Accounting for Temporal Inflow Variation in the Inverse Solution for Infiltration in Surface Irrigation

M.H. GILLIES, R.J. SMITH AND S.R. RAINE

National Centre for Engineering in Agriculture and Cooperative Research Centre for Irrigation Futures, University of Southern Queensland, Toowoomba, Queensland, 4350, Australia

gilliesm@usq.edu.au

0746311715

Abstract

A simple modification of the volume balance equation of the IPARM model is presented to facilitate the use of variable inflow. Traditional approaches for estimating infiltration from advance and/or runoff have merely considered the constant or step inflow case. Whenever this assumption is violated, significant uncertainty is introduced into the estimated infiltration parameters. Evaluation of the procedure with a number of data sets has demonstrated significant improvements in the estimates of infiltration parameters. Furthermore, the technique has shown that a portion of the apparent variability in estimated soil intake rates between furrows in the same field is a consequence of the constant inflow assumption. Accounting for the variable inflow to estimate infiltration functions, both standardised the shape of the infiltration curve and reduced the magnitude of the variation between curves. The proposed technique remains restricted by limitations similar to that of other volume balance models but offers greater performance under typical inflow variations often experienced in practice.

Surface irrigation; Infiltration; Runoff; Inflow; Variable inflow; Optimisation; Simulation; IPARM; Kostiakov; Volume balance

Introduction

Many studies (e.g. Jurriëns and Lenselink 2001; Raine et al. 1997) have demonstrated that substantial improvements in irrigation performance can be achieved through relatively minor alterations in irrigation management. Furrow irrigation optimisation generally requires the use of numerical methods to simulate various changes in irrigation management. However, the models must be calibrated prior to optimisation to represent the measured furrow conditions. In this calibration process, the inflow, furrow cross section, slope and field length are normally measured directly in the field while the infiltration and surface roughness must be estimated.

The cumulative infiltration, Z (m^3/m) is typically described as a function of opportunity time, τ (minutes) and should reflect the irrigation management and soil hydraulic properties. The modified Kostiakov equation is the most commonly used (e.g. Elliott et al. 1983; McClymont and Smith 1996; Walker 2005) empirical function representing soil infiltration rates in surface irrigation:

$$Z = k\tau^{a} + f_0\tau \qquad (1)$$

where k and a are empirical constants while f_o is the steady infiltration rate (m^3/min per m length). A number of techniques are available to determine the infiltration function but the most appropriate remains the inverse solution using measured field data. Estimation of the infiltration parameters may be carried out using the measured advance data (e.g. Elliott et al. 1983; McClymont and Smith 1996) or by using a combination of the advance and runoff hydrograph (e.g. Gillies and Smith 2005; Scaloppi et al. 1995).

The volume balance approach is the preferred choice for the inverse solution methods due to its simplicity and speed of application. While the volume balance model neglects the momentum equation it has been found (e.g. Guardo et al. 2000) to provide an adequate fit during the advance phase and the simplifying assumptions facilitate rapid irrigation simulations making it ideal for the iterative procedures required to determine infiltration parameters. The general form of the volume balance equation used in these procedures is:

$$Q_0 t = V_I + V_s + V_r \qquad (2)$$

where Q_0 is the steady inflow rate (m^3/min), t is elapsed time (minutes), V_s is the volume stored on the soil surface, V_r is the volume of runoff from the end of the field, V_I is the volume infiltrated (m^3) from the integration of equation 1 over the wetted length of the furrow (*x in metres*):

$$V_I = (\sigma_{z1} k t^a + \sigma_{z2} f_o t) x \tag{3}$$

σ_{z1} and σ_{z2} are sub-surface shape factors given by.

$$\sigma_{z1} = \left[1 - \frac{a r \lambda}{r+1} + \frac{a(a-1) r \lambda^2}{2!(r+2)} - \frac{a(a-1)(1-2) r \lambda^3}{3!(r+3)} + \frac{a(a-1)(a-2)(a-3) r \lambda^4}{4!(r+4)} - ....+....\right] \tag{4}$$

and:

$$\sigma_{z2} = 1 - \frac{r\lambda}{r+1} \tag{5}$$

where λ is the ratio of the current time to the complete advance time and r is the exponent of the power curve for the advance (Gillies and Smith 2005); consequently in the storage phase both sub-surface shape factors are functions of time (Scaloppi et al. 1995).

Variations in slope and roughness can both influence the advance curve but the variation in the inflow has an overriding effect (Renault and Wallender 1996). The inflow rate influences the volume of surface storage and hence determines the rate of advance. Estimates of infiltration parameters and the longitudinal variation in water application are sensitive to inflow rate variation. Renault and Wallender (1996) found that initial variations in inflow rates often cause the resulting Kostiakov infiltration functions to have low *a* but high *k*. Experience with the INFILT optimisation of McClymont and Smith (1996) suggests that a seemingly small change in the inflow rate can have a considerable impact on the estimated infiltration function. However, inflow variation is often overlooked. Typically a constant (or step) inflow hydrograph is assumed to simplify the calculations. In this case, the inflow commences at time zero and remains at a constant rate until the cut-off time when the flow ceases instantaneously. The step inflow is merely an idealised representation as the inflow will always exhibit some degree of temporal variation (e.g. Gharbi et al. 1993; Mailhol et al. 1999).

Volume balance models assume that the average flow area during the advance phase is equal to the upstream cross sectional flow area multiplied by a constant typically taking the value of 0.77. Hence, the volume balance model may generate substantial errors whenever the surface storage is a large fraction of the inflow volume. DeTar (1989) found that accurate furrow geometry measurements are crucial when the infiltrated volume is small relative to the cumulative inflow. Inaccuracies in inflow measurement will cause large uncertainties in estimates of surface storage and infiltration (Trout and Mackey 1988). These uncertainties increase rapidly as the proportion of inflow that has infiltrated decreases. Valiantzas (1997) used the kinematic wave equation to develop an algebraic expression for the storage portion of the volume balance that enables the average cross sectional area to change with time. An other approach is to ignore the surface storage volume but this may lead to significant errors in the predicted advance (Valiantzas 2000).

