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Abstract

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Keywords

Soil hydraulic properties, Solute transport properties, TDR, Solute breakthrough curves

Disciplines

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A dripper-TDR method for in situ determination of hydraulic conductivity and chemical transport properties of surface soils [☆]

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Abstract

Field determined hydraulic and chemical transport properties can be useful for the protection of groundwater resources from land-applied chemicals. Most field methods to determine flow and transport parameters are either time or energy consuming and/or they provide a single measurement for a given time period. In this study, we present a dripper-TDR field method that allows measurement of hydraulic conductivity and chemical transport parameters at multiple field locations within a short time period. Specifically, the dripper-TDR determines saturated hydraulic conductivity (K_s), macroscopic capillary length (λ_c), immobile water fraction (θ_{im}/θ), mass exchange coefficient (α) and dispersion coefficient (D_m). Multiple dripper lines were positioned over five crop rows in a field. Background and step solutions were applied through drippers to determine surface hydraulic conductivity parameters at 44 locations and surface transport properties at 38 locations. The hydraulic conductivity parameters (K_s , λ_c) were determined by application of three discharge rates from the drippers and measurements of the resultant steady-state flux densities at the soil surface beneath each dripper. Time domain reflectometry (TDR) was used to measure the bulk electrical conductivity of the soil during steady infiltration of a salt solution. Breakthrough curves (BTCs) for all sites were determined from the TDR measurements. The K_s and λ_c values were found to be lognormally distributed with average values of 31.4 cm h⁻¹ and 6.0 cm, respectively. BTC analysis produced chemical properties, θ_{im}/θ , α , and D_m with average values of 0.23, 0.0036 h⁻¹, and 1220 cm² h⁻¹, respectively. The estimated values of the flow and transport parameters were found to be within the ranges of values reported by previous studies conducted at nearby field locations. The dripper TDR method is a rapid and useful technique for in situ measurements of hydraulic conductivity and solute transport properties. The measurements reported in this study give clear evidence to the occurrence of non-equilibrium water and chemical movement in surface soil. The method allows for quantification of non-equilibrium model parameters and preferential flow. Quantifying the parameters is a necessary step toward determining the influences of surface properties on infiltration, runoff, and vadose zone transport.

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1. Introduction

Understanding the mechanisms by which water and land-applied chemicals move through the vadose zone

is of considerable importance for managing soil and groundwater resources. Hydraulic and chemical transport properties are required by models to predict contaminant movement towards groundwater resources. Therefore, field and laboratory studies have been conducted for the last three decades to estimate hydraulic and chemical transport properties of the vadose zone. Such initiatives have provided a conceptual understanding of the processes that control transport. However, the complexity associated with transport mechanisms necessitates the need for further research exploration, especially for non-equilibrium flow conditions.

Most field methods for measuring hydraulic and chemical transport properties are hampered by either time and/or energy constraints or by a limited range of measurements; i.e., they provide a snapshot of parameters at a given period of time. Therefore, there is need for reliable field procedures that can provide quick real-time measurements with relatively minimum energy requirements.

Zhang et al. [33] recently introduced a method to measure unsaturated soil hydraulic properties using multi-purpose TDR probes below a surface line source (sprinkler) with constant flux of water. The technique is useful under unsaturated conditions, but it involves installation of several probes at one location and determines only the soil hydraulic properties.

Or [20] presented an experimental setup utilizing a dripper method to measure in situ distribution of saturated hydraulic conductivity (K_s , LT^{-1}) and the macroscopic capillary length (λ_c , L) with relatively minimum labor requirements. The hydraulic conductivity parameters can be determined from the solution for shallow, circular ponded infiltration as presented by Wooding [29]:

$$q = \frac{Q}{\pi r^2} = K_s \left(1 + \frac{4\lambda_c}{\pi r} \right) \quad (1)$$

where Q is the volumetric flux rate (L^3T^{-1}), q is the total flux density (LT^{-1}), and r is the ponded radius over the soil surface. Eq. (1) is valid for $r/\lambda_c \leq 10$. The total steady flux density, q , is the sum of gravitational flow (K_s) through the ponded circular area and flow due to capillary forces. The λ_c parameter quantifies the capillary forces relative to gravity forces on water movement [21]. The movement of water due to capillary forces can exceed gravitational flow in the soils having small values of r/λ_c . Water infiltrating from a shallow surface pond should consist of more lateral movement in fine-textured soils than in coarse-textured soils. The flux density inside a ponded circle (q_i) is approximately equal to K_s in soils with large values of r/λ_c (~ 10), and is closely related to the flux measured within an inner ring of a ring infiltrometer. Relatively small values of r/λ_c (< 10) are associated with relatively

large capillary movement and hence as water spreads out, the mean vertical flux rate decreases with depth as follows:

$$q_i(r, z) = P(r/\lambda_c, z)q \quad (2)$$

where $P(r/\lambda_c, z)$ is the fraction of the total surface flux at depth z which varies with different values of r/λ_c . The values of $P(r/\lambda_c, z)$ can be determined by the streamline curves of flux rate presented by Wooding [29, Fig. 8(a)–(f)], for different values of r/λ_c .

