Variability of Furrow Infiltration and Estimated Infiltration Parameters in a Macroporous Soil

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Abstract: Understanding the spatial and temporal variations of infiltration in furrows is essential for the design and management of furrow irrigation systems. A key difficulty in quantifying the process is that infiltration depends on the depth of flow, which varies along a furrow and with time. An additional difficulty is that under many field conditions, a large fraction of the infiltrated water flows through cracks and/or macropores. This study examines the spatial and temporal variability of a furrow-irrigated field and evaluates a proposed semiphysical furrow infiltration model that accounts for flow-depth and macroporosity effects. Parameter estimation techniques were used to determine two parameters of the infiltration model, the hydraulic conductivity and the macroporosity term, in addition to the Manning roughness coefficient. The methodology was tested using published data from 30 furrow irrigation data sets collected in six furrows over five irrigation events. The evaluation revealed substantial variations in the final infiltrated volume among furrows and from one irrigation event to the next. Variability patterns differed markedly for infiltration measured during the advance phase compared with infiltration measured during the storage phase of the irrigation. Advance-phase infiltration varied systematically between irrigations for all furrows. Interfurrow inflow rate variability contributed to the variability of the infiltration during the postadvance phase, but not during the advance phase. Thus, cracks and/or macropores were an important contributor to the variability of infiltration during the advance phase. The analysis produced reasonable estimates of hydraulic conductivity relative to values reported in the literature. Hydraulic conductivity and post-advance infiltration volumes exhibited similar patterns of temporal variability. Hydraulic conductivity estimates were statistically correlated to the applied inflow rate. Although the reasons for this correlation are not clear, a possible explanation is that they are the result of systematic differences in the applied inflow rate among furrows. As with the advance-phase infiltration volumes, the estimated macroporosity term exhibited greater variation among irrigation events than among furrows during an event. The estimation procedure produced smaller differences between volume balance computed infiltration volumes and predicted values when using the semiphysical infiltration model than when using an empirical infiltration equation. Overall, the results show that the proposed furrow infiltration model represents the infiltration process adequately and that, at least for the studied data sets, the proposed estimation procedure yields a coherent set of infiltration and hydraulic resistance parameter values.

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Introduction

The variability of infiltration in space and/or time has been the subject of numerous investigations. Jaynes and Hunsaker (1989), and Childs et al. (1993) among others, showed that irrigated fields can exhibit patterns of spatial variation that are relatively stable with time due to the dominant role of soil texture. Temporal variations can be accounted for, in part, by differences in average antecedent water content and, thus, differences in the soil water pressure gradient, from one irrigation event to the next (Hunsaker et al. 1991).

In soils with relatively high clay content, the antecedent water content also affects the development of cracks and macropores (Enciso-Medina et al. 1998). Flow through these pathways dominates infiltration at short opportunity times and can account for two-thirds of the total infiltration volume under typical irrigation conditions (Mitchell and van Grenchem 1993). Cracks and macropores are key contributors to the variability of measured infiltrated volumes over an irrigated field, but quantifying their contribution is difficult, because the scale at which the process takes place is difficult to define. As a result, different measures of variability can be developed depending on the measurement technique or the measurement scale (Bautista and Wallender 1985; Tarboton and Wallender 1989; Hanson et al. 1998). Various concepts have been proposed to model macropore flow (Enciso-Medina et al. 1998; Ahuja et al. 1993; Simůnek et al. 2003), but their use remains limited for practical irrigation analyses.

In the case of furrow irrigation systems, hydraulic factors—namely, the combined effects of inflow rate, furrow cross-sectional geometry, and hydraulic resistance—also contribute to the variability of infiltration. These variables determine the wetted perimeter, that is, the length of the soil–water interface through which water infiltrates. Some studies have found that average infiltration rate varies proportionally to the wetted perimeter (Fangmeier and Ramsey 1978), which is consistent with infiltration theory. However, other studies have not been able to correlate wetted perimeter with infiltration variation or have measured only a weak
correlation. Several factors may mask the role of hydraulic factors on infiltration variability. One factor is variations in soil texture and structure (Izadi and Wallender 1985; Trout 1992a; Oyonarte et al. 2002). Another factor is the reduction in infiltration rates caused by large flow velocities, which offset the increases in wetted perimeter with inflow (Trout 1992b). Irrigation-induced variations in cross-sectional geometry and hydraulic resistance have also been suggested to offset the effect of variable wetted perimeter along the furrow (Walker and Kasilingam 2004). Finally, some authors have noted that irrigation-induced erosion and deposition alter the hydraulic characteristics of the infiltrating layer (Trout 1992b).

The objective in quantifying infiltration variability is, ultimately, to develop information that can be used for hydraulic analyses of irrigation systems. That information is summarized in the form of infiltration functions—mathematical expressions of the process based on a user-selected equation and calibrated parameters. Empirical equations are most commonly used to model furrow infiltration. These equations express infiltration only as a function of opportunity time. The calibrated parameters are representative of the conditions under which they were calibrated, including the effects of initial and boundary conditions and any other factors that may induce variations in infiltration. As a result, they are difficult to interpret and extrapolate. Nevertheless, various authors have expressed the variability of furrow infiltration in terms of the variability of the parameters of empirical functions (Oyonarte et al. 2002; Khatri and Smith 2006; Gillies et al. 2011).

Furrow infiltration models derived from porous media flow theory potentially offer a more rational approach for studying infiltration variability because they account for hydraulic properties related to soil texture and for initial and boundary conditions (i.e., wetted perimeter effects). While several authors have modeled furrow irrigation flows by coupling the equations of unsteady open-channel flow to the two-dimensional Richards equation (e.g., Wöhling and Schmitz 2007; Banti et al. 2011), those models are difficult to use because of their computational complexity. Semiphysical models currently represent a more promising approach for modeling infiltration in practical furrow irrigation models (Fonteh and Podmore 1993; Enciso-Medina et al. 1998; Warrick et al. 2007; Bautista et al. 2016), because the computations are simpler and because fewer soil parameters need to be determined.

A semiphysical furrow infiltration model (Bautista et al. 2016) was added to WinSRFR (Bautista et al. 2009), a software package for the hydraulic analysis of irrigation systems. Testing of this infiltration model with field data is still limited. A significant challenge for using the model for practical studies is determining the relevant soil parameters. Procedures for the estimation of these parameters from irrigation evaluation data were recently developed (Bautista and Schlegel 2017a, b). In contrast with estimation procedures for empirical furrow infiltration models, estimation procedures for the semphysical model need to account for the spatial and temporal variation of flow depths. Initial testing of the estimation procedures produced reasonable results. The semi-physical infiltration functions reproduced the observed irrigation flow measurements with, at least, comparable accuracy to empirical infiltration functions. Additional testing is needed to better understand the strengths and limitations of the semiphysical furrow infiltration model and of the proposed procedures for estimating its parameters.

