

## Soil Hydraulic Conductivities and their Spatial and Temporal Variations in a Vertisol

Surajit Das Gupta, Binayak P. Mohanty,\* and J. Maximilian Köhne

### ABSTRACT

Knowledge of soil hydraulic parameters and their spatiotemporal variation is crucial for estimating the water and solute fluxes across the land-atmosphere boundary and within the vadose zone at different scales. The objective of this study was to determine soil hydraulic conductivities [saturated hydraulic conductivity,  $K_{\text{sat}}$ , and unsaturated hydraulic conductivity,  $K(\Psi)$ ] and their spatial and temporal variations in a clay-dominated biporous Vertisol near College Station, TX, using tension infiltrometers. The study was conducted within a 20- by 16-m plot across several seasons during a 21-mo period (May 2003–January 2005) to investigate the impact of varying disk sizes (measurement support) on  $K(\Psi)$ , and the spatial and temporal variations of  $K(\Psi)$  under natural environmental conditions due to pore space evolution. Infiltration occurred in a bimodal fashion consisting of preferential flow (occurring at soil water pressure heads [ $\Psi$ ] =  $-0.05$  to  $0$  m) and matrix flow (at  $\Psi$  =  $-0.2$  to  $-0.1$  m). Biological and structural macropores present in the soil resulted in gravity-dominated flow near saturation ( $\Psi$  =  $-0.05$  to  $0$  m) for all experiments. The Student's *t*-test of analysis of variance indicated that hydraulic conductivities were not affected by changes in the infiltration disk sizes. Although the  $K(\Psi)$  values at four different locations within the plot did not show significant spatial variability, they demonstrated strong temporal variation during the 21-mo period based on the evolution of natural environmental conditions due to seasonal precipitation, root growth and decay, and structural pore space dynamics. Temporal trends of  $K(\Psi)$  indicated that hydraulic conductivities close to saturation were positively correlated with antecedent moisture conditions reflecting liquid cohesion, water films bridging across cracking peds, and the activation of flow in biological and structural macroporosity in the biporous soil system.

SATURATED AND UNSATURATED soil hydraulic conductivities are important for characterizing the rate of water flow and the fate of contaminant transport across the land-atmosphere boundary and through the vadose zone. In the past, various studies (Clothier and White, 1981; White and Sully, 1987; Messing and Jarvis, 1993; Logsdon and Jaynes, 1993; Mohanty et al., 1994a, 1994b) have been conducted to determine in situ near-saturated hydraulic conductivities of agricultural soils using tension infiltrometers. Hydraulic parameters near saturation ( $\Psi$  between  $0$  m and the bimodal hydraulic conductivity inflection point  $\Psi^*$ , approximately  $-0.03$  to  $-0.1$  m) are important in characterizing preferential flow processes (Mohanty et al., 1997, 1998; Mohanty, 1999) in biporous soil systems. The in situ measurements of  $K(\Psi)$  using a tension infiltrometer provide a better representation of near-

saturated flow conditions compared with those obtained from laboratory analysis of soil cores (Shouse and Mohanty, 1998). Furthermore, tension infiltrometers can be used to measure both saturated and unsaturated hydraulic properties at the same location, which eliminates spatial variability between samples (Lin, 1995).

It is well known that infiltration of water and chemicals in many field soils is enhanced by macropores (Logsdon and Jaynes, 1996; Mohanty et al., 1997, 1998; Shouse and Mohanty, 1998). Thus, the spatial variation, size, and interconnectedness of biological and structural macropores would play a key role in determining the rate of influx through soils. Or et al. (2000) formalized a stochastic modeling framework describing the evolution of soil (textural and structural) porosity following tillage operations and subsequent wetting and drying cycles, which was then linked to soil water characteristics and soil hydraulic conductivity functions. In an experimental study (Lin et al., 1998), the shrink-swell characteristics of soils caused by drying and wetting along with annual tillage practices showed temporal variations in the soil hydraulic parameters. Hence, precise predictions of water flow and the fate of chemicals applied to soils would require a comprehensive understanding of the spatiotemporal variations of soil hydraulic parameters at different scales. Such studies considering both spatial and temporal aspects of the transport of water and chemicals through the vadose zone would support water balance calculations and the assessment of groundwater vulnerability to potential contamination.