Based on Eq. (1) the K_s - and λ_c -parameters can be determined from the resulting intercept and slope of a linear regression between q and $1/r$. Knowing q , r , and λ_c , the flux density inside the circle (q_i) at depth z can be determined by Eq. (2). Once q_i is determined for a particular z , the mean pore water velocity, v , at z is estimated as q_i/θ .

Studies have reported that water and dissolved constituents can move through the vadose zone along preferred pathways, such as soil cracks, worm holes and root channels (e.g. [22,16]). This non-equilibrium phenomenon, known as preferential flow, causes asymmetry in breakthrough curves (BTCs), i.e., contaminants can reach great depths (through large openings of the soil) in relatively short times. This phenomenon cannot be predicted by the classical convection-dispersion equation (CDE) as cited by van Genuchten and Wierenga [26,27].

Coats and Smith [8] modified the CDE to better describe the asymmetry of BTCs. The modified CDE, often called the mobile-immobile model (MIM), was found to better predict flow through structured soils than the classical CDE [28]. The MIM partitions the water-filled pore space (θ) into two domains: a mobile domain (θ_m), where chemicals move by advection and an immobile domain (θ_{im}), where water is relatively stagnant and chemicals move by diffusion only. The chemical dispersion in the mobile domain is similar to that in the CDE. For one-dimensional movement of conservative non-sorbing chemicals, the MIM can be written as [26]:

$$\theta_m \frac{\partial C_m}{\partial t} + \theta_{im} \frac{\partial C_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - \theta_m v \frac{\partial C_m}{\partial z} \quad (3)$$

where C_m and C_{im} are the concentrations of chemicals in the mobile and immobile domains (ML^{-3}), D_m is the dispersion coefficient (L^2T^{-1}) in the mobile domain, v is the pore water velocity in the mobile domain (LT^{-1}), t is time (T) and z is depth (L). The water in the immobile domain (θ_{im}) acts as a source or sink for the dissolved chemicals in the mobile domain. Therefore, chemical transfer between the two domains is a function of the concentration difference between the domains and can be described as a first-order rate diffusion process [26]:

$$\theta_{\text{im}} \frac{\partial C_{\text{im}}}{\partial t} = \alpha(C_m - C_{\text{im}}) \quad (4)$$

where α is the first-order mass exchange coefficient (T^{-1}).

Extending the work of Clothier et al. [7], Jaynes et al. [13] and Jaynes and Horton [14] solved Eq. (4) to give estimates for the immobile water content (θ_{im}) and the mass exchange coefficient (α). Their solution involved applying a sequence of conservative tracers into the soil using tension infiltrometers. Lee et al. [15] presented a procedure to solve Eq. (4) using a single conservative tracer and real-time measurements of relative concentration. They used time domain reflectometry (TDR) to measure the change in relative concentration with respect to time ($\bar{C}(t)$) from TDR-measured impedance load (Z) as follows:

$$\bar{C}(t) = \frac{C(t) - C_i}{C_0 - C_i} = \frac{Z^{-1}(t) - Z_i^{-1}}{Z_0^{-1} - Z_i^{-1}} \quad (5)$$

where $C(t)$ is the chemical concentration at any time (ML^{-3}), is the background solution of the chemical, C_0 is the input chemical concentration, Z_i is the TDR impedance load for C_i , Z_0 and is the impedance load for C_0 .

Lee et al. [15] used the TDR-technique with probes installed diagonally at a depth of 2-cm from the surface of intact soil columns. They estimated all of the MIM transport parameters (θ_{im} , α , D_m) from the observed TDR and effluent BTCs. They reported a good agreement between estimated parameters from the Jaynes et al. [13] solution and the TDR method. Moreover, their estimated transport parameters from the TDR method were in general agreement with the estimated parameters from the effluent data. Gaur et al. [11] tested the surface TDR technique in a greenhouse disturbed soil pit. The surface measurements were useful in predicting subsurface solute transport. To date the full set of MIM surface parameters of a field soil have not been reported. There exists a need for developing and applying a method for measuring a full set of surface properties of field soils.

Al-Jabri et al. [1] demonstrated that the Or [20] setup could be utilized to estimate related hydraulic conductivity (K_s and λ_c) and chemical transport properties ($\theta_{\text{im}}/\theta$ and α). Al-Jabri et al. [2] adapted the drifter method to determine the distributions of K_s , λ_c , $\theta_{\text{im}}/\theta$, and α under field conditions. In the Al-Jabri et al. [1,2] studies, sequential tracers were used to determine $\theta_{\text{im}}/\theta$ and α . A need for field determination of surface values of D_m still remained.

One objective of this study is to combine the TDR method of Lee et al. [15] with the drifter method of Or [20] in order to develop a field method for simultaneous and rapid determination of surface K_s , λ_c , $\theta_{\text{im}}/\theta$, α , and D_m at multiple field positions. Another objective

of this study is to determine the distribution of such properties under field conditions.

