MODELING WATER TRANSPORT IN A SILT LOAM SOIL OF THE SOUTHERN MISSISSIPPI VALLEY SILTY UPLANDS

Alton B. Johnson
Mississippi River Research Center
Department of Agriculture, Alcorn State University

INTRODUCTION

There is increasing interest in the agricultural community in using models to guide the application of water and chemicals to soil and crops and subsequently predict the fate of these elements in the environment. Practical management options for reducing contaminant transport in the soil profile have traditionally been identified on the basis of site-specific experimental results. It might not be possible in all cases to extend the results from a small number of research situations to all conceivable scenarios. Furthermore, large-scale field sampling programs designed to determine solute and water transport in the soil profile are too expensive (Hutson and Wagenat 1993). Since the number of variables and/or combinations of variables impacting solute and water transport are large, an indirect method such as simulation modeling can be employed as a surrogate for experimental observations.

For a model to accurately predict solute and water movement in the soil profile, those soil properties that regulate the transport process must be determined. The ability of a soil to transmit and retain solute and water is governed by the hydraulic properties of the soil. Hydraulic conductivity (K), water retention, and difusivity (D) as functions of volumetric water content (θ) and/or pore water pressure head (ψ) are those hydraulic properties that are important in understanding solute and water transport phenomena. Transport of solute and water in the soil profile is largely controlled by the K-θ-ψ relationships.

The procedures commonly used in determining the K-θ-ψ relationships are (1) core method, (2) in-situ method, and predictions based on soil particle-size distribution. Of the three methods, the soil core method is widely used, not because of its realistic estimates, but because it is convenient and relatively simple to obtain K and θ over a large range of ψ (-1500 kPa $\leq \psi \leq 0$). The large variability associated with the soil core method, especially in the near-saturated range, makes it essential to derive the K-θ-ψ relationships on large intact (in-situ) soil units (Römkens et al. 1986). The objective of this study was to obtain K-θ-ψ relationships derived from in-situ intact, highly instrumented soil columns and test the predictive capability of LEACHW, a water flow submodel of Leaching Estimation And CHemistry Model (LEACHM) in a dominant soil in southern Mississippi.

MODELING APPROACH

Water transport in the soil profile is described by Darcy's law

$$q = -K(\theta)\cdot\nabla H \qquad [1]$$

and by the continuity equation

$$\partial\theta/\partial t = -\nabla\cdot q \qquad [2]$$

where q is the flux (L T^{-1}) and t is time coordinate. The hydraulic head or total water potential is given in most water transport problems as the sum of the soil pore water pressure head or soil water potential $\psi(\theta)$ and the gravitational head, z:

$$H(\theta) = \psi(\theta) + z \qquad [3]$$

The combination of equations [1] and [2] yields a non-linear partial differential equation known as the Richard's equation. The Richard's equation for a one-dimensional flow is given as:

$$\partial\theta/\partial t = \partial/\partial z[K(\theta)\partial H/\partial z] - \Phi(z,t) \qquad [4]$$

where z is soil depth in cm and Φ is the sink term representing water loss per unit time.

To solve equation [4], the K-θ-ψ relationships must be known. The LEACHW submodel uses the one-dimensional Richards' equation of the form:

$$(\partial\psi/\partial t)C(\theta) = \partial/\partial z[K(\theta)\partial H/\partial z] - \Phi(z,t) \qquad [5]$$

where $C(\theta) = \partial\theta/\partial\psi$ is the differential water capacity relationship. LEACHW currently uses Cambell's equation (1974) to determine the ψ-θ relationship:

$$\psi = a(\theta/\theta_s)^{-b} \quad [6]$$

where θ_s is volumetric water content at saturation and a and b are constants. Since equation [6] is exponential and possesses a sharp discontinuity at $\psi = a$ and $\theta/\theta_s = 1$, it does not represent water retention in field soil. Therefore, the function was replaced by a parabolic function at high ψ. Hutson and Cass (1987) modified equation [6] to:

$$\psi = a[(1-\theta/\theta_s)^{1/2}(\theta_c/\theta_s)^{-b}]/[(1-\theta_c/\theta_s)^{1/2} \quad [7]$$

where ψ_c , $_c\theta$ is the point of intersection of the exponential and parabolic curves:

$$\psi_c = a[2b/(1+2b)]^{-b} \quad [8]$$

and

$$\theta_c = 2b\theta_s/(1+2b) \quad [9]$$

The Cambell K used in LEACHW is based on applying the capillary model to equation [6] to yield:

$$K(\theta) = K_s(\theta/\theta_s)^{2b+2+p} \quad [10]$$

where K_s is saturated hydraulic conductivity and p is a pore interaction parameter.