This study examines the spatial and temporal variability of furrow infiltration using a semiphysical infiltration model and parameter estimation methods. Specific objectives are:

- to examine the temporal and spatial variation of infiltration at the scale of irrigated furrows based on irrigation evaluation data and to examine factors that contribute to the spatial and temporal variation of the infiltration;
- to evaluate the ability of the proposed model to represent the infiltration process in a macroporous soil; and
- to characterize the temporal and spatial variation of infiltration and hydraulic resistance parameters estimated from irrigation evaluation data.

### Materials and Methods

#### Field Evaluation Data

Elliott (R. L. Elliott, “Furrow irrigation field evaluation data. Summers of 1977–1979,” unpublished report) compiled irrigation evaluation data collected by Colorado State University researchers from several farms. The Benson farm data set, consisting of 30 free-draining furrow evaluations, was selected for this analysis. The evaluations were conducted during five irrigation events at approximately 10-day intervals. During each irrigation, six furrows were evaluated. The furrows were divided into two groups with slightly different soil texture, varying from clay to clay loam. The same furrows were evaluated during each irrigation. In the Elliott report, the furrows are identified by farm (Benson), irrigation number (1–5), group number (1–2), and furrow number (1, 3, and 5) (i.e., 1_2_3 refers to irrigation event 1, group 2, and furrow number 3).

All furrows in the Benson data set have the same average slope $S_0$ (0.0044) and field length $L_f$ (625 m). Both inflow and outflow rates were measured until near cutoff time $t_{co}$ (the time when inflow to the field was shut off). Advance and recession times were measured every 25 m, but recession was not measured to the end of the field. Flow depths were measured every 50 m, but at most at three times. Every other furrow was irrigated and thus, the reported furrow spacing (FS) was 1.52 m. Extensive cross-sectional data were obtained for these furrows before and after each irrigation, which were used to derive average cross-sectional parameters for each furrow. The data were fitted to a trapezoid and similar parameters were derived for all furrows. A sensitivity analysis showed that volume balance and parameter estimation results, described subsequently, were not very sensitive to the furrow cross-section data, within the range of measured values. Other data included soil texture, bulk density, and gravimetric soil water content before and after the test. The soil water content data were obtained for a single furrow within a group.

#### Infiltration Analysis and Parameter Estimation

The analysis was conducted using a prerelease version of the WinSRFR 5.0 EVALUE parameter estimation component (Bautista and Schlegel 2017a). EVALUE uses volume balance analysis and unsteady flow simulation to evaluate infiltration and then to estimate the parameters of a selected infiltration model. EVALUE was also used to characterize furrow hydraulic resistance.

In volume balance analyses, infiltrated volume $V_z$ ($L^3$) is calculated at selected times $t_i$ (T) as the residual of the inflow, surface, and runoff volumes $V_{in}$ ($L^3$), $V_y$ ($L^3$), and $V_{ro}$ ($L^3$), respectively

$$V_z(t_i) = V_{in}(t_i) - V_y(t_i) - V_{ro}(t_i)$$

(1)

The values of $V_{in}$ and $V_{ro}$ needed to solve this equation are measured values. For the Benson data set, $V_y$ values were estimated hydraulically as

$$V_y = A_0 \sigma_y x_A$$

(2)
where \( A_0 \) (L\(^2\)) = upstream cross-sectional area, which is a function of the flow-depth \( y_0 \) (L); \( \sigma_y \) = dimensionless shape parameter, assumed to vary in the range 0.5–1.0; and \( x_A \) (L) = stream length (i.e., the advance distance). Since both the upstream depth \( y_0 \) needed to calculate \( A_0 \) and \( \sigma_y \) depend on the unknown infiltration function (Bautista et al. 2012), the EV ALUE component uses unsteady flow simulation to help refine these estimates (Bautista and Schlegel 2017a).

The times \( t_i \) used for the volume balance calculations depend on the available data and the computational strategy used for parameter estimation (Bautista and Schlegel 2017a). The EV ALUE component suggests calculation times, which can be modified by the user. For the Benson data set, volume balance can be calculated at the measured advance times and at arbitrary postadvance times up to about 30 min before the reported cutoff time. This was the time at which inflow and/or outflow rate measurements stopped for nearly all furrows.

**Infiltration Variability Analysis**

This part of the analysis aimed to characterize the spatial and temporal structure of furrow infiltration variability and to identify factors that contribute to that structure. Typically, infiltration variability studies compare volumes determined for a common intake opportunity time (the time that the water is in contact with the soil surface) and under similar hydraulic conditions (length, slope, cross section, inflow rate, resistance). A key difficulty in comparing infiltration volumes measured over entire furrows is that advance times, and therefore opportunity times as a function of distance, may vary substantially among the evaluated furrows. Differences in hydraulic conditions exacerbate differences in opportunity time and, furthermore, create differences in the magnitude of the infiltrating surface. This is the case for the Benson data set, for which inflow rates varied systematically among furrows while cutoff times varied from one irrigation event to the next.

Recognizing the dissimilarity of opportunity times and hydraulic conditions for these furrows, infiltration variability was examined from three measurements of infiltration, namely infiltration at the end of the advance phase, infiltration at a common average intake opportunity time, and infiltration determined at the final volume balance calculation time, that is, the maximum time allowed by the data (about 30 min before the reported cutoff time for each furrow, as explained previously). These three measurements are identified subsequently as, respectively, \( V_{cude} \), \( V_{ziot} \), and \( V_{sf} \). In principle, comparison of infiltration at the end of the advance phase with infiltration at later times should provide measures of the contribution of macropore and porous media flow to total infiltration.

The average intake opportunity time \( IOT_{avg} \) of a furrow, for times less than the initial recession time, is given by

\[
IOT_{avg} = \frac{\int_{t_0}^{t_i} \left( t_i - t_{ade}(x) \right) dx}{x_A}
\]  

where \( t_{ade}(x) = \) advance time to distance \( x \); and other variables are as previously defined. For \( t_i \geq t_L \) (the final advance time), \( x_A = Lf \). An \( IOT_{avg} \) value was calculated for each furrow, initially with \( t_L \) equal to the maximum time at which inflow rate was measured. Trapezoidal rule integration was used to solve Eq. (3) using the field-measured values of \( t_{ade}(x) \). The smallest \( IOT_{avg} \) = 367 min, was selected as the common value. For each furrow, \( t_i \) was adjusted to force \( IOT_{avg} = 367 \) min. This value of \( t_i \) identified as \( t_i' \), was used in combination with Eq. (1) to calculate \( V_{ziot} \).

Multivariable regression analyses were conducted to assess the contribution of interfurrow flow rate variability and of the categorical variables furrow group and irrigation number to the variability of the infiltrated volumes \( V_{cude} \), \( V_{ziot} \), and \( V_{sf} \). Although it would have been desirable to do so, initial water content was not included in the analysis as an independent variable because of the paucity of those data. The contribution of furrow-to-furrow variation was not examined either because, as will be explained subsequently, furrow-to-furrow variation effects are confounded with inflow rate variability. The analysis was conducted with the R version 3.5.0 software package (R Core Team 2017). The analysis first tested the model

\[
V_z = Q_{in} + Irr + \text{Group} + \varepsilon
\]  

using the R lm function. In Eq. (11), \( V_z \) stands for either \( V_{cude} \), \( V_{ziot} \), or \( V_{sf} \), and \( \varepsilon \) is the random error. Unneeded predictors were then eliminated by testing nested submodels and comparing the nested models with the model defined by Eq. (4) using the anova function. Quantile-quantile plots were developed to confirm that the raw data and the residuals of the regression followed a normal distribution (Caffo 2015). Possible interactions were also explored but were not significant. Details of the analyses are provided in Guzmán-Rojo (2017).

