_L are closest to the measured advance curves. For furrows where *r* is the same as that for the model curve all of the advance curves (measured and predicted) coincide. This suggests that the performance of the scaling process is entirely dependent upon the consistency of the shape of the advance curves for a particular field or set of furrows.

Insert figures 3 & 4 about here

The effect on the predicted (scaled) infiltration characteristics is shown for the same two furrows (C1 and C12) in Figures 5 and 6, respectively, in the form of plots of the scaled infiltration curves superimposed over the actual curves as calculated by the INFILT program. As would be expected from the above discussion the infiltration curves calculated using F_L are closest to the actual infiltration characteristic. For the majority of furrows (where *r* is not far removed from that of the model curve) the scaled infiltration characteristics are much closer to the actual or measured characteristic than the examples shown in Figures 5 and 6.

Insert figures 5 & 6 about here

In a normal application of the scaling process the value of *r* would not be known for the target furrows. It would only be known for the model furrow. Hence it would not be known if the scaled infiltration curve for a particular lay above or below the actual curve for that furrow. Khatri and Smith (2006) argued that it was not necessary to model the infiltration characteristic for each individual furrow with any great degree of precision. They suggested that it was more important to provide a sufficiently accurate estimate of the spread or range of infiltration curves for a field or set of furrows to allow best management of the field or set, assuming that the flow rate and time to cut-off are the same for all furrows in the set. The data presented in this paper suggest that if the scaling is performed using the advance to 0.5L or later, then on average the scaling factors and hence the infiltration characteristics will be sufficiently close to the correct values for practical purposes.

Scaling factor and wetted perimeter

Changes in wetted perimeter (or cross sectional area) with inflow rate, surface roughness or slope are known to cause differences in the infiltration characteristic for a given furrow (termed the hydraulic variability in this paper) and considerable work has been undertaken to develop methods for adjusting infiltration to accommodate this source of variability. Use of the scaling process of Khatri and Smith (2006) removes the need for any special adjustment of the infiltration characteristic, the scaling factor *F* accounts for the effects of all forms of infiltration variability including the spatial, temporal and hydraulic. This is illustrated in Figures 7 and 8.

Insert figures 7 & 8 about here

In Figure 7 the scaling factor at L is plotted against wetted perimeter for the Bura site. The regression line (R^2 = 0.687) suggests that nearly 70% of the infiltration variability observed at this site. It is assumed that the remainder of the infiltration variability is as a result of the spatial and temporal variability in the infiltration characteristic. Wetted perimeter data were not available for site C. In this case the cross sectional area at the upstream end of the furrow is used as a surrogate for wetted perimeter (Figure 8). Again the regression (R^2 = 0.741) suggests that the hydraulic factors are responsible for a similar proportion of the infiltration variability at this site.

Conclusion

Real-time control of furrow irrigation is the obvious way in which to overcome the effects of the spatial, temporal and hydraulic variability in the soil infiltration characteristic and to maximize irrigation performance. For this it is necessary to be able to obtain estimates the infiltration characteristics for the furrows in real time and with the minimum of advance data. In this paper a process is evaluated that uses scaling from a single advance measurement and a model infiltration curve to give the infiltration characteristic for any other furrow in a field or set of furrows.

Data from multiple irrigation events at two sites were analysed with scaling factors calculated at 25, 50, 75 and 100% of the advance distance. The results showed that the calculated scaling factors varied with distance down the furrow. The extent and nature of that variation was shown to be a function of the shape of the advance curve as reflected in the power curve parameter r, relative to that for the model curve.

It is concluded that any advance point used for scaling the infiltration should be taken at least at the half way point down the field (0.5L). When used for real-time control this introduces a tension between the accuracy required from the scaling process and the desire to estimate the infiltration characteristic in sufficient time to provide adequate control of the irrigation.

The scaling process was applied to a series of furrows in which the inflow rate and slope varied considerably, resulting in substantial variation in the wetted perimeter and hence in the infiltration characteristic. Scaling factor was strongly correlated with the wetted perimeter (R^2 = 0.68 to 0.72) suggesting that the scaling is an appropriate way of both predicting and accommodating the effect of the hydraulic variability. It is assumed that the remainder of the variability in the magnitude scaling factor was due to the inherent spatial and temporal variability in the infiltration of the soils at the two sites.