2. Material and methods

2.1. Site description and experimental setup

The study was conducted in a no-till cornfield at the Agronomy-Agricultural Engineering Research Center, Iowa State University, Ames, IA. The soil at the research site is predominantly Nicollet loam (0.389 sand, 0.366 silt, 0.245 clay mass fraction), and classified as fine loamy, mixed, mesic, Aquic Hapludolls. The average bulk density of the top 10-cm was 1.43 Mg m^{-3} . The study was conducted on a 6- by 15-m field grid after fall harvest. Five parallel transects were selected on corn rows. Transects were about 15-m long and about 1.5-m apart. A drifter-line setup similar to that described in Al-Jabri et al. [2] was placed on the five transects. The setup consisted of three drifter tubes positioned over each transect. Each tube was equipped with one type of pressure-compensating (55–83 kPa) emitter (Blue Stripe Drip model, Toro Co., Bloomington, MN) designed to deliver one (i.e., constant) discharge rate. Emitters were designed to deliver discharge rates of 2, 4, and 8 L h^{-1} with a coefficient of discharge among the drippers of 7%. With this setup, each location was equipped with three types of emitters that could discharge water at almost the same spot on the soil surface. Sets of emitters on the bundled tubes were spaced 1.5-m apart. Therefore, there were 10 field locations on each transect and 50 locations for the whole site. Tubes on transects were connected so that they could be operated individually or simultaneously. From a total of 50 sets of emitters, 6 emitters experienced partial clogging of the emitters during the experiment. Because of the clogging problem, the surface hydraulic conductivity parameters at 44 locations were determined. After completing the hydraulic conductivity property measurements TDR probes were placed at 38 locations beneath the drifter lines in order to determine surface transport properties. Fig. 1 illustrates the experimental arrangement of the drifter-TDR setup.

2.2. Measurements of hydraulic conductivity parameters

Experimental work started with estimation of the hydraulic conductivity parameters (K_s , λ_c) from the Wooding solution. This was achieved by applying three consecutive discharge rates (2, 4, 8 L h^{-1}) at each soil surface site. We started by applying the lowest discharge rate at all locations. The diameters of the ponded circular areas were measured as a function of time until each pond reached a constant size when steady state conditions were assumed. It took about 1 h to reach a steady

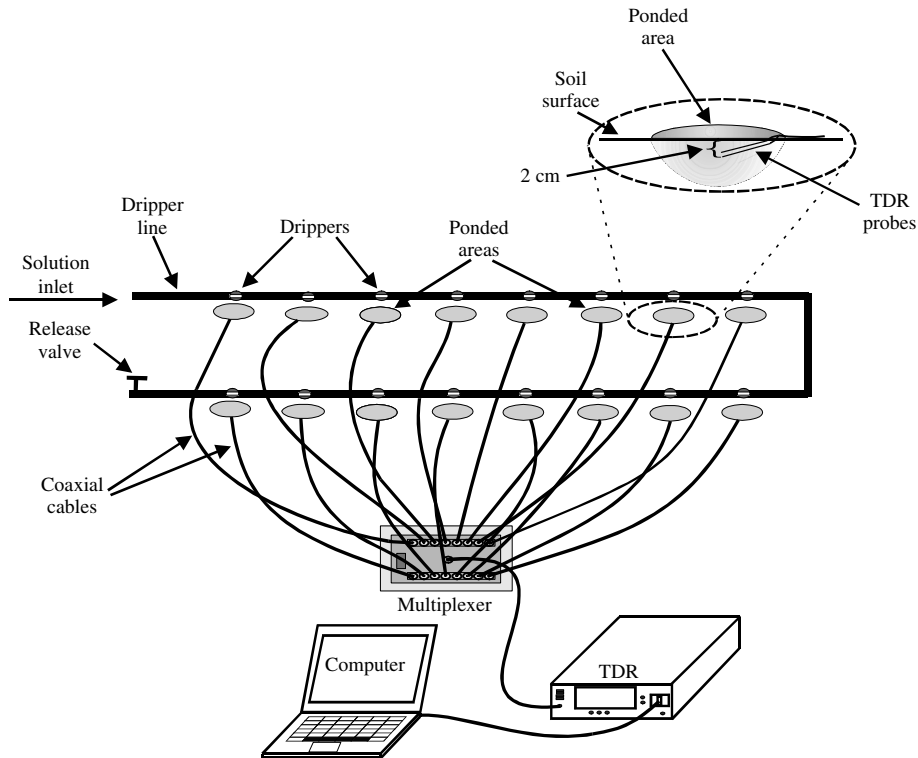


Fig. 1. Drinker-TDR setup in the field (2 transects are shown).

state condition. Similar measurements (ponding diameters) were repeated for the second and third discharge rates. Steady state pond diameter at each site for each discharge rate was measured and recorded. Linear regressions of the surface flux density (q) versus the inverse of ponded radii (i.e., $1/r$) were performed to estimate the hydraulic conductivity parameters for each site.

2.3. Measurements of chemical transport properties

The TDR-setup (Fig. 1) consisted of a 1052B Tektronix cable tester (Tektronix, Beaverton, OR)¹, a multiplexer (Dynamax, Houston, TX), TDR probes, and a computer. The TDR probes (each is 2 rods, 3.8-mm diam. by 100-mm long) were connected to the cable tester through the multiplexer. Each TDR probe was connected to the multiplexer with a 50 Ω coaxial cable (10-m long). The cable tester was connected to the computer, where the TACQ program [10] was used to acquire the data required for measuring $Z(t)$. The real time measurements of $Z(t)$ were determined using the TDR-waveform analysis presented by Wraith et al. [31].