While several spatial variability studies of saturated and unsaturated hydraulic conductivities of agricultural soils have been conducted by different researchers, very few studies relating to their long-term seasonal and temporal variations have been reported to date. Several studies have been conducted in the past to study the spatial and temporal variations of  $K_{\text{sat}}$ , with contrasting results. Cassel and Nelson (1985) demonstrated a large temporal variation in  $K_{\text{sat}}$  at different depths in a laboratory soil column. Starr (1990) reported that conservation tillage gave rise to more variation in  $K_{\text{sat}}$  and sorptivity values during a single growing season than a plow treatment. Few independent spatial (Mohanty et al., 1994a) or temporal (Lin et al., 1998) variability studies have been conducted for unsaturated hydraulic conductivity parameters. Messing and Jarvis (1993) and Logsdon and Jaynes (1996) investigated the temporal variations in unsaturated hydraulic properties due to agricultural operations.

Messing and Jarvis (1993) performed tension infiltrometer studies on plowed and unplowed plots in a clay soil between June and October 1991 in Sweden to

Dep. of Biological and Agricultural Engineering, 2117 TAMU, Texas A&M Univ., College Station, TX 77843-2117. J. Maximilian Köhne now at Univ. of Rostock, Germany. Received 26 May 2006. \*Corresponding author (bmohanty@tamu.edu).

Published in Soil Sci. Soc. Am. J. 70:1872–1881 (2006).

Soil Physics

doi:10.2136/sssaj2006.0201

© Soil Science Society of America

677 S. Segoe Rd., Madison, WI 53711 USA

**Abbreviations:** AMC, antecedent moisture content; REV, representative elementary volume.

monitor the spatiotemporal variations of both saturated and unsaturated hydraulic parameters. They observed strong temporal trends in  $K(\Psi)$  values that resulted from changes in the climatic conditions as well as tillage practices. They observed that reductions in the  $K(\Psi)$  values were most prominent in the soil water pressure range between  $-0.04$  and  $-0.06$  m. They also showed (using the  $t$ -test for analysis of variance) that temporal variations of  $K(\Psi)$  within soil water pressure heads of  $\Psi = -0.04$  to  $-0.06$  m were statistically more prominent than their spatial variations. Logsdon and Jaynes (1996), who conducted infiltration experiments in a cultivated field in Iowa, observed strong temporal variability of  $K(\Psi = -0.15$  m) from July 1991 to May 1992 matching four different (precultivation, late season, predisk, and postdisk) agricultural operations. They asserted that  $K(\Psi)$  variability reflected the evolution in micropores with tillage. The  $K_{\text{sat}}$  values did not show consistent temporal variations, but were more spatially correlated. They attributed this phenomenon to the influence of macropores, which were unstable due to tillage, shrink-swell phenomena, and root activities. Lin et al. (1998) observed that the spatial variability of  $K(\Psi)$  at low soil water tension could be related to soil macropore distribution in Vertisols and vertic intergrades, which are typical soils (i.e., soils frequently found) in Texas. They also noticed marked temporal variations of  $K(\Psi = -0.03$  m) and  $K_{\text{sat}}$  values during a 3-mo period between August and October 1997. They attributed this behavior to the shrink-swell characteristics of the clay due to the variations in precipitation during the measurement period.

Another aspect of past infiltration studies that has received limited attention is whether infiltration rate varies with different measurement support sizes. Using three different infiltrometer ring sizes of 5-, 25-, and 127-cm diameters, Sisson and Wierenga (1981) demonstrated the spatial variability of infiltration rate across a 6.35- by 6.35-m plot in a fine silty clay loam soil at Las Cruces, NM. One important observation of that study was while spatial (transect) mean infiltration rate varied a little across the three ring sizes, variability within a transect was generally higher for the smaller rings. Also, based on the comparison of probability distributions of infiltration rate for the three ring sizes, they determined that, to obtain a more reliable estimate of the field-mean infiltration rate, the rings with larger area of support are more reliable than a larger number of measurements with the smaller rings. Furthermore, based on their findings, Sisson and Wierenga (1981) recommended that the infiltration measurements should be conducted by sampling within a limited area with time to minimize the effect of spatial variability while investigating for temporal variations. In a more recent study by Wang et al. (1998) in a fine sandy loam soil, using two different tension infiltrometer disk sizes (i.e., 10- and 20-cm diameters), no statistically significant difference was found for saturated hydraulic conductivity based on Wooding's (1968) parameter estimation method.

