SOLUTE TRANSPORT IN SIMULATED CONDUCTIVITY FIELDS UNDER DIFFERENT IRRIGATIONS

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ABSTRACT: The interactive effect of irrigation methods and spatial variability of saturated hydraulic conductivity (K_s) on solute transport was determined with the combined use of a two-dimensional deterministic solute transport model and a stochastic parameter generator. In a homogeneous K_s field, the time required to infiltrate a prescribed amount of water or chemical increased from sprinkler to furrow to drip irrigation. Furrow irrigation appeared to leach the chemical more rapidly than either drip or sprinkler irrigation. Assuming the spatial distribution of K_s to be a stationary stochastic process, increased spatial variability in K_s reduced the infiltration rate. When K_s is spatially correlated, sprinkler irrigation appeared to be less susceptible to cause ground-water contamination than furrow or drip irrigation. The concentration distributions in the uncorrelated K_s field were not very different from those in the homogeneous field.

INTRODUCTION

The presence of pesticides and fertilizers in ground water has become an increasing problem in modern irrigated agriculture. Contamination of ground water is to be expected when a substantial fraction of surface-applied chemical is leached out of soil root-zone. Transport of the chemicals in the soil is affected by many factors including soil physical, chemical, and hydrologic properties; soil surface microrelief; and irrigation practices (Wallach et al. 1991). While soil hydraulic parameters such as capillary head, moisture content, and parameters for describing the retention characteristics are fundamental to a soil and important to water and solute transport (Mantoglou and Gelhar 1987), saturated hydraulic conductivity is a parameter that directly translates the hydraulic characteristics of a soil to the transport processes. This paper examines the interactive effect of combinations of different irrigation methods with spatially variable saturated hydraulic conductivity fields on the subsurface transport of nonsorbing chemicals using both stochastic and deterministic modeling approaches. The porous medium is assumed to be either an unknown realization of a random field or a field that is subjected to some prescribed degree of spatial correlation. Parameter fields (e.g., saturated hydraulic conductivity) are described as stationary stochastic processes, and a deterministic solute transport model is used to estimate two-dimensional spatial distributions of the solute concentration.

Irrigation is one of the main factors governing the fate and transport of agrochemicals in arid and semiarid region soils (Yaron et al. 1985). Because most irrigation methods apply water at the soil surface (except subsurface drip), differences between irrigation methods are mainly a consequence of the input boundary conditions that define how water and surface-applied chemicals are transferred into the underlying semiinfinite soil profile. Due to historic, technical, and economic reasons, the most commonly applied irrigation methods in arid and semiarid agricultural regions include sprinkler, furro drip irrigation. Neglecting the effect of application n formity, sprinkler irrigation is designed to apply wate the entire soil surface in a way similar to rainfall. Infil and solute transport under sprinkler irrigation most close proximate one-dimensional flow. By contrast, furrow irri delivers water from geometrically well-defined field f through gravitational force (low pressure). Solute tra from the surface furrows would be generally a two-c sional process with a ponded surface condition. In dri gation, water and dissolved chemicals, if any, are a through evenly spaced point sources (emitters). Transpc redistribution of water or solutes from these surface sources would create a three-dimensional flow regime. ever, the emitters in many drip irrigated row crops ar being replaced with drip tapes having closely spaced op (2–6 per m). Surface wetting from such drip systems le continuously wetted strips centered at the crop rows. F this case is still two-dimensional, except that the s boundary is not ponded as for furrow irrigation and the of water and dissolved solute is located at the top of crop How different irrigation methods would affect solute tra is not well understood. Limited publications on the eff irrigation methods on solute transport include Troianc (1993), who found more leaching of herbicide atrazir furrow irrigated soil than in a sprinkler irrigated soil. erature is found on the interactive effect of irrigation m and soil heterogeneity on solute transport.

Quantitative descriptions of chemical transport hav well advanced for soils with homogeneous medium pro (van Genuchten and Shouse 1989). Experimental and t ical studies suggest, however, that deterministic soluti transport models may not represent the field conditions, due to field-scale variability in hydraulic parameters s hydraulic conductivity (Sudicky 1986; Tseng and Jury

The saturated hydraulic conductivity (K_s) has been fo be spatially variable for many natural porous media, in soil. Many studies have been carried out in efforts to stand how K_s changes in space, including methods fo acterizing a variable K_s field. Wierenga et al. (1991) fou the hydraulic conductivity of a saturated field soil range 1.4 to 6,731 cm/d. However, despite the wide range ductivity values, they observed a relatively homogeneo ting front, thus indicating the absence of preferential f describe the variable nature of field saturated hydraul ductivity over space, scaling has been adopted by m searchers (Tillotson and Nielsen 1984; Neuman 1990; ' 1990; Vogel et al. 1991; Dagan 1994). This technique ally evolved from the early work of Miller and Miller on microscopic geometric similitude. Other stocha

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Note. Discussion open until March 1, 1998. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on December 6, 1996. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 123, No. 5, September/October, 1997. ©ASCE, ISSN 0733-9437/97/0005-0336–0343/$4.00 + $.50 per page. Paper No. 13475.

proaches in characterizing the heterogeneous nature of K_s include Monte-Carlo (Freeze 1980), turning bands (Tompson et al. 1989), and many other methods. A log-normal probability density function has generally been assumed for K_s values (Persaud et al. 1985; Yeh et al. 1985; Rubin 1990). Rather than assuming a random distribution of log-normally transformed K_s values, spatially structured (autocorrelated) saturated hydraulic conductivity fields have been used in the simulation of water infiltration in heterogeneous soils (El-Kadi 1987; Matias et al. 1989; Tseng and Jury 1993). Using autocorrelated K_s fields, Freeze (1980) simulated the hydrology of a hillslope and concluded that the spatially structured K_s played a significant role in subsurface hydrology.

The development of simulation models has greatly enhanced our quantitative description and prediction of solute transport in the unsaturated zone. These models, with variable degrees of sophistication, include LEACHM (Wagenet and Hutson 1987), GLEAMS (Knisel et al. 1989), PRZM (Carsel et al. 1984), RZWQM ("Root" 1992), and more recently CSUID (Garcia et al. 1995). Although they remain useful tools in research and management, most of these deterministic models are designed such that they are not easily modified to include spatially and temporally varying soil hydraulic parameters. A recently developed deterministic finite-element model, CHAIN_2D (Simunek and van Genuchten 1994), for simulating the two-dimensional movement of water, heat, and multiple solutes in variably saturated porous media is written in a way that one can easily incorporate spatially varying hydraulic parameters (including K_s) as scaled variables. Hence, CHAIN_2D is the transport model used in this research.

The following specific objectives are addressed in this study. First, we are interested in the transport and concentration distribution of solute when the soil is subjected to sprinkler, furrow, or drip irrigation. Next, we would like to know the behavior of solutes in soils that have either a homogeneous saturated hydraulic conductivity value or conductivities that are either spatially autocorrelated or uncorrelated. Finally, we hope that by gaining more insight about how solutes move and distribute under different irrigation and K_s fields, we can better select the appropriate irrigation method to minimize the potential for ground-water contamination.

