0038-075C/02/16706-353–368
Soil Science

June 2002
Vol. 167, No. 6
Printed in U.S.A.

TECHNICAL ARTICLES

FIELD DETERMINATION OF SOIL HYDRAULIC AND CHEMICAL TRANSPORT PROPERTIES[1]

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Hydraulic and chemical transport properties are the major inputs in predictive models that simulate the movement of water and chemicals through the vadose zone. However, there is a lack of field measurements of such properties to verify models describing water and chemical movement through the soil. One of the objectives of this study was to use a point source method to determine simultaneously the hydraulic and chemical transport properties at multiple field locations. A second objective was to determine the spatial distribution of such properties across a field. A total of 50 field locations within a 7 × 15-m area were rapidly and simultaneously evaluated for such properties. The hydraulic properties were the saturated hydraulic conductivity (K_s) and the macroscopic capillary length (λ_c). The chemical transport properties were the immobile water content, expressed as a fraction of water content (θ_{im}/θ) and the mass exchange coefficient (α). The hydraulic properties were determined by applying three discharge rates from irrigation dripper lines and measuring the resultant steady-state flux densities at the soil surface beneath each emitter. The chemical transport properties were determined by applying a sequence of three conservative tracers at a steady-state infiltration rate and measuring their resident concentration in the soil. The K_s values ranged from 7.5 to 79.0 cm h^{-1}, with a median of 27.4 cm h^{-1} (± 16.8). The λ_c values ranged from 0.03 to 13.1 cm, with a median of 2.6 cm (± 3.6). The θ_{im}/θ values ranged from 0.36 to 0.88, with a median of 0.57 (± 0.098). The α values ranged from 0.002 to 0.12 h^{-1}, with a median of 0.034 h^{-1} (± 0.027). The values of the hydraulic and chemical transport parameters were found to be comparable with values reported by studies conducted on nearby field locations on similar soil. Based on semivariogram analysis, the measured properties were not spatially correlated. Because the method required only 2 days to collect data it should prove useful for future studies that require extensive field measurements of hydraulic and chemical transport properties. (Soil Science 2002;167:353–368)

Key words: Solute transport properties, hydraulic conductivity, spatial variability.

PUBLIC concerns about the quality of drinking water have increased, in part, as a result of published reports from, for example, the United States Environmental Protection Agency (USEPA, 1989) about contamination of groundwater resources by agricultural and industrial chemicals. In Iowa, for example, field application of fertilizers and pesticides has resulted in some chemical contamination exceeding the USEPA advisory levels (Jayachan-

[1]Journal paper No. J-19148 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 3287. Supported by CSREES, USDA, NRICGP Soils and Soils Biology Program award No. 2001-35107-09938 and by Hatch Act and State of Iowa funds.

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Received Sept. 14, 2001; accepted Feb. 28, 2002.

dran et al., 1994). Thus, there exists a need to protect water resources from land-applied chemicals.

Hydraulic and chemical transport properties are considered to be the major inputs in predictive models to simulate movement of water and chemicals through the vadose zone. Moreover, screening models would predict the movement of chemicals toward groundwater resources better if such properties were used to describe preferential flow patterns (USEPA, 1992). Therefore, evaluating the hydraulic and chemical transport properties under field conditions is considered to be an important step in developing management practices to protect our groundwater resources.

Many studies have shown that water and chemicals often move through the vadose zone along preferred pathways (Biggar and Nielsen, 1962; Ehlers, 1975; van Genuchten and Wierenga, 1977; Priebe and Blackmer, 1989; McKay et al., 1993) such as large cracks, macropores, root channels, or worm holes. This preferential flow is characterized by the rapid movement of water and chemicals through the large openings in the soil. Thus, water and chemicals can reach great depths in a relatively short time, which increases the risk of groundwater contamination. Studies with structured soil columns (e.g., Khan and Jury, 1990) have shown that preferential flow causes asymmetry (i.e., early breakthrough and distinct tailing) in the effluent breakthrough curves (BTCs). The early arrival of chemicals is often attributed to the preferential movement of water and chemicals through larger pores between soil aggregates. The long tailing of chemicals is often attributed to the diffusion of chemicals from smaller pores and dead-end pores into the mainstream flow.

Preferential flow often cannot be described using the convective-dispersive equation (van Genuchten and Wierenga, 1976). Alternatively, a two-domain model introduced by Coats and Smith (1964) is better used to describe the asymmetry in BTCs (van Genuchten and Wierenga, 1977). The two-domain model, often called the mobile-immobile model (MIM), divides soil water (θ) into two domains: a mobile water domain (θ_m), where water and chemicals move with mean pore velocity (v_m), and an immobile water domain (θ_{im}), where water (relative to θ_m) is stagnant and chemicals move by diffusion only. Dispersion of chemicals takes place in the mobile domain and is similar to that in the convective-dispersive equation (CDE). The water in the immobile domain acts like a source or sink for chemicals to the mobile domain. The MIM model is written as follows:

$$\theta_m \frac{\partial C_m}{\partial t} + \theta_{im} \frac{\partial C_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - q \frac{\partial C_m}{\partial z} \quad (1)$$

where C_m and C_{im} are the concentrations of chemicals in the mobile and immobile domains (M L^{-3}), D_m is the dispersion coefficient (L T^{-2}) in the mobile domain, q is the flux density (L T^{-1}), t is time (T), and z is depth (L). Chemical transfer between the two domains is proportional to the concentration difference between the two domains and is described as a first-order process (van Genuchten and Wierenga, 1976):

$$\theta_{im} \frac{\partial C_{im}}{\partial t} = \alpha(C_m - C_{im}) \quad (2)$$

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

The transport parameters of the MIM are usually found by inverse methods, where solutions to Eqs. 1 and 2 are fitted to observed BTCs (van Genuchten and Wagenet, 1989). However, BTCs are difficult to obtain in the field. As an alternative to BTCs in the field, Clothier et al. (1992) provided a solution to Eq. 2 to estimate θ_m from field studies. Their approach involved applying a single conservative tracer into the soil using a tension infiltrometer. Assuming negligible D_m and α within the sampling zone, Clothier et al. (1992) determined θ_m from the product of the water content and concentration of the tracer in the soil sample divided by the input concentration. Jaynes et al. (1995) extended the solution of Clothier et al. (1992) to further estimate α. They applied a sequence of conservative tracers from a tension infiltrometer into the soil. Assuming piston displacement of tracers in the soil, Jaynes et al. (1995) produced the following solution to Eq. 2:

$$\ln\left(1 - \frac{C}{C_o}\right) = \ln\left(\frac{\theta_{im}}{\theta}\right) - \left(\frac{\alpha}{\theta_{im}}\right)t^* \quad (3)$$

where C is the concentration of tracers in the soil sample, C_o is the concentration of tracers in the input solutions, and $t^* = t - z'/v$ is the time required for the solution front to pass the sampling depth (z'). Jaynes et al. (1995) assumed negligible tracer concentration in the soil prior to any tracer application, tracer concentration within the mobile domain (C_m) to be equal to the input concentration (C_o), and dispersion to be negligible within the sampling depth. They used multiple fluorobenzoate tracers to conduct their procedure. Fluorobenzoate tracers were found to have nearly identical transport properties in many soils (Jaynes, 1994) and similar diffusion coefficients (Bowman and Gibbens, 1992; Benson and Bowman, 1994). As given by Eq. 3, the results reported by Jaynes et al. (1995) showed good linearity between resident concentrations of tracers in the soil, $\ln(1 - C/C_o)$, and the application time, t^*. As shown by Eq. 3, the immobile water content (θ_{im}) and the mass exchange coefficient (α) can be computed from the resulting intercept and slope.