Variations in inflow between furrows have been found to be the most important factor in the variability of the infiltrated depth and advance (Schwankl et al. 2000). In general, non-intentional inflow rate variation has a detrimental impact on irrigation performance. Inflow rate variation has a significant impact on application efficiency and distribution uniformity (Alazba 1999), particularly when a flow reduction is large enough to prevent the advance from reaching the end of the field (Gharbi et al. 1993). However, long furrows appear to be less susceptible to variations in inflow rate than shorter furrows (Eldeiry et al. 2005). Application efficiency has also been found to be more sensitive to changes in the inflow rate on a heavy soil rather than a light soil (Jurriëns and Lenselink 2001).

In this paper the volume balance model used in the estimation of infiltration parameters from advance and runoff data is modified to account for temporal variations in the inflow rate. Several sets of field data are presented to evaluate the ability of this model to provide improved estimates of the parameters and the resulting infiltrated volume. It is also hypothesised that a proportion of the apparent infiltration variability between furrows and over time is actually the result of errors in the estimation of the infiltration functions associated with temporal variations in the inflow rate.

Model Development

The Infiltration Parameters from Advance and Runoff Model (IPARM) was developed to calculate Kostiakov infiltration functions using advance and run-off data (Gillies and Smith 2005). A further development of this model is proposed here that allows the optional use of a full inflow hydrograph where available. The model is essentially as described in Gillies and Smith (2005). The only significant change for the work reported in this paper is a re-interpretation of the inflow term on the LHS of equation 2. The steady $Q_o t$ is replaced by a summation of the inflow volume up to time t: $\sum_t Q(t)\delta t$

Implicit in this modification is the assumption that the advance or run-off at any time is determined largely by the inflow up to that time. In the original model, the inflow volume corresponding to each advance or run-off point was calculated by simply multiplying the average inflow rate by the appropriate value of time. In this new version of IPARM, the model uses linear interpolation on the inflow hydrograph to calculate the total inflow volume for each advance point and each runoff point. It is also assumed that the volume temporarily stored in the furrow at any time can be described by the same simple function used in the constant inflow version of the model, where it is a function of the instantaneous inflow rate. In essence this assumes that the rate of change of the inflow is slow and that the volume stored has time to adjust to the changed inflow.

The general approach to calibration of the infiltration function remains as specified in the previous paper. The process involves the minimisation of either the advance error alone or a combination of the advance and runoff errors as in Eq. 17 of Gillies and Smith (2005). The advance and runoff errors are given by:

$$Advance\_error = 100 * \sqrt{\frac{\sum\left(x_{measured} - x_{calculated}\right)^2}{\sum\left(x_{measured}\right)^2}} \tag{6}$$

$$Runoff\_error = 100 * \sqrt{\frac{\sum\left(V_{r\,measured} - V_{r\,calculated}\right)^2}{\sum\left(V_{r\,measured}\right)^2}} \tag{7}$$

Evaluation

Four irrigation data sets (Benson, Kooba, Merungle Hill and Huntawang) with different inflow hydrographs were chosen to evaluate the effect of using a variable inflow for estimating the infiltration parameters. For each data set, the infiltration parameters were calculated using each of four different data combinations:

- advance data with a constant inflow set to equal the measured average inflow,
- advance data with the measured variable inflow,
- advance data and runoff hydrograph with a constant inflow set to equal the measured average inflow, and
- advance data and runoff hydrograph with the measured variable inflow.

The Benson irrigation (Walker 2005) was carried out in Colorado on a clay loam soil. A significant decrease in inflow (1.11 to 0.79 L/s) occurred during the advance phase. The value of the Manning *n* was assumed to be 0.02, where as Walker (2005) used a roughness of 0.015.

The Kooba irrigation data set (Hornbuckle 1999) was obtained on a cracking clay soil planted to maize. This site consisted of furrows 443 m long at 1.93 m spacings with a slope of 0.0005. The data set included measurements collected from four furrows over three separate irrigations. The inflow rate for irrigation 1 (e.g. Fig. 1b) and irrigation 2 increased with time while irrigation 3 used a cutback regime. No information was available regarding the furrow surface condition or flow depth and the Manning *n* was assumed as 0.04.

The Merungle Hill data (Hornbuckle 1999) was obtained from a citrus orchard where the furrow bed had not been cultivated for some time and weed growth was controlled by herbicide application. The inflow hydrograph (Fig. 1c) increased during the event and the roughness parameter *n* was assumed to be 0.2.

The Huntawang data set (Hornbuckle 2005, pers comm) was collected on a cotton field near Griffith in southern New South Wales. The inflow hydrograph (Fig. 1d) for this irrigation showed a decrease during the first 100 minutes of water application. The value of the Manning *n* (0.032) used in this irrigation was calculated from the measured upstream depth of flow.