The experimental work was started by applying a background solution composed of 0.005 M CaCl_2 from the drippers (at each site) to the soil surface at a dis-

charge rate of 4 L h^{-1} . The discharge rate of each dripper was measured and recorded. The ponded area at the steady-state conditions (at each site) was measured and recorded. After steady-state conditions prevailed, a TDR probe (at each site) was carefully installed beneath the ponded area at an angle to a depth equal to 20-mm from the soil surface. The background solution was used to determine C_i . After measuring C_i , a step solution composed of 0.2 M CaCl_2 was applied by the same dripper. The step solution was applied for a time long enough to allow the solution to pass the 2-cm depth. Continuous measurements of $Z(t)$ were made with the TDR system.

After the application of the solution for a sufficient time (about 1.5 h), a 2-cm deep soil sample (equal to the probe depth) was taken from beneath each dripper using stainless steel rings. Each soil sample was split into two subsamples for determination of soil water content and the resident Cl^- concentration of the soil solution, C . Distilled water was added to one subsample at a ratio of approximately 1:2 soil–water to water–mass ratio. Samples were shaken for about 5 min and extracted using No. 11 filter paper. Filtered solutions and input solutions were analyzed for Cl^- concentration using a digital chloridimeter (HAAKE Buchler, Saddle Brook, NJ). Knowing the final concentration of soil solution, $C(t)$, input tracer concentration, C_0 , and background concentration, C_i , it was possible to determine the final value of the relative resident concentration; $\bar{C}(t)$ in Eq.

¹ Company and product names do not imply endorsement.

(5). Subsequently, the corresponding final value of $C(t)$, was determined and used to normalize the $\bar{C}(t)$ for each location.

Additional details describing the determination of $\bar{C}(t)$ from the TDR-measured $Z(t)$ can be found in Lee et al. [15].

2.4. Determining chemical transport parameters

Breakthrough curves (BTCs) from the TDR-measured $\bar{C}(t)$ were determined for each site. All transport parameters (θ_{im} , α , D_m) were inversely estimated by curve-fitting the MIM solution to the observed BTCs. The CXTFIT package [25] was used to inversely fit the appropriate MIM model to the BTC's. The soil depth, at which the transport parameters were fitted, was the middle point of the vertical depth of the TDR probes [15]. The flux density (q) and hydraulic property (λ_c) measured at each surface location were used to determine the flux rate (and pore water velocity, v) inside the ponded area (r) at the equivalent depth (z) of TDR probes by using Eq. (2). Initial work with the CXTFIT package revealed a non-uniqueness problem with the data, whereby the predicted values, D_m in particular, were sensitive to initial guesses. To overcome this problem, we determined the immobile water content and the α -parameter from the log-linear method developed by Lee et al. [15] from Eq. (2) and set them as initial guesses in the input files. Moreover, we tested a wide range of initial D_m values against a range of initial θ_{im} and α values and then chose the initial D_m value ($100 \text{ cm}^2 \text{ h}^{-1}$), which led to a global minimum. To as-

sure that initial guesses led to a global minimum, we conducted a direct simulation with the CXTFIT using fitted parameters. Generated BTCs from direct simulations were almost identical to those produced from the TDR measurements ($r^2 > 0.95$).

2.5. Spatial distribution of hydraulic conductivity and chemical transport properties

Tests of normality [19] and a non-parametric correlation test (Pearson coefficient test [19]) were performed to study the distribution of parameters. Spatial correlation of the hydraulic conductivity and chemical transport parameters across the 7- by 15-m field area was evaluated using the directional semivariogram test [9]. No directional effects in the semivariograms were identified. Therefore, semivariograms with all directions combined, i.e., along rows, across rows, diagonal to rows, were computed. The spatial variability of all computed parameters was tested at 1.5-m lag intervals. Contour plots of the properties were drawn with the Surfer software package (version 7, Golden Surfer Inc., Golden, CO).

3. Results and discussions

3.1. Soil hydraulic conductivity parameters

Fitting measured flux densities, q , versus the inverse of corresponding ponded radii ($1/r$) of each location, yielded a straight line (Fig. 2) where the intercept was

