Title
Furrow Irrigation Model Development and Evaluation

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Technical Completion Report

by

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ABSTRACT

Spatially-varying infiltration, geometry, and roughness along with spatially- and temporally-varying wetted perimeter effects on furrow advance and application uniformity were investigated. Extensive field-gathered infiltration, geometry, roughness, and advance/recession data was collected and used to calibrate and validate the simulation model.

Model simulation was done for both a single furrow as well as on a field-wide basis. Variable furrow inflow was incorporated into the field-wide analysis. Model simulations were evaluated to determine the importance to irrigation performance of each spatially-varying model input. Flow rate, infiltration function variability, furrow geometry and furrow roughness influence irrigation performance in decreasing order of importance.

I. INTRODUCTION

Irrigated agriculture in the western United States is dominated by surface irrigation systems. In California, for example, 70 percent of the state's 10 million irrigated acres are irrigated by surface (furrow or border) irrigation systems. The remaining acreage is irrigated by pressurized system such as sprinklers (25%) and drip/trickle (5%). With 85 percent of California's water use occurring in the agricultural sector, it is evident that a very substantial amount of water is being distributed by surface irrigation systems.

While we are living in a high-tech world today, surface irrigation systems and their operation have changed little over the past decades. Siphon tubes and open ditches still account for approximately 75 percent of the surface irrigation systems. Because of its lack of complicated hardware, surface irrigation systems are often assumed to be the simplest of irrigation systems. In fact, to do an efficient and uniform job of irrigating with a surface system requires substantially more knowledge and water management skill than is required for operation of pressurized systems. This requirement stems from the use of the soil as the transfer medium for moving water to various field locations. Pressurized systems use pipelines or drip tubing to facilitate this transfer.

Using the soil to transport irrigation water results in different amounts of water infiltrating throughout the field (non-uniformity). This is due to both time differences water is in contact with the soil (intake opportunity time) and differences in the field's infiltration characteristics (spatial variability of infiltration). Unlike well-designed pressurized irrigation systems, surface systems apply water at a rate equal to or greater than the soil's intake rate; thereby making the spatial variability of infiltration characteristics a major source of application non-uniformity.

To provide a management tool to improve the operation of surface irrigation systems, surface irrigation simulation models have been developed. These simulation models have been based on a variety of hydraulic principles, but almost all have determined application uniformity based solely on differences in intake opportunity time throughout a field.

The major objective of this work is to incorporate spatial variability of field characteristics in furrow irrigation simulation modeling. These field characteristics include infiltration, furrow geometry, and furrow roughness. Furrow inflow rate, while not a field characteristic, is variable across the field and is investigated.

The work falls into two stages: (1) the development and verification of a furrow simulation model capable of incorporating variable input parameters, and (2) investigation of the impacts on irrigation performance of incorporating spatial variability into the model simulation. As part of the simulation model development, ease of future use by field practitioners is of major importance.

II. COMPUTER MODEL AND FIELD STUDY

A zero-inertia computer model written and run with Microsoft QuickBasic was developed to operate on an IBM-compatible personal computer. One of the objectives of this work was to develop a user-friendly model so effort was taken to allow ease of model input data and useful model output.

Screen Graphics

Screen graphics of depth of flow, infiltrated water, and water advance along the furrow are displayed while the simulation model is operating. The series of photographs in Fig. II-1 are black-and-white representations of this display. On a color monitor, the screen graphics are more striking. The tick marks along the vertical axis each represent increments of 5 cm flow depth or infiltrated depth. Tick marks along the horizontal axis represent 5 meter increments of distance along the furrow.

Model Input, Code, and Output

Model inputs required include:

(1) Furrow inflow,

(2) Length of furrow,

(3) Furrow slope,

(4) Furrow roughness,

(5) Reach length,

(6) Depth/area relationship, and

(7) Wetted perimeter/area relationship.

The compiled model, with variable infiltration, geometry, and roughness at 5-meter increments, takes approximately 7 minutes to complete calculations for a 250-meter furrow. The model's memory requirements are such that it can be run in an uncompiled form on a computer with 640 k or more memory. Early, more simplified versions of the model, indicated that running the model in a compiled version decreased calculation time by a factor of 15 to 20 over uncompiled run times.

Model output includes:

(1) An echo of critical input parameters such as furrow length, furrow inflow, and furrow slope.

(2) Advance times to furrow locations at increments specified by user.

(3) Flow depth, flow area, and infiltrated depth at same locations as in (2).

Verification of the furrow simulation model incorporating spatial variability of model inputs requires both irrigation advance/recession data as well as pre- and post-irrigation soil moisture measurements. Furrow simulation model input parameters include: furrow inflow, furrow cross-sectional geometry, furrow roughness, and furrow infiltration characteristics.

Model input requirements and verification data were gathered during field testing in the summer of 1985. The field tests were done on a Yolo clay loam soil located at the LAWR Campbell Tract. This field (Fig. II-2) had been prepared with 76 cm beds for furrow irrigation and planted with sorghum. The field consisted of 100 furrows, each 300 meters long. To minimize edge effects, only 75 furrows were utilized, each being monitored for 250 meters. Advance/recession, soil moisture and infiltration measurements were made.

III. SUMMARY AND DISCUSSION

Model simulation analyses including positioning of furrow physical characteristics (infiltration, geometry, and roughness) both randomly and as field-measured; as well as both randomly-varying and constant furrow inflow are summarized in Table III-1.

The titles of the various simulation series have been abbreviated with acronyms. To assist the reader, simulation series titles along with their narrative descriptions are listed below.

The following are single, deterministic model simulations.

Q/VIC-CFR

Single model simulation in which constant furrow inflow; furrow-averaged infiltration characteristics with constant, final infiltration determined from inflow/outflow measurements; furrow-averaged geometry characteristics; and a single, furrow-averaged n-value are used.

Q/VAR VI-CFR

Single model simulation in which constant furrow inflow; spatially-varying infiltration characteristics oriented along the furrow as field-measured and constant, final infiltration determined from inflow/outflow measurements; furrow-averaged geometry characteristics; and a single, furrow-averaged n-value are used.

The following are stochastic simulation series incorporating multiple simulation runs to simulate field-wide irrigation performance.

Q/RDM VI-CFR

Constant furrow inflow; randomized spatial positioning of furrow infiltration characteristics with constant final infiltration determined from inflow/outflow measurements; furrow-averaged geometry characteristics; and a single, furrow-averaged n-value.

RDM Q/Var VI-CFR

Randomly-varying furrow inflow; spatially-varying infiltration characteristics oriented along the furrow as field-measured and constant, final infiltration determined from inflow/outflow measurements; furrow-averaged geometry characteristics; and a single, furrow-averaged n-value.

RDM Q/VIC-CFR

Randomly-varying furrow inflow; furrow-averaged infiltration characteristics with constant, final infiltration determined from inflow/outflow measurements; furrow-averaged geometry characteristics; and a single, furrow-averaged n-value.

