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A Point-Source Method for Rapid Simultaneous Estimation of Soil Hydraulic and Chemical Transport Properties

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Abstract

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Disciplines

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A Point-Source Method for Rapid Simultaneous Estimation of Soil Hydraulic and Chemical Transport Properties

Salem A. Al-Jabri, Robert Horton,* and Dan B. Jaynes

ABSTRACT

Hydraulic and chemical transport properties are needed for accurate prediction of water and chemical movement through the vadose zone. Field methods used to estimate such properties are often hampered by extensive labor and time constraints. One of the objectives of this study was to develop an experimental setup and a procedure for a point-source method that facilitates rapid and simultaneous measurements of soil hydraulic and chemical transport properties at multiple locations. Another objective was to evaluate the point-source method by comparing the parameters with those produced by ponded and tension infiltrometers. The experimental setup consisted of three dripper lines equipped with pressure-compensating drippers. The setup was evaluated on a greenhouse soil pit. Determined hydraulic properties were the saturated hydraulic conductivity (K_s) and the macroscopic capillary length (λ_c). Hydraulic properties (from the point-source method) were determined by applying four consecutive discharge rates on the soil surface and measuring their corresponding steady-state saturated areas. Determined chemical transport parameters were the immobile water fraction (θ_{im}/θ) and the mass exchange coefficient (α). They were determined by applying a sequence of conservative fluorobenzoate tracers. The point-source method gave consistent and reliable estimates for both sets of properties. Except for α , there was no significant difference between the two procedures (point source vs. infiltrometers) in determining both sets of properties. The study showed that the point-source setup could be utilized for rapid and simultaneous estimation of soil hydraulic and chemical transport properties at multiple locations with minimum labor requirements.

DETERMINING HYDRAULIC and chemical transport properties of field soils is a fundamental requirement for managing soil and water resources. Hydraulic properties (hydraulic conductivity and water retention) are needed to predict the movement of water and chemicals through the vadose zone towards groundwater resources. Characterizing hydraulic and chemical transport properties helps in developing best management practices that minimize potential contamination of natural resources. Hydraulic and chemical transport properties are also needed for efficient management of different irrigation systems.

Adequate evaluation of field hydraulic and chemical transport properties requires a large number of measurements to reflect spatial and temporal variability. Despite the availability of mathematical analysis and models describing the steady flow of water (Philip, 1969; Warrick, 1974, 1985) and transport of chemicals (Gelhar

and Collins, 1971; van Genuchten and Wierenga, 1976; Clothier et al., 1992; Jaynes et al., 1995), there have been only a few studies conducted in the field. One reason for a lack of field studies is that field procedures require extensive time and labor resources. Current field methods are confined to produce a single measurement at a single field location. For example, Casey et al. (1998) used tension infiltrometers to estimate hydraulic and chemical transport properties across a field. They estimated hydraulic properties using the multiple-tension method (Logsdon and Jaynes, 1993), and chemical transport properties using the sequential-tracer method proposed by Jaynes et al. (1995). Their study, however, required extensive labor allocations and was time-consuming (~4 wk). Thus, there exists a need for a method that facilitates rapid determination of both hydraulic and chemical transport properties.

A point-source method has been developed for measuring in situ hydraulic properties (Shani et al., 1987; Revol et al., 1991, 1997; Yitayew et al., 1998) and solute transport parameters under controlled environments (O'Brien et al., 1994, Ward et al., 1994, 1995). The simplicity of this method makes it ideal for rapid and repeatable measurements of field hydraulic properties (Yitayew et al., 1998). Recently, Or (1996) introduced an experimental setup for determining hydraulic properties using the point-source method. His setup consisted of a multiple-dripper permeameter that facilitated determining the properties with minimum labor requirements. Perhaps, his setup can be a foundation for simultaneous estimation of the hydraulic and chemical transport properties within a short time.

One objective of this study was to develop an experimental setup and a point-source procedure to rapidly and simultaneously determine soil hydraulic and chemical transport properties with minimum labor requirements. Another objective was to evaluate the point-source method by comparing it with the ponded and tension infiltrometer methods. Determined hydraulic properties were K_s and λ_c . Wooding's (1968) solution was used to estimate K_s and λ_c . Chemical transport properties were immobile water content (expressed as θ_{im}/θ) and α . The sequential-tracer method proposed by Jaynes et al. (1995) was used to estimate θ_{im}/θ and α .