These limited studies document the need for more in situ experiments using tension infiltrometers for de-

termining the saturated and unsaturated soil hydraulic parameters for different soil and environmental conditions. Moreover, such studies would help to address the impacts of spatiotemporal variations of hydraulic parameters across different space and time scales as well as the influence of measurement support size on various applications such as agricultural activities, surface hydrology, land-atmosphere feedback, and groundwater contamination.

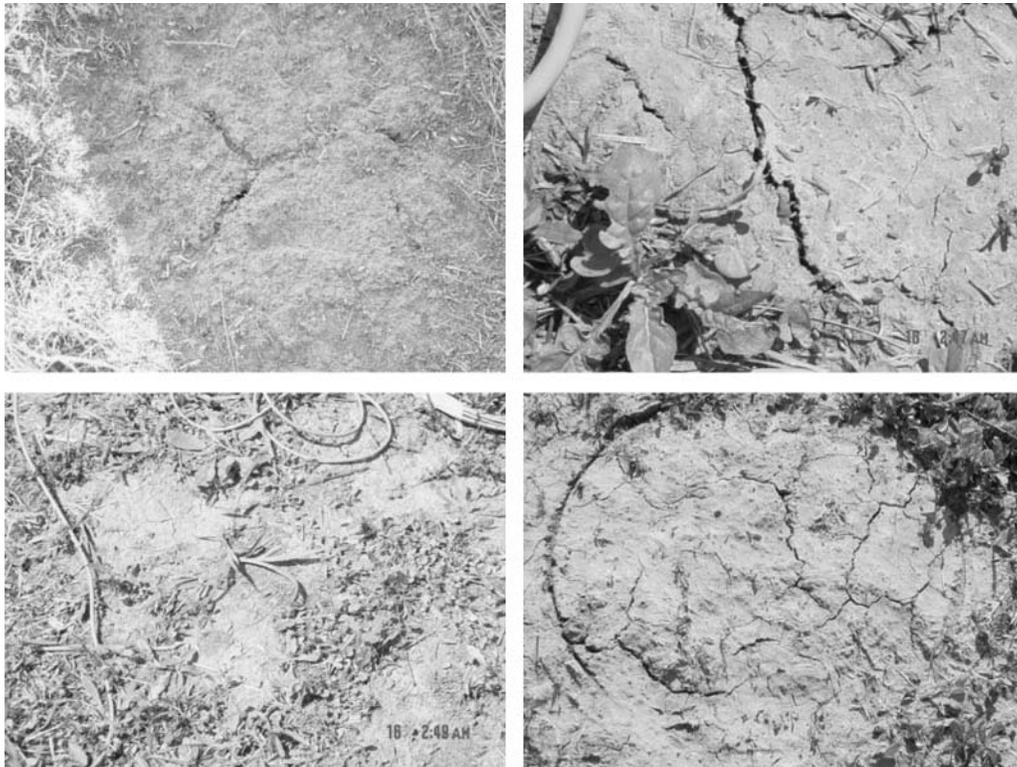
In this study, we focused on the natural spatial and temporal dynamics of saturated and unsaturated hydraulic conductivities of a Texas Vertisol during several seasons (a 21-mo period) at one field plot. The objectives of this study were to: (i) estimate the spatial variability of  $K(\Psi)$  from tension infiltration experiments within the experimental plot, (ii) investigate the temporal dynamics of  $K(\Psi)$  during the 21-mo period (May 2003–January 2005) based on natural environmental conditions, and (iii) detect temporal changes in soil hydraulic responses [ $K(\Psi)$  values] when two different (0.2 and 0.24 m) infiltration disk sizes are used.