METHODS

Generation of Two-Dimensional Autocorrelated and Uncorrelated K_s Fields

Two major steps were involved in the methods development. First we needed to generate the two-dimensional saturated hydraulic conductivity fields. An autocorrelated conductivity field was generated by adding random frequency harmonics sampled from a spectral density function using the Monte-Carlo technique. The theory for this procedure was proposed by Mejia and Rodriguez-Iturbe (1974) and a FORTRAN code was modified from El-Kadi (1986) to perform the parameter generation. The generated conductivity fields, both the autocorrelated and uncorrelated, were log-normally distributed, and the same fields (from the same realizations of a Monte-Carlo simulation) were used in simulating sprinkler, furrow, and drip irrigation conditions. To generate the two-dimensional fields for the saturated hydraulic conductivity, we assumed that K_s can be described with a stationary log-normal probability density function. If we define a parameter Y such that

$$Y = \ln(K_s) \quad (1)$$

then Y should follow a normal distribution function. We further assumed that the parameter Y has an autocorrelation structure given by

$$\rho_Y(l) = e^{-\lambda_Y|l|} \quad ($$

where $\rho_Y(l)$ = autocorrelation function as of lag l; and λ_y = autocorrelation parameter (correlation length = $1/\lambda_y$). The values of Y are, therefore, generated from the population $N[\mu$ σ_Y; $\lambda_Y]$, in which μ_Y and σ_Y are, respectively, the mean an standard deviation of the population.

Procedures for generating autocorrelated and uncorrelat conductivity fields have been described in detail by Free (1980) and El-Kadi (1986). We used the original generati algorithm given by Mejia and Rodriguez-Iturbe (1974). O correction was made in the procedure, compared to Free (1980) and El-Kadi (1986). The residuals ε_{ij} from a stochast process $N[0, 1; \lambda_Y]$, where subscripts $i = 1, 2, \ldots, I$; $j =$ $2, \ldots, J$ denote the grid for the two-dimensional field of values to be generated, were taken as

$$\varepsilon_{ij} = \varepsilon(x_i, z_j) = \left(\frac{2}{N}\right)^{1/2} \sum_{m=1}^{N} \cos[W_m(x_i \cos \gamma_m + z_j \sin \gamma_m) + \phi_m \quad (3$$

rather than

$$\varepsilon_{ij} = \varepsilon(x_i, z_j) = \left(\frac{2}{N}\right)^{1/2} \sum_{m=1}^{N} \cos[W_m(x_i \sin \gamma_m + z_j \cos \gamma_m + \phi_m) \quad (3$$

where x_i and z_j = horizontal and vertical directions of the tw dimensional field; $N \geq 50$; γ_m and ϕ_m are chosen from a un form distribution over the range 0–2π or $U[0, 2\pi]$; and W is given by

$$W_m = \lambda_Y \left\{\left[\frac{1}{1 - G(W_m)}\right]^2 - 1\right\}^{1/2} \quad ($$

In (4), $G(W_m)$ is chosen from a uniform distribution over t range 0–1. Eq. (3a) should be the correct form for ε_{ij} becau the product of $[x_i z_j]$ and the transpose of [cos γ_m sin γ_m] is (cos γ_m + z_j sin γ_m), which is further multiplied by W_m a cording to Eq. (61) from Mejia and Rodriguez-Iturbe (1974 We also performed a numerical comparison in which usi (3*a*) generated ε_{ij} conformed to $N[0, 1; \lambda_y]$. However, usi (3*b*) and the same sets of x_i, z_j, W_m, γ_m, and ϕ_m data, the me of generated ε_{ij} was about 8.6 for $x_i = z_j$, 6.9 for $x_i = 10z_j$ $z_j = 10x_i$, and 0.2 for $x_i = 100z_j$ or $z_j = 100x_i$, respectivel Discrepancies of (3*b*) from (3*a*) were probably only typ graphic errors in Freeze (1980) since the generated K_s had mean similar to the input (10^{-5} m/s). In El-Kadi (1986), hov ever, the generated K_s had a mean that was many times larg than the unit input.

The input parameters for generating the two-dimensional fields are the mean (μ_y) and standard deviation (σ_y) of t population and the autocorrelation parameter λ_Y. The valu of μ_Y and σ_Y are calculated from the following equations (Wa rick and Nielsen 1980):

$$\sigma_Y = \left[\ln\left(\frac{\sigma_{K_s}^2}{\mu_{K_s}^2} + 1\right)\right]^{1/2} \quad ($$

and

$$\mu_Y = \ln \mu_{K_s} - \frac{1}{2}\sigma_Y^2 \quad ($$

where μ_{K_s} and σ_{K_s} = mean and standard deviation, respectivel of the log-normally distributed saturated hydraulic conducti ity before transformation. The points at which saturated h draulic conductivity values are generated have the same x a z coordinates as those in the finite-element mesh used for t transport simulation.

According to a preliminary single-ring infiltrometer mea urement, estimated K_s for an Arlington fine sandy loam (coarse-loamy, mixed, thermic Haplic Durixeralf), on which the nonsorbing tracer chemical transport and concentration distribution will be simulated, averaged about 5.0 cm/d. While Warrick and Nielsen (1980) reported that the coefficient of variation (CV) of K_s ranged from 86 to 190%, we assumed a 150% CV value for this soil. Therefore, values of 5.0 and 7.5 cm/d were used for the input parameters μ_{K_s} and σ_{K_s}, respectively.

Freeze (1980) used 0.003 (l/cm) as the autocorrelation parameter λ_Y, for ground-water flow simulations. El-Kadi and Brutsaert (1985) used, in four out of six experiments, 25% of the total length as the correlation length (= $1/\lambda_Y$). Tseng and Jury (1993) applied 25–40% as the horizontal and 5–15% as the vertical correlation length. In this research, we used 25% of the horizontal length (= 90 cm) as the correlation scale for both horizontal and vertical directions, which resulted in an λ_Y value of 0.044 (1/cm).

Solute Transport Simulated with CHAIN_2D, Code Modification, Input Parameters, and Boundary and Initial Conditions

The next step in the method development was to simulate the flow and transport using the computer model CHAIN_2D (Simunek and van Genuchten 1994), which numerically solves Richards' equation for water flow and the Fickian-based convection-dispersion equation for solute transport using Galerkin-type linear finite-element schemes. Simulations were carried out in a two-dimensional vertical plane (see Fig. 1 for geometry). Simulated scenarios included combinations of the three irrigation methods and three saturated hydraulic conductivity fields (including a homogeneous field). Besides solving the nonsorbing chemical concentration distribution for only one realization of the autocorrelated and uncorrelated K_s field, we also obtained averaged solute concentration distributions of 50 simulations for both the autocorrelated and uncorrelated conductivity fields. This was readily achieved by modifying the CHAIN_2D computer code to include an additional subroutine for generating the autocorrelated or uncorrelated parameters. The transport model, CHAIN_2D, numerically