THEORY

Water flow into soils can be described using Richards (1931) equation. For one dimensional water flow into rigid isothermal

Abbreviations: CDE, convection-dispersion equation; CV, coefficient of variance; D_m , dispersion coefficient; K_s , saturated hydraulic conductivity; PVC, polyvinyl chloride; q , steady-state flow per unit area; Q , discharge rates; r_0 , steady-state pond radius; α , mass exchange coefficient; θ_{im} , water content in the immobile domain; θ_m , water content in the mobile domain; θ_{im}/θ immobile water fraction; λ_c , macroscopic capillary length.

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soils, Richards equation can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right] \quad [1]$$

where θ is soil water content ($L^3 L^{-3}$), $K(h)$ is hydraulic conductivity ($L T^{-1}$), h is soil-water pressure head (L), t is time (T), and z is depth (L). Some methods of solving Eq. [1] for steady-state conditions require a linearization method using the matrix-flux potential, ϕ , (Philip, 1968):

$$\phi(h) = \int_{h_i}^h K(h) dh \quad [2]$$

where h_i and h are dry and wet soil-water pressure heads (L).

Water supplied to a level soil surface from a point-source dripper causes a circular or nearly circular pond to develop on the surface. For steady-flow discharge from the dripper the ponded area will reach a constant size at steady-state infiltration. Wooding (1968) presented an approximate solution for steady-state flow per unit area, q , from a shallow saturated pond on the soil surface as:

$$q = \frac{Q}{\pi r_o^2} = K_s \left(1 + \frac{4\lambda_c}{\pi r_o} \right), \quad r_o/\lambda_c \leq 10 \quad [3]$$

where Q is discharge rate of the point source ($L^3 T^{-1}$), K_s is saturated hydraulic conductivity ($L T^{-1}$), r_o is steady-state pond radius (L), and λ_c is a scaling parameter (L). The λ_c parameter quantifies the importance of capillary forces relative to gravity forces (Philip, 1969). Wooding (1968) assumes that the soil is uniform, homogenous, nonswelling and has an exponential hydraulic conductivity function (Gardner, 1958):

$$K(h) = K_s \exp(h/\lambda_c) \quad [4]$$

The first term on the right side of Eq. [3] represents the contribution of gravity to the flow, and the second term represents the contribution of capillarity and geometry of the source. If a disc source is used, such as ponded or tension infiltrometers, the same principle applies (Ankeny et al., 1991). Using the definition of the matric-flux potential (Eq. [2]) and substituting Eq. [4] for $K(h)$, Wooding's solution (Eq. [3]) can be rewritten to describe water flow from disc sources as:

$$q = K_s \exp(h/\lambda_c) \left(1 + \frac{4\lambda_c}{\pi r_o} \right), \quad K(h_i) \ll K(h) \quad [5]$$

where r_o is disc radius (L). Equation [5] has been widely used to determine the hydraulic parameters ($K(h)$, λ_c) from steady infiltration data produced by ponded and tension infiltrometers (Ankeny et al., 1988; Ankeny et al., 1991; Reynolds and Elrick, 1991; Prieksat et al., 1992; Logsdon and Jaynes, 1993; Hussen and Warrick, 1993).

Applying water to the soil surface from a point-source produces a circular (or nearly circular) saturated area on the soil surface. This occurs when the discharge rate is higher than the infiltration rate of the soil. When a constant flux of water is applied to the soil from a source the saturated area increases with time, but eventually reaches a constant size (Bresler, 1978). Once steady-state conditions occur, Wooding's solution can be applied (Shani et al., 1987). Applying increasing Q s from a point source at the soil surface would yield ponded areas of increasing r_o . Following Eq. [3], plotting the values of q versus the corresponding $1/r_o$ results in a straight line with an intercept equivalent to K_s , and λ_c can be determined from the resulting slope, $4\lambda_c K_s/\pi$.

Chemical movement through soils is often described by the convection-dispersion equation (CDE). However, many studies have reported the occurrence of preferential flow,

which often cannot be described by the classical CDE (Jaynes and Horton, 1998). Preferential flow can be described as the rapid movement of water and chemicals through large pores, such as cracks or pores made by earthworms (*Lumbricus terrestris*) and plant roots. Thus, a small quantity of water is needed for chemicals to reach great depths in the soil. A two-domain model was proposed by Coats and Smith (1964) and later extended by van Genuchten and Wierenga (1976) to better describe preferential flow into structured soils. This model suggests that wetted pore volume is a combination of mobile and immobile domains. For one-dimensional movement of nonsorbing chemicals, the CDE can be written in the form of the two domains as (Coats and Smith, 1964):