Q/RDM VI-CFR/RDM Geo/n

Constant furrow inflow; randomized spatial positioning of furrow infiltration characteristics with constant final infiltration determined from inflow/outflow measurements; randomly-varying geometry characteristics linked spatially to infiltration characteristics; and a single furrow-averaged n-value.

RDM Q/RDM VI-CFR/RDM Geo/n

Randomly-varying furrow inflow; randomized spatial positioning of furrow infiltration characteristics with constant final infiltration determined from inflow/outflow measurements; randomly-varying geometry characteristics linked spatially to infiltration characteristics; and a single furrow-averaged n-value.

Q/RDM VI-CFR/RDM Geo/RDM n

Constant furrow inflow; randomized spatial positioning of furrow infiltration characteristics with constant final infiltration determined from inflow/outflow measurements; randomly-varying geometry characteristics linked spatially to infiltration characteristics; and randomly-varying furrow roughness characteristics linked spatially to infiltration and geometry characteristics.

It is difficult to rank the importance of furrow characteristics (inflow, infiltration, geometry, and roughness) as to their relative impact on irrigation performance. Difficulty arises due to both interaction of furrow physical characteristics and uncertainty as to which irrigation performance criteria best measures impact.

Furrow inflow has the most substantial effect on irrigation performance. Furrow inflow variability affects variability (σ and CV) and range of average infiltration $\text{infil}_{\text{avg}}$. It also substantially impacts the rang eof furrow CU and DU predictions. Furrow inflow variability also had substantial impact on the range of predicted EOF advance times.

Furrow infiltration variability is next in relative impact on irrigation performance. Infiltration variability increases variability of water applied (σ and CV) of $\text{infil}_{\text{avg}}$. Comparing RDM Q/VIC-CFR (randomized furrow inflow/single, furrow-averaged infiltration function) and RDM Q/VIC-CFR (randomized furrow inflow/variable infiltration characteristics, spatially-oriented as field-measured) results in a decrease in predicted CU and DU for the RDM Q/Var VI-CFR simulations. Not accounting for spatially-varying infiltration characteristics resulted in over-prediction of irrigation uniformity (CU and DU).

Including randomizing infiltration characteristics in model simulations reduces variability (σ and CV) and range of $\text{infil}_{\text{avg}}$. It results in an increase in CU and DU average values and a decrease in range of CU and DU predictions. Minimal changes in end-of-field advance time predictions result from including randomized infiltration characteristics in model simulations. The interaction between randomized furrow inflow and randomized infiltration characteristics (RDM Q/RDM VI-CFR) appears to average out a portion of the variability evident in the RDM Q/Var VI-CFR simulations.

Furrow geometry variability is third in relative importance of the model simulation inputs (inflow, infiltration, geometry, and roughness) investigated. Variability (σ and CV) of $\text{infil}_{\text{avg}}$ is decreased when randomized geometry is added to model simulations. Little change in average value of CU and DU results from incorporation of randomized geometry, but there is some resulting decrease in range of CU and DU values. Randomized geometry appears to have an impact on end-of-field advance time, but the results do not indicate a consistent pattern.

Variability in **furrow roughness** had the least impact on simulated irrigation performance of the four furrow physical characteristics investigated. None of the four irrigation performance measures ($\text{infil}_{\text{avg}}$, CU, DU, nor EOF advance times) was substantially impacted by adding randomized roughness to the simulation model.

Comparisons in the previous sections have been among simulation series utilizing randomized furrow inflow, randomized infiltration characteristics, randomized furrow geometry, or randomized furrow roughness; and series utilizing comparable furrow-averaged values of furrow inflow, infiltration, geometry, or roughness. It is important to note that the furrow-averaged values were accurate average approximations. For example, the average characterizations used for furrow infiltration and geometry were the average of 51 values (5-meter increments) along a 250-meter furrow. These same 51 values of infiltration or geometry were used in the simulations incorporating variable infiltration/geometry.

Field gathering of furrow simulation model input parameters (inflow, infiltration, geometry, and roughness) is limited by time and economic constraints. This may detrimentally impact simulation model predictions unless appropriate average input parameter values are determined. An example may best illustrate this point.

An extreme but not unlikely case, is for only a single infiltration test to be performed along a furrow and the resulting infiltration function generalized to describe the entire furrow. To illustrate the possible impact of such a procedure on irrigation performance, three simulations were run and results summarized in Table III-2. The simulations all had common furrow inflow, furrow geometry, and furrow roughness values; differing only in their furrow infiltration characteristics. The three infiltration characteristics used were: (1) furrow infiltration characteristics determined by averaging 51 field measurements and assuming the resulting infiltration function applied to all points along the furrow ("average infiltration simulation"), (2) a single, field-measured furrow infiltration function of the 51 measured with the slowest intake characteristics was assumed to describe the entire length of furrow ("low infiltration simulation"), (3) the field-measured furrow infiltration function of the 51 measured, with the highest intake characteristics was assumed to describe the entire length of furrow ("high infiltration simulation"). The low or high infiltration characteristics would be analogous to a single, field infiltration test being taken at the furrow site with extreme high/low infiltration characteristics.

It is evident from Table III-2 that choice of infiltration function to characterize infiltration in a furrow simulation model is critical due to its effects on both volume infiltrated and application uniformity (CU and DU). End-of-field (EOF) advance time is also substantially affected by choice of infiltration characterization (Table III-2), but EOF advance time is an unreliable indicator of infiltration characterization quality since it is highly dependent on choice of furrow roughness (n-value). Furrow roughness is very difficult to quantify or measure and has frequently been used as the calibration parameter of furrow simulation modeling. An accepted procedure has been to estimate or measure furrow simulation inputs - furrow inflow, infiltration, geometry, and roughness. The model-predicted water advance trajectory is compared to field observations. If agreement is unsatisfactory, roughness values are adjusted until acceptable agreement is reached. Thus, infiltration or geometry characterization could be inaccurate but "corrected for" through adjustment of the n-value. The final n-value is checked for its reasonableness based on ranges of recommended n-values.

As has been shown in previous sections, agreement between predicted and measured water advance trajectories does not guarantee that the simulation model will adequately predict infiltrated volume.

The relative ranking of importance of incorporating furrow physical characteristics in furrow simulation modeling is dependent on variability of model input parameters. The analysis has been done for a field with relatively uniform physical characteristics. Furrow infiltration, geometry, and roughness were relatively uniform in comparison to many field conditions. The relative ranking between furrow inflow, infiltration, geometry, and roughness may change if field characteristics are more variable. For example, it may be that for a field which has highly variable soil and infiltration conditions, spatially-varying infiltration may have greater impact on irrigation performance than does variable furrow inflow.

In summary, variability of furrow physical characteristics, in decreasing order of their relative impact on furrow irrigation performance, are: furrow inflow, furrow infiltration characteristics, furrow geometry, and furrow roughness. This comparison addresses the effects of field-wide spatial variability of furrow physical characteristics versus furrow-averaged physical characteristics.