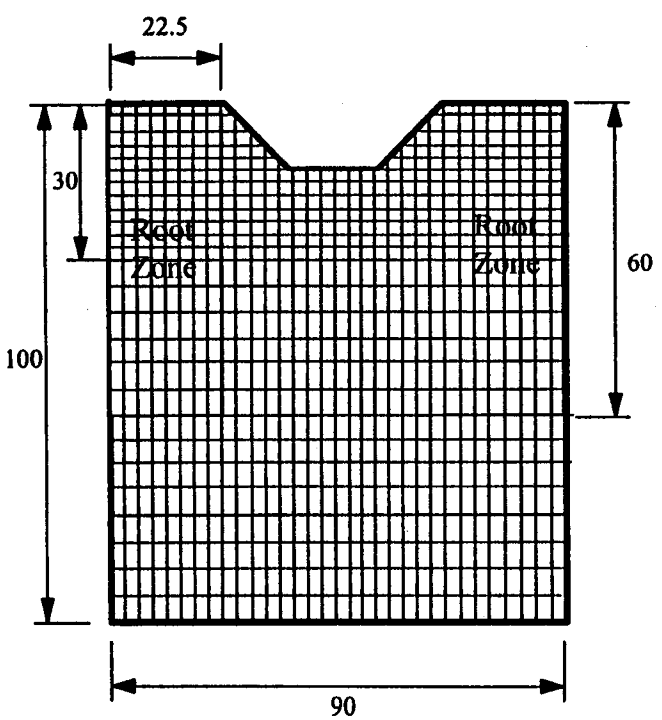

FIG. 1. Schematic of Cross-Section Subjected to Sprinkler, Furrow, and Drip Irrigation (Units in cm)

solves the partial differential equations for two-dimensi nonlinear nonequilibrium solute transport involving a firs der solute decay chain reaction during transient water flo a variably saturated porous medium. For a nonsorbing cl ical without decay and volatilization, the governing tran: equation can be simplified to

$$\frac{\partial \theta C}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D^w_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial q_i C}{\partial x_i}$$

where θ = volumetric water content; C = solute concentr: in soil solution; t = time; x_i and x_j = spatial coordinate represents the Darcian fluid flux density; and $\mathbf{D}^w_{ij}$ is the persion coefficient tensor for the liquid phase and desc as follows (Bear 1972)

$$\theta \mathbf{D}^w_{ij} = D_T|q|\delta_{ij} + (D_L - D_T)\frac{q_i q_j}{|q|} + \theta D_w \tau_w \delta_{ij}$$

where D_L and D_T = longitudinal and transverse dispersi δ_{ij} = Kronecker delta function; D_w = molecular diffusio efficient in free water; and τ_w = a tortuosity factor. Dispers values for field conditions can range from 5 to 20 cm (et al. 1991; Beven et al. 1993). In this simulation stud used 10 and 5 cm for the longitudinal and transverse di sivity, respectively.

Variably saturated water flow was simulated using the I ards' equation with the unsaturated soil hydraulic func described by a set of closed-form equations resembling t of van Genuchten (1980). Five parameters, θ_r, θ_s, α, n, K_s, are used in the model. Of these, θ_r and θ_s represent res and saturated volumetric soil water content; α and n are acteristic hydraulic parameters of the soil. Because a me value was found to be about 5.0 cm/d, the remaining parameters were taken to be those of the silt loam G.E. van Genuchten (1980), leading to the following values: 0.131, θ_s = 0.396, α = 0.00423 (1/cm), and n = 2.06.

To simulate water and solute transport under field irri conditions, the CHAIN_2D model was modified by creat new boundary code that will switch boundary conditions and forth between an evaporative and a ponded or a flux condition at: (1) prescribed time intervals; or (2) elapsed t when the total water or solute inflow had reached a presc amount. The program was also made to apply to chemig Chemigation has become a common practice in modern gation technology because of its ability to more easily cc chemical input in irrigated soils. The time and duratio chemical injection was determined in a similar fashion a water input, i.e., by starting at a prescribed time and t nating when a prescribed amount was reached. To obt spatially weighted concentration distribution, we average ute concentration for each nodal point from 50 simulatior for both the autocorrelated and uncorrelated conduc fields.

The boundary conditions used in the simulation are mined by the type of irrigation methods involved. For kler irrigation, a flux input (36 cm/d) was used over the soil surface (90 cm wide). A maximum ponding depth cm) was permitted in the simulation. For furrow irrigatio applied a ponded condition with a fixed depth (=7.5 c areas in the bottom of the furrow (20 cm wide, includin sides of the furrow). The remainder of the surface was jected to evaporation. For drip irrigation, water and che were applied to the top of the rows, assuming a wetting of 25 cm. Because of symmetry, each side of the furrov 12.5 cm wetting. The wetted area was assumed to be at saturation ($h \geq 0$). The remaining part of the soil surfac again subjected to evaporation.

The following fixed boundary and initial conditions applied to all three irrigation methods. A region 45 cm

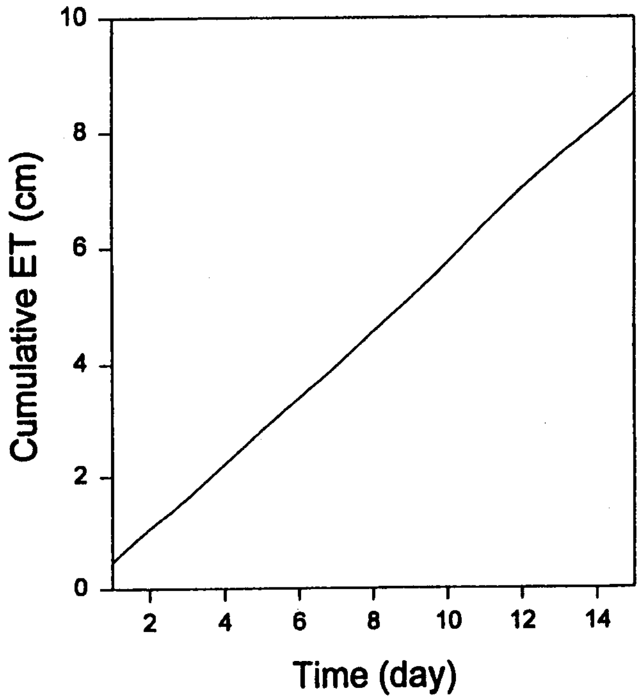

FIG. 2. Cumulative Potential Evapotranspiration (ET) Obtained from Weather Station Located on University of California-Riverside Campus; Data Is from July 1–15, 1994

by 60 cm deep (excluding the surface 2.5-cm layer) beneath the top of each row was assumed to be subjected to root water uptake with a maximum transpiration rate of 0.508 cm/d (Fig. 1). This rate approximates the peak growth for dry beans in southern California. Evapotranspiration (ET) was the sum of root water uptake and surface water evaporation. We used a set of actual measured potential ET data from a California irrigation management information system's weather station located at Riverside for the input in our simulations (Fig. 2). Total irrigation and chemical injection (at unit concentration) were 6 and 3 cm for each of the three irrigation methods, respectively. Because of symmetry, a zero flux boundary condition was used for the sides of the simulation domains. A unit flux boundary condition was used for the bottom boundary. An initial soil water pressure head of −150 cm was used. The simulation involved only one irrigation event, which was initiated on the fifth day, whereas the simulation itself was run for 15 d to allow sufficient time for redistribution.