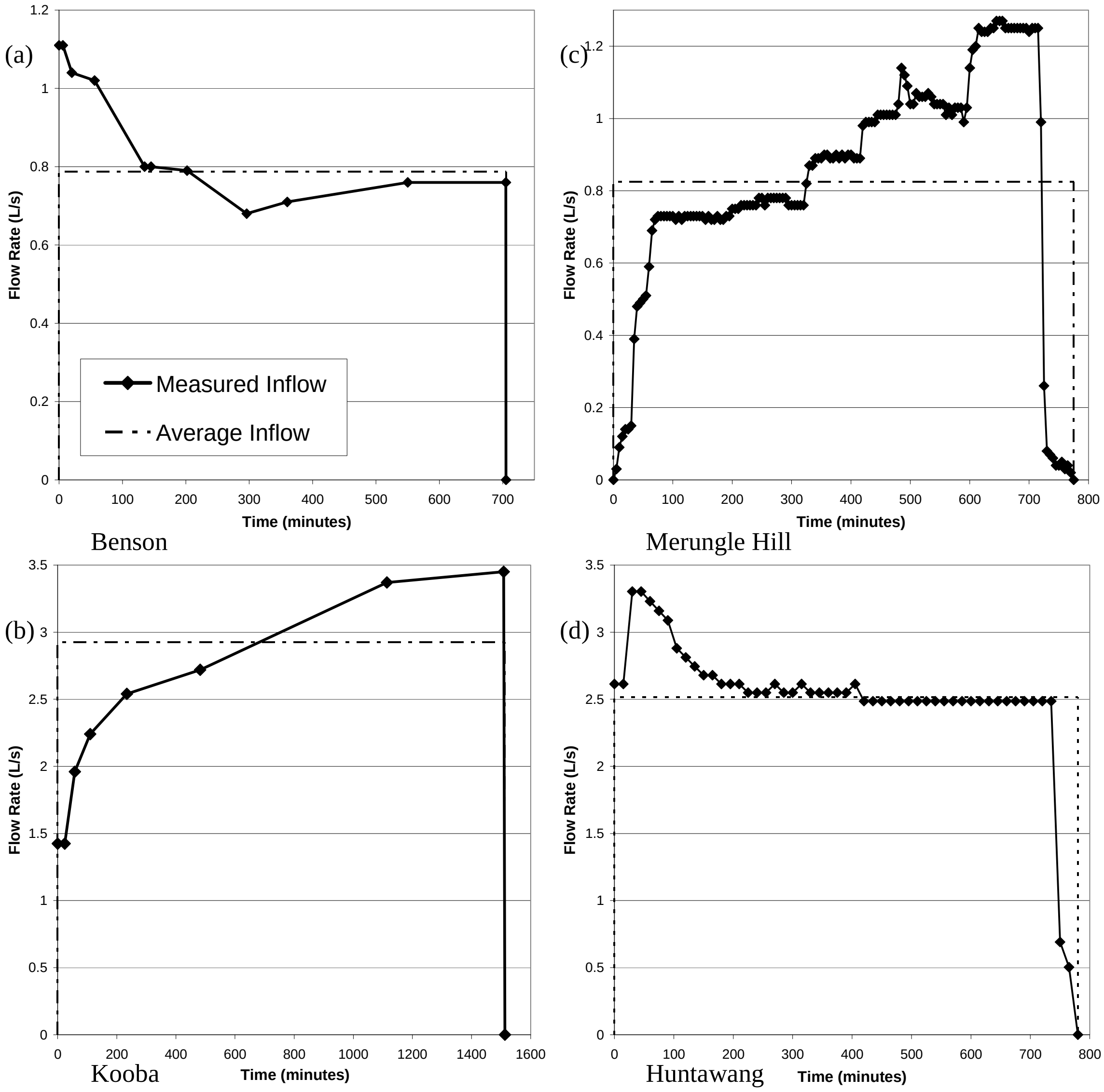


Fig. 1 a - d - Measured inflow Hydrographs

For the Benson, Kooba and Merungle Hill data sets, neither the upstream flow area nor depths of flow were measured hence, the assumed Manning *n* values were used to calculate the area of flow in the volume balance. The same *n* values were used in the subsequent simulations of the irrigations conducted using SIRMOD III (Walker 2003). Evaluation of the IPARM estimates of the infiltration parameters was based on the fit of the run-off hydrographs produced by the SIRMOD simulations.

The inflow at Kooba (Fig. 1b) and Merungle Hill (Fig. 1c) increased with time while the inflow rate decreased with time for the Benson (Fig. 1a) and Huntawang (Fig. 1d) irrigations. The advance phase occupied 71%, 35%, 74% and 28% of the total inflow period for the Kooba, Merungle Hill, Benson and Huntawang irrigations respectively.

Results and Discussion

Infiltration functions

The infiltration parameters estimated using the IPARM optimisation for each furrow and for each data combination are included in Table 1 with the corresponding cumulative infiltration curves shown in Fig. 2. The characteristic shape of the Benson and Huntawang curves (Fig. 2a and d) are similar for the different sets of input data. In general, where the actual inflow is decreasing, the infiltration function derived using a constant inflow underestimated the initial infiltration rate but tended to over estimate the infiltration during later stages of the irrigation. The opposite behaviour can be seen in the Kooba (Fig. 2b) and Merungle Hill (Fig. 2c) functions where the use of a constant inflow overestimated the initial infiltration and under predicted later in the irrigation. Hence, using the average inflow to estimate the cumulative infiltration function introduces a systematic error into the function. The form of the error appears to depend on the shape of the measured inflow hydrograph.

It is also possible to estimate the final infiltration rate f_0 using the difference between the inflow and final runoff rate. This procedure is only valid where the inflow rate is constant and for times after the runoff has reached steady state. Both the Benson and Huntawang hydrographs and to a lesser extent the Kooba data possibly satisfy the criteria. From final inflow and outflow rates the f_0 values were found to be 0.000047 for Benson, 0.000212 for Huntawang and 0.000172 m3/min/m for Kooba. In all three cases these values are greater than the values estimated using the advance and runoff data (Table 1), presumably indicating that either the final steady intake rate was not achieved during the irrigation time or that the IPARM optimisation routine biases an underestimation of this parameter.

The small advance and runoff errors in table 1 (Eq 6 and 7) indicate that the volume balance model is predicting values close to the measured data. The inclusion of the variable inflow hydrograph in the estimation typically decreased the volume balance errors. In the Benson and Huntawang furrows there was also a small trade off between advance and runoff errors. This demonstrates that use of the variable inflow in the optimisation results in an improved fit to the measured data and hence, improved estimates of the infiltration parameters.