## MATERIALS AND METHODS

### Site Description

The experimental site ( $30^{\circ}31'$  N and  $96^{\circ}21'$  W) was an abandoned agricultural plot (20 by 16 m) located on the Brazos River floodplain within the Texas A&M University field station near College Station. The plot had previously been used for growing cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and grain sorghum [*Sorghum bicolor* (L.) Moench]. In recent years, the vegetation in the plot has consisted of Bermuda grass [*Cynodon dactylon* (L.) Pers.] and bunchgrass (*Festuca idahoensis* Elmer). The plot contained Ships clay (2% sand, 32% silt, and 66% clay), a very-fine, mixed, active, thermic Chromic Hapludert (Lin, 1995). Figure 1 illustrates the vegetation cover at the field plot and typical (millimeter-scale) structural crack formation on the soil surface, suggesting a biporous soil system consisting of textural micropores and biological-structural macropores. Tension infiltrometers based on the design of Perroux and White (1988) were used to conduct the in situ infiltration experiments. Before starting each experiment, the ground was prepared by carefully clipping the patches of grass cover with a pair of scissors. The root structure of the grass was left undisturbed. Care was taken to avoid soil compaction or alteration of the existing network of pores and cracks at the site. The clipped vegetation was carefully removed and a layer ( $\sim 1$  cm) of contact sand was placed to provide good contact between the soil surface and the tension infiltrometer disks. The 600- $\mu\text{m}$  contact sand was selected after determining its  $K_{\text{sat}}$  value ( $5.5 \times 10^{-2}$  m  $\text{s}^{-1}$ ) using a constant-head permeameter in the laboratory. Since the  $K_{\text{sat}}$  value of the sand was several orders of magnitude higher than that of the Vertisol on which the experiments were being conducted, we believed this was ideal as contact sand.

A metal ring was placed and inserted ( $\sim 1$  cm) into the ground around each disk. The infiltration experiments were conducted at six different soil water pressure heads ( $\Psi = -0.2, -0.15, -0.1, -0.05, -0.02,$  and  $0$  m). The tension infiltrometer was pre-set to  $\Psi = -0.2$  m, then the infiltration disk was placed on the contact sand. Infiltration was conducted until steady-state infiltration was reached ( $\sim 1$  h). Once steady-state infiltration was achieved, flow was briefly interrupted ( $\sim 1$  min) to switch the pressure



**Fig. 1.** Representative vegetation and surface cracks in soil within the experimental plot. Structural crack apertures ranged between submillimeter to a few millimeters.

head to the next highest value and fill the water reservoir. This procedure was followed sequentially, from lowest soil water pressure head to highest, until all steady-state infiltration measurements for each pressure head were made. Although, infiltration was stopped during refilling, we believe that this would not cause any major hysteresis or air-entry errors because of the short time ( $\sim 1$  min) required to refill the infiltrmeters. Furthermore, the infiltration disk was kept intact during the entire refilling process. Initial test experiments were conducted at the site and the data were analyzed to determine the time required to obtain a steady-state infiltration rate. It was observed from five such tests that it took between 45 and 50 min to obtain steady-state infiltration rates. The ascending sequence of pressure heads was chosen over a descending sequence since the latter might cause air entrapment, leading to hysteresis (Reynolds and Elrick, 1991).