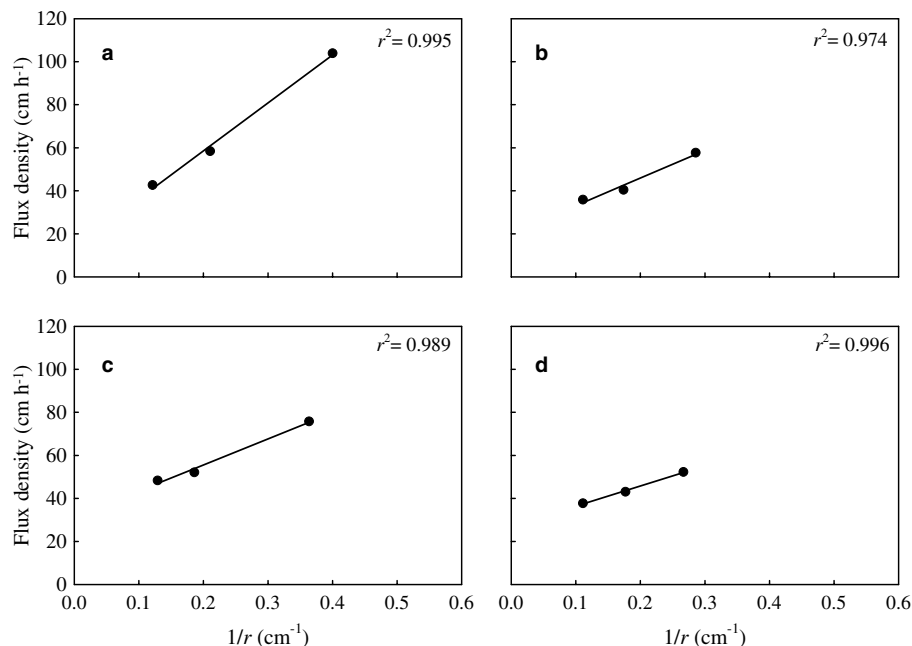


Fig. 2. Examples of flux densities versus $1/r$ of some selected sites. The points and solid lines are the measured and fitted values, respectively.

the saturated hydraulic conductivity, K_s , and the λ_c parameter was determined from the resulting slope, $4K_s\lambda_c/\pi$. The median coefficient of determination (r^2) of the fitting procedure was 0.89.

The Kolmogorov–Smirnov and goodness-of-fit tests verified that K_s and λ_c were best represented by lognormal distributions. Table 1 presents summary statistics of the log-transformed hydraulic conductivity parameters measured across the field. Measurements were taken at the end of the growing season on corn rows, where macropores usually exist due to the rooting system [23]. The presence of macropores help to explain why K_s values tended to be quite large [32].

Estimated K_s was used to estimate λ_c from the resulting intercept. In terms of variability, therefore, estimated λ_c was expected to have more variability than estimated K_s . This was clearly shown in terms of coefficient of variability (CV) values for the two parameters. The CV of λ_c (169%) was more than double that of K_s (70%). Mohanty et al. [17] used ponded and tension infiltrometers to measure the hydraulic parameters (K_s , λ_c) on a nearby no-till cornfield during an earlier corn-growing season. Their K_s -values ranged from 1.0 to 260 cm h^{-1} , with an average of 40 cm h^{-1} and a CV of

91%. Our study average (31 cm h^{-1}) and CV were comparable to their values. Their measured λ_c ranged from 7.8 to 55.6 cm with an average value of 24.4 cm. Their CV value for λ_c was 44%, which was considerably lower than that of our study. Quality of data and methods of analysis could be sources of such differences in numbers between the studies, but the main cause of differences is most likely caused by natural spatial and temporal variability of soil surface properties. The Mohanty et al. [17] measurements were obtained during the summer growing season while our measurements were obtained after fall harvest. Cultivation, plant growth stages, root distribution patterns and weather all affect surface soil hydraulic properties temporally. In cultivated fields the surfaces are influenced by human and by natural processes. Hydraulic properties do not remain constant in time. Thus, timing of observations is important relative to determination and comparison of surface hydraulic parameters [4].

Fig. 3 presents a contour map and the corresponding histogram for the distribution of measured K_s values across the plant rows. There was no obvious trend in the distribution of measured K_s , however it was clear that single large values do cause quite a few contours to appear on the plot. The histogram indicated that about 77% of the measured K_s values fell between 20 and 40 cm h^{-1} . The log K_s -semivariogram (figure not shown) indicated a nugget effect with little spatial correlation between the nearest sites for the measured K_s values. Therefore, there was no obvious spatial correlation of K_s that could be detected on the corn rows at distances >1.5 m under no-till conditions.

Fig. 4 presents a contour map and the corresponding histogram for the distribution of measured λ_c values. The contour map indicated the locations of a few distributed large single values. The histogram indicated

Table 1
Summary of log-transformed surface hydraulic properties

	K_s (cm h^{-1})	λ_c (cm)
Mean	31.4	6.0
Median	27.2	2.2
Minimum	7.5	0.03
Maximum	79.0	13.1
Std. Dev. ^a	18.1	15.7
CV (%) ^b	70	169

^a Standard deviation.

^b Coefficient of variability.

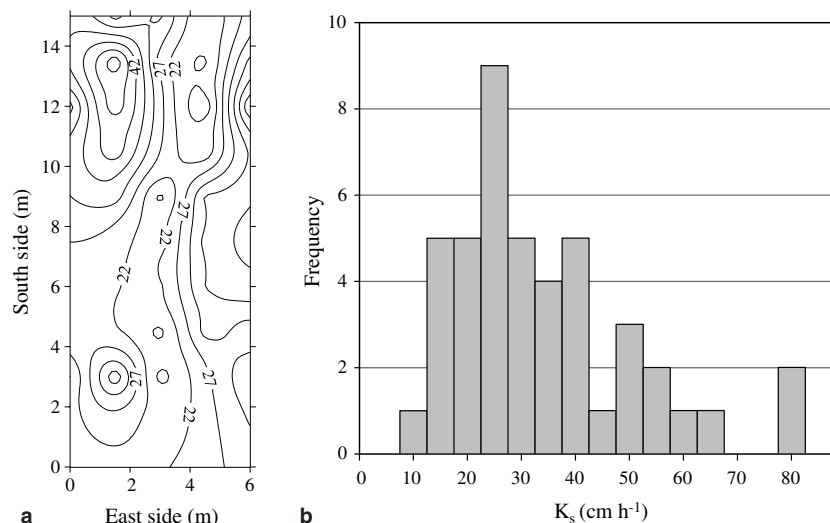


Fig. 3. Contour map and corresponding histogram for the distribution of measured saturated hydraulic conductivity (K_s).