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Table 1: Furrow characteristics for Bura Scheme (from Mwatha and Gichuki, 2000).

Parameter	Value
Furrow length	275-300m
Furrow spacing	0.9 m
Furrow slope	0.05 %- 0.3%
Cross-section	parabolic
Top-width (m)*	$T = 2.8y^{0.62}$
Wetted perimeter (m)*	$WP = 2.8y^{0.65}$
Area of flow (m^2)*	$A = 1.48y^{1.55}$

* where y = furrow depth

Table 2: Advance curve parameters for the fifth irrigation at the Bura site (from Mwatha and Gichuki 2000)

Irrigation	**Slope (%)**	**Inflow (ls^{-1})**	**Advance parameters**		
			p	***r***	**t_L (mins)**
5	0.09	1.5	12.7	0.49	572
		2.0	6.1	0.67	308
		3.0	10.2	0.57	345
	0.13	1.5	12.6	0.56	262
		2.0	11.3	0.57	290
		3.0	18.3	0.53	177
	0.25	1.5	13.5	0.56	231
		2.0	22.2	0.46	256
		3.0	16.2	0.61	110
	0.31	1.5	16.5	0.55	179
		2.0	17.9	0.53	186
		3.0	13.4	0.68	90

Table 3: Scaling factor *F* at different advance distances along the furrow for the Bura site

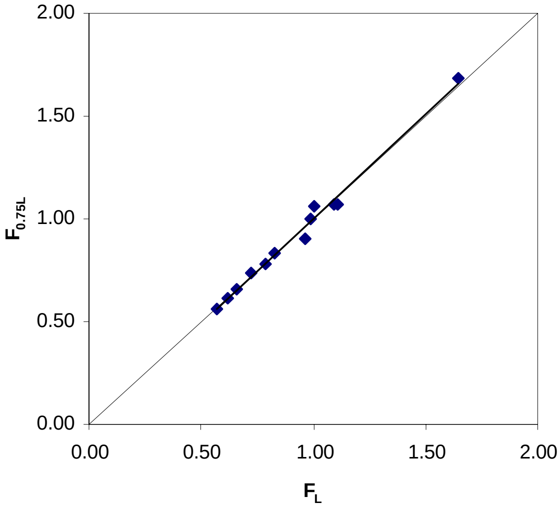
Field	Q_o (ls^{-1})	A_o (m^2)	*WP* (m)	*r*	Scaling factor *F* *0.25L*	*0.5L*	*0.75L*	*L*
9S	1.5	0.017	0.600	0.49	0.84	1.01	1.07	1.09
	2	0.021	0.655	0.67	1.28	1.15	1.06	1.00
	3	0.028	0.740	0.57	1.63	1.70	1.68	1.65
13S	1.5	0.015	0.568	0.56	0.39	0.56	0.61	0.62
	2*	0.019	0.619	0.57	0.94	1.01	1.00	0.99
	3	0.025	0.700	0.53	0.66	0.99	1.07	1.11
25S	1.5	0.012	0.514	0.56	0.58	0.65	0.66	0.66
	2	0.015	0.561	0.46	0.50	0.80	0.90	0.96
	3	0.020	0.634	0.61	0.68	0.81	0.83	0.83
31S	1.5	0.011	0.498	0.55	0.43	0.54	0.56	0.57
	2	0.014	0.543	0.53	0.58	0.74	0.78	0.79
	3	0.018	0.614	0.68	0.76	0.77	0.74	0.72

* model furrow inflow

Table 4: Scaling factor *F* at different advance distances along the furrow for the field C

Furrow	Q_o (ls^{-1})	A_o (m^2)	*r*	Scaling factor *F* *0.25L*	*0.5L*	*0.75L*	*L*
C1	0.83	0.011	0.714	0.15	0.26	0.26	0.26
C2	0.83	0.011	0.679	0.21	0.25	0.27	0.29
C3	0.83	0.011	0.639	0.14	0.30	0.33	0.32
C4	0.83	0.011	0.684	0.28	0.36	0.38	0.39
C7	2.60	0.026	0.694	0.45	0.67	0.74	0.74
C8	2.60	0.026	0.808	0.73	0.82	0.75	0.77
C9	2.60	0.026	0.693	0.51	0.57	0.61	0.66
C10	3.74	0.034	0.678	0.97	1.09	1.20	1.27
C11	7.92	0.061	0.730	0.88	0.97	1.03	1.11
C12	1.89	0.019	0.942	0.44	0.44	0.40	0.38
C13	3.80	0.034	0.728	0.45	0.61	0.60	0.65
C14	4.50	0.039	0.703	0.89	1.15	1.15	1.23
C15	4.50	0.039	0.850	1.08	1.12	1.08	1.06
C16*	4.50	0.039	0.808	0.99	1.01	1.00	1.00
C17	4.50	0.039	0.800	0.92	0.95	0.98	0.97