RESULTS AND ANALYSIS

Two-dimensional saturated hydraulic conductivity fields, both autocorrelated and uncorrelated, were generated using a single realization of the Monte-Carlo simulation (Fig. 3). The correlation length used in the autocorrelated case was 22.5 cm, which created bands of high conductivity regions with a band width ranging from 20 to 40 cm [Fig. 3(a)]. The realization in Fig. 3(a) exhibited lower K_s values in the upper left region of the cross section as compared to the rest of the vertical plane. In the uncorrelated case, occurrences of high and low conductivities appear to be spatially random with no trend of high or low regions [Fig. 3(b)]. Besides later multirealization averaging, these two conductivity fields were used repetitively in comparing different irrigation methods. While the results of solute transport under different irrigation methods was very dependent on the chosen realization of K_s fields, we believe the use of a randomly chosen realization was appropriate because it provided the comparison of the effect of irrigation methods on solute transport.

For homogeneous K_s, field, the time needed to apply 6 cm of water increased from sprinkler irrigation to furrow to irrigation (Table 1 and Fig. 4, homogeneous case). The l overall infiltration rate with the sprinkler method as comp to furrow or drip irrigation was due primarily to the avail infiltration area, where the whole soil surface was subjecte infiltration for sprinkler method. In furrow irrigation, a p tive head (or ponding) would increase the local infiltra flux, while the rest surface area would not contribute to i tration. Drip irrigation had the lowest infiltration rate bec of the reduced application rate and small infiltration area ative to sprinkler or furrow irrigation. Furthermore, infiltra in drip irrigation was mainly induced by capillary-driven f When compared on a single-realization basis, e.g., using conductivity fields in Fig. 3, the autocorrelated field red the overall water inflow rate relative to that in the hom neous conductivity field (Fig. 4). This effect is more evi for furrow irrigation, whether about twice the time is ne to infiltrate 6 cm of water in the autocorrelated hydraulic ductivity field than in the homogeneous field (Table 1). the high K_s regions coincided with the ponding portion o soil surface, however, the infiltration rate would have l higher and possibly exceeded that of sprinkler irrigation. spatially uncorrelated conductivity field also reduced the i tration rate, but not as much as in the correlated case. indicates that isolated high K_s values are not effective i creasing the overall infiltration rate, especially for sprir

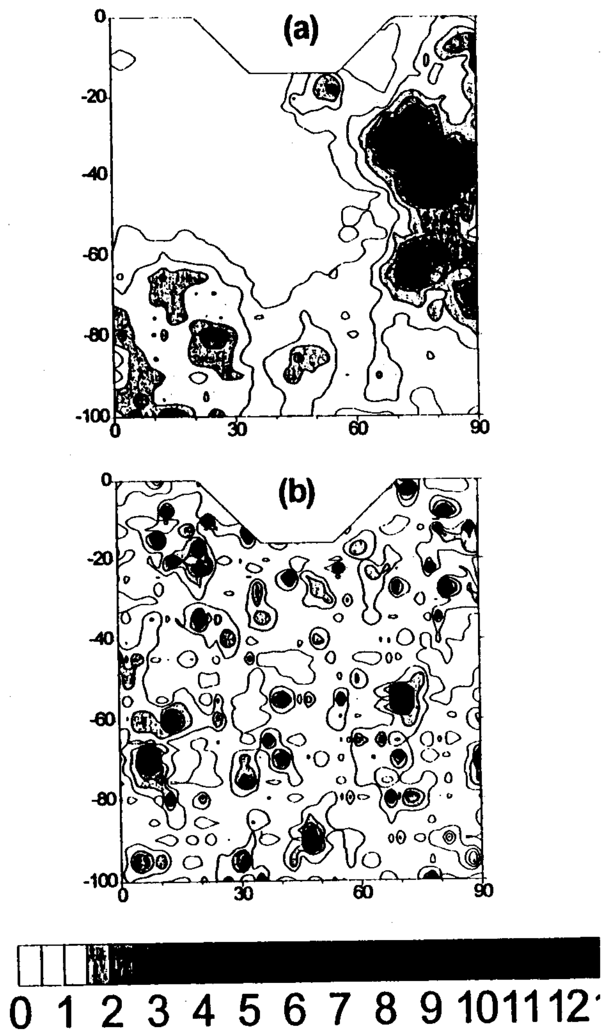

FIG. 3. Generated Saturated Hydraulic Conductivity F (Scaled to Mean of 5 cm/d, i.e., value of 1 corresponds to 5 by Assuming: (a) Autocorrelated K_s with $\lambda_Y = 0.044$ (1/cm), 5.07 cm/d; (b) Uncorrelated K_s with $\lambda_Y \rightarrow \infty$, $\sigma_{K_s} = 5.58$ cm/d (in cm)

TABLE 1. Time Taken to Infiltrate 6 cm Water and 3 cm Tracer under Combinations of Drip, Furrow, and Sprinkler Irrigation wi tocorrelated, Uncorrelated, Homogeneous Saturated Hydraulic Conductivity Fields

Time	Drip			Furrow			Sprinkler		
(h) (1)	Autocorrelated (2)	Homogeneous (3)	Uncorrelated (4)	Autocorrelated (5)	Homogeneous (6)	Uncorrelated (7)	Autocorrelated (8)	Homogeneous (9)	Uncorı (1
t_w [a]	24.04	16.89	21.17	25.33	12.30	15.94	15.61	9.13	11
t_c [a]	9.36	6.48	8.40	9.60	5.04	6.48	4.56	2.88	3

[a] t_w = Time needed to infiltrate 6 cm water; t_c = time needed to infiltrate 3 cm tracer.

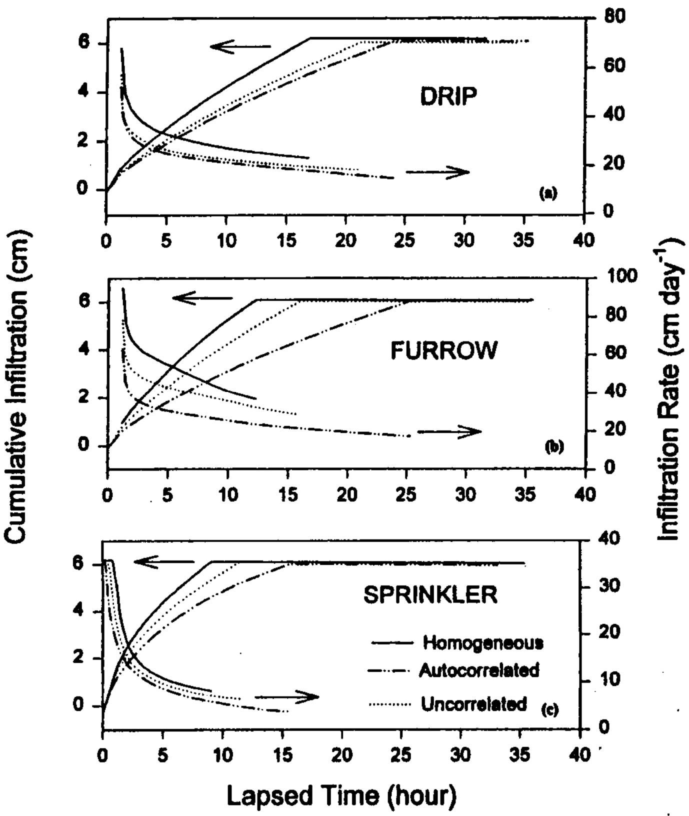

FIG. 4. Instantaneous Accumulative Infiltration Rate for Drip, Furrow, and Sprinkler Irrigation Compared on Single-Realization Basis between Autocorrelated, Uncorrelated, and Homogeneous K_s Fields