MATERIALS AND METHODS

Two intact soil columns (20-cm i.d. and 70 cm long) of Memphis silt loam (Fine-silty, mixed, thermic, Typic Hapludalfs) were taken 4 m apart from a dairy pasture near Alcorn State University, Lorman, Mississippi. The field has been in continuous pasture for 35 years. Mean K_s, bulk density, texture and %OC of the columns from 0 to 70 cm are presented in Table 1.

The columns ware positioned vertically and instrumented at 10-cm depth interval with tensiometers and thermistors to measure ψ and θ, respectively (Fig. 1). This was a modification of the device constructed by Johnson et al. (1993) and similar to that of Smith et al. (1995). Each tensiometer was constructed from standard flow -100 kPa round bottom, tapered neck, porous ceramic cup of 2.2 cm dia. by 6.98 cm long (Soilmoisture Equipment Corp., Santa Barbara, CA) and about 2.2 cm i.d. polyvinlychloride (PVC) pipes; and installed horizontally in the soil. The part of the tensiometer extending outside the column was constructed at 45° and tensiometers were read with a tensimeter (Soil Measurement Systems, Inc., Tucson, AZ). The thermistors (ELE International, Inc., SoilTest, Lake Bluff, IL) were installed horizontally opposite the tensiometers at the corresponding soil depths.

To retain the soil in each column, a layer of cheese cloth was placed over acid-washed crushed rocks (average dia. = 1 cm) that were place in a PVC end cap. The main column was then attached to the end cap with PVC sealant. An outlet was made in the middle of the end cap and connected to a constant head buret with tygon tubing (Johnson et al. 1993; Smith et al. 1995). This allowed easy change in pressure head for saturation of the soil from the bottom by depth and removal of air in the soil.

Soil hydraulic properties (ψ and θ) were determined using tensiometers and thermistors for each of the 10-cm depth increment. To minimize the presence of air in the system, de-aired water was used during saturation and q determination. Saturation was achieved by moving the constant head buret up along the column in 10-cm increment. This process continued until 15 cm of water was ponded on the soil surface in each column. Flux was determined for each column using the constant head method (Klute and Dirksen 1986) and q was imposed on soil depth increment to determine corresponding K_s. The K_s for each depth increment (i) was calculated as

$$K_{s(i)} = q(\Delta z/\Delta H)_i; \quad i = 1,2,3,...,7 \quad [11]$$

where $K_{s(i)}$ is measured in L T^{-1} and $(\Delta z/\Delta H)_i$ is inverse of hydraulic gradient for corresponding depth. The bulk K_s value (K_{sh}) of each column was calculated by determining the harmonic mean of the $K_{s(i)}$ values:

$$K_{sh} = n/\Sigma^n_{i=1}K^{-1}_{s(i)}; \quad i = 1,2,......,7 \quad [12]$$

Geometric mean values of K_s for the two columns per soil depth were used as input for LEACHW:

$$K_{sb} = [K_{s(1)}\,K_{s(2)}........K_{s(n)}]^{1/n}; \quad n = 7 \quad [13]$$

All other input parameters were averaged across columns. Soil water retention data (ψ vs. θ) were obtained directly using tensiometers and thermistors per soil depth in each column. Retentivity data across columns were pooled and the parameters, a and b, in Eq. [7] determined using the RETFIT program within LEACHM (Hutson and Wagenet 1992). The least square fitting procedures in JUMP (SAS Institute 1995) were used to compare measured and LEACHW predicted H and θ profiles. Criteria for estimating goodness-of-fit of LEACHW predicted to measured data were coefficient of determination (r^2), correlation coefficient (r) and root mean square error (rms).