Few studies have been performed under field conditions to determine soil surface hydraulic properties (Or, 1996; Casey et al., 1998; Yitayew et al., 1998) and chemical transport properties (Clothier et al., 1992; Angulo-Jaramillo et al., 1996; Casey et al., 1997, 1998). Field methods for determining such properties are time and energy consuming because they are limited to a single measurement on a single observation site for a given time period. Because of this limitation, the advancements in field studies have lagged behind the advancements in theoretical concepts and simulation-transport models (Ward et al., 1995). Therefore, there exists a need for methods that allow conducting field measurements of such properties at multiple field locations in a short period of time.

A point source method has been developed to estimate the soil hydraulic properties *in situ* (Shani et al., 1987; Or, 1996; Revol et al., 1991, 1997; Yitayew et al., 1998). Wooding (1968) presented an approximate solution for water flow, at steady state flow conditions, from a shallow circular pond on the soil surface (point source) as:

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

where Q is the discharge rate from a source ($L^3\ T^{-1}$), q is the steady flux density ($L\ T^{-1}$), r_o is the pond radius (L), K_s is the saturated hydraulic conductivity ($L\ T^{-1}$), and λ_c is the macroscopic capillary length (L). The scaling parameter, λ_c, quantifies the importance of capillary forces, i.e., the attraction of water to dry soil, relative to gravity forces on water movement (Philip, 1969). It is large for fine-textured soils and small for coarse-textured soils. Thus, water flow from a point source into a fine-textured soil will have more lateral flow than that flowing into a coarse-textured soil. According to Wooding's solution, applying water from a point source results in a circular (or near circular) saturated ponded area beneath the source on the soil surface. The size of the ponded area increases with time, but it eventually reaches a constant size (Bresler, 1978) where steady-state conditions are assumed (Shani et al., 1987). Based on Eq. 4, regressing different flux densities (produced from applying different Q) rather than corresponding $1/r_o$ yields K_s as the intercept, and λ_c can be determined from the resulting slope, $4K_s\lambda_c/\pi$.

Or (1996) introduced an experimental setup and utilized the point source method to determine the hydraulic properties in the field. His setup allowed estimating the hydraulic properties with minimum labor requirements. Al-Jabri et al. (2002) developed and extended further the setup that was introduced by Or (1996). They presented a procedure for estimation of both hydraulic and chemical transport parameters from the point source method at multiple locations. Al-Jabri et al. (2002) demonstrated that the setup and procedure were able to determine both sets of properties rapidly and simultaneously. Moreover, the point source method worked well with the procedure of sequential application of tracers (Eq. 3). Compared with the estimates produced by ponded and tension infiltrometers, the point source method showed a consistency (i.e., less variability) in estimating the hydraulic and chemical transport properties.

Al-Jabri et al. (2002) evaluated the setup and the procedure on a disturbed soil pit under greenhouse conditions. They conducted their experimental work on six observation sites. The point source method of Al-Jabri et al. (2002) has not been used to determine hydraulic and chemical transport properties of natural field soil, nor has it been used at more than six observation sites. As a follow-up to the results reported by Al-Jabri et al. (2002), the point source method should be tested to determine the hydraulic and chemical transport properties at multiple locations under actual field conditions. Therefore, one of the objectives of this study was to apply the point source method to determine hydraulic and chemical transport properties at multiple field locations. Another objective was to study the spatial distribution of such properties across the field. A total of 50 field locations were evaluated simultaneously for both sets of properties. The hydraulic properties included the saturated hydraulic conductivity (K_s) and the macroscopic capillary length (λ_c). The chemical transport properties were the immobile water content, expressed as a fraction of total water content (θ_{im}/θ), and the mass exchange coefficient (α).

MATERIALS AND METHODS

The study took place in a no-till corn field at the Agronomy and Agricultural Engineering Research Station, Iowa State University, Ames, IA.

The soil at the research site is predominantly Nicollet loam (0.39 sand, 0.37 silt, 0.24 clay mass fraction), with an average bulk density of 1.43 Mg m^{-3} for the top 10 cm. The soil is classified as fine-loamy, mixed, superactive, mesic Aquic Hapludoll and is derived from glacial till. Slope of the field is about 1%. The study was conducted on plant rows. Corn plants were cut, and plant residues and weeds were removed from rows. Soil was carefully hand leveled with minimum disturbance to the surface.

Five parallel transects on plant rows were chosen on a 7 × 15-m rectangular grid (Fig. 1). Each transect was 15 m long, and the transects were 1.5 m apart. A drip irrigation system, consisting of three dripper lines (irrigation tubes), was positioned on the five transects. The dripper lines of all of the transects were interconnected so that all lines could be operated simultaneously. Each dripper line (on each transect) was equipped with one type of pressure-compensating emitter (point source). Such emitters were designed to deliver a steady discharge rate, Q, for a given pressure range. These emitters, designed to deliver discharge rates of 2, 4, or 8 L h^{-1} (Hooks Point, Startford, IA), were installed at intervals of 1.5 m on each transect. Thus, a total of 50 sites could be evaluated simultaneously for hydraulic and chemical transport properties. The dripper lines at each end of the system were connected to PVC manifolds, with a separate valve for each line. Using different valves for the dripper lines enabled us to introduce water into any line and, thus, maintain the same discharge rate at all sites. A pump was installed at one end of the system to deliver water from a reservoir into the dripper lines. A pressure gauge was installed at the other end of the system to monitor the applied pressure through the dripper lines. A release valve was installed at the far end of the system to facilitate quick flush of the system from different applied chemical solutions. With this setup, it was possible to apply water or different chemical solutions, simultaneously, at the 50 sites at controlled discharge rates.