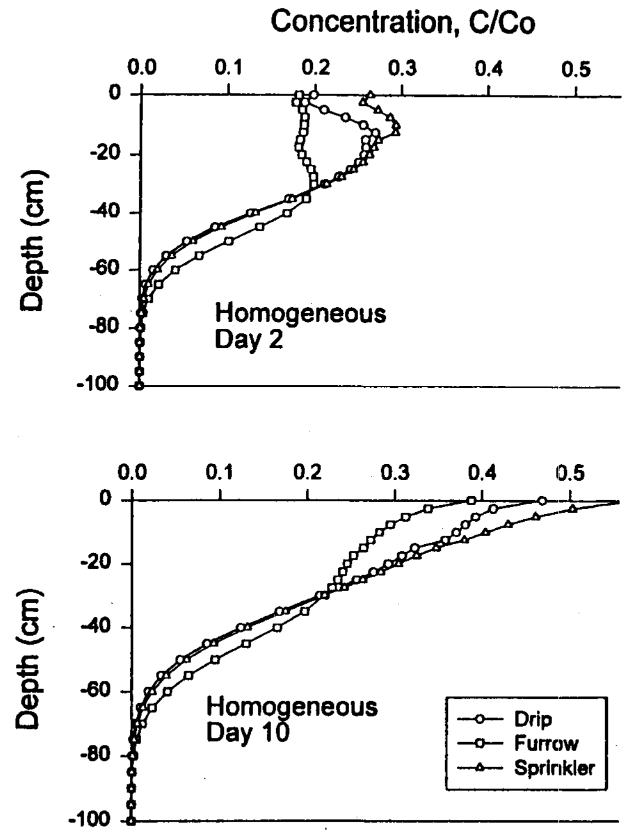

FIG. 5. Horizontally Averaged Solute Concentration tained for Homogeneous K_s Field under Drip, Furrow, and kler Irrigation, 2 (top) and 10 (bottom) d after Irrigation St

irrigation. A similar conclusion was made by El-Kadi (1987), who reported a reduced infiltration rate for structured hydraulic conductivity fields as compared to homogeneous media. This result is caused by the stationary process of generating two-dimensional K_s values.

Using the homogeneous K_s field an an example, vertical distribution of solute concentration profiles were obtained for each irrigation method at 2 and 10 d after the initiation of irrigation (Fig. 5). This was achieved by averaging solute concentrations within each horizontal depth increment (every 2 cm). Nonsorbing tracers traveled deeper into the soil in furrow irrigation than in drip or sprinkler irrigation, due primarily to surface ponding. These horizontally averaged concentration profiles also reflected the effects of evaporation and root water uptake on solute transport, which led to upward water and solute movement and increased solute concentrations in the soil after water had been either evaporated from the surface or uptaken by plant roots. The surface solute concentration increased from about 0.25 on the second day to 0.50 on the fourth day.

Figs. 6–8 show two-dimensional tracer concentration distributions for homogeneous, autocorrelated, and uncorrelated hydraulic conductivity fields on a single-realization basis for drip, furrow, and sprinkler irrigation, respectively. Surface-applied solutes always traveled farther into the profile alo high conductivity regions of the autocorrelated field. fore, preferential flow may occur under any of the thre gation methods if there is a region with elevated hyd conductivity values. Two days after irrigation started, th ter of solute mass reached a depth of about 40 cm for th and furrow irrigation methods, but remained at about a depth for the sprinkler irrigation in the high condu regions of the autocorrelated fields (Figs. 6–8). Ten day the initiation of irrigation, the center of solute mass wa depth of about 30 cm for the drip and furrow irrigation ods, but moved to about a 10-cm depth for the sprinkle gation in the high conductivity regions of the autocorr fields (Figs. 6–8). Conversely, if the source for water ar ute happened to occur at places where the K_s was the l opposite results would have been obtained between sp and other localized application methods such as furro drip. The relation between irrigation methods and K_s bution indicates that water infiltration and solute trans sprinkler irrigation is less likely affected by the spatiall iable nature of saturated hydraulic conductivity than in f or drip irrigation. A potential practical application is t lection of irrigation methods for soils of known spatial bility. For soils with highly variable K_s values (with corr

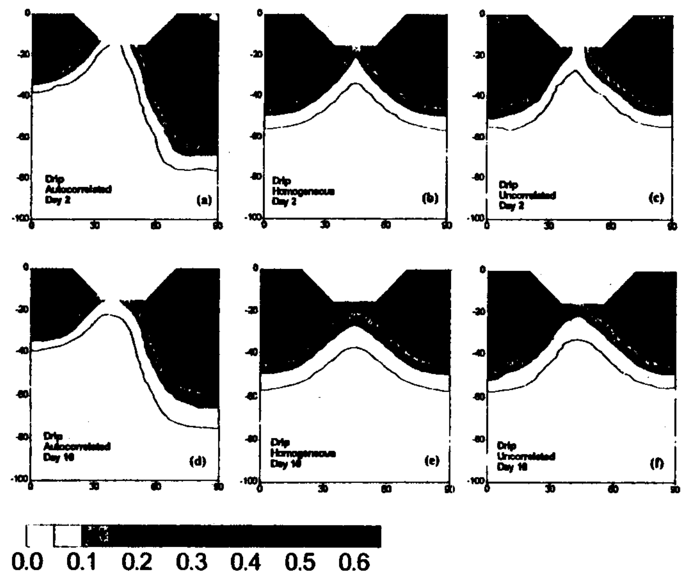

FIG. 6. Simulated Relative Concentration Distributions at 2 and 10 d after Drip Irrigation for Homogeneous and Autocorrelated and Uncorrelated K_s Field Shown in Fig. 3