RESULTS AND DISCUSSION

Estimated a and b from fit to Eq. [7] and associated statistics are presented in Table 2. Model fit to measured θ_s showed good fit as indicated by the rms (Table 2). Figures 2 and 4 illustrate measured and predicted θ_s and H profiles. Measured soil water content ranged from 0.547 to 0.506 $cm^3\ cm^{-3}$ in the 0 to 40 cm soil depth and from 0.476 to 0.468 $cm^3\ cm^{-3}$ in the 60 to 70 cm soil depth. This trend was followed by LEACHW predicted θ_s. Hydraulic head decreased with depth but was smoother in decreasing trend for both measured and predicted values than the θ_s profile. The decrease in measured and predicted θ_s and H profiles at saturation suggests that layering occurred in the profile as was evident by the increase in bulk density with depth (Table 1). In general, best agreement was found between measured and LEACHW predicted data (Figures 3 and 5; $r = 0.969$ and 0.994; $P \leq 0.01$). Figure 6 shows LEACHW predicted θ and K as functions of ψ in the profile. The trend of the profile θ and K is typical in that decrease in θ will decrease K. Under conditions where the water conducting pores are void of water, K will decrease drastically.

Determining K-θ-ψ relationships for solute and water transport model validity is essential. However, in adopting the model(s) to describe a specific scenario, all parameters required for model input must be derived independently. Since soil transport properties are spatially and temporally variable, LEACHW, which is deterministic in nature, must be tested on a quasi stochastic basis to address these intrinsic variabilities. Simulation models in general are cost-saving and aid in sound decision making processes. LEACHW for its intended purpose in this study was a good research model in describing θ, H and K for the soil under study. Further testing of LEACHW on different dominant soils in Mississippi is needed for complete validation and verification. Understanding water flow in the soil and the effects of soil physical, chemical and biological properties on water transport patterns will provide pertinent information on contaminant movement to the groundwater.

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Table 1. Selected soil properties used as input for LEACHW.

Soil depth	Bulk density	10^5 K_s	Clay	Silt	OC
cm	g cm^{-3}	cm s^{-1}	------------	%	------------
10	1.20	2.10	5.6	70.6	1.5
20	1.20	2.66	5.6	70.6	1.5
30	1.25	2.93	2.7	73.8	1.5
40	1.27	3.22	2.5	75.2	1.2
50	1.30	2.93	2.4	72.7	0.5
60	1.39	2.94	2.6	62.8	0.5
70	1.41	3.22	2.6	62.8	0.5
Mean	1.29	n/a	3.4	69.8	1.0
Harmonic mean	n/a	2.41	n/a	n/a	n/a

Table 2. Estimated a and b from fit of Eq. [7] with r^2 and rms of measured retentivity data.

Soil depth	a	b	r^2	rms
cm				
10	-0.545	5.845	0.959	0.0312
20	-0.509	5.905	0.978	0.0315
30	-3.260	3.483	0.982	0.0265
40	-3.380	3.875	0.983	0.0246
50	-2.880	5.283	0.985	0.0208
60	-4.420	5.343	0.970	0.0283
70	-5.480	5.488	0.968	0.0290

