

Measurement of Soil Hydraulic and Chemical Transport Properties

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Abstract

Hydraulic and chemical transport properties are required to predict movement of water and chemicals through soils. Field methods used to determine such properties are often hampered by extensive time and energy constraints. The objectives of this study are to present an experimental setup and a procedure for rapid and simultaneous measurements of hydraulic and chemical transport properties of a field soil. Hydraulic properties are saturated hydraulic conductivity and macroscopic capillary length. Chemical transport properties are immobile water fraction and mass transfer coefficient. A total of 15 sites of a field soil are evaluated for hydraulic and chemical transport properties. The setup allows simultaneous measurements to be made at multiple locations with minimum labor requirements. The procedure produces reasonable values for all transport parameters. We recommend the use of the setup and procedure for studies involving spatial and temporal evaluation of soil hydraulic and chemical transport properties.

Keywords. hydraulic properties, chemical transport properties, preferential flow, point source method.

Introduction

Hydraulic and chemical transport properties are needed for managing soil and groundwater resources. They are used as major inputs in different numerical models in order to predict movement of water and transport of chemicals through soils. Thus, characterizing hydraulic and chemical transport properties help in developing management practices to minimize potential contamination of groundwater resources.

Water flow from a point source into soils is three-dimensional and can be described by a relationship described by Richards (1931). Wooding (1968) solved a linearized form of Richards' equation and presented a relationship that describes water infiltration into the soil from a shallow pond over the soil surface as:

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

where q is flux density (LT^{-1}), Q is volumetric flux rate (L^3T^{-1}), r is saturated pond radius (L), K_s is saturated hydraulic conductivity (LT^{-1}), and I is macroscopic capillary length (L). The I parameter quantifies the importance of capillarity (the attraction of water to dry soil) to that of gravity on water movement. Water flow from a point source into a soil with a large I (fine-textured soil) will have more lateral flow than would flow into a soil with a small I value (coarse-textured soil). Applying water from a point source, at certain Q , on a soil surface results in creating a ponded, i.e. saturated, area at the surface. Based on Eq. (1), plotting q versus $1/r$ yields a straight line with an intercept equivalent to K_s and a slope, $4K_s I/\pi$ from which I can be computed.

Preferential transport of chemicals, such as fertilizers and pesticides, has been reported by many researchers; such as Kanwar et al. (1985). Such nonequilibrium transport often cannot be described with the convective-dispersive equation (van Genuchten and Wierenga, 1976). Alternatively, Coats and Smith (1964) introduced a two-domain model, often called mobile-immobile model (MIM), to better describe transport of chemicals into porous media. The model divides the water filled porosity, i.e. q into two domains: a mobile domain (q_m) where chemicals are moving with flowing water, and an immobile domain (q_{im}) where water is stagnant and chemicals move by diffusion only. For noninteracting chemicals, the MIM can be written as:

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

where C_m and C_{im} are concentrations of chemicals into mobile and immobile domains (ML^{-3}), and D_m is dispersion coefficient of chemicals (L^2T^{-1}) (active in the mobile domain only). The movement of chemicals between the two domains is proportional to the concentration gradient of each chemical and described as a first-order process (van Genuchten and Wierenga, 1976):

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$$q_{im} \frac{\partial C_{im}}{\partial t} = a(C_m - C_{im}) \quad (3)$$

where a is first-order mass transfer coefficient (T^{-1}). Jaynes et al. (1995) presented a solution to Eq. (3) to determine chemical transport parameters, q_m/q and a from field experiments. They applied a sequence of conservative tracers into the soil using tension infiltrometers. Assuming piston displacement of tracers, they presented the following solution to Eq. (3):

$$\ln(1 - C/C_o) = \ln(q_{im}/q) - (a/q_{im})t^* \quad (4)$$

where t^* is time for the tracer's front to pass the sampling depth, C is concentration of tracers in the soil and C_o is input concentration from the source.

Adequate measurements of field properties are required to fully characterize water and chemical transport. However, this is hampered by limitations of the methods used to determine such properties. Most of the current field methods produce a single measurement in a given time period. For example, tension infiltrometers are widely used to characterize distribution of hydraulic properties in the field. They are, however, limited to a single measurement for a specific field site. Thus, it is time consuming to use them with studies that determine the spatial and temporal distribution of properties. New methods that enable rapid determination of hydraulic and chemical transport properties at multiple field locations are needed.