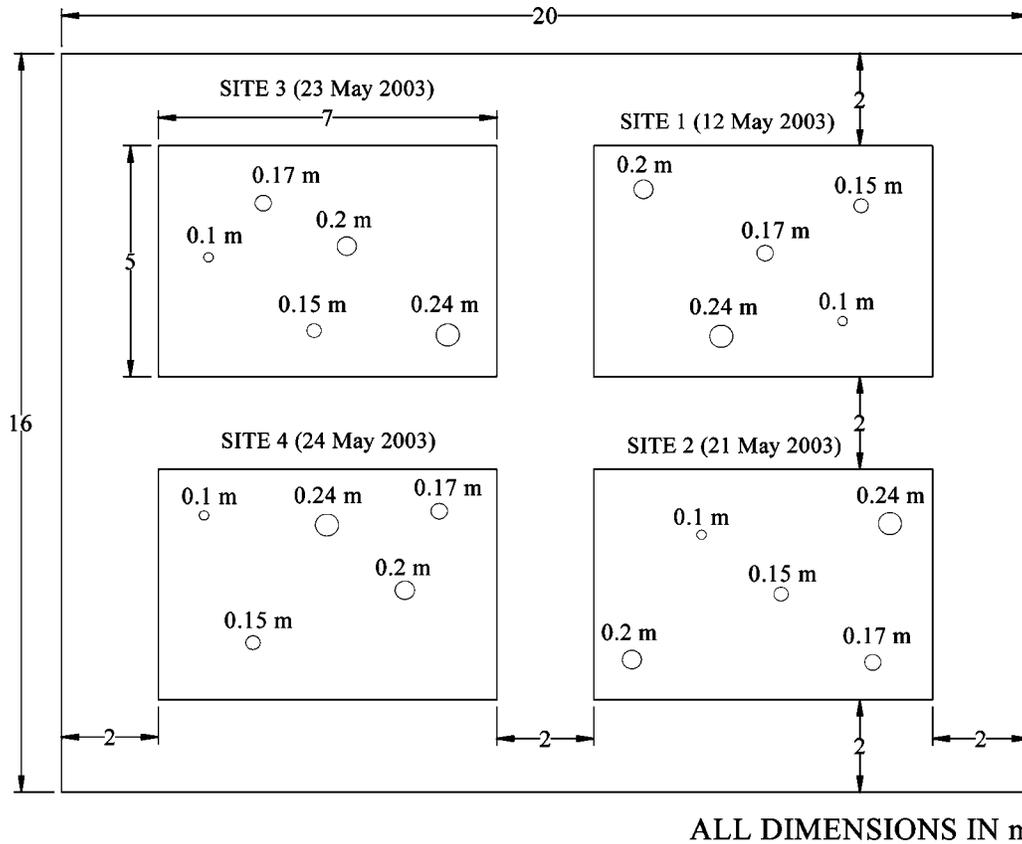
A differential pressure transducer was attached to the upper and lower ends of the supply tower of each infiltrmeter to determine and monitor the flow rate by calibrating with water height (pressure head) during the experiment. Data were collected using a Campbell Scientific (Logan, UT) data logger (CR-10X) using their PC208W Version 3.3 software. The transducers were connected to the data logger, which was programmed to record data at 30-s intervals. The antecedent volumetric moisture content (AMC) of the soil at each location (within 1 m of the infiltrmeter experiment) was measured using ML2 theta probes (Dynamax, Houston, TX). This instantaneous measurement was taken by inserting the 6-cm-long theta probe vertically into the ground surface.

The experimental plot (20 by 16 m) was divided into four zones or sites (7 by 5 m) as shown in Fig. 2. The infiltration experiments at different soil water pressure heads were performed on each site on a particular day. During each experiment, five tension infiltrmeters with different disk diameters ( $d = 0.24, 0.2, 0.17, 0.15,$  and  $0.1$  m) were placed

randomly in each site. Four experiments were conducted during a 12-d period (with no precipitation event) in May 2003 and the data set was used to determine the spatial variability of  $K(\Psi)$  values within the plot. Subsequent to this short-duration (12-d) spatially extensive experiment and observing spatial uniformity across the four sites using statistical analyses (described below), only the two largest disk diameters ( $d = 0.2$  and  $0.24$  m) were used to conduct follow-up experiments at Site 1 during a 21-mo period for determining the temporal variability of  $K(\Psi)$ . This could be explained by the fact that hydraulic conductivities estimated using the larger disks encompass the representative elementary volume (REV) of the soil and not specific flow paths such as macropores and root channels. In other words, our (lumped) approach of using disks (with diameters of 0.2–0.24 m) eliminated the independent effects of specific preferential flow path(s), resulting in homogeneous hydraulic characteristics throughout the experimental plot. To minimize any possible confounding effect of spatial variability on long-term temporal variability of soil hydraulic conductivity, however, only Site 1 (7- by 5-m area) was selected based on the findings of Sisson and Wierenga (1981), who recommended conducting infiltration experiments at the same location to investigate temporal dynamics. Table 1 lists the dates and design details of all the experiments performed in the plot. Note that due to resource limitations, time lags between measurements were not uniform, including a few sparse data points. Nevertheless, this extended 21-mo-long data set provides new insights into the seasonal variations of soil hydraulic properties in a biporous Vertisol, which is currently lacking in the literature.