The first step in the experimental work was to determine the hydraulic parameters. This was achieved by applying multiple discharge rates to the soil surface. We first applied water at a discharge rate of 2 L h^{-1}. The discharge rate from each emitter (i.e., at each site) was measured and

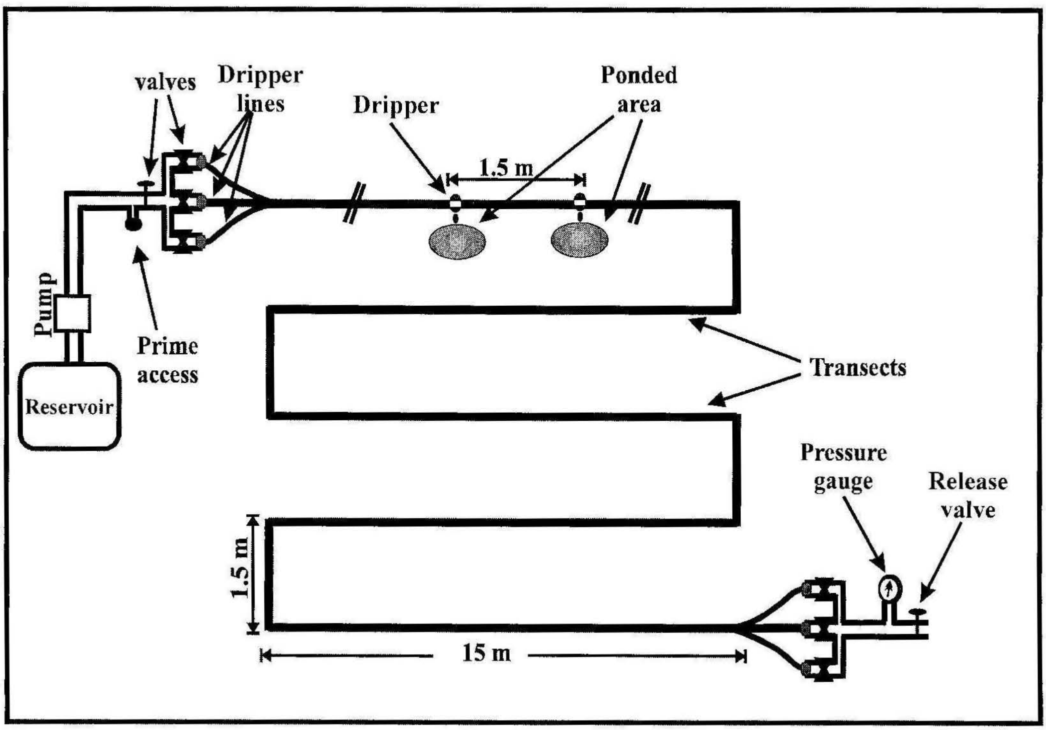


Fig. 1. The experimental setup for the point source method at the field.

recorded. Water application at each site was continued until steady-state conditions prevailed (i.e., the ponded area at each site reached a constant size). The steady-state conditions for all sites were reached after 30 to 45 min of water application. Inasmuch as the soil surface was nearly level, the resultant ponded areas were nearly circular in shape. To determine the effective size of the ponded area at each site, the diameter of the pond was measured from three different axes. This procedure was conducted to minimize any error caused by shape irregularity. The average value of the measured diameters was used to infer the effective circular ponded area. After recording the diameters of ponded areas produced by the first Q, the next higher discharge rate (4 L h^{-1}) was applied. This was achieved by closing the valve of the 2 L h^{-1} discharge rate and opening the valve of the 4 L h^{-1} discharge rate. The same procedure used for the first discharge rate was followed for the second discharge rate. This procedure was also followed for the last Q, which was 8 L h^{-1}. Thus, a total of three discharge rates were applied. The emitters among the sites produced some variability in maintaining the desired discharge rate, with an average coefficient of variability (CV) value of about 7.0% for all discharge rates applied. The experimental work for the first day (for determining hydraulic properties) was halted after the data for the steady-state areas produced by the last discharge rate were recorded.

Field experiments for determining the chemical transport properties were resumed the next day. The procedure of sequential application of tracers, as described by Jaynes et al. (1995), was followed to determine θ_{im}/θ and α. We used fluorobenzoate tracers to determine the transport parameters. Tracers used were 2,6-difluorobenzoate (DFBA), *o*-trifluoromethylbenzoate (TFMBA), and pentafluorobenzoate (PFBA) acids. We started the experiment by applying water at a discharge rate of 4 L h^{-1}. The discharge rate and steady state pond diameter at each site were measured and recorded. Solution 1 containing 0.001 *M* (1 m*M*) of DFBA (Tracer 1) was then introduced to the system. Application time was chosen to allow the wetting front of the solution to pass a sampling depth of 2.0 cm. This was followed by applying Solution 2, which consisted of 1 m*M* of DFBA and 1 m*M* of TFMBA (Tracer 2). Again, Solution 2 was applied for a sufficient period of time for the solution front to pass the sampling depth. Finally, Solution 3, which consisted of 1 m*M* each of DFBA, TFMBA, and PFBA (Tracer 3), was applied. With this procedure, Tracer 1 was applied for the longest time, and Tracer 3 was applied for the least time. A soil sample from each site was taken immediately after the ponded water on the surface had disappeared. Each soil sample was taken from the center of the area beneath the emitter. Soil samples were taken using stainless steel rings, which had an inside diameter of 5.1 cm and a height of 2.0 cm. Soil samples were placed in sealed, labeled plastic containers and stored in a cold environment at 2 °C. In the laboratory, soil samples were mixed thoroughly, and a soil subsample was taken from each sample for gravimetric determination of water content. Distilled water was added to the rest of each sample 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. The input and sample solutions were analyzed for tracers using an ion chromatograph. Detailed procedures for tracer analysis can be found in Bowman and Gibbens (1992) and Jaynes et al. (1995).

After the sequential application of tracers had ceased, undisturbed soil cores (7.6 cm long by 7.6 cm i.d.) were taken from all transects. A core sampler was used to collect a total of 50 undisturbed soil cores. Soil cores were also taken from locations along transects (between sites). In the laboratory, cores were saturated from the bottom with 5 m*M* $CaCl_2$. The saturated hydraulic conductivity of each soil core was then determined using the constant head method described by Klute and Dirksen (1986).

After determining individual property values, statistics of the property distributions were computed, e.g., mean, median, standard deviation, coefficient of variability, and 95% confidence interval. Statistical tests such as test of normality (Neter et al., 1996) and a nonparametric correlation test (Pearson coefficient test; Neter et al., 1996) were also performed. To identify the spatial correlations within the hydraulic and chemical properties, a directional semivariogram test (Davis, 1973) was conducted for each parameter for all measured values in the field. No directional effects in the semivariograms were detected. Therefore, semivariograms with all directions combined, e.g., along rows, across rows, and diagonal to rows, were computed. The spatial variability of all computed parameters was tested over the 7 × 15-m grid at 1.5-m lag intervals. The semivariograms were used to determined the extent of spatial correlation of the measured properties.