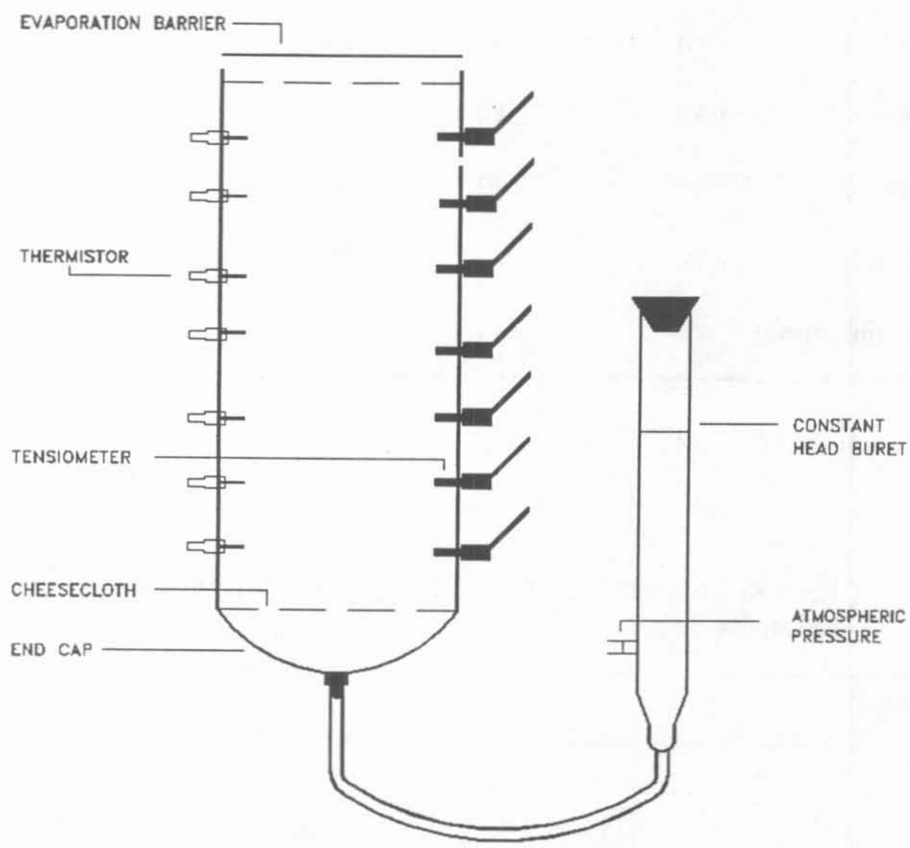

Fig. 1. Schematic diagram of column.

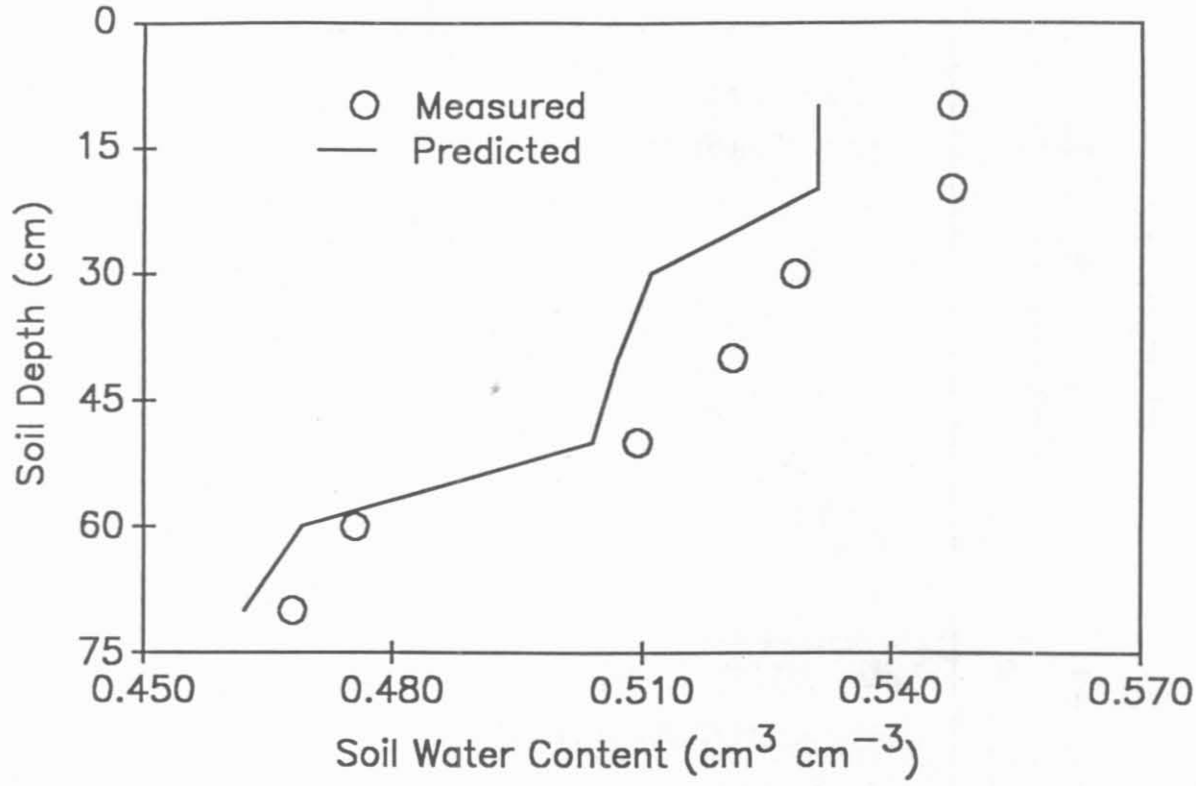

Fig. 2. Measured and LEACHW predicted saturated water content as a function of soil depth.