**Infiltration Model**

Warrick et al. (2007) proposed a furrow infiltration model based on an approximate solution to the two-dimensional Richards equation. Following modifications suggested by Bautista et al. (2014), the model can be written as

\[
A_z(t) = z(t)WP + \frac{\gamma S_0^2}{\Delta \theta}
\]  

where \( A_z = \) infiltration volume per unit length (L\(^2\)); \( z = \) one-dimensional infiltration volume per unit area (L); \( WP = \) wetted perimeter (L); \( S_0 = \) soil sorptivity (L/T\(^{0.5}\)); \( \Delta \theta = \) difference between saturated and initial water content (L\(^2\)/L\(^2\)); \( t = \) time (T); and \( \gamma = \) dimensionless empirical parameter related to boundary conditions, geometry, and initial conditions, typically in the range 0.6–1.0 (Warrick et al. 2007; Bautista et al. 2014). In this model, infiltration is the result of vertical and lateral flow components, represented by, respectively, the first and second terms in the equation. Eq. (5) was developed under the assumption of a constant ponding depth.

Eq. (5), modified to account for the effect of a variable ponding depth (Bautista et al. 2016), was used in this study. The one-dimensional infiltration term \( z \) was computed with the Green and Ampt (1911) equation:

\[
z = z_0 + K_s(t - t_0) + \Delta \theta \Delta h_k \cdot \ln \left( \frac{z + \Delta \theta \Delta h_k}{z_0 + \Delta \theta \Delta h_k} \right)
\]  

where \( z = \) infiltrated depth (L\(^2\)/L\(^2\)); \( z_0 = \) infiltration at time \( t_0 \); \( \Delta h_k = \) difference between the average water pressure at the infiltrating surface \( h_{1i} \) (Bautista et al. 2014) and the wetting front pressure head \( h_1 \) (a negative value, also referred to as the wetting front capillary suction); \( K_s = \) saturated hydraulic conductivity (L/T); and other variables are as previously defined. The Green-Ampt parameters can also be used to estimate \( S_0 \) in Eq. (5) (Warrick et al. 2007):

\[
S = \sqrt{2K_s \Delta \theta \Delta h_k}
\]  

Eqs. (5)–(7) were developed based on porous media flow theory. In practice, large volumes of water can bypass the soil matrix and flow instead through macropores and cracks. Clemmens and Bautista (2009) noted that the Green-Ampt equation often fails...
to fit field-measured infiltration data due to the effects of macropore flow. Although several authors have attempted to describe macropore flow using physical principles, Clemmens and Bautista (2009) suggested adding a macropore depth term (volume per unit area) to the Green-Ampt equation, under the assumption that such a volume infiltrates instantaneously. Here, the macropore term is labeled \( c_{GA} \). To use this concept with furrows, we assume that macropore flow does not depend on the wetted perimeter, but rather, on the furrow spacing FS. After adding these terms and expressing \( S_0 \) with Eq. (7), Eq. (5) becomes

\[
A_z = z \cdot WP + c_{GA} \cdot FS + 2\gamma K_s \Delta h \cdot t
\]

which depends on the parameters \( \theta_0, \theta_s, h_f, K_s, c, \) and \( \gamma \). This expression, in combination with Eq. (6), is identified in the following discussion as the Warrick-Green-Ampt (WGA) model.

**Estimation of the Flow-Depth Dependent Infiltration Parameters**

In EV ALUE, infiltration parameters are found by minimizing the objective function

\[
OF = \sum_{i=1}^{I} (V_z - V_z^i)^2
\]

where \( V_z \) = volumes calculated with Eq. (1); \( V_z^i \) = infiltration volumes calculated by integrating the infiltration profile with a selected infiltration model over the length of the stream at the given time, \( x_i(t) \); and \( I \) = number of times \( t \) is used for volume balance calculations. For these data sets, the software selected 11 or fewer volume balance calculation times.

In typical applications of the volume balance method, for parameter estimation, infiltration is assumed to depend on opportunity time only. Various procedures are available to calculate \( V_z^i \) under such conditions (Strelkoff et al. 2009). In this analysis, Eqs. (8) and (6) depend on the flow depth variation along the field and with time, \( y(x, t) \), and on the unknown parameters \( K_s \) and \( c_{GA} \), hence

\[
V_z^i(t) = \int_0^{x_i(t)} A_z(y(x, t), K_s, c_{GA})dx
\]

EV ALUE uses a two-step process for the estimation of flow-depth dependent infiltration parameters (Bautista and Schlegel 2017b). The first step consists of the estimation of an empirical infiltration function, dependent on opportunity time only and, thus, independent of wetted perimeter variations along the furrow and with time. The modified Kostiakov equation was used in this initial stage:

\[
A_z = W_1(k\tau^n + b\tau) + W_2c
\]

where \( k \) (L/T\(^n\)), \( a, b \) (L/T), and \( c \) (L) are empirical parameters; \( k \) and \( a \) represent transient infiltration; \( b \) = steady state infiltration rate; \( c \) = instantaneous macropore infiltration, similar to the term \( c_{GA} \); and \( W_1 \) and \( W_2 \) are transverse widths (L). For these analyses, both \( W_1 \) and \( W_2 \) were set equal to the furrow spacing FS. Eq. (10) was expressed as a function of the parameters of Eq. (11) and used to solve Eq. (9) based on the available volume balance data. This first step also yielded estimates for the resistance coefficient of the selected hydraulic resistance model, as will be explained subsequently.

In the second step, an unsteady flow simulation was conducted with the estimated infiltration function. This simulation produces the \( y(x, t) \) needed to solve Eq. (10), and, subsequently, Eq. (9). This step relies on the nonuniqueness of solutions to the infiltration parameter estimation problem; nearly identical flow depth and flow rate conditions can be simulated with different infiltration functions, as long as the functions predict the same average infiltration (Bautista 2016). This analysis estimated the parameters \( K_s \) and \( c_{GA} \) from field evaluation data; \( \theta_0 \) was measured, and \( \theta_s \) and \( h_f \) were estimated from pedotransfer functions. Since \( \gamma \) often is close to unity, its value was assumed to be subsumed in the estimated \( K_s \).

**Determination of \( \theta_0, \theta_s, \) and \( h_f \)**

As was previously indicated, Elliott reported preirrigation gravimetric water content and bulk density data. Those data were measured in one furrow only for each group and at three distances along the furrow. At each location, samples were obtained at five soil depth intervals and at three locations across the furrow spacing. Considering the paucity of the data and the fact that the analysis assumes a uniform soil profile, those data were averaged to determine \( \theta_0 \) for each group and irrigation event.