* model furrow



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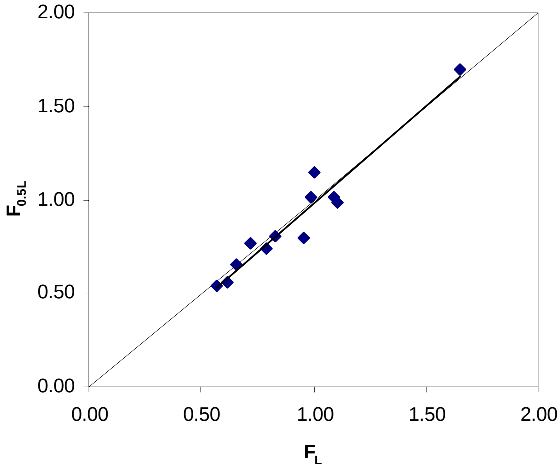

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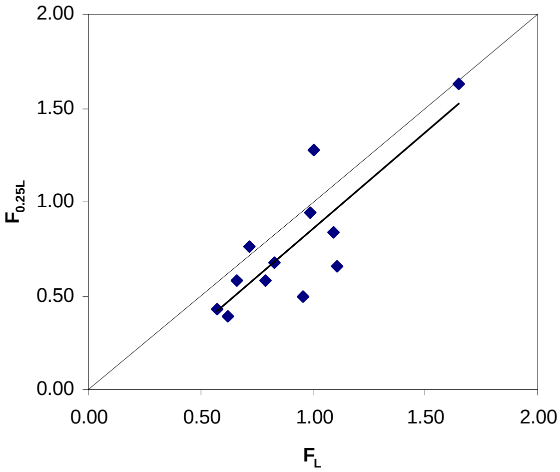

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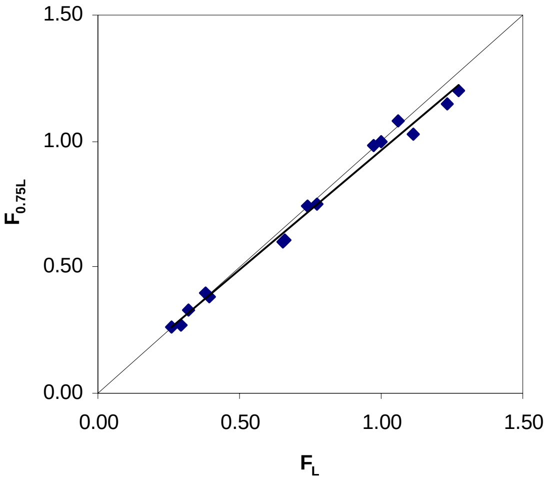
Figure 1: Variation of scaling factors with advance distance for the Bura site



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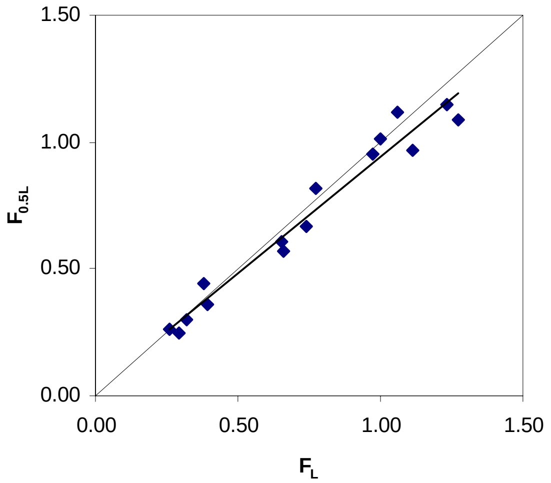