RESULTS AND DISCUSSION

Hydraulic Properties

Examples of measured flux densities, q, versus the inverse of the pond radius, $1/r_o$, for some selected sites are shown in Fig. 2. These sites were selected to show the trend of goodness of the linear fitting produced among the sites. Six sites were excluded from analysis for the hydraulic properties because emitters at those sites had some clogging problems. Thus, the hydraulic properties of 44 sites are reported in this study. The fitting procedure of q

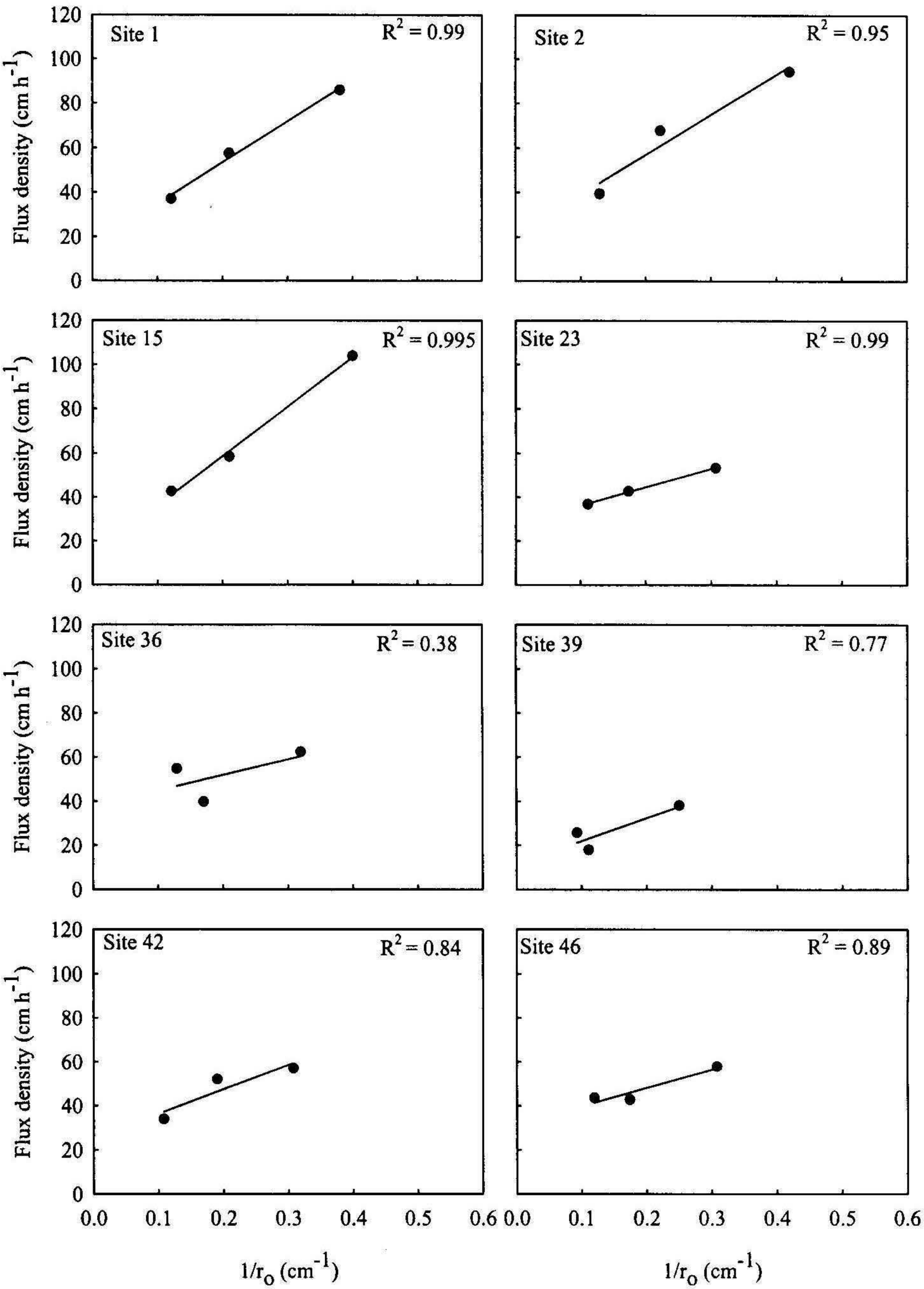


Fig. 2. Examples of flux densities versus $1/r_o$ of some selected sites. The point and solid lines are the measured and predicted (fitted) values, respectively.

versus $1/r_0$ produced some variability among the sites. We excluded the differences in the discharge rates, Q, among the sites as a source of variability because of their low CV value (≈7%). The degree of such variability is considered marginal when compared with the variability produced by the natural heterogeneity of the soil (Or, 1996). The fitting procedure produced a median value for the coefficient of determination (r^2) of 0.89. A possible source of error in the measurements may have been the presence of macropores (vented macropores were visible). The presence of macropores can cause water to move preferentially into them, leading to a smaller than expected ponded area, and, thus, the linear relationship presented by the Wooding's solution is not satisfied. Wu et al. (1997) reported that the presence of the macropores yielded unreasonable values for K_s (negative values) from the borehole permeameter. Thus, the presence of macropores can play a major role in the variability of the estimated hydraulic properties.

Statistics for the hydraulic properties (K_s and λ_c) for the 44 sites are presented in Table 1. The CV value for the K_s values was about half of the CV of the λ_c values. Large variability associated with λ_c is expected because it is affected by the level of the variability of the corresponding K_s value (see Eq. 4). The effects of K_s variability nearly double the degree of variability in estimating λ_c (when compared with the CV of K_s). The large values of K_s are attributed to the presence of macropores. The measurements were taken on plant rows at the end of the growing season, where the macropores commonly exist because rooting systems are fully developed (Prieksat et al., 1994).

TABLE 1

Statistics of the hydraulic properties as estimated by the point source method

	K_s (cm h^{-1})	λ_c (cm)
N	44	44
Mean	31.2	4.0
Median	27.4	1.6
Minimum	7.5	0.03
Maximum	79.0	13.1
Std. Dev.†	16.8	3.6
CV (%)‡	53.8	89.8
CI (%)§	5.1	1.1

†Standard deviation.

‡Coefficient of variability.

§95% confidence interval.

The constant head method applied to the soil cores produced K_s values ranging from 0.7 to 62.4 cm h^{-1}, with an average of 15.9 cm h^{-1} (± 13.7) and a median of 12.4 cm h^{-1}. These values were, in general, smaller than those produced by the point source method in the field. The analysis of variance (ANOVA, single factor) indicated that the K_s values produced in the field were significantly different from those produced by the constant head method at the 5% probability level. Smaller K_s values obtained from the constant head method could be caused by slight compaction of soil and/or surface smearing of cores during sampling.

Figure 3 represents a map figure of the distribution of the measured K_s values across the grid and their corresponding histogram. The five columns (from the east side) represent the transects, where measurements were taken. The missing places along the transects represent the data discarded because of the clogging of the emitters. The map figure shows a trend in the distribution of measured K_s. However, there is no overriding (strong) pattern in the distribution within each transect. Most of measured K_s values (about 77%) fall between 20 and 40 cm h^{-1}. A test of normality at the 5% probability level indicates that the K_s histogram is skewed and not normally distributed. However, it shows that K_s values are normally distributed on a log-normal scale. The distribution of K_s measured on the soil cores showed a distribution similar to that of the field measurements (figure not shown).

Figure 4 represents a map figure of the distribution of the measured λ values across the grid and their corresponding histogram. The distribution of the measured λ is similar to that of the measured K_s because measured K_s is used to find λ_c for each specific site. The histogram of measured λ_c indicates that about 55% of λ_c values were in the range of 0 to 5 cm. The test of normality ($P = 0.05$) showed that the distribution of λ_c values is skewed and not normally distributed at the normal or log-normal scales.