Table 1 – Modified Kostiakov infiltration function parameters estimated using various combinations of input data from four different irrigations

			Infiltration Parameters			Advance	Runoff
			a	k	f_0 [a]	Error [b]	Error [c]
Benson	Advance	C. Inflow	0.0000	0.003343	0.000070	1.252	
		V. Inflow	0.0292	0.005313	0.000069	0.701	
	Advance + Runoff	C. Inflow	0.2951	0.001595	0.000045	3.191	1.753
		V. Inflow	0.2234	0.003334	0.000039	1.955	2.808
Kooba	Advance	C. Inflow	0.0496	0.303953	0.000000	2.603	
		V. Inflow	0.2234	0.096727	0.000000	2.610	
	Advance + Runoff	C. Inflow	0.0236	0.295273	0.000136	4.278	7.183
		V. Inflow	0.2053	0.092881	0.000100	3.622	4.534
Merungle Hill	Advance	C. Inflow	0.0000	0.049425	0.000000	1.107	
		V. Inflow	0.0155	0.018645	0.000104	0.000	
	Advance + Runoff	C. Inflow	0.2359	0.014862	0.000055	7.346	3.311
		V. Inflow	0.0000	0.016006	0.000138	1.702	3.364
Huntawang	Advance	C. Inflow	0.2597	0.021271	0.000169	0.900	
		V. Inflow	0.3038	0.024447	0.000070	1.834	
	Advance + Runoff	C. Inflow	0.3017	0.019854	0.000118	1.754	1.788
		V. Inflow	0.1724	0.040619	0.000159	2.205	0.735

[a] f_0 is measured in m^3/min/m. [b],[c] sum of the square errors from the IPARM optimisation ([b] eq 6 and [c] eq 7)

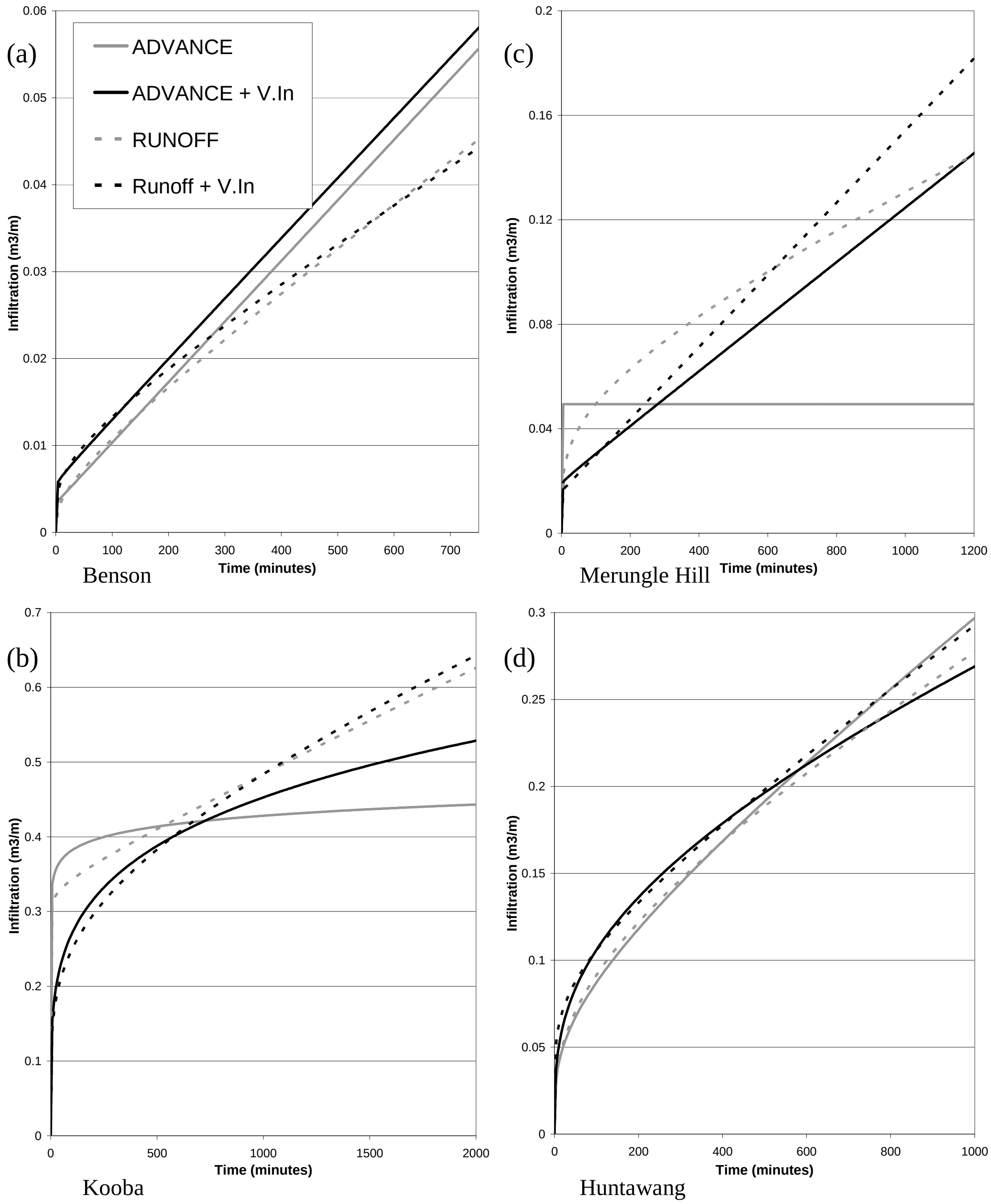


Fig. 2 a - d - Cumulative infiltration functions estimated using various combinations of measured input data

The accuracy of the calculated infiltration parameters can be further illustrated by a comparison between predicted and actual infiltration volumes (Fig. 3). In this figure the *Predicted Infiltration* is taken from Eq. 3 and the measured advance data (x and t). The *Actual Infiltration* is determined from Eq. 2 rearranged to make V_I the dependent variable.