IV. CONCLUSIONS

Evaluation of furrow irrigated fields has historically been based on analysis of a single furrow described by spatially-uniform furrow characterization. The results of the analysis have then been used to describe the entire field. This work has investigated, through field-calibrated furrow model simulation, the impact of spatial variability of furrow inflow rate, furrow infiltration characteristics, furrow geometry, and furrow roughness on field-wide irrigation performance.

Furrow irrigation modeling, based on the St. Venant equations and utilizing the zero-inertia assumption with an approximation of the water surface slope term of the momentum equation, was done. The furrow model incorporated spatially-varying infiltration, geometry, and roughness. Model simulation was used to not only investigate the impact on single furrow irrigation performance of incorporating spatial variability, but also to examine spatial variability effects on field-wide irrigation performance. Furrow inflow rate variability was incorporated into the field-wide irrigation performance analysis.

Calibration and validation of the furrow simulation model was done utilizing extensive field data gathered on furrow infiltrated water, geometry, roughness, and water advance/recession.

Conclusions resulting from model simulation include:

(1) Variability of furrow inflow rate plays the most important single role in field-wide irrigation performance.

(2) Modeling and/or evaluation of a single representative furrow may convey an average irrigation performance measure for a field, but does not describe the variability of field-wide irrigation performance.

(3) For the field investigated, average depth infiltrated and application uniformity (CU) varied by as much as 31 percent and 17 percent, respectively, depending on which furrow was selected for evaluation. Approximately half of this variability is due to furrow physical characteristics (infiltration, geometry, and roughness) and half due to furrow inflow variability.

(4) Spatially-varying furrow infiltration and geometry characteristics may be satisfactorily incorporated into a furrow simulation model, but spatially-varying furrow roughness, due to its temporal variability, is difficult to satisfactorily characterize for the entire irrigation event. Furrow roughness characterization has not been adequately addressed even in spatially-uniform furrow modeling. Roughness has been used as a "calibration parameter" for furrow modeling. The limited work previously done on field measurement of furrow roughness was done over 20 years ago and while appearing satisfactory for the conditions under which it was done, does not lend itself to use in spatially- and temporally-varying simulation modeling.

Recommendations for future work include investigating temporal variability of furrow geometry and roughness. Measurements of pre- and post-irrigation furrow geometry and roughness have been made by this author and other researchers, but investigation into furrow physical changes occurring <u>during</u> an irrigation needs to be done in order to accurately incorporate such changes into furrow simulation modeling.

The results herein concerning relative importance of furrow physical characteristics are predicted on their variability as measured in a field considered uniform in its infiltration, geometry, and roughness characteristics. Results may vary for soils with greater variability. Future work should consider in greater depth how magnitude of furrow physical characteristics' variability impacts irrigation performance.

As a management-oriented recommendation, the impact of furrow inflow variability needs to be addressed. Variability of furrow inflow can be minimized by an irrigator's management practices. Field physical characteristics (infiltration, geometry, and roughness) are important to furrow irrigation performance, but are difficult, if not impossible, for an irrigator to modify. The irrigation performance which can be attained using a surface irrigation system is therefore constrained by field physical characteristics.

PUBLICATIONS

Schwankl, L. J. and W. W. Wallender. 1989. Zero inertia-furrow modeling with variable infiltration and hydraulic characteristics. TRANSACTIONS of the ASAE, (In press).

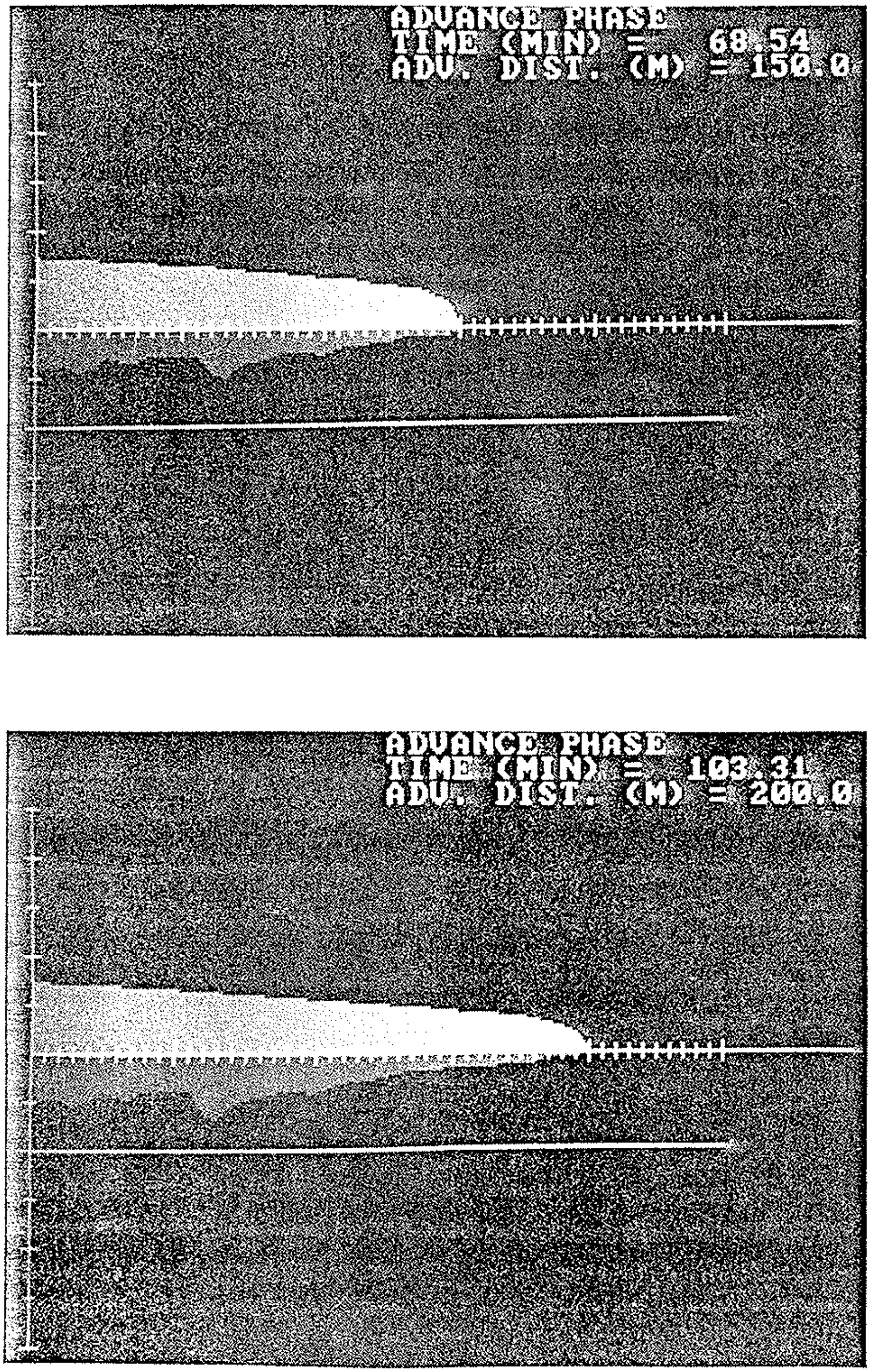
Schwankl, L. J. 1989. Stochastic furrow irrigation modeling. Dissertation in partial fulfillment of the requirements for the Doctor of Philosophy in Engineering, University of California, Davis.