Rawls et al. (1983) reported values for parameters of the Green-Ampt equation based on soil texture. The average values reported for a clay loam soil, \( \theta_s = 0.45 \) and \( h_f = -43 \) cm, were selected for this study.

**Modeling Hydraulic Resistance and Estimation of the Resistance Parameter**

The Manning equation is commonly used to model hydraulic resistance in surface irrigation:

\[
S_f = \frac{n^2v|v|}{c_R^{5/3}}
\]

where \( S_f \) = friction slope (L/L); \( v \) = flow velocity (L/T); \( R \) = hydraulic radius (L); \( c_R \) = units coefficient (= 1 m\(^{0.5}\)/s in SI units); and \( n \) (L/\( c_R \)) = resistance coefficient.

Estimates of the Manning \( n \) were developed with the EV ALUE component by fitting the simulated flow depths as a function of distance and time to measured values. Since estimates of \( V_z \) with Eq. (2) depend on the roughness parameter, the analysis required first estimating the infiltration function based on an assumed \( n \) value. Unsteady simulation was then conducted with that infiltration function and the resulting depths were used to manually adjust \( n \). Goodness-of-fit indicators provided by the software were used to compare simulated with observed values. The adjusted \( n \) was used to refine the volume balance computations and estimate a new infiltration function. No further adjustments to \( n \) were required after this step, even with further changes to the infiltration parameters. Additional details on the process used to determine \( n \) with EV ALUE are provided in Bautista and Schlegel (2017b).

**Wetted Perimeter Contribution to Infiltration Variability**

A premise of this study is that wetted perimeter variability among furrows contributes to the spatial and temporal variability of infiltration. Inflow rate variability is a key factor contributing to wetted perimeter variability. This inflow rate/wetted perimeter effect can be examined with free-draining furrows by comparing the inflow rate with the furrow infiltration rate \( Q_z \), calculated as the difference between the inflow \( Q_z \) and runoff rates \( Q_{z0} \). In principle, this calculation should be made when the runoff rate is at or near steady-state. For the Benson data set, the calculation was made near cutoff time, depending on the inflow and outflow measurements available for each furrow and was not, in all cases, near steady conditions.
This field-measured relationship was then compared with a theoretical relationship determined via simulation using the simulation component of WinSRFR. Simulations were conducted with infiltration given by the WGA model and with the $K_s$ and $c_{GA}$ parameters set equal to the mean of the estimated parameters. In these simulations, inflow rates were varied between 1.2 and 2.8 L/s, which is nearly the range of inflows reported for the Benson furrows, and cutoff time was set equal to 600 min, which is approximately the average cutoff time for these evaluations. An average value was also used for the Manning resistance coefficient. The infiltration rate for each furrow was calculated as the difference between the inflow and outflow rates at cutoff time.

Results

Background Information

This section provides background information that is needed to understand the variability of infiltration measurements for the evaluation data set. Fig. 1 summarizes the soil texture information for the Benson furrows. These data were obtained on a single transect for each furrow group. As was noted previously, the soil for furrows in Group 1 was primarily clay loam, while the soil for furrows in Group 2 was mostly a combination of clay loam and clay. While limited, these data suggest fairly uniform soil conditions along each field, and moderate differences between the two furrow groups.

Fig. 2 presents the average inflow rate applied to each furrow during each irrigation. As indicated by the $x$-axis labels, the furrows are separated by group number (G1 and G2, respectively). Different symbols and lines are used to represent different irrigation events (identified in the graph as Irr1–Irr5). The Elliott report does not explain the criteria used to set the inflow rate for each of the 30 evaluations. However, systematic inflow rate variations are evident from the data. With the exception of the first irrigation, the inflow rate applied to each furrow was nearly the same throughout the irrigation season, but inflow rates differed among furrows. Larger inflow rates were applied to furrows in Group 1 than to those in Group 2. Since cutoff times were nearly the same for all furrows during each irrigation, infiltration variations can be expected among the furrows for each irrigation event and between irrigation events simply due to the differences in the applied volume. In other words, with this data set, soil texture and/or structural effects on infiltration are confounded with the effect of variable inflow rates and applied volume.

Elliott (1980) reported irrigation requirement depths, calculated from weather and crop development data, but did not explain whether irrigation cutoff times were determined based on the irrigation requirements. Fig. 3 displays the irrigation requirement volume ($V_{req}$) (the product of irrigation requirement depth, furrow length, and spacing) and also summarizes the average application volume ($V_{in}$) by irrigation. With the exception of the first irrigation, the average applied volume was only slightly greater than required volume, and in the case of Irrigation 5, it was even less. In fact, for all irrigations except the first, the application did not satisfy the reported requirements for one or more furrows, particularly the furrows in Group 2. The significance of these results is that, just as with the variation in applied volume among furrows, there is a variation in applied volume among irrigations that is unrelated to the irrigation requirements. It is likely that cutoff time and
applied water were determined by labor constraints and/or by irrigator experience.

The aforementioned discussion of results implies differences in initial water content among furrows, especially differences between furrows in Groups 1 and 2. The available water content data allows for examination of this issue, but only in a limited way. Water contents were measured in only one furrow per group, different from the furrows where flow variables were measured. Fig. 4 illustrates the preirrigation volumetric soil water content with depth for each irrigation (Irr) and group (G). Each point is the average of measurements obtained at three transverse locations. Except for the lower soil depth, water content appears to have been fairly similar before each irrigation. The decline in water content at the lower depth would appear to confirm that the water applications did not meet the irrigation requirement. Therefore, water was mined from the lower profile. The results also show a declining water content trend with distance, which is consistent with variations in opportunity time with distance typical of surface irrigation systems but could also be related to the presence of sandy clay loam toward the end of both fields (Fig. 1).

Average preirrigation water content for each irrigation and soil group are given in Table 1. These results show that preirrigation water content was, on average, similar for all irrigations, although the average water application amounts (Fig. 3) varied substantially among irrigations. Also, the water content for Group 2 was slightly greater than for Group 1, which is consistent with differences in textural characteristics (Fig. 1), but not consistent with the systematic differences in water application (Fig. 3). Table 1 also displays the interval between irrigations. For purposes of the following discussion, it is important to note that Irrigation 4 had the shortest interval, while Irrigations 3 and 5 had the longest interval. Except for Irrigation 5, the preirrigation water content seems unrelated to the irrigation interval. The relatively low initial water content for irrigation 5 (Table 1) is consistent with a long interval between irrigations and an advanced crop development stage. Since no measurements were obtained for Irrigation 3, Group 2, the initial water content was assumed equal to 0.32 based on the values given in the table for other irrigations in the same group.