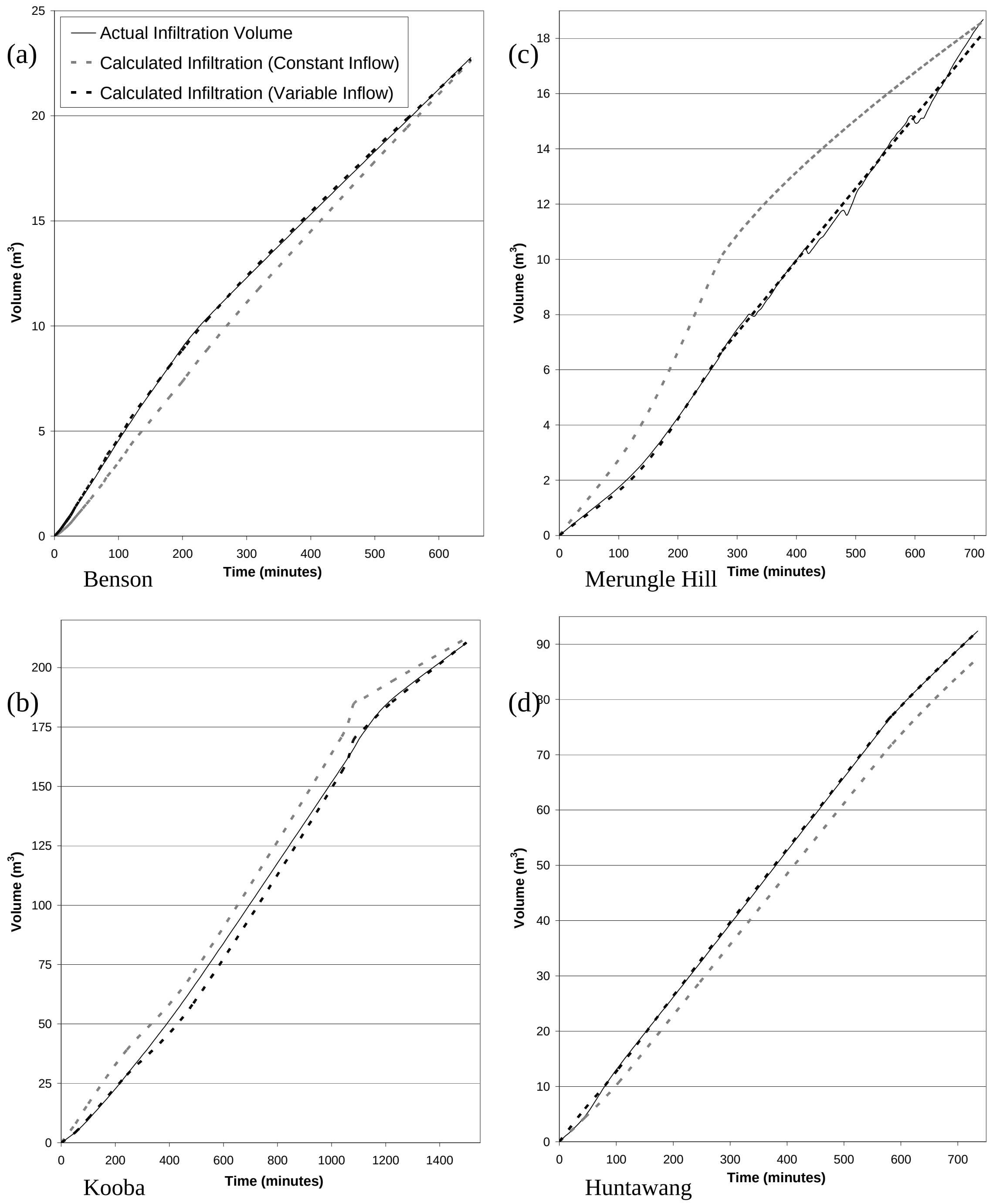


Fig. 3 a - d - Cumulative infiltrated volumes – Comparing infiltration from the volume balance (Actual) with predicted infiltration from parameters estimated from the advance and storage phases

Fig. 3 shows that in all cases there is little difference between the actual infiltration and that predicted using the parameters determined from the variable inflow. The infiltration parameters determined from the constant inflow failed to give a reasonable prediction of the infiltrated volume. The perturbations in the actual infiltrated volume for the Merungle

Hill site result from the surface storage term reacting too quickly to the rapid variations in the inflow rate.

Effect on simulated irrigation performance

The SIRMOD model (Walker 2003) was used to calculate advance trajectories, runoff hydrographs and performance indicators from the infiltration functions. Simulations in this section refer to analysis of the SIRMOD results. The summary results from the SIRMOD irrigation simulations for the four data sets and combinations of input data are shown in Table 2. The run-off hydrographs from the simulations are shown in Fig. 4. The dashed line (*Runoff (Constant Inflow) with V.In*) in Fig. 4 and 5. represents a simulation where the infiltration function calculated assuming constant inflow is used in conjunction with the actual inflow hydrograph. In Table 2, the runoff and infiltration errors are expressed as a percentage of the measured volumes. The *Advance SSE/Point* is the sum of squares difference between the measured and simulated advance points divided by the total number of points and is a useful measure of the accuracy of the simulated advance curve.

All of the infiltration parameters from the various data combinations gave acceptable predictions of the irrigation advance (Table 2). In general this prediction was improved (the error in the advance was reduced) when the variable inflow was used to calculate the infiltration function. The only exception was the Benson data where both the constant inflow and variable inflow gave a very good fit to the advance data. In all cases the error in the advance was increased slightly when the runoff was included in the IPARM optimisation.