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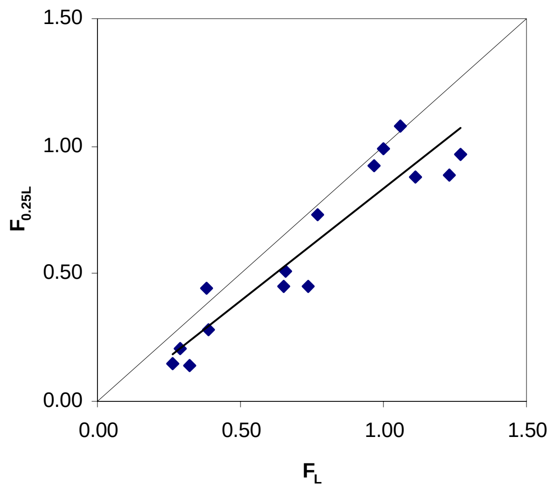

(c)

Figure 2: Variation of scaling factors with advance distance for field C

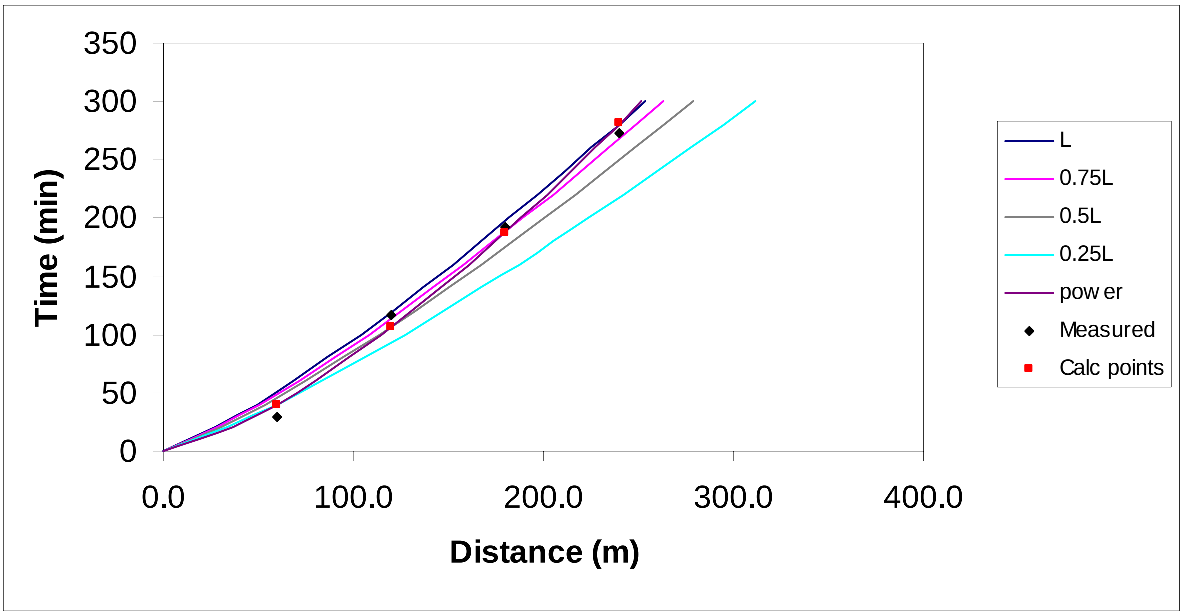

Figure 3: Predicted advance curves for furrow C1