The effects of K_s on measured λ_c are shown in Fig. 5. The two parameters are correlated (see Eq. 4). This is expected, because both parameters are related to soil pore geometry (White and Sully, 1992). For a specific pore size, the general trend of the data suggests an inverse relationship: as K_s increases λ_c decreases. Any discrepancy in this trend is attributed to the occurrence of macropores, i.e., a structure-controlled condition (Or, 1996). In other words, the presence of the macropores causes the contribution of capillary

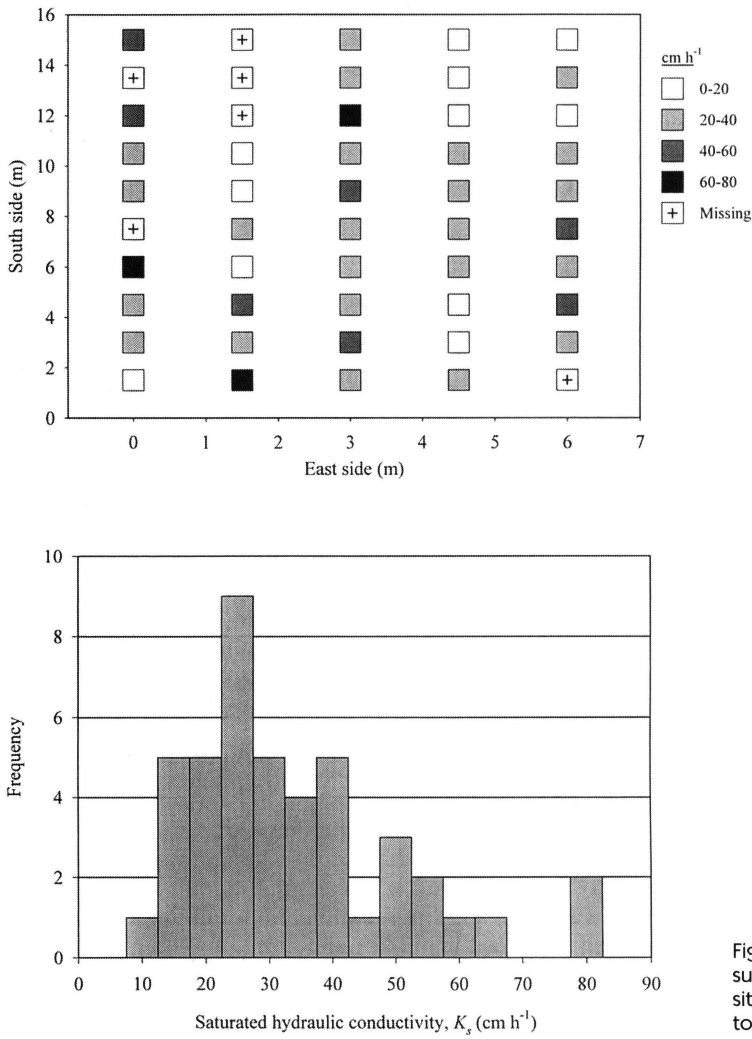


Fig. 3. Spatial distribution of measured K_s values across the research site and their corresponding histogram.

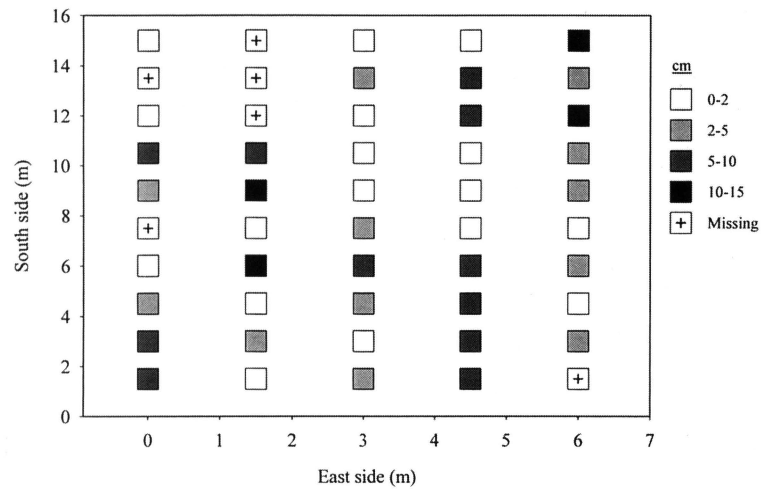
flow to be marginal because water flows mainly through the macropores. A similar trend between λ_c and K_s was also reported by Or (1996).

Spatial Analysis of Hydraulic Properties

Figures 6(a) and 6(b) represent the semivariograms calculated for K_s and λ_c, respectively. There is no spatial correlation between neighboring samples when values of the semivariogram estimator, γ, are similar at all lag distances to the variance of the property. The K_s-semivariogram shows primarily a nugget effect, with, perhaps, minor spatial correlation between the nearest sites for the measured K_s. However, the λ_c semivariogram shows only a pure or complete nugget effect, i.e., there is no spatial correlation between the sites for the measured λ_c. There are no obvious spatial correlations of K_s or λ_c that can be deduced along corn rows (at distances $>$ 1.5 m) under these no-till conditions.

Comparison of Hydraulic Properties with Previously Reported Values

The reported values from this study can be compared with those reported in previous studies. Mohanty et al. (1994) measured K_s and λ_c of a nearby no-till cornfield. They used ponded and tension infiltrometers to determine the hydraulic properties. Their reported values for K_s ranged from 1.0 to 260.4 cm h^{-1}, with an average of 39.9 cm h^{-1} ($\pm$36.4) and a CV of 91%. The average of this study, 31.2 cm h^{-1}, was comparable to their average. However, our study produced less variable K_s values than their study, with a CV



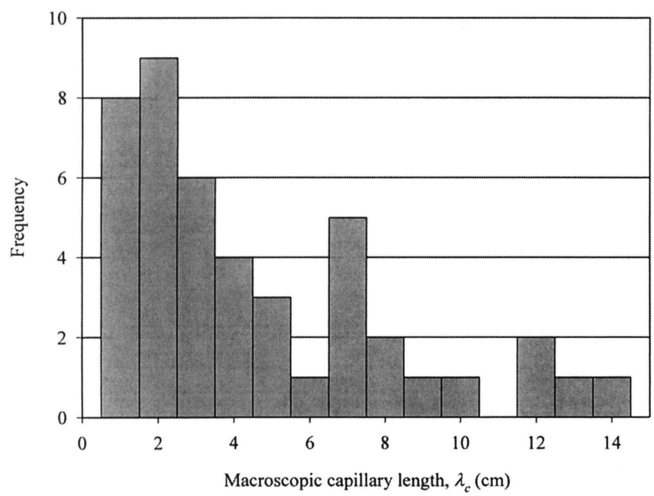


Fig. 4. Spatial distribution of measured λ_c values across the research site and their corresponding histogram.

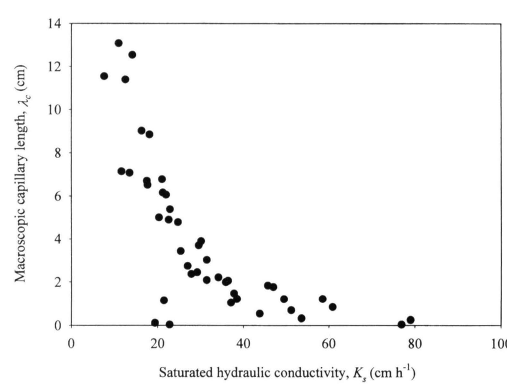


Fig. 5. Relationship between measured macroscopic capillary length (λ_c) and saturated hydraulic conductivity (K_s).