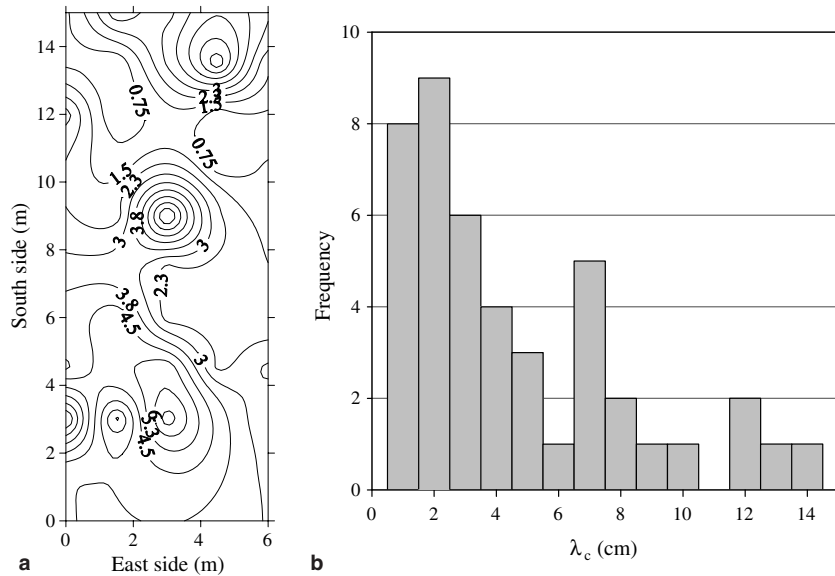


Fig. 4. Contour map and corresponding histogram for the distribution of measured macroscopic capillary length (λ_c).

that about 55% of λ_c values were in the range of 0–5 cm. The log λ_c -semivariogram (figure not shown) indicated that there was no obvious spatial correlation of λ_c on corn rows for lag distances >1.5 m.

3.2. Soil chemical transport properties

The TDR measurements responded well to the travel time of the chemical solutions in the soil. Examples of observed breakthrough curves (BTCs) of the step solu-

tion from the TDR measurements are shown in Fig. 5. The points and solid lines in Fig. 5 represent the measured and fitted, respectively, relative concentration values. The CXTFIT-fitting produced an average coefficient of determination (r^2) of 0.985. Differences between the observed BTCs are indicative of the natural variability of soil across the field. Most sites had a maximum relative concentration, $\bar{C}(t)$, greater than 70% of the total maximum concentration. For the time scale of these measurements this implied that mobile flow

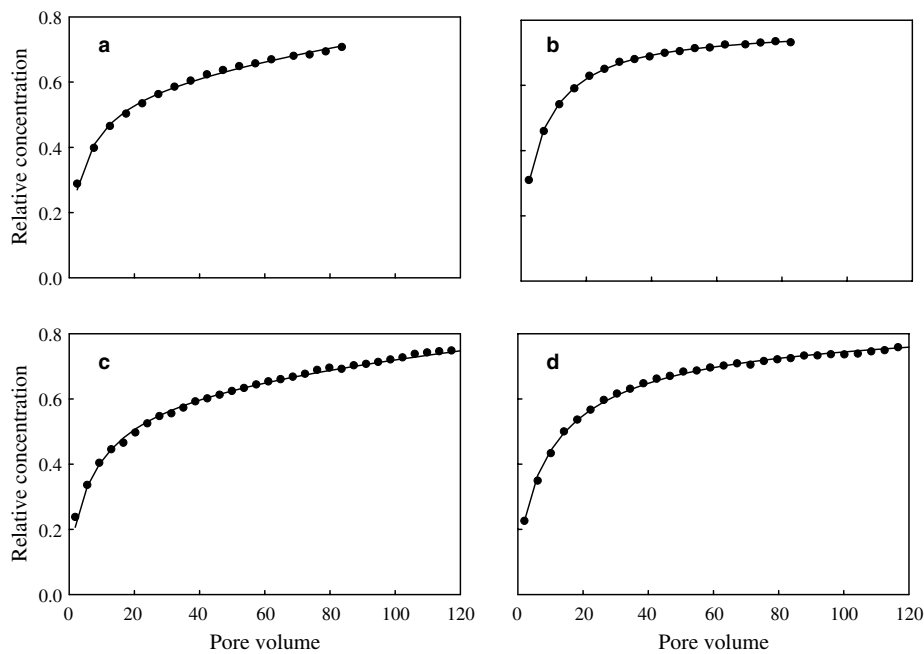


Fig. 5. Examples of observed (measured) resident relative concentration breakthrough curves based on TDR measurements. The points and solid lines correspond to measured and fitted data, respectively.

occurred in about 70% of the pore space. Because $\bar{C}(t)$ did not reach 1.0, some of the soil water was not involved in transport. Maximum relative concentrations less than 100% indicated that preferential flow was a contributor to solute transport in this soil. The dripper-TDR method enabled determination of the occurrence and distribution of preferential flow in surface soil. This finding has important implications on water infiltration and runoff and on chemical leaching through the vadose zone.