More important than the advance prediction are the predictions of the irrigation performance in the later stages of the irrigation, that is, when the infiltration characteristic is projected to times greater than the advance time. This ability is best reflected in the predictions of the runoff outflow hydrograph and volumes infiltrated (Table 2). As would be expected, the infiltration parameters derived using the runoff data and the variable inflow gave the best predictions. The simulations based on infiltration parameters derived from only the advance data with constant inflow generally yielded the poorest predictions. For example, the Benson data runoff hydrograph (Fig. 4a) based only on the advance data resulted in poor reproductions of the measured runoff data. The simulations using

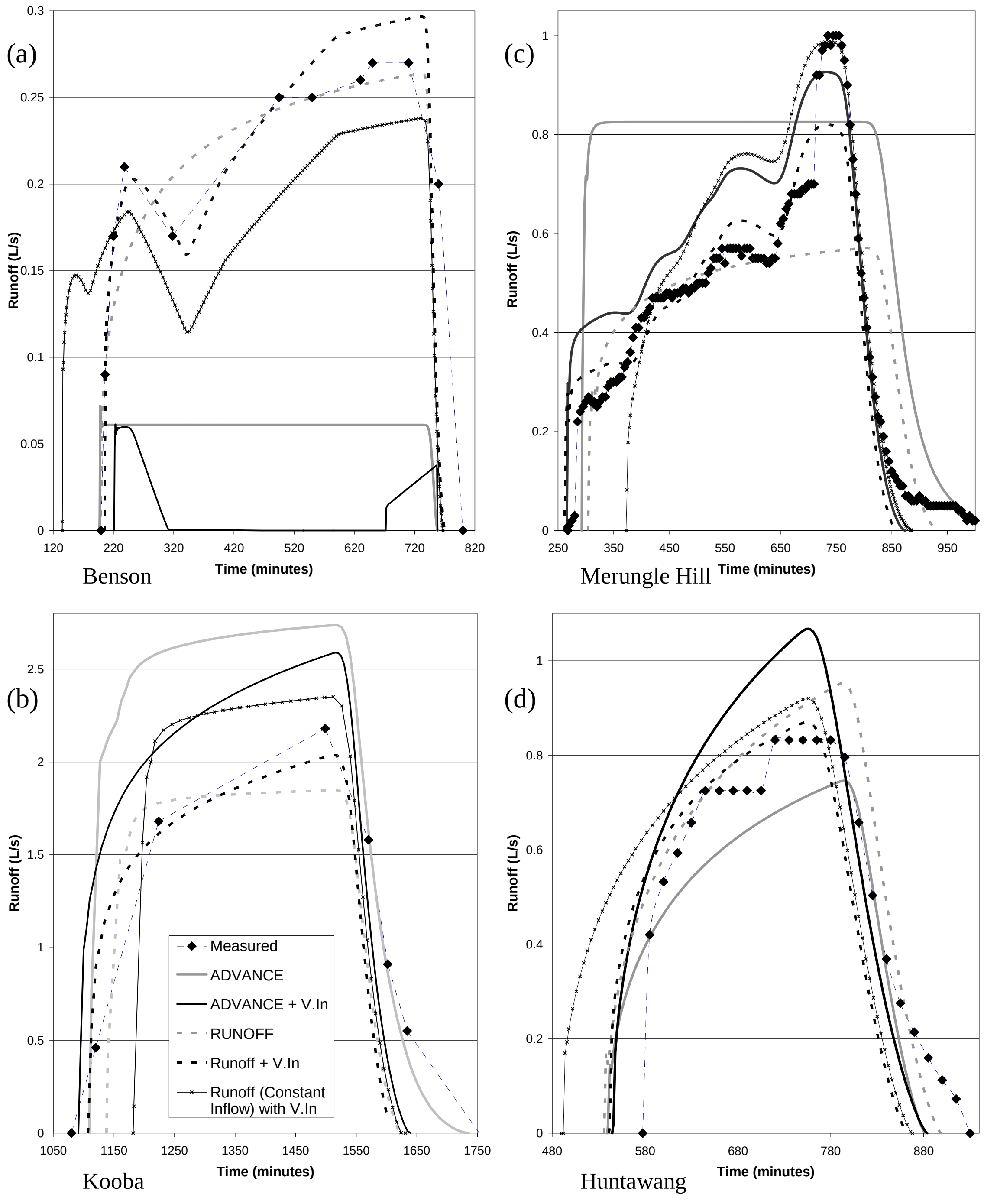


Fig. 4 a - d - Measured and predicted runoff hydrographs estimated using various combinations of measured input data.

infiltration functions estimated using the runoff and constant inflow were able to predict the magnitude of runoff accurately (Table 2) but not the shape of the hydrograph (Fig. 4). However, when the variable inflow and run-off data were used to estimate the infiltration function the simulations were also able to accurately reproduce the shape of the runoff hydrographs (Fig. 4).

Table 2 – Summary of simulations conducted with infiltration parameters estimated using various combinations of input data from four different irrigations

			Runoff Error (%)	Infiltration Error (%)	Advance SSE per point
Benson	Advance	C. Inflow	-73.91	22.45	6.8
		V. Inflow	-95.58	29.04	24.2
	Advance + Runoff	C. Inflow	-3.27	0.99	13.6
		V. Inflow	0.06	-0.02	16.2
		C. Inflow V. Sim	-12.05	3.66	691.7
Kooba	Advance	C. Inflow	40.17	-9.97	279.1
		V. Inflow	20.00	-4.96	248.6
	Advance + Runoff	C. Inflow	-13.74	3.41	985.0
		V. Inflow	-10.22	2.54	649.9
		C. Inflow V. Sim	-3.22	0.80	3199.1
Merungle Hill	Advance	C. Inflow	56.64	-52.36	232.5
		V. Inflow	14.91	-13.78	1.5
	Advance + Runoff	C. Inflow	-6.52	6.03	502.7
		V. Inflow	-3.79	3.51	23.9
		C. Inflow V. Sim	2.31	-2.13	4104.9
Hunatwang	Advance	C. Inflow	-9.85	1.09	611.5
		V. Inflow	17.40	-1.93	472.7
	Advance + Runoff	C. Inflow	17.17	-1.90	516.5
		V. Inflow	-0.55	0.06	487.7
		C. Inflow V. Sim	18.34	-2.03	2658.8

The infiltrated depth at a point in the furrow is determined by the infiltration function and the opportunity time at that distance. The above analysis has indicated that using an assumption of constant inflow to determine the infiltration function introduces errors into both the predicted infiltration parameters and simulated advance distance. Differences in either or both of these quantities will undermine the ability of the simulation model to predict the distribution of water applied in the field. For example, the choice of data used in estimating the infiltration function was found to produce differences in both the volumes and pattern of water application along the field (Fig. 5). For the Merungle Hill data, the use of a constant inflow and advance data only in estimating the infiltration function resulted in an under estimation of the volume infiltrated and a relatively constant infiltrated volume along the field (Fig. 5). However, using the variable inflow hydrograph and/or the incorporating the run-off data resulted in a doubling of the estimated infiltration and a less uniform pattern of infiltration along the furrow (Fig. 5). The simulation based on infiltration parameters estimated from advance using constant inflow is incapable of predicting the infiltrated depth along the furrow length, and therefore substantial errors will be present in the calculated irrigation performance measures, such as application efficiency and distribution uniformity. This is particularly important considering that the primary objective of field evaluation and simulation is to calculate and optimise these measures.