### Table 1. Intervals between irrigations and average initial volumetric water content for each furrow group and irrigation

<table>
<thead>
<tr>
<th>Irrigation number</th>
<th>Irrigation interval (days)</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>—</td>
<td>0.28</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>0.28</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>0.26</td>
<td>0.29</td>
</tr>
</tbody>
</table>

### Variability of Infiltration Determined from Volume Balance

Fig. 5 depicts $V_{zadv}$, $V_{zlot}$, and $V_{zf}$ for each furrow, grouped by irrigation event. If infiltration was due only to porous media flow, infiltration variations for the postadvance phase would resemble those observed during the advance phase. Except for Irrigation 1,
different infiltration patterns were produced by the advance and postadvance phase data. From one irrigation to the next for each furrow, $V_{\text{zadv}}$ exhibited substantial variations. Particularly noticeable are the results of Irrigation 4, which produced the smallest $V_{\text{zadv}}$ values for all furrows. This large infiltration variation among irrigation events is consistent with the presence of soil macropores and/or cracks. It is likely that those flow conduits did not develop as extensively for Irrigation 4, due to the short irrigation interval (Table 1).

A factor that contributed to differences in the variability patterns for $V_{\text{zadv}}$ and $V_{\text{ziot}}$ is that the former were calculated for a wide range of IOT$_{\text{avg}}$ values while the latter were computed for a single IOT$_{\text{avg}}$. During advance, the mean IOT$_{\text{avg}}$ was 151 min, with a CV of 48%, while $V_{\text{ziot}}$ values were computed for IOT$_{\text{avg}} = 367$ min. In contrast, $V_{\text{zadv}}$ and $V_{\text{ziot}}$ exhibited similar variability patterns, even though the former were computed for IOT$_{\text{avg}}$ values ranging from 480 to 627 min (mean = 498 min, CV = 13%). This similar pattern of variation for $V_{\text{zf}}$ and $V_{\text{ziot}}$ is consistent with porous media flow theory, as it persisted from one irrigation event to the next.

Tables 2 and 3 display the mean and COV computed for the data in Fig. 5, the former by irrigation event and the latter by furrow. The infiltration event-averaged $V_{\text{zadv}}$ (Table 2) varied between 9 and nearly 33 m$^3$, while the furrow-averaged $V_{\text{zadv}}$ (Table 3) varied between about 23 and 25 m$^3$. In contrast, the COV varied between 12% and 29% for the irrigation event-averaged data but between 33% and 54% for the furrow-averaged values. These results emphasize again the substantial differences in advance-phase infiltration among irrigation events. During the postadvance phase, differences in average infiltration volume increased among furrows (Table 2), presumably due to spatial differences in furrow inflow and infiltration rates, while relative differences among irrigations decreased (Table 3). Average $V_{\text{zf}}$ values for each irrigation were closely related to the average inflow volume $V_{\text{zf}}$. Those values are displayed in the last row of Table 2.

Fig. 6 displays $V_{\text{zadv}}$, $V_{\text{ziot}}$, and $V_{\text{zf}}$ as a function of the inflow rate $Q_{\text{zf}}$. The data are separated again by irrigation but are also separated by group number. Regression lines through each group of 3 furrows highlight trends in the data. One can expect final advance times to decrease and, consequently, infiltrated volumes to decrease with increasing flow rate during the advance phase. Except for the furrows in Group 2 during the first irrigation, advance times decreased with increasing flow rate, as expected (not illustrated). However, infiltration varied somewhat randomly with inflow rate for these furrows. For the furrows in Group 1, $V_{\text{zadv}}$ increased with $Q_{\text{zf}}$ during the first two irrigations but then decreased during the last three. The furrows in Group 2 exhibited essentially the opposite trend, except for the last irrigation. In contrast, $V_{\text{ziot}}$ and $V_{\text{zf}}$ increased with $Q_{\text{zf}}$ (lower plots), and the regression lines exhibited similar slopes, especially during the last three irrigations. Again, macropore flow can help explain why infiltrated volume seems unrelated to $Q_{\text{zf}}$ during advance. A key reason for the increased postadvance infiltration is that larger inflow rates increased the opportunity times during the storage phase of each irrigation due to the reduced time needed to reach the end of the field. Another potential contributing factor is that the wetted perimeter, and therefore the infiltrating surface, increased with $Q_{\text{zf}}$, but this effect cannot be assessed from these data.

Hanson et al. (1998) examined infiltration on the scale of furrows in a cracking clay soil. As with the evaluations reported herein, Hanson et al. (1998) tested different inflow rates on furrows on the same field and conducted evaluations over several irrigations. While they did not examine advance-phase infiltration separately from postadvance infiltration, they found that when cracks were visible, final infiltration was unrelated to the applied inflow rate. When tillage operations removed the cracks, infiltration increased with inflow rate. Hence, the results in Figs. 5 and 6 support those of Hanson et al. (1998).

Results of the multivariable regression analysis for the three infiltration variables are summarized in Tables 4–6. Group number was eliminated as a predictor in all analyses, which, again, may be related to the fact that the applied inflow rate systematically differed between groups and among furrows within each group. Since the analysis for $V_{\text{zadv}}$ also eliminated $Q_{\text{zf}}$, the variation of $V_{\text{zadv}}$ was explained by irrigation number alone (adjusted $R^2 = 0.74$). Only Irrigation 4 produced a highly significant predictor estimate (Table 4). According to this model, nearly 19 m$^3$ less water was required to advance to the end of the field during Irrigation 4 than during Irrigation 1, with Pr < 0.001. Less volume was also required for the last irrigation, although the difference was much smaller.

In contrast, differences in $V_{\text{ziot}}$ (Table 5) and $V_{\text{zf}}$ (Table 6) were explained by both $Q_{\text{zf}}$ and irrigation number (adjusted $R^2 \geq 0.77$). As expected, the predictor estimate for $Q_{\text{zf}}$ was positive and highly significant (Pr < 0.001) in both analyses. As with $V_{\text{zadv}}$, the predictor estimate associated with Irrigation 4 was negative and highly significant. Note, however, that predictor estimates for $V_{\text{zf}}$ became either negative or increasingly negative in comparison with those computed for $V_{\text{ziot}}$ and that the estimate for Irrigation 3 became statistically significant. This shows that post-advance-phase infiltration, presumably controlled by porous media flow effects, eventually overshadowed advance-phase infiltration variability.

A final issue to examine in this section is the correlation for the different infiltration volumes between consecutive irrigation events.

![Table 2. Statistical summary by irrigation for infiltration and inflow volumes](image)

![Table 3. Statistical summary by furrow for infiltration volumes](image)
No correlation was determined for the advance-phase infiltration volumes. Values of $V_{ziot}$ produced larger correlation coefficients, but only Irrigations 2 and 3 produced statistically significant results. Highly significant ($Pr < 0.01$) correlations were determined for the $V_{zf}$ values between Irrigations 2 and 3, 3 and 4, and 4 and 5. These results support previous studies that showed that well-defined patterns emerged after the first irrigation, likely due to soil consolidation (Childs et al. 1993). Limited cultural practices were reported for the Benson furrows during the irrigation seasons. The results also suggest that similarities in infiltration patterns between consecutive irrigations were due to porous media flow, which, as was previously indicated, overshadowed the advance-phase infiltration. The systematic variation in applied inflow rate could also help explain the strong correlation between consecutive events. Childs et al. (1993) examined infiltration volumes measured in furrow sections and reported that the correlation between

### Table 4. Multiple linear regression results for $V_{zadv}$ (m$^3$)

| Predictor   | Estimate | Standard error | Pr($>|t|)$ |
|-------------|----------|----------------|-----------|
| Intercept   | 28.33    | 1.97           | <0.001$^a$|
| Irr2        | 0.26     | 2.79           | 0.927     |
| Irr3        | 4.57     | 2.79           | 0.114     |
| Irr4        | -19.33   | 2.79           | <0.001$^a$|
| Irr5        | -6.41    | 2.79           | 0.030$^b$ |

Note: Multiple $R^2$: 0.78; adjusted $R^2$: 0.75.