$$\theta_m \frac{\partial C_m}{\partial t} + \theta_{im} \frac{\partial C_{im}}{\partial t} = \theta_m D_m \frac{\partial^2 C_m}{\partial z^2} - q \frac{\partial C_m}{\partial z} \quad [6]$$

where θ_m and θ_{im} are water contents of mobile and immobile domains ($L^3 L^{-3}$), C_m and C_{im} are concentrations in mobile and immobile domains ($M L^{-3}$), and D_m is the dispersion coefficient ($L^2 T^{-1}$), active in the mobile domain only. The movement of chemicals between the two domains is described as a first-order process (van Genuchten and Wierenga, 1976):

$$\theta_{im} \frac{\partial C_{im}}{\partial t} = \alpha (C_m - C_{im}) \quad [7]$$

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

Jaynes et al. (1995) provided a simple procedure to estimate θ_{im} and α parameters of the mobile-immobile model without the need for extensive breakthrough experiments. Their method involves using a sequence of conservative tracers having similar transport characteristics. Assuming piston movement of chemicals in the mobile domain of the soil, Jaynes et al. (1995) integrated Eq. [7] to give:

$$\ln(1 - C/C_o) = \ln(\theta_{im}/\theta) - (\alpha/\theta_{im})t^* \quad [8]$$

where C is the chemical concentration of soil solution, C_o is the chemical concentration of input solution, θ is total water content, $t^* = t - z'/v$ is the time required for the tracer front to reach sampling depth, z' , and v is the average pore velocity ($m s^{-1}$) in the mobile domain. Jaynes et al. (1995) assumed no prior concentration of chemicals in the soil, chemical concentration in the mobile domain equal to C_o , negligible D_m within the sampling zone, and C as a combination of chemicals in the mobile and immobile domains. Based on Eq. [8], plotting $\ln(1 - C/C_o)$ versus t^* results in a straight line with a negative slope. The immobile water fraction can be determined from the resulting intercept, and α can be computed from the slope.

MATERIALS AND METHODS

A greenhouse soil pit was used in this study. The soil in the pit was disturbed having a loam texture (0.344 sand-, 0.416 silt-, and 0.240 clay-mass fraction), a bulk density of $1.26 Mg m^{-3}$, and a particle density of $2.63 Mg m^{-3}$. The soil pit was about 60 cm deep, underlined by sawdust and undisturbed soil (Jaynes et al., 1995), and was continuously cropped for the past 15 yr. A dripper-line setup was constructed on a transect 7 m long on the soil surface (Fig. 1).

The setup consisted of three dripper lines mounted on the soil surface. The three-dripper lines were connected to a polyvinyl chloride (PVC) manifold with a separate control valve for each line. Water was pumped from a reservoir to the system through a PVC pipe, which had a prime access to facilitate priming the pump. Each dripper line was equipped with drippers that could deliver a designed discharge rate within an applied pressure range (pressure-compensating drip-

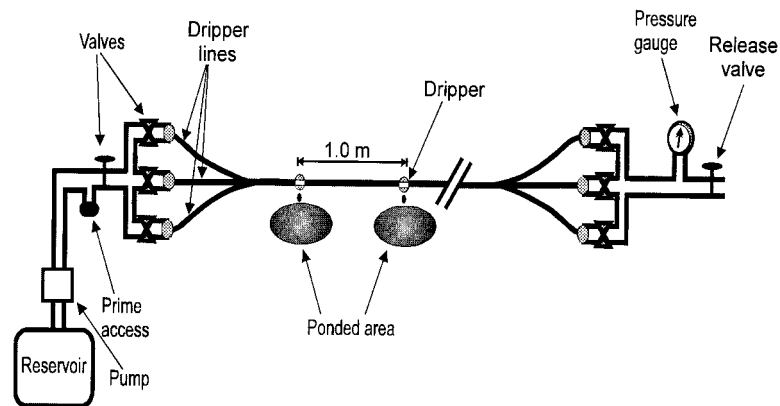


Fig. 1. Experimental setup for the point-source method showing the ponded areas on the soil surface.

pers). Drippers (Hooks Point, Stratford, IA) used were designed to deliver discharge rates of 2, 4, and 8 L h⁻¹. A pressure gauge was installed in the system to monitor the applied pressure. A release valve was installed at the far end of the setup to facilitate quick flushing of the system for different applied chemical solutions. This setup allowed application of water or chemical solutions to the soil surface at multiple locations for the same time period. Different discharge rates could be applied at the same location, which minimized effects of spatial variability. The drippers were 1 m apart. Thus, a total of six observation sites, i.e., six tests with four discharge rates each, were included. The local soil surface at each observation site was leveled with minimal surface disturbance before water application.