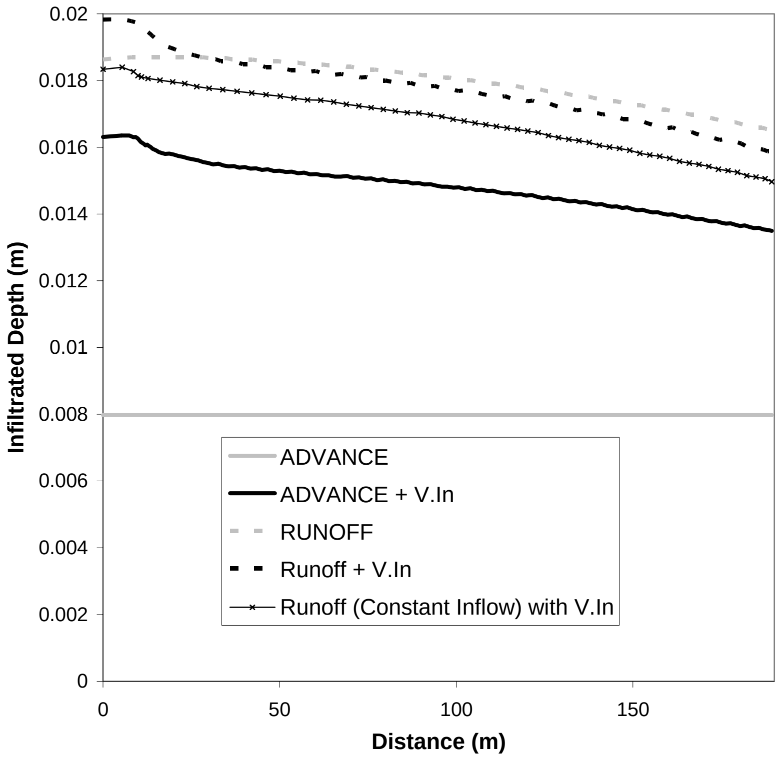
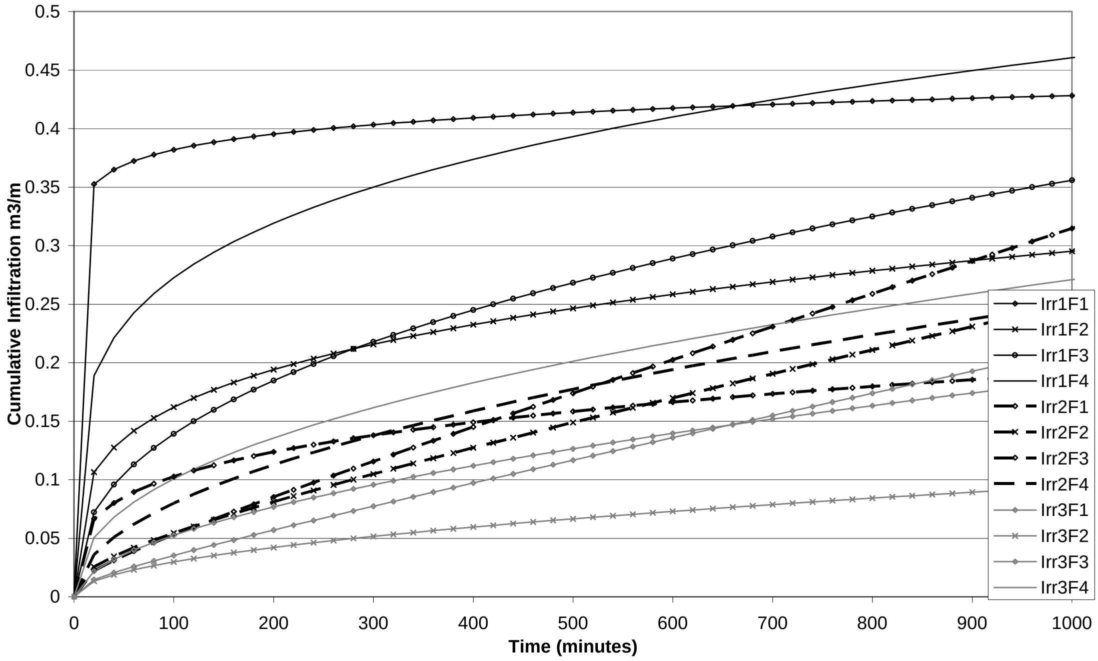


Fig. 5 - The effect of infiltration function estimation on the infiltrated depth profile for the Merungle Hill data set

Inflow as a source of variability in spatial estimates of infiltration

Data from all furrows and irrigations from the Kooba site (Hornbuckle 1999) were analysed to further illustrate the importance of accounting for the varying inflow when assessing infiltration variability at a field scale. Infiltration functions were calculated for all furrows at this site from the advance data using both the constant average inflow and variable inflow (Fig. 6). The use of the variable inflow was found to standardise the general shape of the infiltration curves reducing the apparent variation in infiltration between events. The coefficient of variation in the depths infiltrated at 100, 200, 500 and 1000 minutes were 87.3, 71.8, 51.3 and 37.8% where the function was calculated using a constant inflow and 68.7, 58.5, 39.8 and 28.9% respectively, where the measured inflow hydrograph was used. In this case, the errors in the infiltration caused by assuming constant inflow are larger during the initial stages of the irrigation and gradually decline as time increases up to the advance time. This suggests that accounting for the temporal variation in inflow should in many cases reduce the apparent variability between estimated infiltration rates for furrows in the same field.