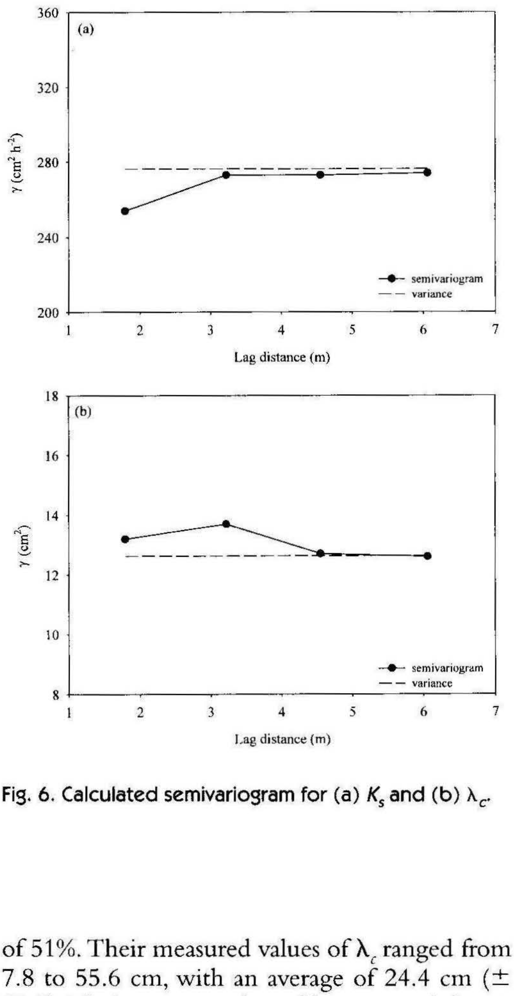


Fig. 6. Calculated semivariogram for (a) K_s and (b) λ_c.

of 51%. Their measured values of λ_c ranged from 7.8 to 55.6 cm, with an average of 24.4 cm (± 55.5). Their average value of λ_c was much larger than the average of this study. Their CV from estimating λ_c was about 44% (compared with 90% in our study). Differences in the values reported in this study and in the study of Mohanty et al. (1994) are caused, in part, by the natural spatial and temporal variability of the soil. However, different fitting procedures used by the two studies to determine K_s and λ_c can also be considered to be a source of variability for values reported. We used simple linear regression between the flux density and the inverse of the steady-state pond radius with negligible head over the soil surface (Wooding's solution). Mohanty et al. (1994) used the piece-wise linear fitting procedure developed by Ankeny et al. (1991) with known (controlled) pressure heads over the soil surface as their boundary conditions. The semivariograms presented by Mohanty et al. (1994) for the hydraulic properties are similar to the semivariograms reported in this study.

Chemical Transport Properties

Figure 7 gives some examples of the normalized resident concentration, $\ln(1\text{-}C/C_o)$, compared with the application time of tracers, t^*. The sites shown in Fig. 7 are those sites shown in the sections of the hydraulic properties. The chemical transport properties are determined from the regression output of $\ln(1\text{-}C/C_o)$ versus t^*. The sequential tracer method developed by Jaynes et al. (1995) worked well with the point source method at field conditions. This is indicated by the median r^2 value of 0.80 for the linear fitting procedure. The linearity of the data indicates that Eq. 3 describes well the physical processes occurring in the soil (Jaynes et al., 1995).

The measured θ_{im}/θ and α values are presented in Table 2. The measured soil water content (θ) ranged from 0.45 to 0.60 $m^3\ m^{-3}$, with a median of 0.57 $m^3\ m^{-3}$ (±0.04). Consistent values of θ can be attributed to the uniformity of the soil along the corn rows. Uniformity of the soil along the plant rows is indicated by uniform values of bulk density (ρ_b) as measured from soil cores. Measured ρ_b along plant rows had a CV of only 7%. Therefore, a uniform distribution of water content could be expected.

The estimated immobile water fraction (θ_{im}/θ) ranged from 0.36 to 0.88, with a median of 0.57 (± 0.098). The consistency and uniformity of θ_{im}/θ is indicated by a low CV value of about 17%. Estimated values for the mass exchange coefficient (α) ranged from 0.002 to 0.123h^{-1}, with a median of 0.034 h^{-1} (± 0.027). Estimated values of α were highly variable (as compared with θ_{im}/θ, with a CV value of 71%). The degree of variability of α is expected because estimated α is affected by the degree of variability of corresponding θ_{im}/θ.

Figure 8 presents a map figure of the distribution of the estimated θ_{im}/θ values across the research grid and their corresponding histogram. The map figure represents the θ_{im}/θ values for 46 of the 50 sites in the field. The map figure also shows that the first two transects have some spatial patterns in estimated immobile water content (similar values of θ_{im}/θ are close to each other). However, the trend is not obvious within the rest of the transects; there is no obvious spatial pattern in estimated θ_{im}/θ within each transect. The histogram figure of θ_{im}/θ indicates that about 89% of the estimated values were in the range of 0.4 to 0.7, which means that most of the estimated θ_{im}/θ values were concentrated toward the middle range of possible values. The test of normality ($P = 0.05$) indicated that the θ_{im}/θ-