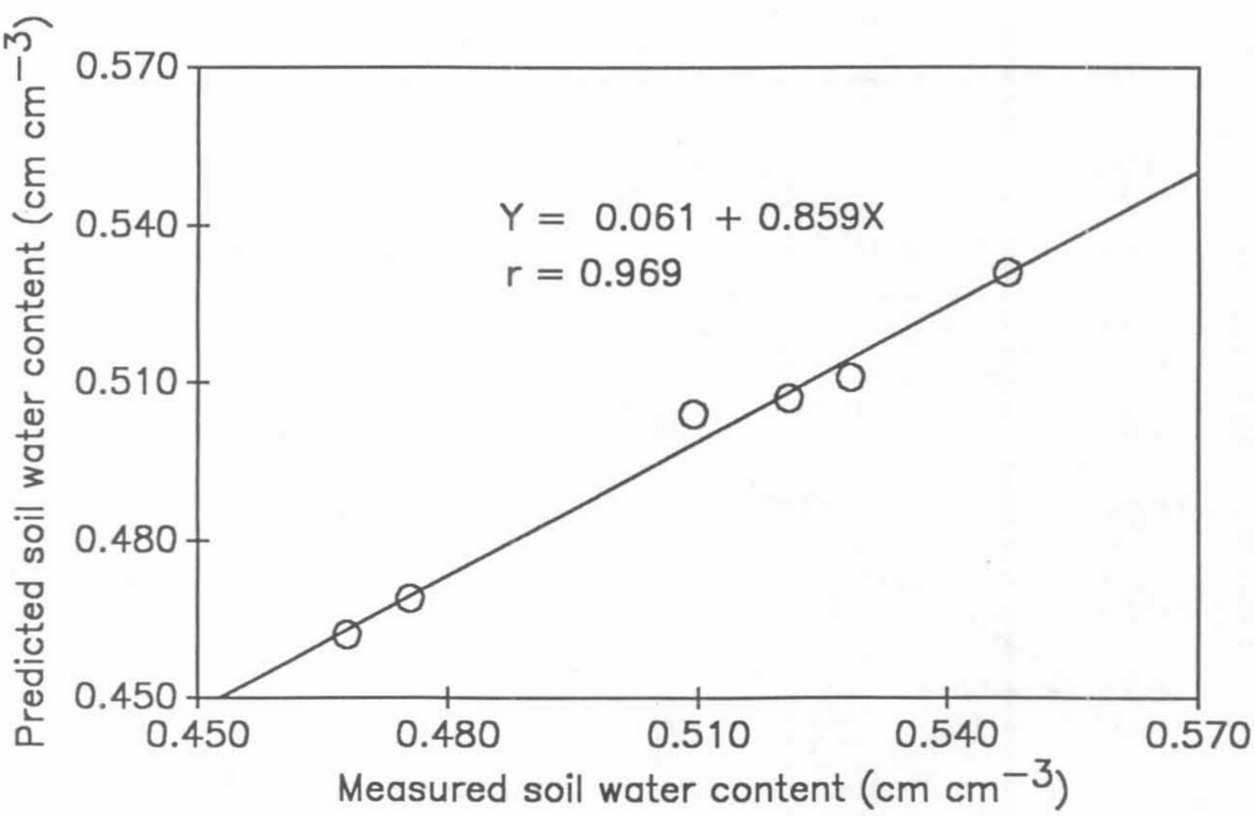

Fig. 3. LEACHW predicted vs. measured saturated water content.