Table III-1. Summary table of average, standard deviation (σ), and range (Δ) of infil$_{avg}$; average value and range of CU and DU; and range of end-of-field advance time (EOF Adv.) for the simulation series presented in the RESULTS section.

	Infil$_{avg}$				CU		DU		EOF Adv.
	Avg. (cm)	σ (cm)	CV	Δ (cm)	Avg. (%)	Δ (%)	Avg. (%)	Δ (%)	Δ (min)
Q/RDM VI-CFR	7.57	1.770	0.234	0.14	80.8	4.7	67.8	5.5	10
RDM Q/Var VI-CFR	7.55	2.105	0.279	2.46	76.1	15.1	63.0	28.7	180
RDM Q/VIC-CFR	7.35	1.611	0.219	1.89	81.7	12.0	69.5	25.9	154
RDM Q/RDM VI-CFR	7.53	1.917	0.255	2.14	78.9	11.5	65.3	22.9	185
Q/RDM VI-CFR/ RDM Geo/n	7.60	1.752	0.231	0.96	81.1	5.8	69.0	8.8	61
RDM Q/RDM VI-CFR/ RDM Geo/n	7.59	1.854	0.244	2.05	79.8	17.3	66.9	27.7	140
Q/RDM VI-CFR/ RDM Geo/RDM n	7.54	1.670	0.221	1.24	81.5	5.6	70.3	9.5	51
RDM Q/Var VI-CFR/ Var Geo/Var n	7.10	2.045	0.288	2.46	75.2	17.1	60.1	32.8	203
RDM Q/RDM VI-CFR/ RDM Geo/RDM n	7.51	1.783	0.237	2.32	81.2	13.8	68.3	27.9	143
FIELD DATA	7.47	2.577	0.345		77		64		

Table III-2. Infil_{avg}, DU, CU, and end-of-field advance time for field data and model simulations using: low intake infiltration characteristics, high intake infiltration characteristics, and furrow-averaged infiltration characteristics.

	Infil_{avg} (cm)	DU (%)	CU (%)	End-of-field Advance time (min)
Low Infiltration Simulation	6.83	85	90	86
High Infiltration Simulation	7.68	46	66	318
Average Infiltration Simulation	7.42	72	83	134
Field Data	7.47	64	77	156



ADVANCE PHASE
TIME (MIN) = 68.54
ADV. DIST. (M) = 150.0

ADVANCE PHASE
TIME (MIN) = 103.31
ADV. DIST. (M) = 200.0

Figure II-1. Screen display of simulation model.

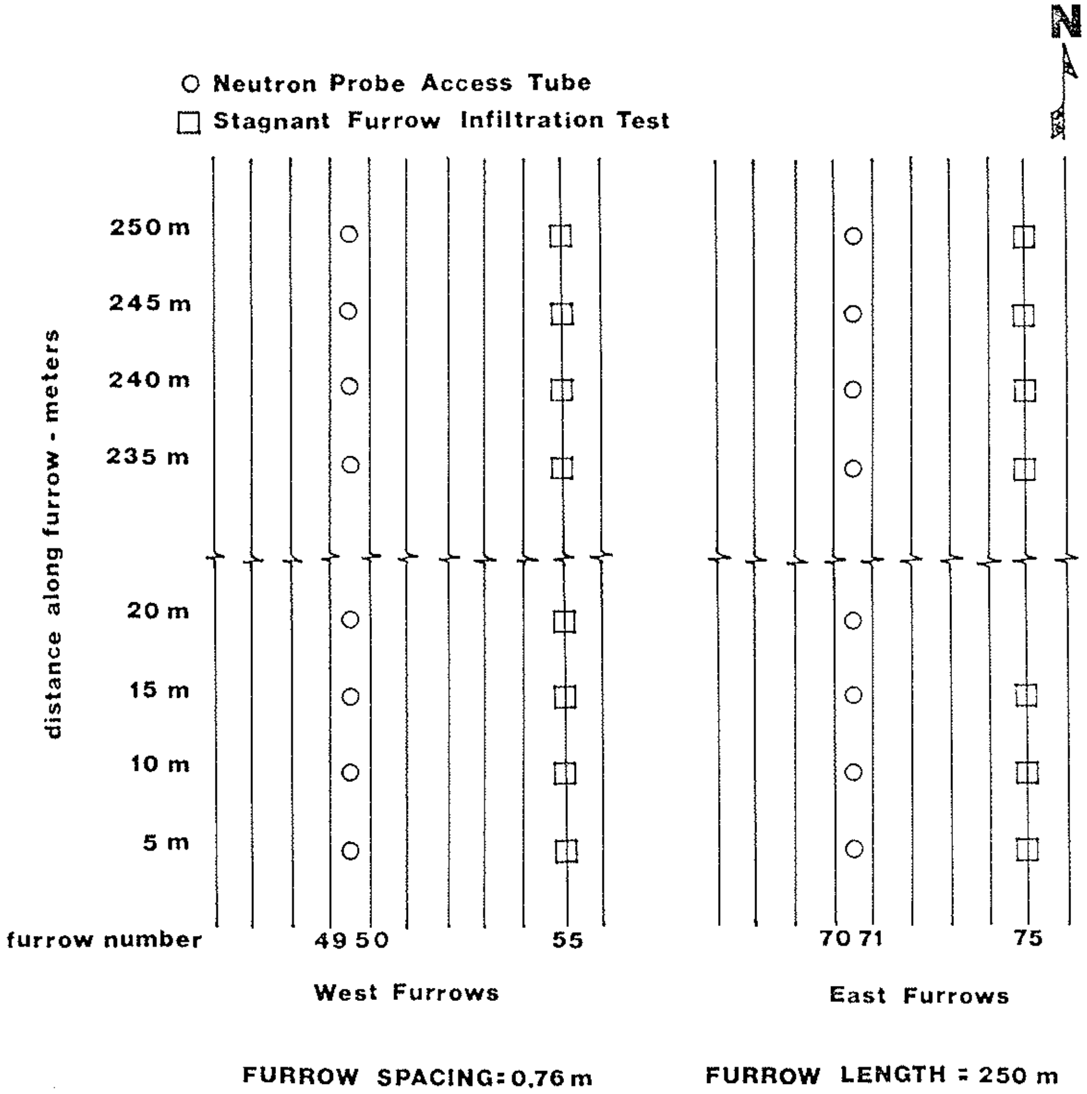


Figure II-2. Field layout identifying neutron probe access tube and infiltration test locations.