Table 2 presents a summary of the surface chemical transport parameters. The normality test demonstrated that θ_{im}/θ was normally distributed and pore velocity, v , D_m , and dispersivity, $\gamma(D_m/v)$ were lognormally distributed at a 95% confidence level. The α values did not definitively indicate normal or lognormal distribution, so a normal distribution was considered for the statistical summary. On average, θ_{im}/θ , α , v , D_m , and γ were found to be 0.24, 0.001 h⁻¹, 59 cm h⁻¹, 1220 cm² h⁻¹, and 21 cm, respectively.

Fig. 6 shows the histograms and contour map of the estimated chemical transport parameters. Fig. 6a indicates that about 76% of the estimated θ_{im}/θ fall within the range of 0.05–0.4. About 92% of the estimated values of the α parameter fall within the range of 0 to 0.08 h⁻¹ (Fig. 6b). Fig. 6c indicates that 84% of the estimated D_m values fall within the range of 150 to 2000 cm² h⁻¹.

To evaluate the dripper-TDR procedure, the results from this study were compared with the results reported by other methods and studies. The estimated values of θ_{im}/θ reported in this study were comparable with previously reported values [12]. Al-Jabri et al. [2] used the sequential application of multiple tracers suggested by Jaynes et al. [13] to estimate θ_{im}/θ and α for a loam soil located adjacent to this study site. Their reported mean estimate of θ_{im}/θ was 0.58, which was larger than the values reported in this study. A significant difference between the studies is that Al-Jabri et al. [2] used a reduced, approximate model to estimate parameter values, while the dripper-TDR method used the complete MIM solution to estimate the parameter values. Using ponded infiltrometers and sequential tracers,

Casey et al. [6] reported a log-linear fitted median θ_{im}/θ -value of 0.40 for a no-till loam soil. This was comparable to the log-linear median θ_{im}/θ -value (0.33) for the data collected in this study. Lee et al. [15], using undisturbed soil columns obtained from a field near our study site, reported a mean value of 0.31 for θ_{im}/θ , which was comparable to the values found in this study. Therefore, results from several investigations using a variety of methods have consistently shown that surface soil in central Iowa has an immobile fraction. The consistent finding of an immobile fraction has important implications on surface and vadose zone hydrology and chemical transport. Penetration depths of infiltrating water and chemical leaching are affected by the mobile and immobile fractions. The dripper-TDR technique that we present is the method that can provide the most complete set of parameter distributions across a field site.

Al-Jabri et al. [2] reported a mean α value of 0.04 h⁻¹. This is similar to the mean value reported here. Casey et al. [5], using tension infiltrometers, reported a larger median α value of 0.074 h⁻¹. To date most of the values of α are based upon laboratory measurements. Very few field values of α are available. Development of the dripper-TDR method provides a new opportunity for hydrologists and soil scientists to obtain field α values.

Lee et al. [15] reported a mean value of 245 cm² h⁻¹ for intact soil columns. Lee et al. [15] kept the flow rate small in their laboratory column study. The mean value of 245 for D_m in this study is much larger than that reported by Lee et al. [15] because the flow rates in this field study were much larger than the flow rates in Lee et al. [15]. However, the γ values in this study are comparable to the γ values in the Lee et al. [15] study. In general, the values of this study fall within the typical range of γ values reported in other field experiments [28].

No spatial correlation was detected across the field grid for any of the chemical transport parameters. The calculated semivariograms indicated pure nugget relationships, i.e., there was no spatial correlation in the distribution of transport parameters on the corn rows at distance >1.5 m. The lack of spatial structure found

Table 2
Summary of chemical transport parameters

Distribution	θ_{im}/θ Normal	α (h ⁻¹) Normal	D_m (cm ² h ⁻¹) Lognormal	v (cm h ⁻¹) Lognormal	γ (cm) Lognormal
Mean	0.23	0.036	1220	59.0	21.1
Median	0.24	0.001	921	56.0	16.5
Min.	0.00	0.000	145	30.7	3.47
Max.	0.56	0.418	5110	106	114
Std. Dev. ^a	0.13	0.083	1070	20.0	16.9
CV (%) ^b	57	230	81	64	78

^a Standard deviation.

^b Coefficient of variability.