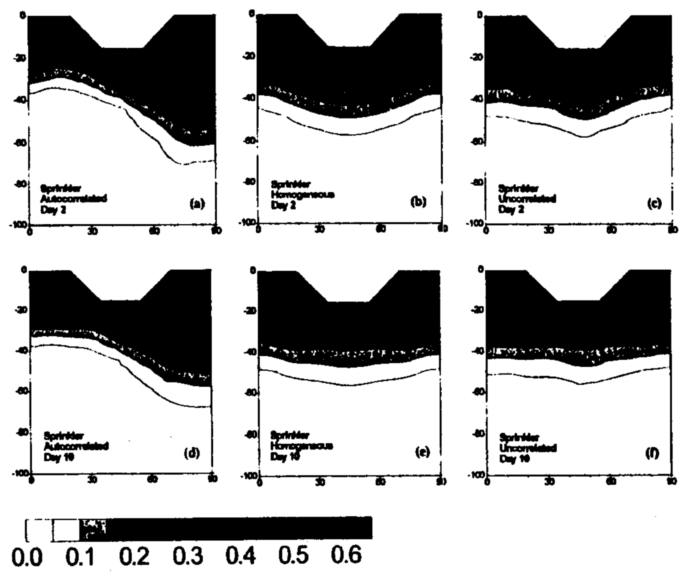

FIG. 7. Simulated Relative Concentration Distributions at 2 and 10 d after Furrow Irrigation for Homogeneous and Autocorrelated and Uncorrelated K_s Field Shown in Fig. 3

length in the order of furrow or emitter spacing), sprinkler irrigation should be used to reduce deep leaching and prevent ground-water contamination. The concentration distributions in the uncorrelated hydraulic conductivity field were not very different from those in the homogeneous field for all three irrigation methods. This would indicate, from a practical stand point, that different irrigation methods would unlikely create preferential movement if the K_s values of a soil is randomly distributed or correlated, but in a distance that is much smaller than the spacing between individual water and solute sources. The other factor affecting the occurrence of preferential flow is the relative difference between correlation length for K_s and local dispersion lengths for water and solute. If the correlation length is the same or smaller than the dispersion length, diffusion would dominate and advective preferential flow would unlikely to occur. The longitudinal and transverse dispersion lengths used in this study were 10 and 5 cm, respectively. The presence of surface evaporation and root water uptake tends to enhance lateral redistribution of a tracer and, hence, may limit excessive leaching. This effect can be seen by comparing

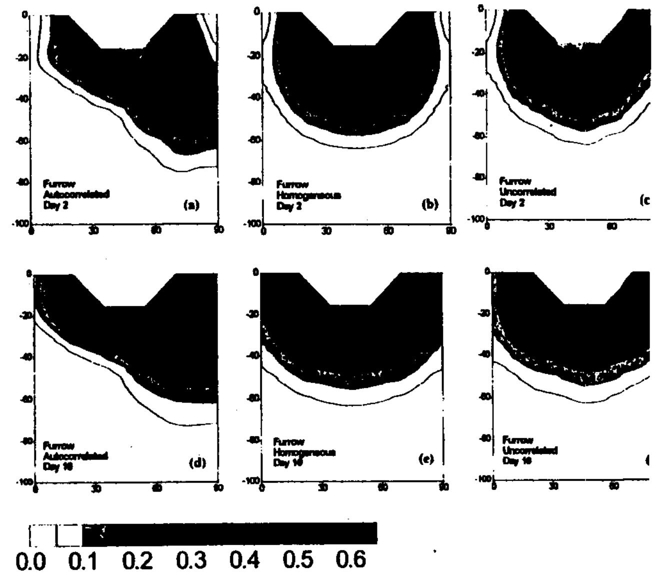

FIG. 8. Simulated Relative Concentration Distributions and 10 d after Sprinkler Irrigation for Homogeneous and A correlated and Uncorrelated K_s Field Shown in Fig. 3

chemical distributions between 2 and 10 d after irriga when upward and possibly lateral movement occurred and solute was concentrated near the soil surface.

Running the transport model 50 times, each time wit different hydraulic conductivity field, we obtained 50 diffe solute concentration distributions. By averaging the 50 c centration values for each nodal point, we obtained a se concentration distributions representing the mean of a stati ary (or close to it) stochastic process. This multirealiza averaging was performed for all three irrigation methods for both the autocorrelated and uncorrelated scenarios. averaged concentration distributions for both the autoco lated and uncorrelated hydraulic conductivity field are similar to the homogeneous field for all three irrigation m ods. This is not surprising since we used the same valu cm/d) as the input mean K_s. Furthermore, as indicated Freeze (1980), among the mean, standard deviation, and tial structure, spatial structure is the least important factor termining the translocation of a solute center mass over sp much larger than the structural correlation length. To fur verify our procedure for generating log-normally distrib K_s field in conjunction with the solute transport simulation created a solute concentration profile similar to Fig. 13.6 f Warrick and Nielsen (1980), using the approaches descri in this paper, and adopting initial and boundary condit similar to those of Warrick and Nielsen (1980) [the pore w velocity and diffusion coefficient were the same as that in Warrick and Nielsen (1980)]. This profile was obtaine first generating 50 log-normally distributed K_s values wi mean of 35 cm/d and standard deviation of 58.2 cm/d. T similar to our homogeneous case, we ran the transport m 50 times, each time with a fixed K_s value sequentially ch from the 50. After taking every nodal point for an averag the 50 solute concentrations and plotting the average va versus depth, we obtained Fig. 9(a). The deterministic c was for the mean K_s (35 cm/d). Comparing Fig. 9(a) with 13.6 from Warrick and Nielsen (1980), we noticed the s trend in that the mean value curve showed a lower conce tion than the deterministic curve at shallow depths, with reverse results occurring at deeper depths. This effect of eraging solute concentrations was not present in our tw mensional simulation [Fig. 9(b)], probably second of two sons. First, solute transport for each realization was base a two-dimensional K_s field for our case and on a single v

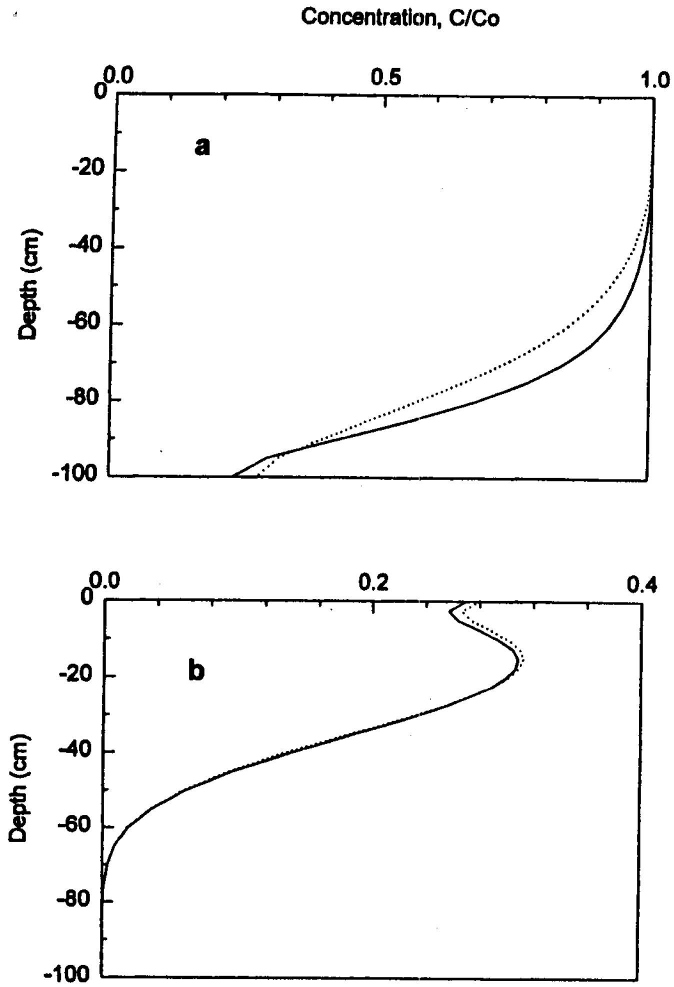

FIG. 9. Mean Solute Concentration versus Depth: (a) 5 d after Starting Continuous Solute Input; (b) 2 d after Completing 3-cm Pulse Input; Solid Line Represents Deterministic Solutions (with Mean K_s); Dotted Line Is Average of 50 Realizations with Means of 35 and 5 and Standard Deviations of 58 and 7.5 cm/d for (a) and (b), Respectively