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Zero Inertia Furrow Modeling Variable Infiltration and Hydraulic Characteristics

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ABSTRACT

A zero inertia furrow irrigation model was developed to run on an IBM-compatible personal computer. The depth gradient term of the momentum equation is approximated by averaging over the wetted length of furrow, thus simplifying the simulation. Model simulation at predetermined space increments rather than at specified time increments was utilized. Spatially-varying infiltration and temporally- and spatially-varying wetted perimeter effects on furrow advance and infiltrated water distribution were investigated.

Model simulation using a combination of spatially-varying infiltration and steady infiltration determined from inflow/outflow measurements was compared to field-gathered advance and infiltration data.

INTRODUCTION

(2)

Spatial variability of infiltration characteristics, furrow geometry, and furrow roughness (Izadi and Wallender, 1985) and their impacts on irrigation performance have not been accounted for in furrow irrigation simulation modeling or furrow irrigation evaluation. In addition to spatial variability of infiltration characteristics, the influence of flow depth (and therefore wetted perimeter) on infiltration volume is a challenging and critical issue in surface irrigation hydraulic modeling. The effect of wetted perimeter on infiltration has been measured in a number of field experiments (Davis and Fry, 1963; Fangmeier and Ramsey, 1978; and Izadi and Wallender, 1985). Strelkoff and Souza (1984) investigated a number of options for characterizing the infiltration/wetted perimeter relationship. Blair and Smerdon (1987) incorporated variable wetted perimeter into a kinematic wave surge/continuous flow model. Variable wetted perimeter and spatially-varying infiltration characteristics were incorporated into a zero inertia furrow simulation model (Schwankl and Wallender, 1987). The model presented herein makes use of the assumption that furrow infiltration is the product of infiltration flux, based on the intake opportunity time, and wetted perimeter.

The purpose of this work is to incorporate infiltration as a flow depth dependent stochastic variable in a furrow simulation model and to investigate its impact on irrigation performance.

MODEL FORMULATION

The zero inertia model presented herein differs from previous models by solving the equations of momentum and mass conservation at specified space increments rather than specified time increments. When solving at specified time increments, incremental advance positions do not necessarily correspond to the location of field measurements. Field measurements of infiltration, furrow geometry and roughness, and advance and recession distances, are generally collected at fixed space increments.

Flow in furrows is shallow, unsteady, and non-uniform. The Saint-Venant Equations of continuity and momentum, respectively, for furrow irrigation are:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + \frac{\partial z}{\partial t} = 0 \quad \ldots\ldots\ldots\ldots [1]$$

$$\frac{1}{g}\frac{\partial v}{\partial t} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{\partial y}{\partial x} - (S_o - S_f + \frac{v}{Ag}\frac{\partial z}{\partial t}) = 0 \quad \ldots\ldots [2]$$

in which
Q = furrow inflow (L^3L^{-1})
x = distance along furrow (L)
z = infiltration volume per unit length (L^3/L
A = flow area (L^2)
t = time (T)
g = gravitational constant (LT^{-2})
S_o = furrow slope (L/L)
S_f = friction slope (L/L)
v = velocity of surface flow (LT^{-1})
y = flow depth (L)

Solution of these equations has followed differing approaches (Bassett et al., 1980) ranging from solving both equations in their full form (full hydrodynamic) to solving only the continuity equation in a simplified form (volume balance). Strelkoff and Katapodes (1977)

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simplify the momentum equation by assuming the inertial terms are equal to zero (zero inertia), giving:

$$\frac{\partial y}{\partial x} = S_o - S_f \quad \ldots\ldots [3]$$

Simulations from the zero inertia model are accurate under flow conditions typical of furrow irrigation.

Friction slope; S_f, following Manning's Equation is:

$$S_f = \frac{Q^2 n^2}{C^2 A^2 R^{4/3}} \quad \ldots\ldots [4]$$

where

n = dimensionless Manning's roughness factor
C = units conversion factor ($L^{1/3}T^{-1}$)
R = hydraulic radius (L)

Substituting equation [4] into equation [3] and solving for Q gives:

$$Q = \frac{CAR^{2/3}}{n}\left(S_o - \frac{\partial y}{\partial x}\right)^{1/2} \quad \ldots\ldots [5]$$

Since hydraulic radius (R) is area (A) divided by wetted perimeter (WP), equation [5] becomes:

$$Q = \frac{CA^{5/3}}{n(WP)^{2/3}}\left(S_o - \frac{\partial y}{\partial x}\right)^{1/2} \quad \ldots\ldots [6]$$

Equation [6] can be further simplified by assuming wetted perimeter is related to area as:

$$WP = \sigma_1 A^{\sigma 2} \quad \sigma_2 \quad \ldots\ldots [7]$$

Values for σ_1 and σ_2 can be determined empirically from field measurement of A and WP. Substituting equation [7] into equation [6] and simplifying results in:

$$Q = \frac{C}{n\sigma_1^{2/3}}\left(S_o - \frac{\partial y}{\partial x}\right)^{1/2} A^{5/3-(2/3)\sigma 2} \quad \sigma_2$$

$$= KA^{5/3-(2/3)\sigma 2} \quad \sigma_2 \quad \ldots\ldots [8]$$

Depth gradient, $\partial y/\partial/x$, is approximated as a linear gradient between the water surface at the inlet end of the first water-covered reach and the water surface at the advancing front or at the end of the furrow after completion of the advance phase (Jaynes, 1986). Substituting equation [8] into equation [1] results in:

$$-\frac{\partial(KA^{5/3-(2/3)\sigma 2})}{\partial x} - \frac{\partial z}{\partial t} = \frac{\partial A}{\partial t} \quad \ldots\ldots [9]$$

$$\sigma_2$$

Finite differencing equation [9] gives:

$$\frac{K_{i-1}\, A_{i-1}^{*\;5/3-(2/3)\sigma 2_i} - K_i\, A_i^{*\;5/3(2/3)\sigma 2_i}}{\Delta x_i}$$

$$\sigma_{2_i} \qquad \frac{5}{3} - \left(\frac{2}{3}\right)\sigma_{2_i}$$

$$-r_i = \frac{A_{i-1}^* + A_i^* - A_{i-1} - A_i}{2\Delta t_j} \quad \ldots\ldots [10]$$

where

r_i = volumetric infiltration rate per unit length of furrow ($L^3T^{-1}L^{-1}$) in reach i
Δx_i = length of reach i
Δt_j = current time step

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Unstarred terms represent variables at the beginning of the time step and starred terms are variables at the end of the time step.