(a)



(b)

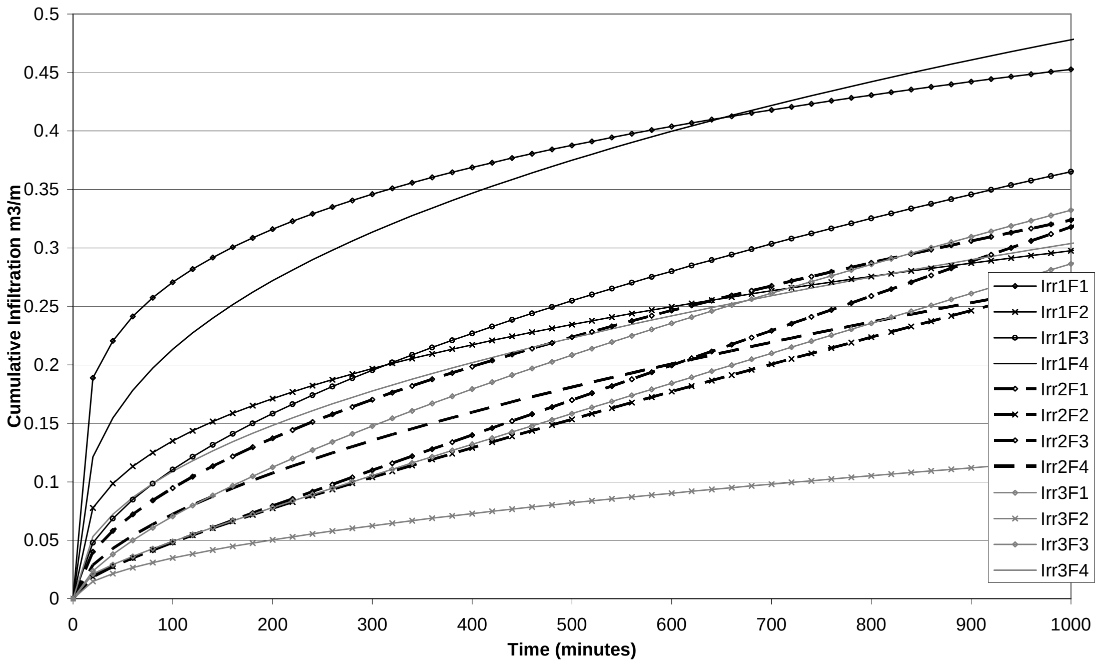


Fig. 6 a – b Estimated infiltration curves for four furrows measured across three different irrigation events using advance data and (a) the constant inflow assumption and (b) measured inflow hydrographs

A number of furrows experienced major inflow fluctuations in the initial stages of the hydrograph. Renault and Wallender (1996) concluded that this would result in larger values of the Kostiakov *k* and lower values of *a* when assuming constant inflow. Comparisons between the irrigation functions estimated using the constant and variable inflow hydrographs confirm this statement. Eight of the furrows experience inflows that undergo a significant increase during the initial stages of the irrigation. In every one of these cases the constant inflow assumption results in infiltration functions where the *k* parameter is higher and *a* is lower than for the variable inflow. In the remaining four furrows where the inflow does not change initially, *k* is lower for the constant inflow assumption and *a* does not favour either direction.

Limitations of the IPARM Model

The IPARM model is based on the volume balance model and is therefore still subject to the limitations of that model, in particular those caused by the assumptions that:

1. The advance can be represented by the power function ($x = pt^r$), and
2. The average cross-sectional area of the flow is proportional to the upstream flow area.

The IPARM model does not attempt to correct for these limitations, it is merely an improvement on existing volume balance based methods.

IPARM takes a simple approach to accommodate variable inflow and an equally simple approach to calculation of the corresponding volume of water temporarily stored in the flow in the furrow. Traditionally this volume of water stored on the soil surface is calculated by multiplying the (constant) upstream area of flow by a predetermined shape factor (typically 0.77). IPARM takes a similar approach but one where the upstream area is allowed to change as the inflow changes. It is assumed that if the variation in the inflow is gradual then the volume stored will continuously adjust at a rate consistent with the rate of change of the inflow.

Problems are likely to occur when using a low resolution inflow hydrograph or when the inflow changes rapidly. For example if the inflow declines rapidly, IPARM incorrectly assumes that the upstream area of flow will decline by a corresponding amount and in a similar time frame. This means that the surface storage is assumed to reduce at a similar rate hence underestimating the true surface storage. This sudden change in the volume balance must either cause an abrupt increase in the runoff term of the equation or in the advance rate. The result will be substantial errors in the infiltration parameters predicted by the model. This is the major limitation of the IPARM model and hence, future work will be directed toward a more rigorous description of the relationship between the surface storage and the variable inflow. Other models based on the hydrodynamic equations do not have this limitation and can readily accommodate variable inflow rate but the additional complexity of these models is rarely warranted.

Conclusions

The volume balance model used for the inverse solution of soil infiltration parameters from irrigation advance and runoff data was modified to accommodate gradually varied inflow. The results presented in this paper show that the variable inflow option of the IPARM model offers significant improvements in the accuracy of infiltration estimates when applied to data consistent with the assumptions inherent in the model. This in turn resulted in improved estimates of the volumes infiltrated and the runoff hydrographs in subsequent simulations of the irrigation events. However it should not be applied where the inflow changes rapidly and cannot be applied to a traditional cutback inflow regime.

Accounting for the variable inflow across an entire irrigated field produced cumulative infiltration curves with a more consistent shape and resulted in a reduction in the apparent variability in the cumulative infiltration across the field.

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