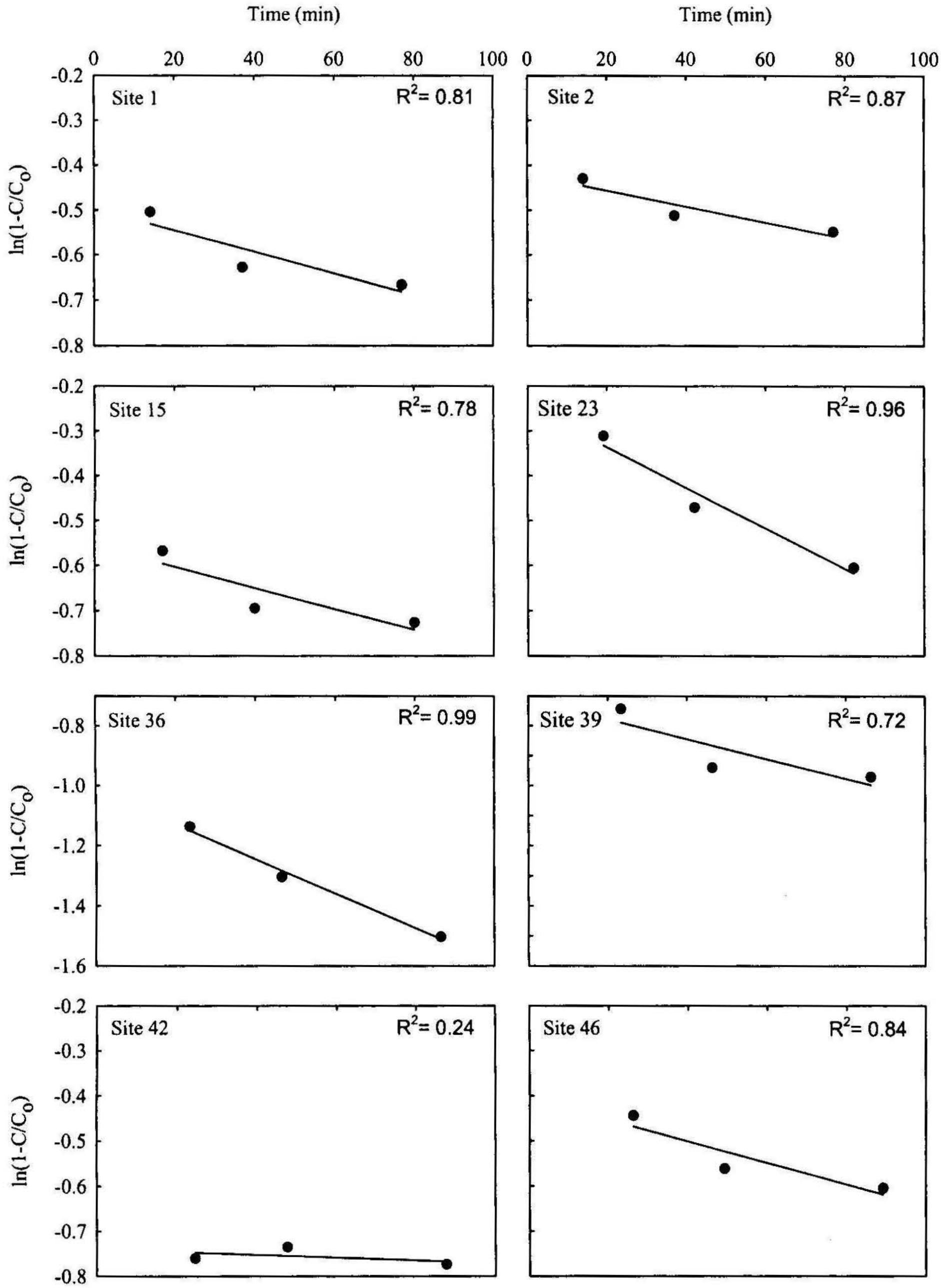


Fig. 7. Examples of normalized resident concentration versus application time of some selected sites. The point and solid lines are the measured and predicted (fitted) values, respectively.

distribution was not normally distributed at either normal or log-normal scales.

Figure 9 presents estimated α values across the research grid and their corresponding histogram. The map figure of estimated α shows more spatial patterns than that of the estimated θ_{im}/θ (similar values in the range are closer to each other). As shown by its histogram, about 78% of the estimated α values were in the range of 0.01 to 0.06 h^{-1}. The measured values of α are not normally

TABLE 2

Statistics for the chemical transport properties as estimated by the point source method

	θ_{im}/θ	α (h^{-1})
N	46	46
Mean	0.583	0.039
Median	0.571	0.034
Minimum	0.361	0.002
Maximum	0.884	0.123
Std. Dev.†	0.098	0.027
CV (%)‡	17.0	71.0
CI (%)§	0.029	0.008

†Standard deviation.
‡Coefficient of variability.
§95% confidence interval.

distributed at either normal or log-normal scales. The distribution of α is skewed toward the left.

The effects of the estimated immobile water fraction (θ_{im}/θ) on the estimated mass exchange coefficient (α) are seen in Fig. 10, where the estimated α parameter is shown to be proportional to θ_{im}/θ. Skopp et al. (1981) and Casey et al. (1997) also reported such a relationship. Large immobile water contents yield large contact regions between the mobile and immobile domains. Consequently, more chemical transfer is expected to occur between the two domains and, thus, a large α is observed. The linear relationship shown by Fig. 10 can also be observed in Eq. 3. The estimated α parameter is the product of the estimated θ_{im} (as determined from the intercept) and the slope of the regression line. Thus, a large

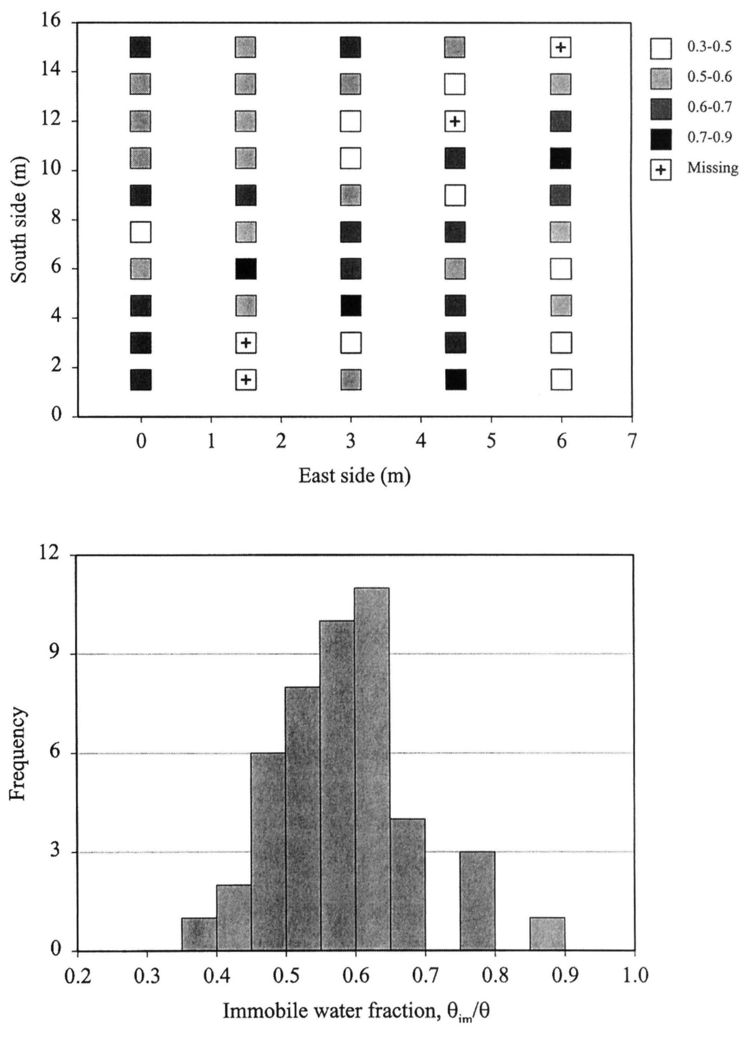


Fig. 8. Spatial distribution of measured θ_{im}/θ-values across the research site and their corresponding histogram.