### Data Analysis

The steady-state infiltration rate ( $i_f$ ) was obtained from the slope of the plot of cumulative infiltration vs. time. The



ALL DIMENSIONS IN m

Fig. 2. The 20- by 16-m experimental plot divided into four (7- by 5-m) sites with 2-m spacing on all sides. The circles in each site denote the different infiltration disk diameters used for the experiments. A typical experimental layout for May 2003 is shown.

calculation of  $K(\Psi)$  was based on the method given by Wooding (1968) as adapted by Ankeny et al. (1991). This method was chosen over other methods because of its mathematical simplicity and convenient in situ measurement techniques. Wooding's relationship for unconfined steady-state water infiltration into soil from a circular pond of radius  $r$  (m) is given by

$$Q(\Psi) = \pi r^2 K(\Psi) + 4r\Phi(\Psi) \quad [1]$$

where  $Q(\Psi)$  ( $\text{m}^3 \text{s}^{-1}$ ) is the steady-state infiltrating flux,  $K(\Psi)$  ( $\text{m s}^{-1}$ ) is the field saturated hydraulic conductivity, and  $\Phi(\Psi)$  ( $\text{m}^2 \text{s}^{-1}$ ) is the matric flux potential given by Gardner (1958). Since five different disk sizes were used for this study, the hydraulic conductivities were calculated for each infiltration disk size or measurement support.

The  $K(\Psi)$  values were used to determine the spatial and temporal variations and distinguish between the effects of using two (0.2- and 0.24-m) disk sizes. Since infiltration experiments at each location were conducted at six different soil water pressure heads ( $\Psi = -0.2, -0.15, -0.1, -0.05, -0.02, \text{ and } 0 \text{ m}$ ), the  $K(\Psi)$  values were separated into six (soil water pressure head) groups. Data collected during the 12-d experimentation period (12–24 May 2003) was used for analyzing the spatial variations within the plot. The  $K(\Psi)$  values for a single soil water pressure head group ( $\Psi = -0.2 \text{ m}$ ), containing values of all five disk sizes ( $d = 0.24, 0.2, 0.17, 0.15, \text{ and } 0.1 \text{ m}$ ) for Site 1 (Fig. 2) were considered as a single block and their mean was compared with the mean of all five disk diameters at the other three sites (Sites 2, 3, and 4) belonging to the same pressure head group. The comparison of means was conducted using Students's  $t$ -test for analysis of

variance (Ott and Longnecker, 2001). Such comparison of means was repeated for all other soil water pressure head ( $\Psi = -0.15, -0.1, -0.05, -0.02, \text{ and } 0 \text{ m}$ ) groups. A significance level of  $\alpha = 0.05$  was used for the Student's  $t$ -tests.

Data collected during the 21-mo experiment (12 May 2003–29 Jan. 2005) were used to identify the effect of using two different infiltration disk sizes on the calculated  $K(\Psi)$  values. For a single pressure head group, all the  $K(\Psi)$  values collected during the 21-mo period at Site 1 using the 0.2-m disk size were considered as a single block. The second block consisted of

Table 1. Number of disks used for each of the infiltration experiments during a 21-mo period.