Experimental work was started by applying water at the soil surface at a discharge rate of 2 L h⁻¹. Discharge rate of each observation site was measured and recorded. Drippers among sites had small variability and their coefficient of variances (CVs) ranged from 0.68 to 2.86%. Water application was continued until steady-state conditions prevailed, i.e., when ponded areas reached a constant size. Steady-state conditions were reached after about 30 to 40 min of water application. The diameter of the ponded area (at steady-state conditions) of each observation site was measured from different axes, and the average was taken to infer equivalent pond radius. After recording the steady-state area of all six observation sites, the next higher discharge rate (4 L h⁻¹) was applied on the same location. Switching between different Q was achieved by opening and closing the valves of the dripper lines. This procedure was repeated for the other applied discharge rates, which were 8 and 12 L h⁻¹. A discharge rate of 12 L h⁻¹ was achieved by opening the valves for the 4 and 8 L h⁻¹ dripper lines. Thus, a total of four discharge rates (2, 4, 8, and 12 L h⁻¹) were applied on the soil surface of each site.

Chemical properties were determined by applying a sequence of three conservative tracers. The tracers used in this study were *o*-trifluoromethylbenzoates, pentafluorobenzoates, and trifluorobenzoates. These conservative tracers have been reported to have similar transport properties in many soils (Benson and Bowman, 1994; Jaynes, 1994). After recording the steady-state ponded area produced from the highest discharge rate, three consecutive solutions containing multiple fluorobenzoate tracers were sequentially injected through the system. Chemical solutions were applied using the highest discharge rate, i.e., 12 L h⁻¹. The first solution (Solution 1) consisted of 0.001 M of Tracer 1. Solution 1 was applied for enough time that the solution front was estimated to have passed the intended sampling depth of 1.5 cm. Estimation of application time was based on the computed pore velocity, v .

This application was followed by applying Solution 2, which consisted of 0.001 M of Tracer 1 and 0.001 M of Tracer 2. Again, application time for Solution 2 was long enough for the solution to have passed the sampling depth. This procedure was followed by applying the third solution, which consisted of 0.001 M each of Tracers 1, 2, and 3. With this procedure, Tracer 1 was applied for the longest time and Tracer 3 for the least time. A soil sample, 1.5 cm deep, was taken from each observation site immediately after the application of the third solution had ceased. Rings used for collecting soil samples from within the ponded area at each observation site had a 7.6-cm i.d. and a 1.5-cm depth. Soil surface samples were taken from the center of the ponded area (after the ponded water had disappeared from the soil surface). Soil samples were put into plastic bags and stored in a cold environment until chemical analysis and water content determination occurred. In the laboratory, soil samples were thoroughly mixed and a soil subsample was taken from each sample for water content determination. Water content was determined gravimetrically by oven-drying samples for 24 h at 105°C. Each remaining soil sample was extracted with distilled water at about 2:1 water mass/soil–water ratio. The extracts and input solutions were analyzed for tracers using an ion chromatograph (high performance liquid chromatography). Detailed procedures for chemical analysis can be found in Bowman and Gibbens (1992) and Jaynes et al. (1995).

Soil samples from sampling rings had relatively small volumes, which led to highly variable bulk densities (ρ_b). Accurate ρ_b is needed to determine θ_{im} , which is used to compute α parameter from Eq. [8]. Thus, a large error could be introduced in estimating α from using ρ_b of the soil samples to determine the volumetric water content (θ_v). Therefore, instead of using ρ_b of soil samples, we assumed the soil samples to be saturated (sampling was done quickly after water application had ceased) and θ_v could be determined from the known mass water content (θ_g) and soil particle density (ρ_s) using the following relationship:

$$\theta_v = \frac{\theta_g \rho_s}{\theta_g \rho_s + 1} \quad [9]$$

Equation [9] does not use the ρ_b term. Thus, it removes any possible error in estimating chemical transport properties from miscalculated θ_v of soil samples.