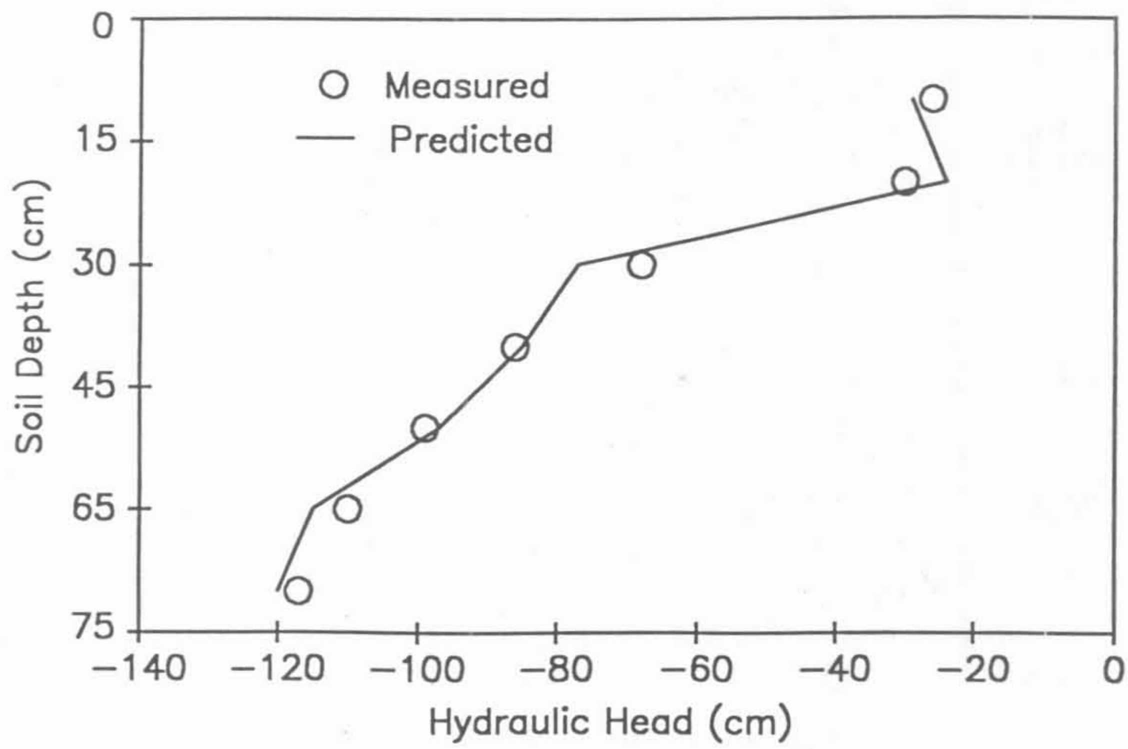

Fig. 4. Hydraulic head as a function of soil depth for measured and LEACHW predicted under saturated condition.

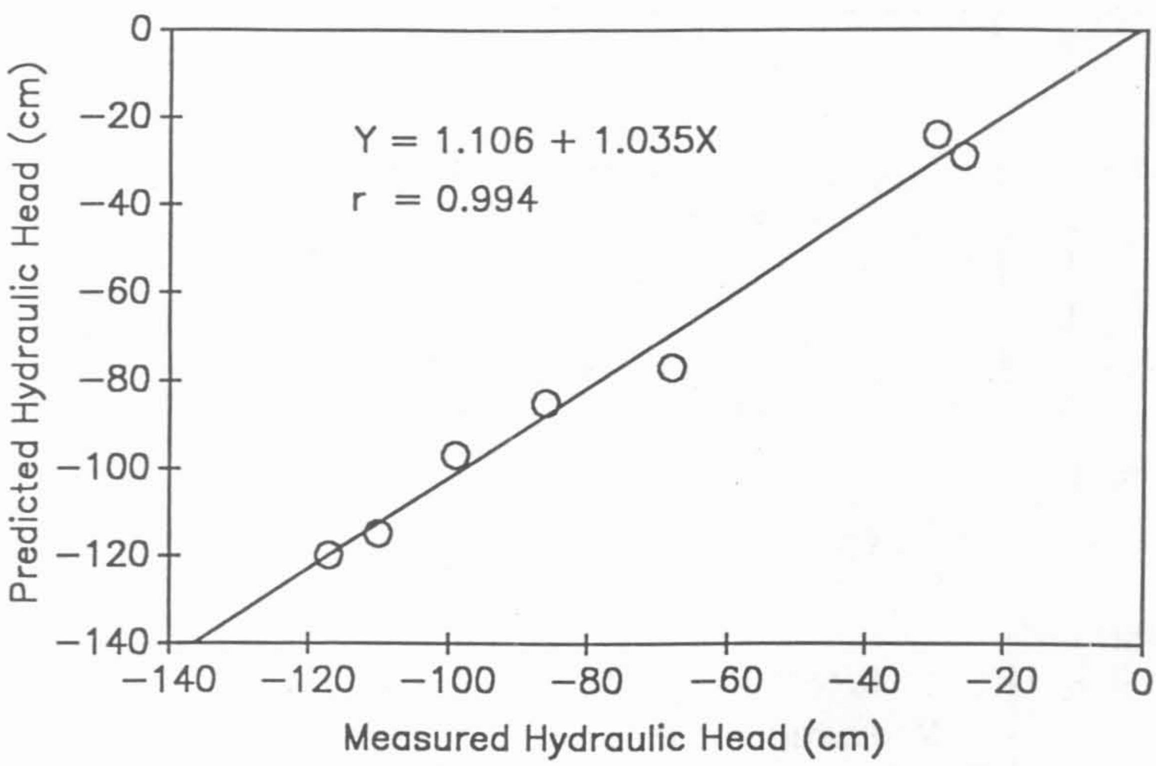

Fig. 5. LEACHW predicted vs. measured hydraulic head under saturated condition.