Date	Location	Tension infiltrometer disk diameter ( $d$ ), m				
		0.1	0.15	0.17	0.2	0.24
		no.				
12 May 2003	Site 1	1	1	1	1	1
23 May 2003	Site 2	1	1	1	1	1
23 May 2003	Site 3	1	1	1	1	1
24 May 2003	Site 4	1	1	1	1	1
24 June 2003	Site 1	-	-	-	1	1
27 Aug. 2003	Site 1	-	-	-	2	2
16 Mar. 2004	Site 1	-	-	-	2	2
29 Sept. 2004	Site 1	-	-	-	2	2
22 Oct. 2004	Site 1	-	-	-	2	2
28 Nov. 2004	Site 1	-	-	-	2	2
28 Dec. 2004	Site 1	-	-	-	2	2
29 Jan. 2005	Site 1	-	-	-	2	2
<b>Total</b>					<b>19†</b>	<b>19†</b>

† A total of 19 infiltration experiments were conducted for the 0.2- and 0.24-m disk diameters during the 21-mo period (12 May 2003–29 January 2005).

values at Site 1 from the 0.24-m disk size. The mean of these two blocks were compared using Student's *t*-test. As explained above, this type of analysis was conducted for each soil water pressure head group. The *t*-test was used for those  $K(\Psi)$  data sets that satisfied the test of normality (Shapiro-Wilk test, Ott and Longnecker, 2001) and the test of equality of variances (Levene's test, Ott and Longnecker, 2001). The remaining  $K(\Psi)$  data sets were analyzed using the (nonparametric) Wilcoxon signed rank test (Ott and Longnecker, 2001). A significance level of 0.05 was used for all statistical tests.

## RESULTS AND DISCUSSION

Box plots of  $K(\Psi)$  for five different disk diameters at six different soil water pressure heads are illustrated in Fig. 3. Each box plot shows data from the four sites that

were collected from infiltration experiments within the plot during the 12-d period in May 2003. It can be seen that  $K(\Psi)$  increases as  $\Psi$  increases from  $-0.1$  to  $0$  m. It can also be seen that the values and variations of  $K(\Psi)$  are more comparable at the pressure range  $\Psi = -0.2$  to  $-0.1$  m than the near-saturation pressure range ( $-0.1$  to  $0$  m). The  $K(\Psi)$  values show a sharp increase from  $\Psi = -0.05$  m to saturation, reflecting a preferential flow phenomenon observed by various researchers in the past (e.g., Clothier and Smettem, 1990; Wilson et al., 1992; Mohanty et al., 1997; Lin et al., 1997). The variability of  $K(\Psi)$  values is maximum at saturation. This behavior can be attributed to the spatial variation of biological macropores (e.g., grass roots and worm holes) and structural cracks that act as preferential flow