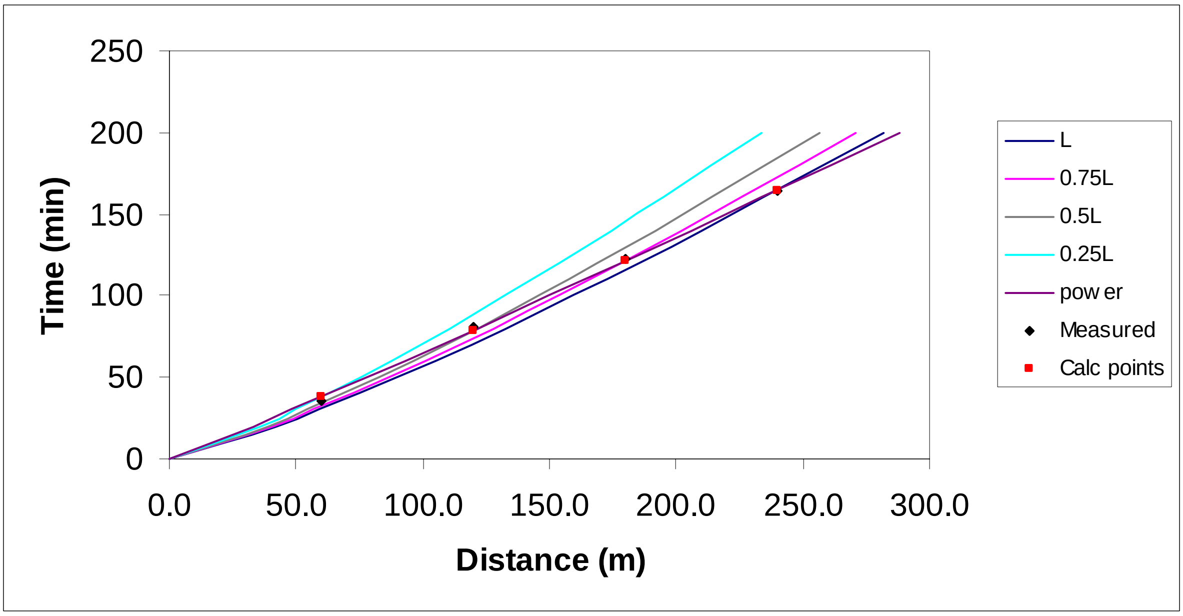

Figure 4: Predicted advance curves for furrow C12

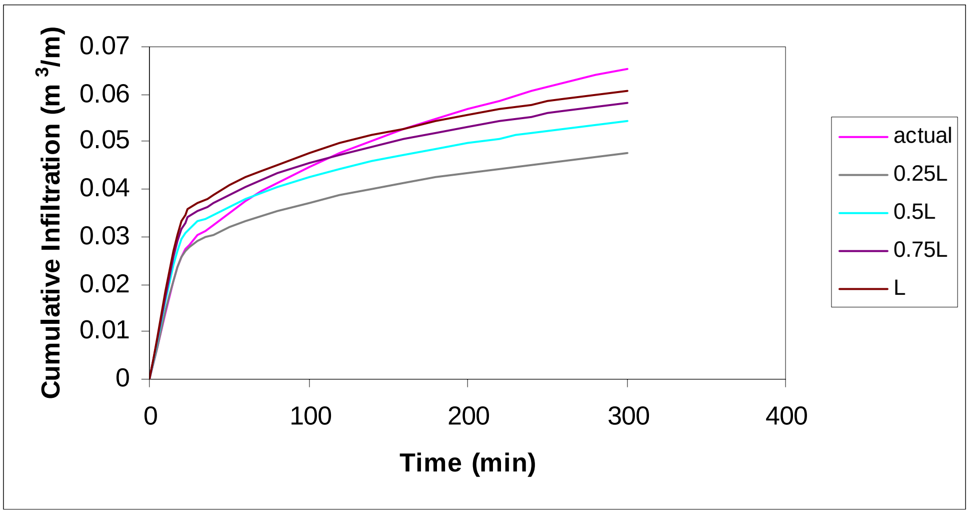

Figure 5: Scaled infiltration curves for furrow C1

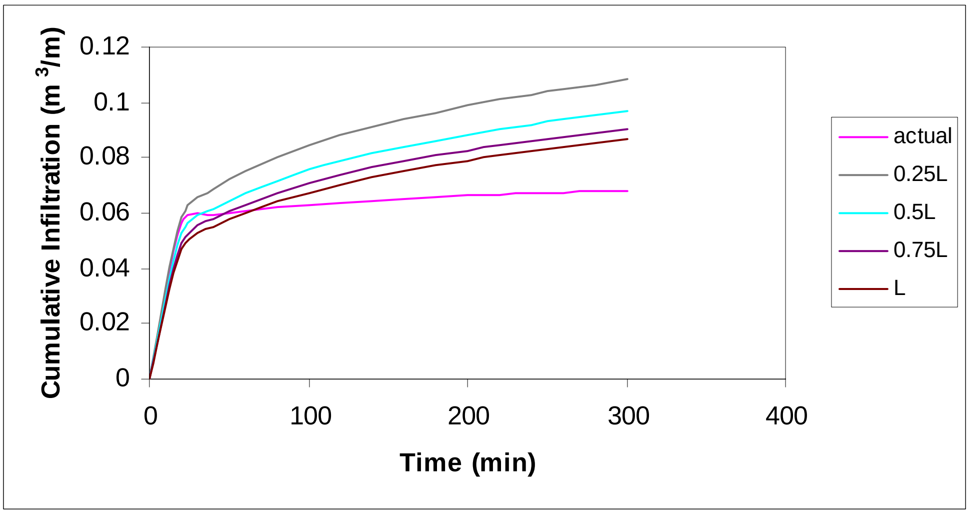