Each reach can be successively solved for A_i^* beginning at the inlet and moving downstream. Solving equation [10] for A_i^* results in:

$$\sigma_{2_i}$$

$$A_i^* = \frac{2\Delta t_j K_{i-1} A_{i-1}^{*\;5/3-(2/3)\sigma 2_i} - 2\,V_i + \Delta x_i\,(A_{i-1} + {}^*A_i - {}^*A_{i-1})}{\Delta x_i + 2\Delta_j A_i^{*\;2/3-(2/3)\sigma 2_i}}$$

$$\Delta t_j \qquad \sigma_{2_i}$$

$$\ldots\ldots [11]$$

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where volume infiltrated (V_i) during Δt_j is the product of incremental infiltration depth (ΔD_i), space-averaged wetted perimeter per reach ($\overline{WP}_i$), and reach length (Δx_i).

$$V_i\,|_{\Delta t_j} = \Delta D_i * \overline{WP}_i * \Delta x_i \quad \ldots\ldots [12]$$

Before continuing the development of equation [11], infiltration is discussed. Early in an irrigation, infiltrating water moves into the soil in the vertical direction due to capillary and gravitational forces and in the lateral direction due to capillary forces only. Later in the irrigation, lateral movement of infiltrating water decreases due to reduced capillary forces resulting from laterally-moving water of adjacent furrows. However, Strelkoff and Souza (1984) assumed this was insignificant and concluded that either wetted perimeter or flow top width could be used to characterize furrow infiltration.

In this model, infiltration depth at location i was calculated using the modified Kostiakov equation:

$$D_i = k_i \tau^{a_i} + f_o \tau \quad \ldots\ldots [13]$$

where

D_i = infiltration depth (L)
k_i = empirical fitting parameter (LT^{-a})
a_i = empirical fitting parameter (dimensionless)
f_o = empirical fitting parameter (L/T)
τ = intake opportunity time (T)

Infiltration depth during the initial stage of the irrigation was approximated by dividing infiltration volume, measured in stagnant, blocked furrow infiltration tests, by section length and by wetted perimeter. A uniform infiltration flux across the wetted perimeter was assumed even though lateral movement decreases faster than vertical movement. Infiltration later in the irrigation was calculated as the difference in measured furrow inflow and outflow divided by furrow length after outflow was steady. Steady rate infiltration at a location was assumed, based on results of field infiltration tests, to occur after 90 min of intake opportunity time. In doing this, a homogeneous, not stochastic, final infiltration rate was assumed for the furrow. This methodology was more appropriate than determining the final infiltration rate from the stagnant furrow infiltration tests since in these tests adjacent furrows were not buffered and excess lateral water movement would inflate infiltrated volume. In addition, determining final infiltration rate from inflow/outflow measurements allows the determination to be made in the furrow being monitored for infiltration and advance/recession. This is not possible with infiltration tests due to their "destructive" nature (Bali and Wallender, 1987).

⑦

Returning to equation [11], flow area (A_i^*) cannot be solved for explicitly since infiltration (V_i) is area dependent. Infiltration is calculated using a trial flow area (wetted perimeter) from which an updated flow area is determined in equation [11]. Model results agree well with field data when iteration continues until the difference between assumed and updated flow area at a location is less than 0.00001 m².

Equation [11] is applicable where flow is in the downstream direction only. This is not a limitation under sloping furrow conditions with free outflow, which is the condition frequently encountered. Downstream boundary effects, such as blocked ends, cannot be modeled.

During the advance phase, the downstream boundary condition is $A_i^* = 0$ and equation [11] becomes:

σ_{z_i}

$$\Delta x_m = \frac{2\,\Delta t_m\, K_{m-1}\, A_{m-1}^{*\,5/3-(2/3)\sigma 2_j}}{A_{m-1}^{*} + 2\Delta t_m\, r_m} \qquad \ldots\ldots\ldots [14]$$

where

m = subscript indicating the downstream-most reach during advance

Examining equation [14], the time to advance a predetermined furrow distance, Δt_m is unknown. In addition, since furrow infiltration depends on intake opportunity time, the time step influences V_i, and therefore A_i^* at each location along the furrow (equation [11]). Solution complexity increases rapidly as the number of furrow reaches increases. In summary, advance time across each reach is solved indirectly by iteration using the Newton-Raphson technique.

Upon completion of advance to the end of the field, the storage phase begins and the water surface gradient is assumed to go to zero. Thus, friction slope equals the furrow slope. Following completion of the storage phase, water is turned off at the furrow inlet. Because recession time differences along the furrow were less than 3%, recession is assumed instantaneous and no recession phase is simulated. Under the majority of sloping furrow irrigation conditions, the time for recession to occur is insignificant in comparison to the advance and storage phase times, and it is assumed that the recession phase has a negligible effect on irrigation performance.

MATERIALS AND METHODS

A summary of the field experiment (Bali and Wallender, 1987) is given herein and the reader is referred to that study for details. Eighty furrows, on 76 cm spacings, were formed in Yolo Clay loam soil at the University of California, Davis. Field slope was 0.002320. Grain sorghum was planted in the center of 30 cm wide beds.

access

Neutron probe acess tubes were installed on 5 m centers in two 250 m long beds between furrows 70 and 71 and between furrows 49 and 50. Stagnant furrow infiltration tests 1.5 m long were conducted on 5 m centers corresponding to the neutron probe locations along the 250 m furrow. Due to the "destructive" nature of infiltration tests, the stagnant furrow tests were conducted in furrow 75. Infiltration coefficients k_i and a_i were determined using a non-linear regression technique to fit equation [13] to the data from the stagnant furrow infiltration tests. Steady-state final infiltration (f_o) of 0.131 L/min/m of furrow was determined from furrow inflow/outflow measurements. Thus, through k_i and a_i, infiltration was stochastic. Other methods of fitting equation [13] to the infiltration data did not give results which agreed as well with neutron probe field measurements.

⑥

Furrows 1 through 72 were irrigated for 390 min with a design furrow inflow rate of 1 L/s. Advance/recession measurements were taken every 5 m along each furrow. Verification of a simulation model's water infiltration predictions require field determination of pre- and post-irrigation soil moisture at multiple locations and depths along a furrow. These time-consuming determinations may be done by soil sampling or neutron probe measurements. As previously mentioned, neutron probe measurements were taken in the center of the bed at 5 m increments along a 250 m furrow. At each location, soil moisture was monitored at 30 cm increments to a depth of 275 cm. In addition, a soil sample was taken at the 15 cm depth to estimate soil moisture in the top 23 cm. Neutron probe measurements were taken the day prior to the irrigation event and then for a series of days beginning 2 days following the irrigation. The sorghum was removed prior to irrigation thus eliminating water extraction. Evaporation from the wet soil surface, occurring between the time of irrigation and neutron probe monitoring, was estimated from data provided by the California Irrigation Management Information Service (CIMIS) weather station located near the test site and research on wet soil evaporation rates conducted using a weighing lysimeter also located near the site.

Syste

RESULTS

Depth of flow at a location influences infiltration and thus simulated irrigation system performance. To exemplify the importance of wetted perimeter on infiltration, the simulation model with a spatially-uniform infiltration function was run for two conditions: (a) wetted perimeter was allowed to vary in space and time, and (b) wetted perimeter was held constant. Constant wetted perimeter was calculated by spatially averaging the flow area for each time step and then time-weighted averaging the spatial averages over the total irrigation time. Because spatially-averaged wetted perimeter increases in time, early in the irrigation event the constant wetted perimeter model overestimates actual wetted perimeter and later in the irrigation wetted perimeter is underestimated. Although roughness decreases during irrigation causing flow depth to decrease, it is assumed that decreasing infiltration causing increased flow depth, dominates the process.