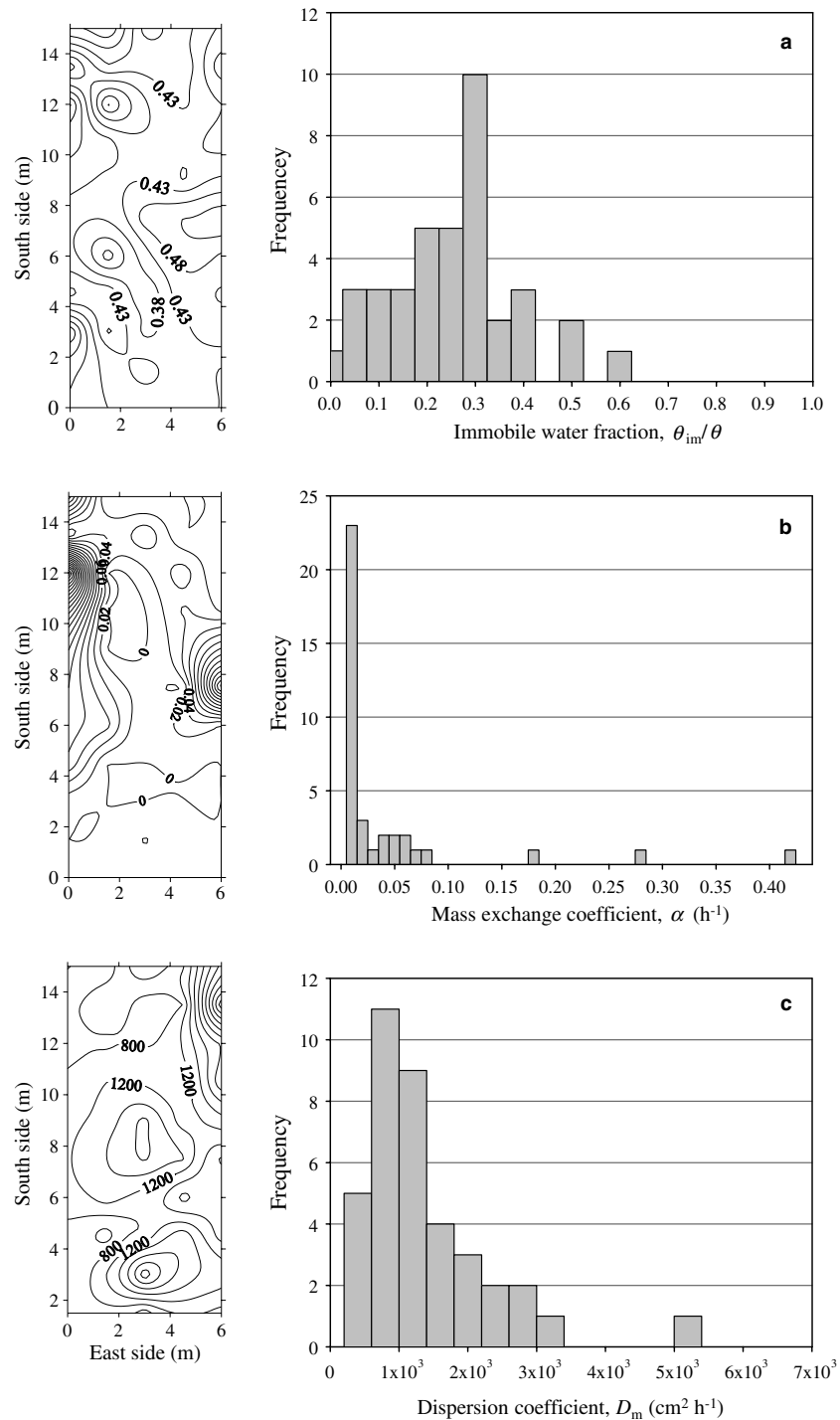


Fig. 6. Contour maps and corresponding histograms for the chemical transport parameters; (a) immobile water fraction, (b) mass exchange coefficient, and (c) dispersion coefficient.

for θ_{im}/θ in this study was similar to that reported by Casey et al. [5] and Al-Jabri et al. [2].

In no-till soils, the dripper-TDR technique successfully determined distributions of hydraulic conductivity and solute transport parameters. The technique has been found to be useful in relatively undisturbed, uniform soil, however, in less uniform or tilled soils, the drip-

per-TDR method has not been tested. Once tested in a variety of conditions, the technique could serve as a useful tool to determine complete sets of hydraulic conductivity and MIM parameters. The technique may provide an important step toward detecting and quantifying the possibility of preferential flow under field conditions.

4. Conclusion

This study presents a procedure for determining a set of hydraulic conductivity and chemical transport parameters for a field site. Hydraulic conductivity parameters at a total of 44 surface locations and chemical transport properties at 38 surface locations were determined within a 2-day period. Hydraulic conductivity parameters (K_s , λ_c) at each location were determined from steady infiltration flux densities determined from three dripper application rates. Chemical transport properties were determined from the real-time measurements of soil bulk electrical conductivity obtained with a TDR system. This procedure requires applying a single salt solution in order to collect and analyze breakthrough curves (BTCs). Estimated parameter values were representative and comparable with results reported by previous studies conducted on soil and soil columns from nearby field locations. The dripper-TDR method has two advantages over existing techniques for determining hydraulic conductivity and chemical transport properties of surface soil. One advantage is that hydraulic conductivity and MIM parameters can be determined with the dripper-TDR method. Other methods focus on determining either hydraulic conductivity (tension infiltrometers or ponded infiltration) or on an incomplete set of MIM parameters (log-linear analysis of a sequential tracer application). Another advantage of the dripper-TDR method is that it can be applied to several surface locations simultaneously so that parameter distributions across a field can be determined in a short time period. For hydrologists this is particularly important because hydrologists have known for some time that surface hydrology varies in time and space. The dripper-TDR method enables hydrologists to determine surface property distribution in space and time. Measurements of the surface property distributions will enable hydrologists to more effectively quantify and analyze surface and vadose zone processes. Furthermore, the simplicity of the dripper-TDR setup and procedure are ideal for rapid estimation of surface hydraulic conductivity and transport parameters across a field site. Measuring surface hydraulic conductivity and chemical transport properties provides a basis for quantitatively evaluating surface hydrologic processes such as infiltration and runoff and vadose zone processes such as preferential leaching of water and chemicals.

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