$^a$Statistical significance: 0.001 level.

$^b$Statistical significance: 0.05 level.

### Table 5. Multiple linear regression results for $V_{ziot}$ (m$^3$)

| Predictor   | Estimate | Standard error | Pr($>|t|)$ |
|-------------|----------|----------------|-----------|
| Intercept   | 20.19    | 3              | <0.001$^a$|
| $Q_{in}$ (L/s) | 11.15   | 1.71           | <0.001$^a$|
| Irr2        | 0.10     | 2.76           | 0.97      |
| Irr3        | 0.98     | 2.74           | 0.72      |
| Irr4        | -14.96   | 2.74           | <0.001$^a$|
| Irr5        | -6.08    | 2.74           | 0.04$^b$  |

Note: Multiple $R^2$: 0.81; adjusted $R^2$: 0.77.

$^a$Statistical significance: 0.001 level.

$^b$Statistical significance: 0.05 level.

### Table 6. Multiple linear regression results for $V_{zf}$ (m$^3$)

| Predictor   | Estimate | Standard error | Pr($>|t|)$ |
|-------------|----------|----------------|-----------|
| Intercept   | 24.09    | 5.90           | <0.001$^a$|
| $Q_{in}$ (L/s) | 18.66   | 2.45           | <0.001$^a$|
| Irr2        | -6.27    | 3.95           | 0.13      |
| Irr3        | -8.43    | 3.91           | 0.04$^b$  |
| Irr4        | -24.35   | 3.91           | <0.001$^a$|
| Irr5        | -10.79   | 3.91           | 0.01$^b$  |

Note: Multiple $R^2$: 0.83; adjusted $R^2$: 0.80.

$^a$Statistical significance: 0.001 level.

$^b$Statistical significance: 0.05 level.

### Table 7. Pearson correlation for infiltration volumes between consecutive irrigations

<table>
<thead>
<tr>
<th>Irrigations</th>
<th>$V_{zadv}$</th>
<th>$V_{ziot}$</th>
<th>$V_{zf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irr 1–2</td>
<td>0.31</td>
<td>0.73</td>
<td>0.71</td>
</tr>
<tr>
<td>Irr 2–3</td>
<td>-0.66</td>
<td>0.84$^a$</td>
<td>0.96$^b$</td>
</tr>
<tr>
<td>Irr 3–4</td>
<td>0.26</td>
<td>0.75</td>
<td>0.94$^b$</td>
</tr>
<tr>
<td>Irr 4–5</td>
<td>0.69</td>
<td>0.8</td>
<td>0.96$^b$</td>
</tr>
</tbody>
</table>

$^a$Statistical significance: 0.05 level.

$^b$Statistical significance: 0.01 level.
irrigation events strengthened as the irrigation season evolved. They attributed the changes in correlation to the presence of cracks and cultural practices during earlier irrigations.

Estimated Parameters

The first step of the estimation procedure was the most difficult, because it involved four infiltration parameters and one roughness parameter. The estimated parameters of the modified Kostiakov Eq. (11) are unimportant for purposes of this study, but it is worth noting that $k$ and $c$ were significantly correlated with $V_{z_{adv}}$ while $b$ was correlated with $V_{zf}$. Pearson correlation coefficients of, respectively, 0.43, 0.74, and 0.75 were computed for each of these variables. The fitting of the Manning $n$ also merits some comment. The fitting involves comparing predicted and measured depth hydrographs. The difficulty of this approach, at least for this particular data set, is that because the measured flows depths were generally very shallow (generally less than 4 cm deep at the inlet), small measurement errors translate into large data scatter. More data is available for the initial irrigations, and the data collected later exhibits more scatter. As a result, Manning $n$ estimates cannot be considered very precise and variations in these values among furrows are difficult to explain. Still, the results suggest that the furrows were smoother during the earlier irrigations than during the latter irrigations (Fig. 7). Hydraulic resistance can increase during the irrigation season as a result of the accumulation of dry plant material on the soil surface. The computed $n$ values were always less than the value typically recommended for bare furrows ($n = 0.04$).

Fitting the WGA model parameters was easier than the first step of the estimation process, because there were only two parameters to consider. In addition, and more importantly, while matching the predicted infiltrated volumes to the values computed from volume balance data, the effect of each parameter was easily discernible; infiltrated volumes during advance were strongly dependent on the parameter $c_{GA}$, while postadvance results mostly depended on $K_s$.

Several metrics are available to assess the goodness-of-fit of the estimated parameters and, consequently, the ability of the WGA equation to represent infiltration under the given field conditions. One metric is the objective function [OF—Eq. (8)], that is, the sums-of-squares resulting from estimation with the modified Kostiakov model compared to values computed with the WGA model. While the OF values were of similar magnitude, smaller values were computed with the latter equation for 29 of the 30 evaluation data sets. Thus, at least for this data set, the WGA equation provided an improvement over the empirical infiltration model. A second metric is the root-mean-square error (RMSE) (the square root of the sums-of-squares divided by the number of observations) expressed as a percent of the applied volume $V_{in}$. This value was only 1.3% for the event with the largest RMSE, while the average value from all 30 evaluations was 0.5%. These values attest to the quality of the field data. Last, for each test, recession times were measured at a limited number of locations. A comparison of the simulated recession times with the measured values, which were not used for estimation, provided an independent verification of the estimated infiltration and resistance parameters. The RMSE of the recession times was computed for each test using the estimated modified Kostiakov and WGA infiltration functions. On average, those values were 7.8 and 4.7 min, respectively. The improved recession predictions were likely related to the diminishing wetted perimeter during recession, which reduced infiltration and slightly increased recession times.

Fig. 8 displays the estimated infiltration parameters $K_s$ and $c_{GA}$. Note that the estimated hydraulic conductivities, which range from 0.28–0.98 cm/h, are consistent with values reported in the literature for a clay loam soil (Rawls et al. 1983; Saxton and Rawls 2006). Since macropore flow appears to be substantial for the Benson furrows, and those effects manifest themselves during advance, it is not surprising that the pattern of variation for $c_{GA}$ values exhibited strong similarities to that of $V_{z_{adv}}$, while the corresponding pattern for the hydraulic conductivity resembled the pattern for $V_{zf}$. Pearson correlation coefficients were computed between $K_s$ and $V_{zf}$ and between $c_{GA}$ and $V_{z_{adv}}$. Strong and statistically significant values were computed in both cases—0.92 and 0.86, respectively.