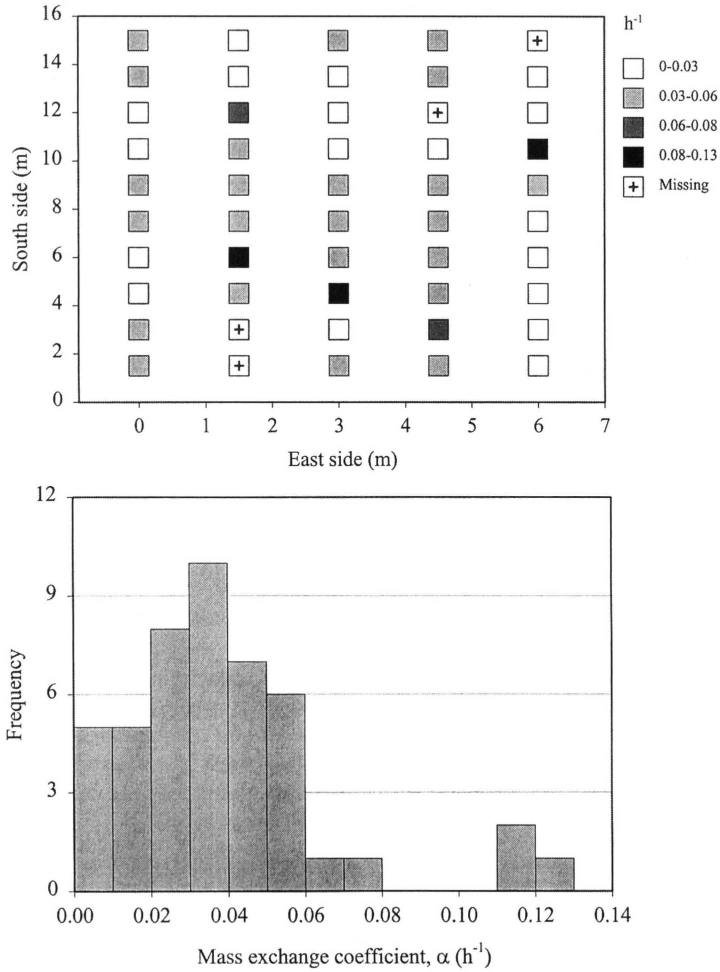


Fig. 9. Spatial distribution of measured α-values across the research site and their corresponding histogram.

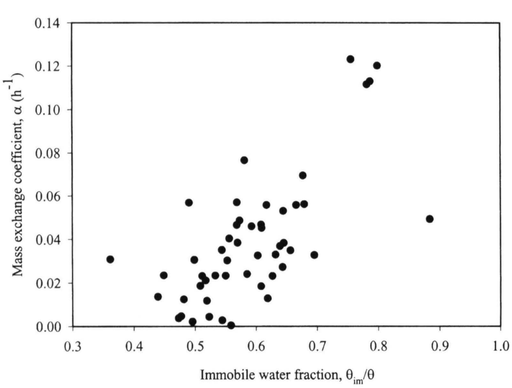


Fig. 10. Relationship between estimated mass exchange coefficient (α) and immobile water content (θ_{im}/θ).

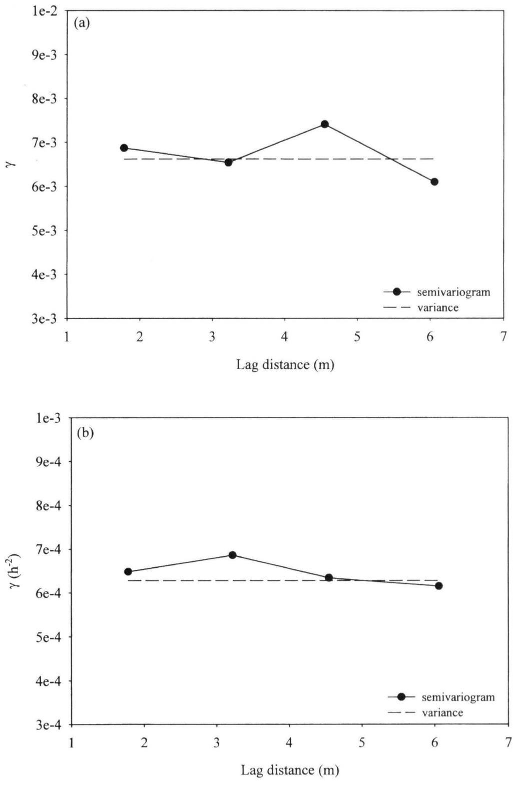


Fig. 11. Calculated semivariogram for (a) θ_{im}/θ and (b) α.

θ_{im} yields a large α. This means that the degree of variability in the estimated α is expected to be higher than that of the estimated θ_{im}. The degree of variability (in terms of CV) is shown in Table 2.

Spatial Analysis of the Chemical Properties

Figures 11(a) and 11(b) represent the semivariograms calculated for θ_{im}/θ and α, respectively. Both semivariograms show a pure or complete nugget effect, which means that there is no obvious spatial correlation in the distribution of the parameters along the corn rows (at distances > 1.5 m) under these notill conditions.

Comparison of Chemical Properties with Previously Reported Values

The results obtained from this study can be compared with results from previous studies. Casey et al. (1997) used tension infiltrometers to estimate chemical transport properties (θ_{im}/θ and α) on the same soil series with similar tillage management on a nearby field. They applied multiple conservative tracers from infiltrometers to the soil using a supply pressure head of -30 mm of water. They reported a median of 0.64 for θ_{im}/θ, with extremes ranging from 0.44 to 0.97. Our study produced a median of 0.57, which is comparable to their computed median. Angulo-Jaramillo et al. (1996) reported an average θ_{im}/θ-value of 0.63 for a loamy soil, which is also comparable to the average obtained from this study. For the α parameter, Casey et al. (1997) reported a median of 0.074 h^{-1}, with extremes ranging from 0.014 to 0.289 h^{-1}. Our study yielded a median of 0.034 h^{-1}. The results obtained from this study showed a linear relationship between the α parameter and the pore velocity (figure not shown). A Pearson coefficient test showed that there is no significant correlation between the flux density (q) and the α parameter. Previous studies, as compiled by Griffioen et al. (1998), showed that there is a positive relationship between the flux density and the α parameter. This indicates that the α values obtained from this study were consistent with the general trend of the α values reported by previous studies. The semivariogram tests reported by Casey et al. (1997) showed a nugget relationship similar to that reported by this study. In general, the measured values of the transport parameters ($\theta_{im}/\theta, \alpha$) were found to fall within the ranges reported by other laboratory studies (Kookana et al., 1993; Griffioen et al., 1998).

CONCLUSION

This study presents measurements of soil hydraulic and chemical transport properties at multiple field locations. A total of 50 field locations were evaluated simultaneously for K_s, λ_c, θ_{im}/θ, and α within a 2-day period with minimum labor requirements. The values of the estimated parameters presented by this study were comparable to those of previously reported studies conducted on nearby field locations with similar soil types and tillage systems. Moreover, the spatial correlation tests conducted by this study showed trends regarding property distribution similar to those reported by previous studies. Compared with the number of observations that other field methods can produce in the same time period, the set-up and procedure presented by this study allowed us to conduct more extensive measurements of the hydraulic and chemical transport properties. This study should provide the needed data for better understanding of the mechanisms by which water and chemicals move through the vadose zone.

ACKNOWLEDGMENTS

Supported by CSREES, USDA, NRICGP Soils and Soils Biology Program award No. 2001-35107-09938, and by Hatch Act and State of Iowa funds.

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