for Warrick and Nielsen (1980). Next, Warrick and Nielsen (1980) used a continuous solute source without upward (evaporation) or lateral driving forces (root water uptake) for solute and water movement. While results and conclusions by Warrick and Nielsen (1980) are theoretically correct, we believe that in field conditions small-scaled variability in soil hydrologic properties may not play a very significant role in terms of transporting the center mass of a surface-applied solute pulse.

Although the mean remained about the same, the cv of the solute concentration from the 50 realizations showed a consistent increase with depth for both the autocorrelated and uncorrelated conditions (Fig. 10). Because different ranges in K_s would occur in regions bounded by the correlation length, autocorrelated K_s fields tended to have higher variations than the uncorrelated fields. The magnitude of variation increased from sprinkler to drip to furrow irrigation. This result further indicated the presence of preferential flow at deeper depths in furrow (or drip) than in sprinkler irrigation.

SUMMARY AND CONCLUSIONS

Assuming a fixed amount of water and chemical input, hydraulic parameters and solute concentration distributions under drip, furrow, and sprinkler irrigation were obtained with a deterministic solute transport model. Because of differences in infiltration area and surface ponding depth, sprinkler irrigation

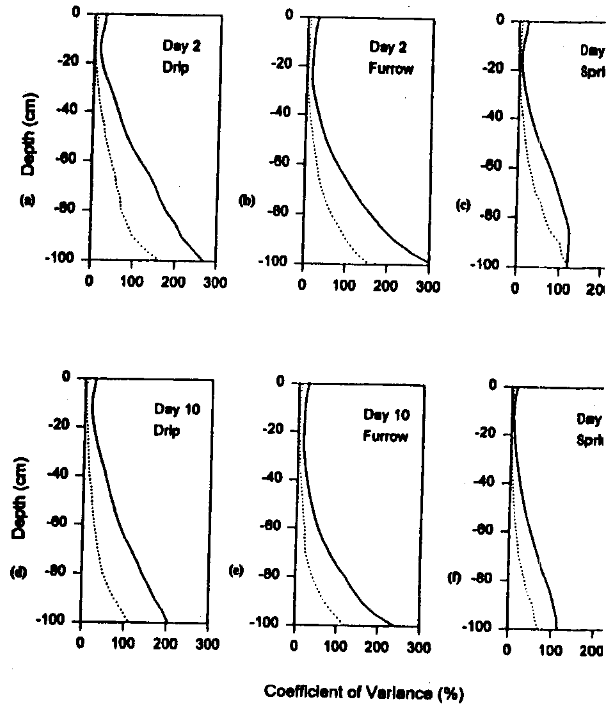

FIG. 10. Coefficient of Variance of Solute Concentration = 67.5 cm) for 50 Realizations of Autocorrelated (Solid I and Uncorrelated (Dotted Lines) K_s Fields under Drip, Fu and Sprinkler Irrigation

required the least amount of time to infiltrate the presc amount of water or chemical, followed by furrow anc irrigation. As compared to sprinkler irrigation, drip irrig took 85% more time to infiltrate the same prescribed an of water and solute. Furrow irrigation appeared to leac tracer chemicals more efficiently than either drip or spri irrigation methods. Two days after starting irrigation, s concentrations in the furrow irrigated soil were 40% l than those in either the drip- or sprinkler-irrigated soils cm depth and 90% higher at 50 cm depth.

Spatial variability in K_s was simulated using Monte- techniques by generating two-dimensional fields of var conductivity values. Simulated scenarios included autoc lated and uncorrelated log-normally distributed hydraulic ductivity fields. Solute transport and concentration dist tions under spatially variable conductivity fields estimated with the solute transport model. Results indicat for a stationary stochastic process, spatial variability in draulic conductivity reduces infiltration rate. Surface ap tracers traveled deeper into the soil through the high con tivity regions of the autocorrelated field under all three gation methods. The concentration distributions for the u related hydraulic conductivity field were not very diff from those for the homogeneous K_s field. When averaging ute concentrations over multiple realizations of the simula distributions for the autocorrelated and uncorrelated hydr conductivity fields were found to be very similar to thos the homogeneous K_s field. This may indicate that spatially iable hydraulic conductivities may not have a significant e on transferring the center mass of a surface applied nonso chemical over a large area, compared to other factors suc preferential flow through macropores. Nevertheless, when ject to spatial variation, solute concentrations vary as d increases. The variation in solute concentration was high the autocorrelated than in the uncorrelated K_s fields. It indicates that sprinkler irrigation has the least potentia preferential transport of water and solutes in soils with s tured hydraulic conductivity fields.

APPENDIX I. REFERENCES

Bear, J. (1972). *Dynamics of fluid in porous media.* Elsevier Science Publishing Co., Inc., New York, N.Y.

Beven, K. J., Henderson, D. E., and Reeves, A. D. (1993). "Dispersion parameters for undisturbed partially saturated soil." *J. Hydro.*, Amsterdam, The Netherlands, 143(3), 19–43.

Carsel, R. F., Smith, C. N., Mulkey, L. A., Dean, J. D., and Jowise, P. (1984). *User's manual for the pesticide root zone model (PRZM): Release 1, Rep. EPA-600/3-84-109,* U.S. EPA, Envir. Res. Lab., Athens, Ga.

Dagan, G. (1994). "The significance of heterogeneity of evolving scales to transport in porous formations." *Water Resour. Res.*, 30(12), 3327–3336.

El-Kadi, A. I. (1986). "A computer program for generating two-dimensional fields of autocorrelated parameters." *Ground Water*, 24(5), 663–667.

El-Kadi, A. I. (1987). "Variability of infiltration under uncertainty in unsaturated zone parameters." *J. Hydro.*, Amsterdam, The Netherlands, 90(5), 61–80.

El-Kadi, A. I., and Brutsaert, W. (1985). "Applicability of effective parameters for unsteady flow in nonuniform aquifers." *Water Resour. Res.*, 21(2), 183–198.

Freeze, R. A. (1980). "A stochastic-conceptual analysis of rainfall-runoff processes on a hillslope." *Water Resour. Res.*, 16(2), 391–408.

Garcia, L. A., Manguerra, H. B., and Gates, T. K. (1995). "Irrigation-drainage design and management model: Development." *J. Irrig. and Drain. Engrg.*, ASCE, 121(1), 71–82.

Jury, W. A., Gardner, W. R., and Gardner, W. H. (1991). *Soil Physics.* John Wiley & Sons, Inc., New York, N.Y.