Figure 6: Scaled infiltration curves for furrow C12

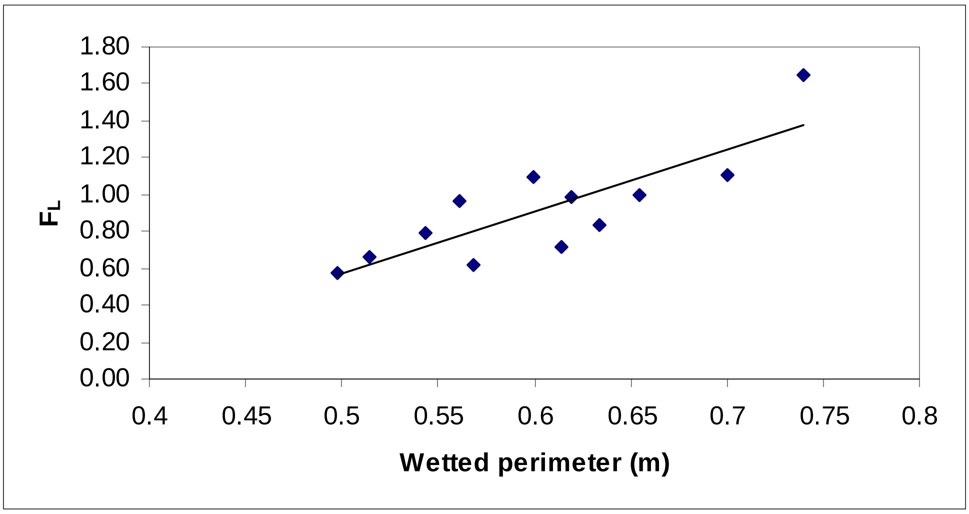

Figure 7: Scaling factor versus wetted perimeter for the Bura site

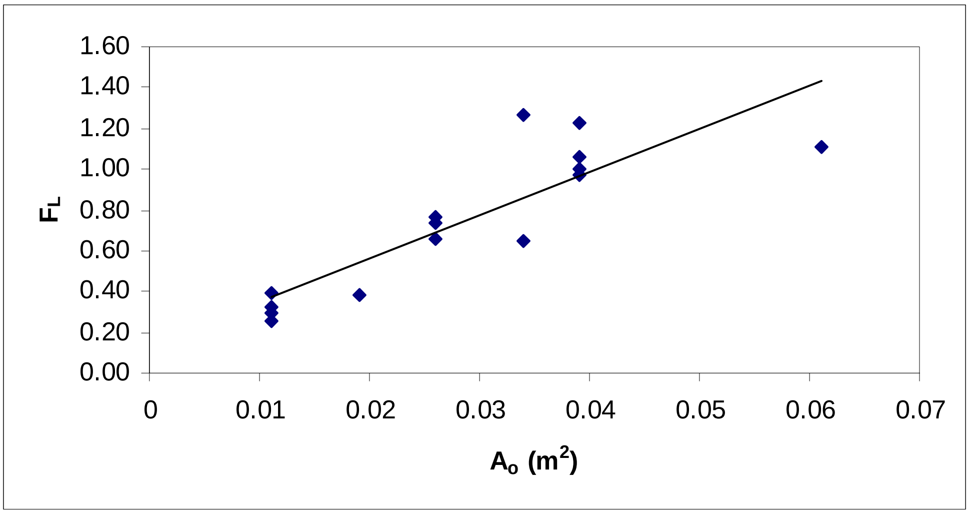

Figure 8: Scaling factor versus cross sectional area for field C