Another set of experiments was conducted for comparison purposes. Hydraulic properties were determined from infiltration experiments using automated ponded and disc tension infiltrometers. Ponded and tension infiltrometers had disc radii of 7.6 cm. Containment rings (1-cm height, 7.6-cm i.d.) were

inserted into the soil to a depth of 5 mm. Pondered infiltrometers were first used to supply water at a pressure head of 5 mm of water. The infiltrometers were equipped with pressure transducers installed at the top and bottom of the water reservoir. The transducers were connected to a data logger to record the change in the water pressure in the reservoir, which was used to determine the infiltration rates. The details of the procedure can be found at Prieksat et al. (1992). Water infiltration from pondered infiltrometers was continued until steady-state conditions prevailed, i.e., a constant infiltration rate was reached. The pondered infiltrometers were then removed and containment rings were filled with a thin layer (~5 mm) of fine sand to establish a good hydraulic contact between the soil surface and the discs of tension infiltrometers. Tension infiltrometers were then placed on the same locations. Water was infiltrated using a sequence of supply pressure heads of -30, -60, and -150 mm of water. Infiltration rates produced by each supply pressure head were measured using pressure transducers. Details of this procedure can be found in Ankeny et al. (1988). Six sites were evaluated for hydraulic properties with pondered and tension infiltrometers. The sites tested by infiltrometers were within 1 m of the point-source transect. Hydraulic properties were determined by taking the log-linear form of Eq. [5] and regressing steady infiltration rates, $\ln(q)$, versus applied pressure heads. The λ_c parameter was the slope of the regression line and K_s was determined from the resulting intercept.

Chemical transport properties were evaluated using pondered infiltrometers by sequentially applying three solutions containing a multiple of the three fluorobenzoic tracers. Solutions were applied using a supply pressure head of 5 mm. The application scheme of solutions for pondered infiltrometers was the same one followed for the point-source experiments. A soil sample was taken from beneath each infiltrometer immediately after the application of the last solution had ceased. Rings used for collecting samples had 4.5-cm i.d. and were 2.0 cm deep. The diameter of the rings was chosen to be smaller than the pondered diameters to avoid edge effects. Because we had a limited volume of tracer solution, only five observation sites were evaluated for chemical transport properties from pondered infiltrometers. Chemical analysis and water content were determined following the same procedure described with the point-source method. A test of significance (analysis of variance, single factor) was conducted to study the variability between the two sets of methods (point-source vs. infiltrometers) in determining the hydraulic and chemical properties of the soil pit. A test of significance (*t*-test at 5% probability level) was conducted to study the variability between the two sets of methods (point-source vs. infiltrometers) in determining the hydraulic and chemical transport properties of the soil pit.

RESULTS AND DISCUSSION

Hydraulic Properties

Figure 2 depicts the relationship of flux densities, q , versus the reciprocal of steady-state radii, $1/r_0$, produced by the point-source method for all observation sites. Increasing discharge rates (Q) from the sources resulted in increasing the size of the pondered area and, thus, decreasing the flux density (q). With the use of four discharge rates, Test 3 (Fig. 2) resulted in a near-perfect relationship ($r^2 = 1.00$), and the other tests also showed good linearity ($r^2 \geq 0.90$). A wide range of discharge rates is useful and helps to minimize error in estimation of hydraulic parameters (Shani et al., 1987).

Table 1. Estimated hydraulic properties from the point-source method and pondered and tension infiltrometers.

Test	Point-source method		Pondered and tension infiltrometers	
	K_s	λ_c	K_s	λ_c
	cm h ⁻¹	cm	cm h ⁻¹	cm
1	9.9	6.6	5.6	5.9
2	8.7	7.3	10.2	4.7
3	12.1	5.8	2.1	8.5
4	14.2	3.5	9.8	4.7
5	12.7	4.2	16.5	4.7
6	15.0	2.3	22.8	4.0
Mean	12.1 ^{ns†}	5.0 ^{ns}	11.2 ^{ns}	5.4 ^{ns}
SD	2.4	1.9	7.5	1.6
CV, %	20.1	38.8	67.0	30.1

† ns = not significant at $P < 0.05$.

The mean value of K_s produced by the point-source method was larger than that produced by the infiltrometers (Table 1). Such difference, however, was not significantly different (based on *t*-test at 5% probability level). For the λ_c , the infiltrometers produced larger mean value than the point-source method. There was no significant difference between the mean values of λ_c produced by the two methods. With the point-source method, estimated K_s is used to determine the λ_c parameter (from the resulting slope). Thus, computed λ_c would be expected to have greater variability than computed K_s . This is clearly indicated by their CV values (Table 1).