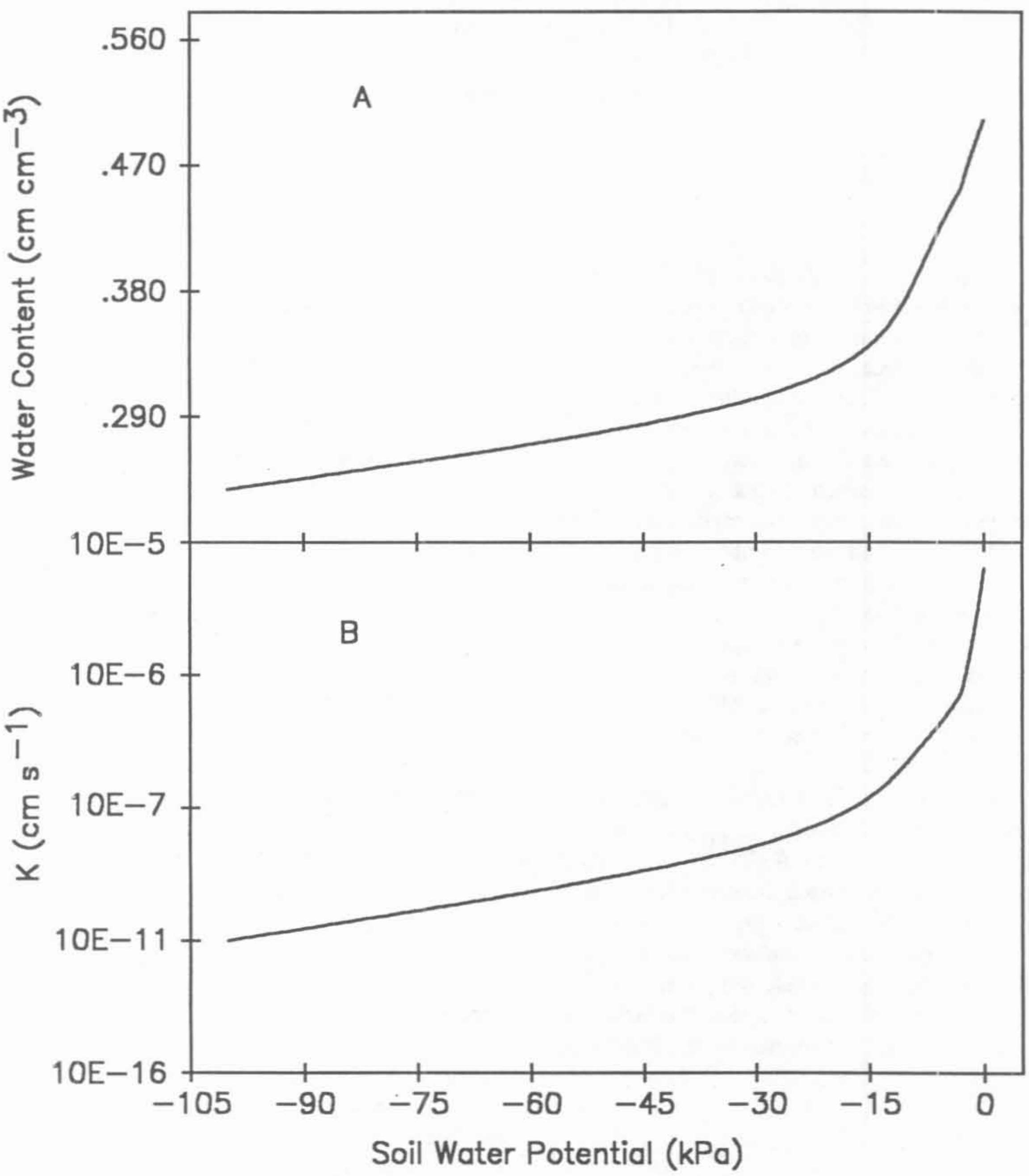

Fig. 6. LEACHW predicted water content (A) and hydraulic conductivity as functions of soil water potential.