The objectives of this study are to present an experimental setup and a procedure that allow rapid and simultaneous measurements of surface hydraulic and chemical transport properties of field soils, and to determine hydraulic and chemical properties across a field. Hydraulic properties are saturated hydraulic conductivity (K_s) and macroscopic capillary length (I). Chemical transport properties are immobile water fraction (q_m/q) and mass transfer coefficient (a).

Materials and Method

The study was conducted at the Agronomy-Agricultural Engineering Research Center, Iowa State University, Ames, Iowa. The field plot was grown with corn (*Zea Mays* L.) under no-till practices. The soil was classified as Nicollet loam (0.389 sand, 0.366 silt, 0.245 clay mass fraction) with an average bulk density of 1.43 Mg m^{-3} .

A transect (24 m long) was selected for conducting the study on a corn row. Corn plants were cut and residues were removed from the soil surface. Three dripper lines were placed over the transect. Each dripper line was equipped with one type of pressure-compensating drippers. Drippers used had discharge capacities of 2, 4, or 8 L h^{-1} . Thus, each dripper line had the ability to deliver one discharge rate. Details of the setup can be viewed in Fig. 1. A release valve was installed at the far end of the system to allow quick flushing of the system from different applied chemical solutions. Drippers were about 1.5 m apart, so a total of 15 sites were measured. The setup allowed simultaneous measurements over all sites along the transect.

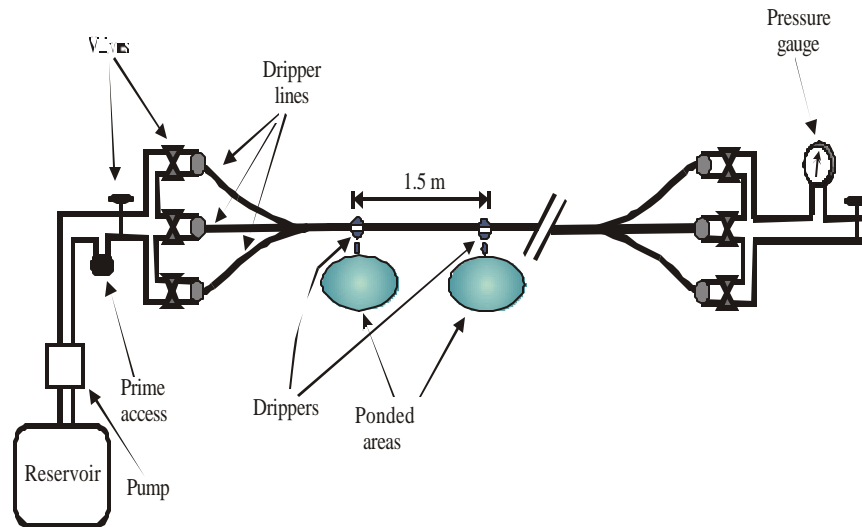


Figure 1. Experimental setup at the field.

The experimental procedure was started by determining hydraulic properties. This involved applying three consecutive discharge rates (Q). A discharge rate of 2 L h⁻¹ was first applied. The discharge rate at each site was measured and recorded. Application of water was continued until steady-state conditions prevailed. Steady-state conditions were reached when the ponded area reached a constant size with respect to application time. Steady-ponded radius of each site was measured and recorded. This was followed by applying the next highest discharge rate, which was 4 L h⁻¹. Switching between different applied Q was achieved by closing and opening valves of different dripper lines. This procedure was repeated for the last discharge rate, which was 8 L h⁻¹. The flux density (q) of each site was determined by dividing measured discharge rate (Q) by measured ponded area. Hydraulic properties were determined, from Eq. (1), by regressing different flux densities (q) versus the resulting reciprocal of saturated ponded radii ($1/r$).

Chemical transport properties were determined by applying a sequence of solutions containing three different conservative tracers as proposed by Jaynes et al. (1995). Tracers were fluorobenzoate tracers, which were reported to have similar transport properties in many soils (Jaynes, 1994). In this study, we used 2,6-difluorobenzoate (DFBA), *o*-trifluoromethylbenzoate (TFMBA), and pentafluorobenzoate (PFBA) acids. Solution 1 was first applied, which consisted of 0.001 M (1 mM) of DFBA. Application time was enough for the tracer to pass the sampling depth (2 cm). This was followed by applying Solution 2, which consisted of 1 mM of each of DFBA and TFMBA. Solution 2 was applied for time enough for solution front to pass the sampling zone. Finally, Solution 3 was applied, which consisted of 1 mM of each of DFBA, TFMBA, and PFBA. A surface soil sample was taken from each site after applying Solution 3 using stainless rings (2.0 cm x 5.1 cm i.d.). Samples were placed into sealed plastic bags and stored in a cold environment. In the laboratory, a subsample from each sample was taken for gravimetric determination of water content. The rest of each sample was mixed with distilled water at a predetermined ratio, shaken, and extracted using filter paper. Chemical analysis for tracers of input solutions and of each sample was conducted using an ion chromatograph (Jaynes et al., 1995). Chemical transport parameters were determined using Eq. (4) by regressing $\ln(1-C/C_o)$ versus t^* .