Knisel, W. G., Leonard, R. A., and Davis, F. M. (1989). *GLEAMS User Manual.* Southeast Watershed Research Lab., Tifton, Ga.

Mantoglou, A., and Gelhar, L. W. (1987). "Capillary tension head variance, mean soil moisture content, and effective specific soil moisture capacity of transient unsaturated flow in stratified soils." *Water Resour. Res.*, 23(1), 47–56.

Matias, P., Correia, F. N., and Pereira, L. S. (1989). "Influence of spatial variability of saturated hydraulic conductivity on the infiltration process." *Unsaturated flow in hydrologic modeling: Theory and practice*, H. J. Morel-Seytoux, ed., Kluwer Academic Publishers, London, U.K., 455–67.

Mejia, J. M., and Rodriguez-Iturbe, I. (1974). "On the synthesis of random field sampling from the spectrum: An application to the generation of hydrologic spatial processes." *Water Resour. Res.*, 10(4), 705–711.

Miller, E. E., and Miller, R. D. (1956). "Physical theory of capillary flow phenomena." *J. Appl. Phys.*, 27(4), 324–332.

Neuman, S. P. (1990). "Universal scaling of hydraulic conductivities and dispersivities in geologic media." *Water Resour. Res.*, 26(8), 1749–1758.

Persaud, N., Giraldez, J. V., and Chang, A. C. (1985). "Monte-Carlo simulation of non-interacting solute transport in a spatially heterogeneous soil." *Soil Sci. Soc. Am. J.*, 49(3), 562–568.

"Root Zone Water Quality Model. version 1.0," (1992). *GPSR Tech. Rep. No. 3,* Agric. Res. Svc., Great Plains Systems Research Unit, Ft. Collins, Colo.

Rubin, Y. (1990). "Stochastic modeling of macrodispersion in heterogeneous porous media." *Water Resour. Res.*, 26(1), 133–142.

Simunek, J., and van Genuchten, M. T. (1994). "The CHAIN-2D code for simulating the two-dimensional movement of water, heat, and multiple solutes in variably-saturated porous media, Version 1.1." *Res. Rep. No. 136.* U.S. Salinity Laboratory, USDA-ARS, Riverside, Calif.

Sudicky, E. A. (1986). "A natural-gradient experiment on solute transport in a sand aquifer: Spatial variability of hydraulic conductivity and its role in the dispersion process." *Water Resour. Res.*, 22(13), 2069–2082.

Tillotson, P. M., and Nielsen, D. R. (1984). "Scale factors in soil science." *Soil Sci. Am. J.*, 48(5), 953–959.

Tompson, A. F. B., Ababou, R., and Gelhar, L. W. (1989). "Implementation of the three-dimensional turning bands random field generator." *Water Resour. Res.*, 25(10), 2227.

Troiano, J., Garretson, C., Krauter, C., Brownell, J., and Huston, J. (1993). "Influence of amount and method of irrigation water application on leaching of atrazine." *J. Envir. Qual.*, 22(2), 290–298.

Tseng, P. H., and Jury, W. A. (1993). "Simulation of field measurement of hydraulic conductivity in unsaturated heterogeneous soil." *Water Resour. Res.*, 29(7), 2087–2099.

Tseng, P. H., and Jury, W. A. (1994). "Comparison of transfer function and deterministic modeling of area-averaged solute transport in a heterogeneous field." *Water Resour. Res.*, 30(7), 2051–2063.

van Genuchten, M. T. (1980). "A closed-form equation for predictin hydraulic conductivity of unsaturated soils." *Soil Sci. Soc. Am* 44(5), 892–898.

van Genuchten, M. T., and Shouse, P. J. (1989). "Solute transpo heterogeneous field soils." *Intermedia pollutant transport: Mod and field measurement*, D. T. Allen, Y. Cohen, and I. R. Kaplan, Plenum Publishing Corp., New York, N.Y., 177–187.

Vogel, T., Cislerova, M., and Hopmans, J. W. (1991). "Porous m with linearly variable hydraulic properties." *Water Resour.* 27(10), 2735–2741.

Wagenet, R. J., and Hutson, J. L. (1987). *LEACHM: A finite-diffe model for simulating water, salt, and pesticide movement in the root zone, continuum 2.* New York State Resources Institute, Co Univ., Ithaca, N.Y.

Wallach, R., Israeli, M., and Zaslavsky, D. (1991). "Small perturb solution for steady nonuniform infiltration into soil surface of a ge shape." *Water Resour. Res.*, 27(7), 1665–1670.

Warrick, A. W. (1990). "Application of scaling to the characterizati spatial variability in soils." *Scaling in Soil Physics: Principles Applications*, D. Hillel and D. E. Elrick, eds., SSSA Special Publ. 25, Soil Sci. Soc. Am., Madison, Wis., 39–51.

Warrick, A. W., and Nielsen, D. R. (1980). "Spatial variability of physical properties in the field." *Applications of Soil Physics*, D. H ed., Academic Press, Inc., New York, N.Y., 319–44.

Wierenga, P. J., Hills, R. G., and Hudson, D. B. (1991). "The Las C Trench site: Characterization, experimental results, and one-di sional flow predictions." *Water Resour. Res.*, 27(10), 2695–2705

Yaron, B., Gerstl, Z., and Spencer, W. F. (1985). "Behavior of herbi in irrigated soils," *Adv. Soil Sci.*, 3, 121–211.

Yeh, T. C. J., Gelhar, L. W., and Gutjahr, A. L. (1985). "Stoch analysis of unsaturated flow in heterogeneous soils. 1: Statisticall tropic media." *Water Resour. Res.*, 21(4), 447–456.

APPENDIX II. NOTATION

The following symbols are used in this paper:

C = solute concentration;
CV = coefficient of variance;
D_L, D_T = longitudinal and transverse dispersivity;
D_w = molecular diffusion coefficient in free water;
$\mathbf{D}_{ij}^w$ = dispersion coefficient tensor;
$G(W_m)$ = values chosen from uniform distribution over range 0–1;
K_s = saturated hydraulic conductivity;
q, q_i, q_j = components of Darcian fluid flux density;
t = time;
W_m = dummy variable;
x_i = coordinate in horizontal direction of two-dimensi field;
x_j, z_i = coordinate in vertical direction of two-dimensi field;
Y = parameter that was used to transform K_s from normal to normal distribution;
α, n = characteristic hydraulic parameters of soil;
γ_m, ϕ_m = random angular variables chosen from uniform d bution over the range $0-2\pi$ or ($U[0, 2\pi]$);
δ_{ij} = Kronecker delta function;
ε_{ij} = residuals from a stochastic process of $N[0, 1; \lambda_Y$
θ = volumetric soil water content;
θ_r, θ_s = residual and saturated volumetric soil water cont
λ_Y = autocorrelation parameter;
μ_{K_s}, σ_{K_s} = mean and standard deviation of log-normally di uted saturated hydraulic conductivity;
μ_Y, σ_Y = mean and standard deviation of population for Y
$\rho_Y(l)$ = autocorrelation function as of lag l; and
τ_w = tortuosity factor in water and solute transport.