Advance/recession trajectories and water infiltration volumes predicted by a furrow irrigation simulation model are both important performance measures. Historically, predicted advance/recession trajectories have been compared to field-gathered advance/recession data to evaluate a model's capabilities. While this comparison is valid, a comparison of actual and measured infiltration is more meaningful since irrigation

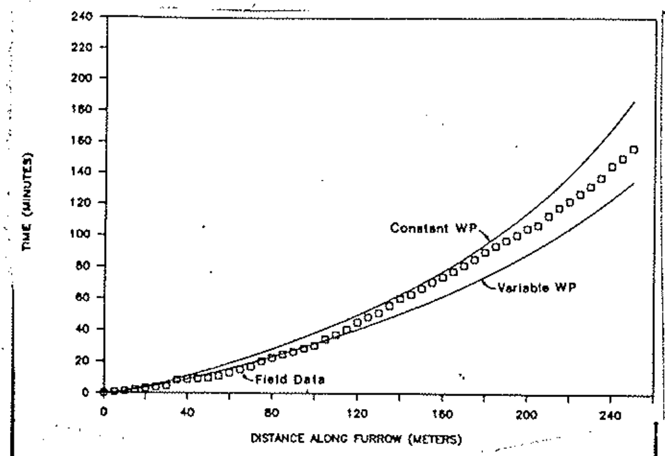

Fig. 1—Advance curves for field-measured data and for uniform infiltration simulation model with constant wetted perimeter and variable wetted perimeter.

performance is calculated from the distribution of infiltrated water.

Advance trajectories for varying and constant wetted perimeter are given in Fig. 1 for the same total irrigation time. Advance is slower for the constant wetted perimeter simulation compared to variable wetted perimeter because flow depth and therefore infiltration is overestimated early in the irrigation. Until the actual flow depth reaches the calculated average depth, infiltration is overestimated. Thereafter, the constant wetted perimeter model begins to underpredict infiltration, but the two curves do not merge.

② The influence of wetted perimeter on final infiltrated water is illustrated in Fig. 2 and Table 1. Infiltration was calculated as the product of infiltration flux and wetted perimeter. Late in the irrigation, wetted perimeter for variable perimeter exceeds average wetted perimeter. Both simulations overestimate measured infiltration, however. As mentioned earlier, by calculating infiltration as the product of infiltration flux and wetted perimeter, infiltration is overestimated because lateral flux from adjacent furrows reduces lateral flux from the furrow being simulated.

TABLE 1. AVERAGE INFILTRATION AMOUNT, CHRISTIANSEN'S UNIFORMITY (CU), AND DISTRIBUTION UNIFORMITY (DU) FOR: INFILTRATION FIELD MEASUREMENTS, UNIFORM INFILTRATION MODEL SIMULATIONS WITH CONSTANT AND VARIABLE WETTED PERIMETER, VARIABLE INFILTRATION MODEL SIMULATIONS WITH CONSTANT AND VARIABLE WETTED PERIMETER, AND VARIABLE WETTED PERIMETER MODEL SIMULATIONS WITH INITIALLY VARIABLE INFILTRATION AND FINAL STEADY INFILTRATION

	Average infiltration amount, cm	Christiansen's uniformity (CU)	Distribution uniformity (DU)
Field infiltration measurements	7.47	77	64
Model w/uniform infiltration and constant wetted perimeter	10.14	89	82
Model w/uniform infiltration and variable wetted perimeter	10.24	74	61
Model w/variable infiltration and constant wetted perimeter	10.18	80	70
Model w/variable infiltration and variable wetted perimeter	10.43	67	52
Model w/variable wetted perimeter and initially variable infiltration and final steady infiltration	7.53	77	65

At the downstream end, although intake opportunity time is greater for the variable wetted perimeter case (Fig. 1), infiltration is less than for constant wetted perimeter (Fig. 2 and Table 1). Wetted perimeter effects overshadow intake opportunity time effects at the downstream end. Greater infiltration upstream and less infiltration at the downstream end for the variable wetted perimeter model is consistent with the decreasing trend in wetted perimeter with distance from the furrow inlet. The variable wetted perimeter model does not

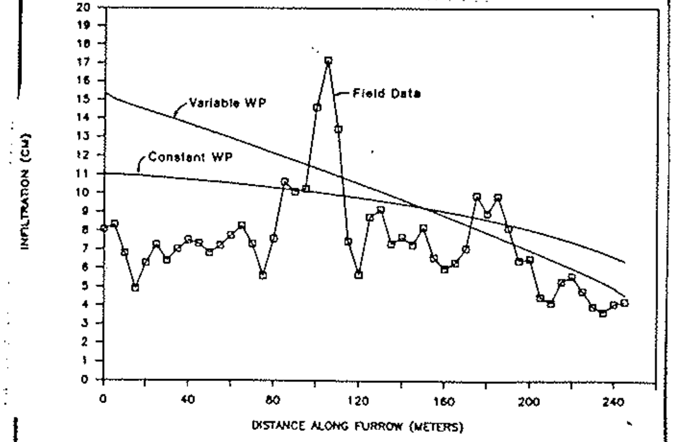

Fig. 2—Simulated infiltrated water during the advance and storage phases for field-measured data and for uniform infiltration models with constant wetted perimeter and variable wetted perimeter.

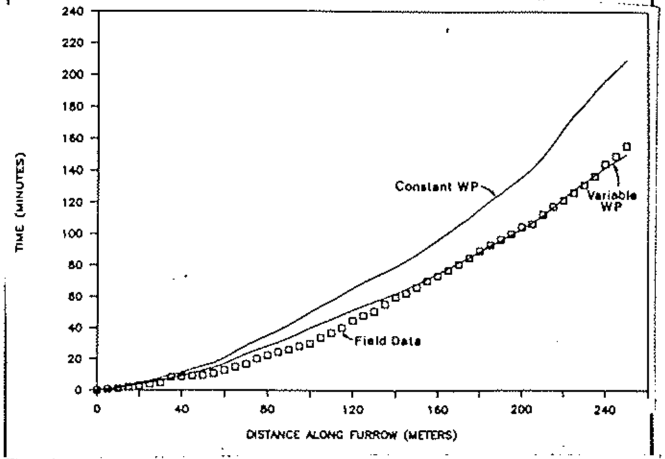

Fig. 3—Advance curves for field-measured data and for variable infiltration model with constant wetted perimeter and variable wetted perimeter.

overpredict infiltration as much near the downstream end compared to the upstream end because intake opportunity time is less and therefore lateral flow is maintained. In addition, uniformity of water application is lower for the variable wetted perimeter case.