The point-source method gave consistent estimates for hydraulic parameters among the tests as indicated by their relatively low CVs (Table 1). Compared with the point-source method, estimated K_s among the tests from the infiltrometers was highly variable. However, estimated λ_c from infiltrometer experiments was less variable than the values produced by the point source λ_c method. Contact sand, used with tension infiltrometers, might have introduced flow impedance (Reynolds and Zebchuk, 1996) and resulted in higher variability in estimated K_s . Small variability among the tests was expected, because complete mixing of the soil in the pit should have produced a somewhat uniform soil.

Practical aspects of using the point-source method can be compared with use of the Ankeny et al. (1991) infiltrometer method. Both methods require application of water to the surface of locally level ground. Both methods require repeated flux measurements at the same surface locations. One difference is that the infiltrometer allows for repeated measurements on the exact same circular area while the point-source method requires different size infiltration areas for the different discharge rates. Furthermore, there is no guarantee that point-source infiltration areas will be exactly circular. Tension infiltrometer base size can be selected to provide the desired diameter of infiltration surface whereas dripper discharge rate can be selected to give approximate diameter of infiltration surface. Because of flexibility in discharge rates and infiltration areas both infiltrometer and point-source methods are flexible for application to a wide range of soil surface conditions. The point-source method does not offer the same level of control as the infiltrometer method. A tension infiltrometer is expensive and sophisticated relative to a dripper point source. A tension infiltrometer can make measurements at a

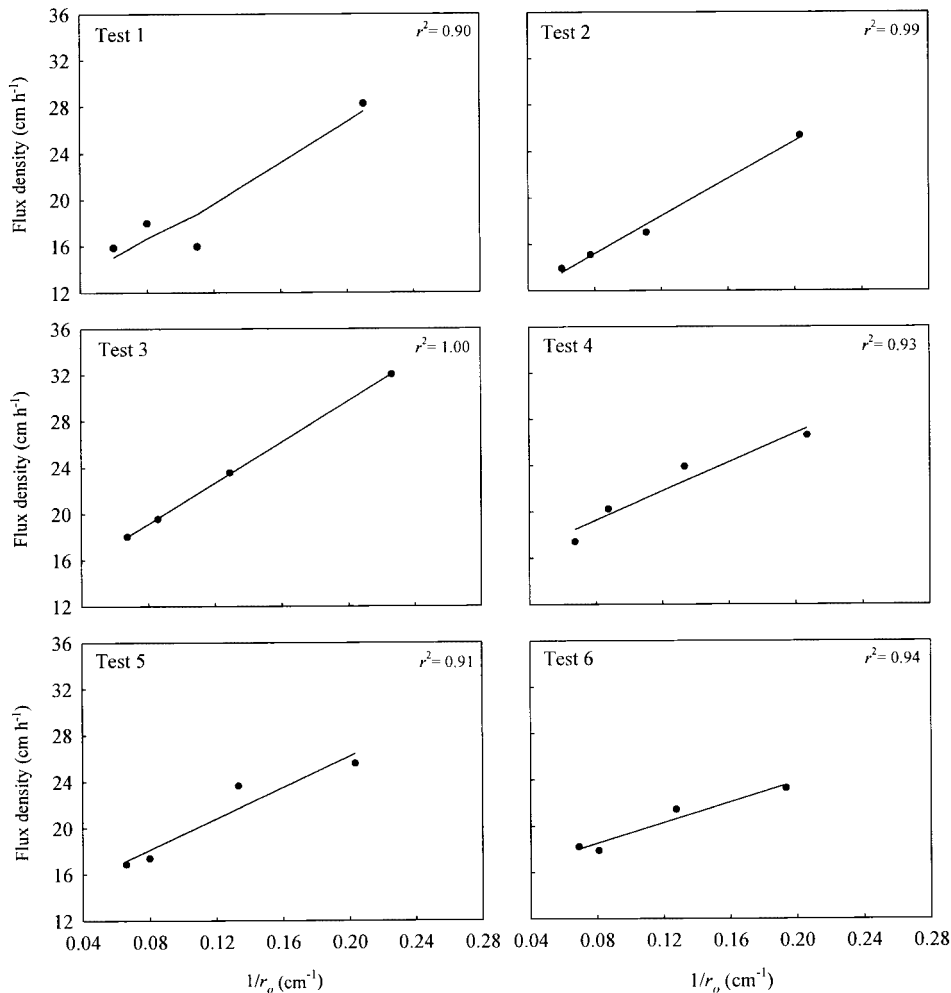


Fig. 2. Flux density versus $1/r_0$ for all observation sites from the point-source method.

single location in a given time period. In contrast, a single supply tube can have several drippers that can allow for application of the point-source method to multiple locations in a given time period. However, to use multiple drippers, a relatively large water supply tank may be required. Some loss of field portability may occur when multiple point-source drippers are used. Overall, relative to the Ankeny et al. (1991) infiltrometer method of determining surface hydraulic conduc-

tivity, the point-source method gives up some control at each given measurement location, but it allows for measurements at multiple locations in a given time period. Like the infiltrometer the point-source method is applicable to a variety of soil conditions.