Results and Discussion

Table 1 presents the hydraulic and chemical transport properties obtained from this study for all sites. Determined values of saturated hydraulic conductivity ranged from 7.5 to 47.0 cm h⁻¹ with an average of 25.8 cm h⁻¹ and a median of 25.3 cm h⁻¹ (± 11.5). Obtained values for I ranged from 0.03 to 13.1 cm with an average of 3.4 cm and a median of 2.6 cm (± 3.6). Estimated K_s produced a lower variability than λ . Large values of K_s were expected because the study was conducted on plant rows at the end of the growing season. The fully developed corn roots created macropores (vented macropores were visible). This enhanced preferential flow and, thus, increased the hydraulic conductivity. The values of λ obtained from this study were within the range reported for this type of soil (Radcliffe and Rasmussen, 2000). However, the small values of I can be attributed to the presence of macropores. Mohanty et al. (1994) used tension infiltrometers (multiple tension method) to determine the hydraulic properties on another central Iowa location close to our study. They reported an average value of 39.9 cm h⁻¹ for K_s and 24.4 cm for I . Their study found larger variability in hydraulic properties than did our study.

Table 1. Hydraulic and chemical transport properties for all sites.

	Hydraulic properties		Chemical properties	
	K_s (cm h ⁻¹)	I (cm)	q_m/q	a (h ⁻¹)
N	15	15	15	15
Mean	25.8	3.4	0.62	0.04
Median	25.3	2.6	0.62	0.04
Max.	47.0	13.1	0.80	0.12
Min.	7.5	0.03	0.41	0.0004
Std. Dev.	11.5	3.7	0.09	0.03
Conf. Limits (95%)	6.6	2.1	0.05	0.02

Average bulk density was consistent with a CV-value of 7%. This yielded consistent water content among the sites. Immobile water fraction (q_m/q) ranged from 0.41 to 0.80 with an average and a median of 0.62 (± 0.09). Estimated values for mass transfer coefficient (a) ranged from 4×10^{-4} to 0.12 h⁻¹ with an average and a median of 0.04 h⁻¹ (± 0.03). About 93% of q_m/q was in the range of 0.5-0.7. The larger the q_m/q the faster water

moves through the soil. The α -values were more variable than q_m/q . This is because estimating α is affected by estimated q_m ; i.e., they are correlated. Casey et al. (1997) reported, for a study conducted at another location close to the location of our study, an average of 0.64 for q_m/q which is very similar to our result (0.62). Their reported average of α was 0.07 h^{-1} , which is about 200% higher than the average of our study. Casey et al. (1997) applied the sequence of tracers using tension infiltrometers with a supply head of -3 cm , which produces lower pore velocity. Based on the ANOVA test (single factor), there was no significant difference between our study and the one by Casey et al. (1997) in estimating q_m/q . However, there was a significant difference between the two studies in estimating α . This indicates that there is need to measure directly properties in the field of interest.

Conclusions

We presented a new experimental setup and a procedure by which hydraulic and chemical transport properties can be rapidly and simultaneously determined in a field. Hydraulic properties included saturated hydraulic conductivity and macroscopic capillary length. Chemical transport properties included immobile water fraction and mass transfer coefficient. A total of 15 sites along a transect were simultaneously tested for both sets of properties. Measurements for both sets of properties were conducted on the same location, which minimizes any error due to natural spatial variability of the soil. Moreover, measurements were made over a very short time period (compared with other field methods). We were able to produce all sets of measurements within two days with minimum labor requirement. The study showed a consistency in estimating both sets of properties. The setup and procedure were simple and easy to operate and allowed simultaneous operation of multiple locations with minimum labor requirements. A complete set of transport parameters, i.e., K_s , I , α and q_m/q were determined for multiple locations at the same time period. Thus, the setup and procedure are potential tools for studies involving spatial and temporal analysis.

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