Of note in Fig. 8(a) is the $K_s$ computed for the first irrigation for Furrow 5 in Group 1. This result is consistent with the large $V_{z_{sto}}$ computed for the same furrow (Fig. 5). However, the difference between $K_s$ values computed for other irrigations for the same furrow seems proportionally larger than the difference for the $V_{z_{sto}}$ values. Thus, this result could be an artifact of the estimation process.

Fig. 7. Estimated Manning $n$ values for each furrow and irrigation.

Fig. 8. Estimated: (a) hydraulic conductivity; and (b) macropore constants for each furrow and irrigation.
Table 8. Statistical summary for hydraulic conductivity and macropore constant for each furrow

<table>
<thead>
<tr>
<th>Group and Furrow</th>
<th>$K_s$ (cm/h) Mean</th>
<th>COV (%)</th>
<th>$c_{GA}$ (cm) Mean</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1F1</td>
<td>0.43</td>
<td>19</td>
<td>1.34</td>
<td>56</td>
</tr>
<tr>
<td>G1F3</td>
<td>0.62</td>
<td>18</td>
<td>1.25</td>
<td>59</td>
</tr>
<tr>
<td>G1F5</td>
<td>0.63</td>
<td>33</td>
<td>1.07</td>
<td>63</td>
</tr>
<tr>
<td>G2F1</td>
<td>0.35</td>
<td>17</td>
<td>1.15</td>
<td>49</td>
</tr>
<tr>
<td>G2F3</td>
<td>0.39</td>
<td>7</td>
<td>1.10</td>
<td>47</td>
</tr>
<tr>
<td>G2F5</td>
<td>0.46</td>
<td>9</td>
<td>1.00</td>
<td>46</td>
</tr>
<tr>
<td>Average</td>
<td>0.48</td>
<td>—</td>
<td>1.15</td>
<td>—</td>
</tr>
</tbody>
</table>

procedure. With the exception of the first irrigation, $c_{GA}$ varied systematically from one irrigation to the next [Fig. 8(b)]. Summary statistics calculated for each furrow (Table 8) show that, on average, $K_s$ and $c_{GA}$ values were greater for the furrows in Group 1 than for the furrows in Group 2. This could be the result of textural differences, inflow rate, or both. Clearly, $c_{GA}$ was more variable than $K_s$ throughout the irrigation season, as shown by the COV values.

As noted previously, $K_s$ and $V_{25}$ values were strongly correlated. A problem with the $K_s$ values is that they were also strongly correlated with $Q_{in}$. The reasons for this correlation are not clear. One explanation is that, because inflow rates varied systematically among furrows, it is possible that inflow rates were determined based on known differences in infiltration rates among furrows. Another possible explanation is that, under the soil conditions of these tests, lower inflow rates and flow velocities caused greater deposition of sediments and reduced infiltration rates.

The aforementioned WGA parameters were estimated using pedotransfer function–derived values for $\theta_s$ and $h_f$. The potential range of variation for $h_f$ can be expected to be greater than that for $\theta_s$, and the results can be expected to be most sensitive to that parameter. Limited sensitivity tests were conducted with the available data, by varying $h_f$ by ±25%. In principle, estimates of $c_{GA}$ depend on crack/macropore flow and are unrelated to $h_f$. However, $h_f$ could change the amount of water attributed to porous media flow during the early infiltration stages and, therefore, change $c_{GA}$. For these tests, $c_{GA}$ estimates were not affected, which attests to the relative magnitude of macropore flow infiltration at short opportunity times. In contrast, $K_s$ estimates were affected; there was a 17% reduction in $K_s$ when $h_f$ was set to −55.3 cm, and a 25% increase when $h_f$ was set to −32.3 cm. Hence, imprecise values of $h_f$ have a substantial effect on hydraulic conductivity estimates, and the effect is inversely proportional, or nearly so. Imprecise $h_f$ values, however, should not affect the variance of $K_s$ estimates.

**Wetted Perimeter Effects on Infiltration**

Fig. 9 depicts the furrow infiltration rates as a function of the inflow rate measured close to cutoff time. The data exhibited substantial scatter, especially those from Irrigation 1. Some of the scatter may be attributable to nonsteady state conditions. Nevertheless, the results support the premise that infiltration rate increases with inflow rate, presumably due to a larger wetted perimeter. The equation of the linear regression model, shown in the graph, was statistically significant. The expectation was that this relationship and the theoretical one would share similar slopes.

The simulation analysis produced a well-defined linear relationship between $Q_{in}$ and $Q_{irr}$. However, the slope of the resulting linear regression model was less than a fifth of that derived from the measured data, $Q_{irr} = 0.99 + 0.072Q_{in}$. Consequently, these results also support the hypothesis that larger inflow rates and, therefore, larger flow velocities, enhance infiltration rates.

**Implications for Irrigation System Management and Performance Assessment**

Infiltration functions were computed from the estimated WGA parameters. Plots of these functions (Fig. 10) help to further understand the spatial and seasonal variations in intake characteristics for these furrows. The curves were computed for a common flow rate, roughness coefficient, and furrow cross section to eliminate the effect of variable flow conditions among the tests. The results suggest again that the furrows in Group 1 had higher infiltration rates than those in Group 2, even though this factor was eliminated as a predictor by the statistical analysis. The results also show that infiltration rates declined as the irrigation season progressed, except between Irrigations 4 and 5. Again, the short interval between Irrigations 3 and 4 may explain why the lowest infiltration rates are associated, mostly, with Irrigation 4. Note also that the functions developed for Irrigation 1 generally predicted larger infiltration rates than for other events. The exceptions were Furrow 5 in Group 2, for which irrigation 1 produced the lowest infiltration rates, and Furrow 3, Group 2, for which irrigation 3 produced the largest infiltration rates. Infiltration characteristics tend to be most variable early in the irrigation season due to differences in soil consolidation, and this may be a factor that can account for these results. Because this was also the first evaluation of the irrigation season, it is also possible that the results could have been affected by measurement errors.

When conducting a hydraulic analysis of an irrigation system, a key consideration is the opportunity time needed to infiltrate the irrigation requirement depth. The infiltrated depth for the Benson irrigations was generally around 6 cm. The plots in Fig. 10 provide a measure of how infiltration variability complicates the design and management of furrow irrigation systems. For a 6-cm irrigation requirement, the required opportunity time varies between about 5 and 17 h. This variation is largely the result of small differences in the values of $K_s$, which, as was noted previously, seem to vary consistently for most furrows from one irrigation event to the next.