Chemical Properties

Figure 3 shows normalized resident concentration, $\ln(1 - C/C_0)$, versus application time, t^* , and their fitted regression lines produced by the point-source method for all observation sites. All tests produced a linear relationship between the resident concentration and application time. Differences between the measured and predicted transport behavior are attributed to some experimental limitations, such as difficulty in measuring the small differences in tracer concentration (Jaynes and Horton, 1998). Linear regression lines for all tests produced a good fit of the measured data, suggesting that the multiple application of tracers from the point-source method produced a good linearity and can be well described using Eq. [8].

Mean total water content (θ) produced by the point-source method was larger than that produced by the ponded infiltrometers (Table 2). Similarly, the mean

Table 2. Total water content (θ), θ_{im}/θ , and α , estimates from the point-source method (six test sites) and ponded infiltrometers (five test sites).

Test	Point source			Ponded infiltrometer		
	θ	θ_{im}/θ	α	θ	θ_{im}/θ	α
	$m^3 m^{-3}$		h^{-1}	$m^3 m^{-3}$		h^{-1}
1	0.60	0.51	0.063	0.44	0.75	0.099
2	0.59	0.53	0.095	0.57	0.57	0.004
3	0.59	0.54	0.074	0.50	0.46	0.002
4	0.51	0.60	0.085	0.52	0.46	0.016
5	0.57	0.56	0.077	0.55	0.30	0.067
6	0.59	0.70	0.137	-	-	-
Mean	0.58*	0.57 ^{ns†}	0.089*	0.52*	0.51 ^{ns}	0.037*
SD	0.03	0.07	0.026	0.05	0.17	0.043
CV, %	5.6	12.1	29.2	9.6	33.3	116.2

* Significant at $P < 0.05$.
 † ns = not significant at $P < 0.05$.