The simulated advance trajectory for the variable wetted perimeter simulation with spatially-varying infiltration function more closely approximates field-measured advance (Fig. 3) than for uniform infiltration (Fig. 1). Advance time (Fig. 3) is overpredicted when wetted perimeter is assumed constant. Although locally as irregular as field measured infiltration, trends in infiltration (Fig. 4) are similar to those in Fig. 2 for uniform infiltration characteristics. The variable wetted perimeter model with variable infiltration overpredicts average amount infiltrated along the furrow and underpredicts uniformity when compared with field measurements (Table 1).

Although an important consideration, wetted perimeter effects are likely overestimated in all cases because lateral flow from the furrow decreases with time and calculating infiltration as the product of wetted perimeter and infiltration flux exaggerates the wetted perimeter effect. Further, despite flow depth increases during an irrigation, furrow geometry changes and furrow roughness decreases. Furrow shape may change from V-shaped to a more hydraulically efficient parabolic shape during an irrigation (Izadi and Wallender, 1985), especially if the furrow is cultivated and formed before the irrigation. Due to this shape change and a decrease in roughness (Izadi and Wallender, 1985), increases in flow rate may not significantly increase depth and wetted perimeter and therefore infiltration. Future research should incorporate temporally as well as spatially-varying hydraulic characteristics.

⑧ In an attempt to more realistically simulate furrow infiltration, both infiltration functions developed from stagnant furrow infiltration tests and quasi-steady furrow infiltration from inflow/outflow measurements were used to characterize infiltration. Early in the irrigation, variable wetted perimeter and the variable infiltration functions from the stagnant furrow infiltration tests were used to calculate infiltration. Quasi-steady intake rate was approached, as mentioned earlier, after 90 min of intake opportunity time, and infiltration was thereafter calculated as a steady rate determined from furrow inflow/outflow measurements.

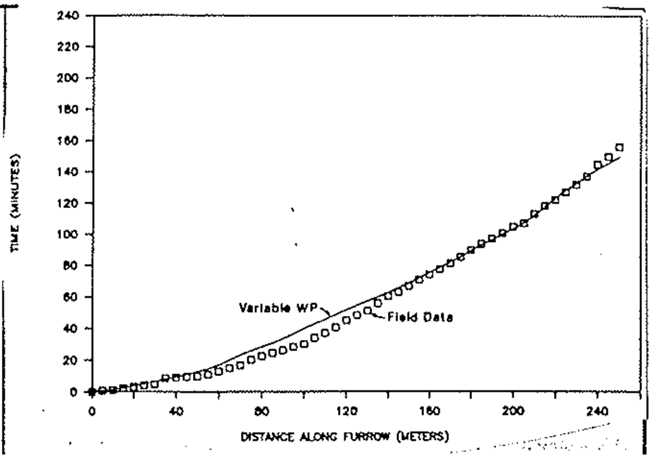

Fig. 5—Advance curves for field-measured data and for model simulation with initially variable infiltration and final, steady infiltration.

Predicted advance curves for the model simulation with initially variable infiltration and final steady infiltration are compared with field data in Fig. 5. Field-monitored recession occurred within 20 to 30 min of cutoff due to the small furrow storage volume. Recession times of this magnitude were small compared to total intake opportunity time, and were therefore assumed to be instantaneous. The model closely predicted field advance.

Predicted infiltration for the initially variable and final steady infiltration simulation and field data are compared in Fig. 6. Average infiltration amount and uniformity are predicted accurately (Table 1). The trend in infiltration is consistent with furrow intake opportunity time. Because variable infiltration functions used during the initial period of model simulation were measured along a furrow 4 m from the neutron probe monitored furrow, cross-field spatial variability of infiltration characteristics could cause the spatial positioning and magnitude of infiltrated water to vary.

CONCLUSIONS

Wetted perimeter plays an important role in furrow

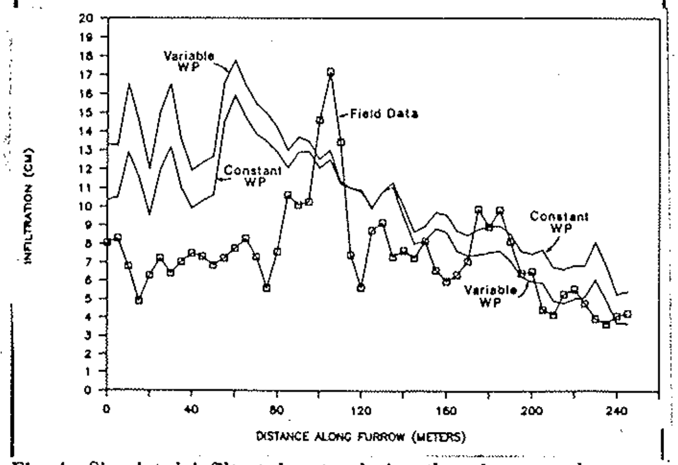

Fig. 4—Simulated infiltrated water during the advance and storage phases for field-measured data and for variable infiltration model with constant wetted perimeter and variable wetted perimeter.

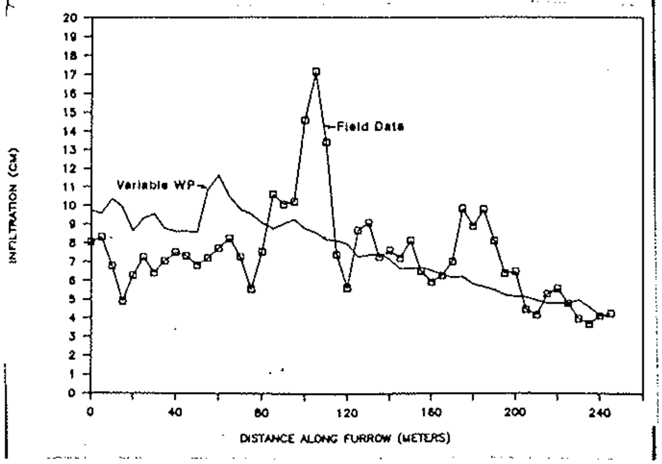

Fig. 6—Infiltrated water for field-measured data and for model simulation with initially variable infiltration and final, steady infiltration.

infiltration simulation. Assuming constant wetted perimeter results in overprediction of both water advance times and application uniformity when compared to variable wetted perimeter simulations.

Furrow infiltration, first calculated as the product of wetted perimeter and infiltration flux and later as a constnt infiltration rate determined from a furrow inflow/outflow measurement more closely simulates actual infiltration than does calculating infiltration as the product of wetted perimeter and infiltration flux during the entire irrigation.

constant

Simulations using spatially-varying infiltration results in lower application uniformity compared to simulations with spatially-uniform infiltration. Modeling an irrigation event using a spatially-uniform infiltration function attributes all nonuniformity to differences in intake opportunity time and ignores the spatial variability of soil characteristics. As such, the spatially-uniform infiltration model places an upper limit on the irrigation application uniformity. Field-measured application uniformity and average depth are predicted more accurately by the spatially-varying simulation model.

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