Despite the large variability, this information can be used to improve the operation of the irrigation system, as will be demonstrated subsequently. An operational strategy (inflow rate and cutoff time) was developed for the Benson furrows based on the 6-cm irrigation requirement. This analysis assumed that infiltration was described by the overall average $K_s$ and $c_{GA}$ parameters. The solution $Q_{in} = 1.5$ L/s and $t_{co} = 960$ was found by trial and error. This solution yields a predicted application efficiency (AE) (the ratio of the volume of infiltrated water stored in the root zone to
the volume applied) of 66% and a requirement efficiency (RE) (the ratio of the volume of infiltrated water stored in the root zone to the volume required to refill the root zone) of 100%. With this operational strategy, nearly half of the losses occur by deep percolation and the rest occur by runoff. In the event that infiltration rates are less than or greater than the rates specified in the analysis, the proposed solution provides some insurance that water will reach the end of the field and that the irrigation requirement will be satisfied for most furrows.

The aforementioned solution was applied to the evaluated furrows using their individually estimated infiltration and resistance parameters. The objective of these simulations was to determine the distribution of AE and RE values, under the assumption that the estimated parameters represent the distribution of infiltration and hydraulic resistance conditions for the field. The average AE from these simulations was 64% with a COV of 6.3%. If the application volume is fixed (by the selected \( Q_{in} \) and \( t_{co} \) values), then the actual AE can only decline with respect to the design value. RE was better than 95% in 77% of the furrows. Advance failed to reach the end of the field in 10% of the furrows; in one of those cases the resulting RE was 74%, while the other two were better than 90%. Other cases of relatively low RE (85%–95%) were furrows with a low infiltration rate (mostly Irrigation 4), where all water losses were as runoff. The average RE was 97% with a COV of 6.3%. These results can help an irrigator understand differences in performance across an irrigated field, assuming a uniform inflow to all furrows.

Another motivation for using a porous-media flow–based infiltration equation in furrow irrigation modeling is to account for wetted perimeter effects. The labels G and F refer to group and furrow numbers, respectively.

**Fig. 10.** Estimated WGA infiltration functions computed for each furrow and irrigation using a common inflow rate (2 L/s) and Manning \( n \) (0.016).

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Discussion and Conclusions

The spatial and temporal variability of infiltration in furrow-irrigated fields can be substantial, even when measured on the scale of complete furrows. Several factors that contribute to this variability were examined in this study.

For the particular field conditions, the structure of infiltration variability was different for infiltration measured at the end of the advance phase than for infiltration measured at later times, during the postadvance phase. As demonstrated by the results of Irrigation 4, the volume of water needed to reach the end of the field can vary substantially from one irrigation event to the next. Furthermore, inflow rate differences among furrows had no measurable effect on infiltration variations during advance for any irrigation event. This suggests that the infiltration process was dominated at short opportunity times by crack and/or macropore flow and that the contribution of other factors to infiltration variability was relatively negligible.
A premise of this study was that inflow rate variation contributes to infiltration variability through its effect on wetted perimeter and infiltrating area. This effect may be difficult to establish due to the influence of other factors. Variation in inflow rate among furrows affects advance times and, consequently, the time available for water to infiltrate during the storage phase. The results suggest that furrow infiltration rates increase with inflow rate but not in proportion to changes in wetted perimeter. As indicated previously, it is possible that furrow infiltration rates may be enhanced by larger inflows and flow velocities by preventing sediment deposition. The results also suggest differences in the porous media characteristics of furrows and that these characteristics vary systematically between irrigations, primarily due to soil consolidation and changes in water content.

The proposed WGA equation in combination with the macropore infiltration component modeled furrow infiltration reasonably well and produced smaller values for the estimation objective function than an empirical infiltration equation for the range of soil and hydraulic conditions examined here. While the concept of a volume of water that infiltrates instantaneously seems overly simplistic, such an approach appears to be a practical way of representing the infiltration flow at short times. One potential way to improve the model is to limit macropore infiltration to the available flow rate at a particular location and time, as determined by an unsteady irrigation simulation model.

The estimation procedure produced coherent results for the infiltration and roughness parameters. Hence, as shown by the results in Fig. 8, those parameters show some spatial and temporal structure. Hydraulic conductivity findings were found to be strongly correlated with \( V_{zf} \) and the values for the macropore constant were correlated to \( V_{cadv} \). The estimated \( K_s \) values were of similar magnitude to values reported in the literature. Differences between \( K_s \) values computed for different furrows tended to vary systematically during the season, and those values mostly displayed gradual changes for each furrow during the irrigation season. The macroporosity parameter \( c_{GA} \) exhibited greater variation than \( K_s \), but mostly between irrigation events and less between furrows for an irrigation event.

This analysis assumes that the macropore term is a function of furrow spacing and that water does not flow between neighboring furrows. The fact that \( c_{GA} \) was relatively consistent for an irrigation event suggests that this assumption is largely true. However, the analysis also assumes that water that infiltrates through macropores does not flow past the root zone. Bypass flow is a mechanism that needs to be studied in order to better understand the ultimate irrigation distribution uniformity.

### Notation

The following symbols are used in this paper:

- **AE** = application efficiency (%);  
- \( A_0 \) = upstream cross-sectional area;  
- \( A_c \) = infiltration volume per unit length;  
- \( c_{GA} \) = WGA empirical macropore term;  
- \( DUlg \) = distribution uniformity of the low quarter;  
- **FS** = furrow spacing;  
- \( h_{1D} \) = wetted-perimeter averaged ponding depth;  
- \( h_f \) = pressure head at the wetting front;  
- \( K_s \) = saturated hydraulic conductivity;  
- \( k, a, b, c \) = parameters of the empirical modified Kostiakov formula for infiltration volume per unit area;  
- \( n \) = Manning roughness coefficient;  
- \( Q_{in} \) = furrow inflow rate;  
- \( Q_s \) = furrow infiltration rate;  
- **RE** = requirement efficiency (%);  
- **RMSE** = root-mean-square error;  
- \( S_0 \) = soil sorptivity;  
- **SD** = standard deviation;  
- **SSQ** = sums of squares;  
- \( T_{adv} \) = advance time;  
- \( V_{in} \) = inflow volume;  
- \( V_{req} \) = irrigation requirement volume;  
- \( V_{ro} \) = runoff volume;  
- \( V_s \) = surface volume;  
- \( V_I \) = infiltration volume;  
- \( V_{cadv} \) = infiltration volume at the end of the advance phase;  
- \( V_{zf} \) = infiltration volumes as determined at the final volume balance calculation time, as determined by the particular data;  
- \( V_{zfin} \) = infiltration volume computed for a specified furrow-averaged intake opportunity time;  
- **W** = transverse width;  
- **WP** = wetted perimeter;  
- \( x_s \) = length of the stream at a given time;  
- \( y_0 \) = flow depth;  
- \( z \) = one-dimensional infiltration volume per unit area;  
- \( z_0 \) = infiltration at time \( t_0 \);  
- \( \gamma \) = empirical parameter related to boundary conditions, geometry, and initial conditions;  
- \( \Delta t \) = difference between the saturated and initial water content;  
- \( \Delta h \) = difference between the average water pressure at the infiltrating surface \( h_{1D} \) and the wetting front pressure head \( h_f \);  
- \( \epsilon \) = random error in a multivariable regression analysis;  
- \( \theta_0, \theta_s \) = initial and saturated volumetric water content; and  
- \( \sigma \) = dimensionless shape parameter for the surface flow.

### References