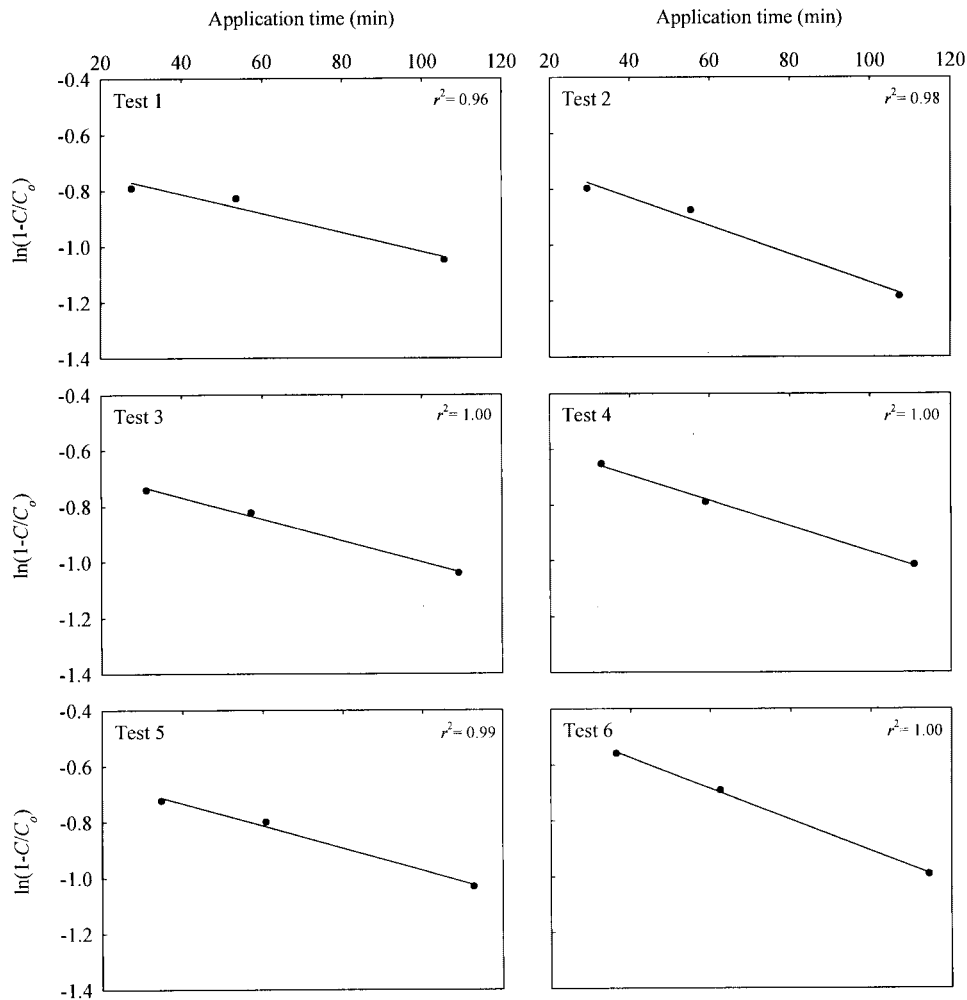


Fig. 3. Resident concentrations vs. application times for all observation sites from the point-source method.

values of θ_{im}/θ and α from the point-source method were larger than those produced by ponded infiltrometers. Measured θ and estimated α produced by the two methods were significantly different at 5% probability level. The estimated mean θ_{im}/θ values from the two methods, however, were not significantly different. For all parameters determined, ponded infiltrometers produced more variable values than those produced by the point-source method as indicated by higher CV values (Table 2).

In general, the point-source method produced larger values for θ , θ_{im}/θ , and α than those produced by ponded infiltrometers. Larger θ_{im}/θ from the point-source method was associated with larger θ . The average θ values produced by the two methods were significantly different as shown in Table 2. However, there was no significant difference between the two methods in estimating θ_{im}/θ . Jaynes et al. (1995) reported an average of θ_{im}/θ of 0.61 for the same soil pit. Their average value of θ_{im}/θ was associated with lower θ . Similar fluctuations of θ_{im}/θ with θ were also reported by Angulo-Jaramillo et al. (1996) and Casey et al. (1998).

Compared with the average value produced by the ponded infiltrometers, the point-source method produced larger average θ_{im}/θ , which meant smaller θ_m at the point-source locations. Moreover, the point-source

method produced larger average K_s than that produced by the ponded infiltrometers (Table 1). The combination of larger K_s and smaller θ_m for the point-source method indicated that pore velocity (v) in the mobile domain of the point-source sites was larger than at the ponded infiltrometer sites. Previous studies, as summarized by Griffioen et al. (1998), reported larger α associated with larger v . Thus, our α results are consistent with the Griffioen et al. (1998) findings. Both sets of methods, the point-source method and the infiltrometers, produced greater average values for α than that reported by Jaynes et al. (1995) for the same soil pit. Jaynes et al. (1995) applied the tracers from tension infiltrometers with a supply tension of -30 mm of water, i.e., unsaturated conditions. Thus, the reported average α value reported by Jaynes et al. (1995) was associated with smaller flux densities than the flux densities in this study. The data from both of our methods (point source and ponded infiltrometers) are therefore consistent with the Jaynes et al. (1995) results.

CONCLUSION

We developed and evaluated an experimental setup for estimating hydraulic and chemical transport proper-

ties using the point-source method and compared the method with ponded and tension infiltrometers. The point-source method showed a consistency in estimating hydraulic and chemical properties. It produced the minimum variability for determination of both sets of properties. Except for α , there was no significant difference between the two procedures in estimating mean hydraulic and chemical transport properties. Compared with the values reported by a previous study conducted on the same soil pit, the point-source method produced reasonable estimates for measured parameters of the chemical transport properties. From the results of this study, it can be concluded that the point-source method is reliable in estimating not only hydraulic properties, but also chemical transport properties (in conjunction with the sequential tracers procedure).

The experimental setup has the advantage of simultaneous estimation of both hydraulic and chemical transport properties at multiple locations within a short time. Another advantage of this setup is that both sets of soil properties can be evaluated on the same location, which minimizes errors because of spatial variability. Moreover, the setup allows rapid and multiple measurements with minimum labor and energy requirements. This enables the conduction of multiple measurements, which provides a better evaluation of distribution of soil properties. Evaluation of the setup and procedure with natural field conditions, such as tillage practices and crop rotations, is required for further establishment of this method.

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