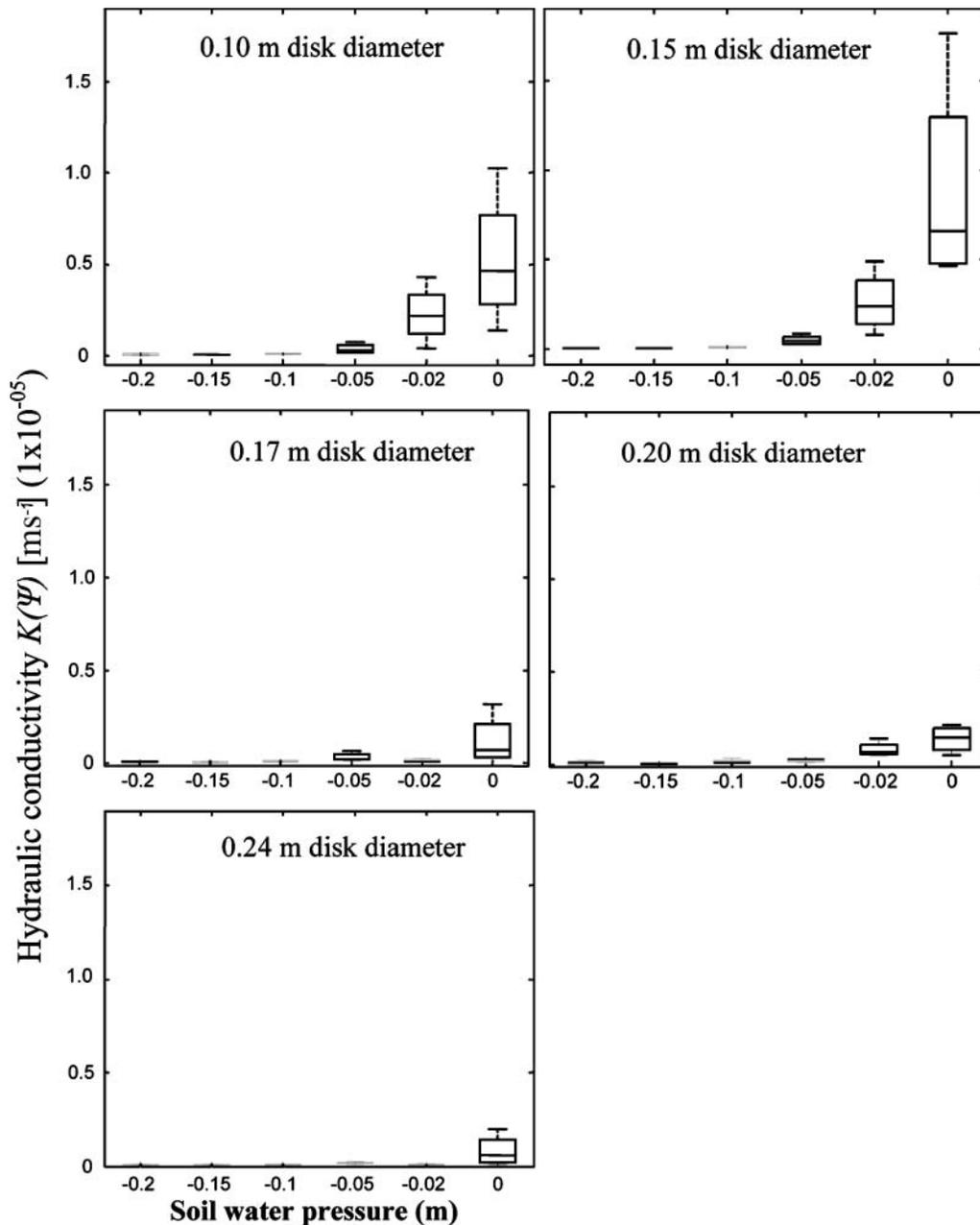


Fig. 3. Box plots of hydraulic conductivity [ $K(\Psi)$ ] values at different pressure heads for different disk sizes.

paths at pressure heads close to saturation. The large variations in  $K(\Psi)$  indicated that the subsurface water flow at the plot was mostly driven by gravity through preferential flow paths at pressure heads close to saturation, as observed in previous experimental studies (e.g., Mohanty et al., 1997; Lin et al., 1997). Because of the small sample size for each disk during the 12-d period in May 2003 for the spatial variability study across the field plot, comparison among the five different disk sizes is qualitative in nature (i.e., no statistical comparison); however, a better comparison between the 0.2- and 0.24-m disks (adopted for the 21-mo temporal variability study) at the field plot is reported below. In this context, it is noteworthy that Wang et al. (1998) found statistically similar saturated hydraulic conductivity [ $K(0)$ ] for their 10- and 20-cm disks (somewhat comparable to the disk sizes used in this study) using Wooding's (1968) solution for a field site at Riverside, CA. Again, Sisson and Wierenga (1981) reported similarity between mean infiltration rates for 25- and 127-cm-diameter disk sizes but are different for the 5-cm-diameter disk in a field plot near Las Cruces, NM. These varying findings by different researchers for different soil and environmental conditions may suggest the inherent variations in REV and other contributing factors affecting the infiltration rate across these regions. Inferences based on comparison among these different studies should be treated with caution, however, as the governing principle of the measurement technique, the functional model for parameter estimation, the measurement support relative to the site-specific REV, the experimental design across space and time, the total sample size, and the measurement accuracy or error are different.

For spatial variability analysis, there were only five infiltration experiments (based on disk sizes) conducted in each site during the 12-d period (12–24 May 2003). The statistical power for conducting the  $t$ -test was low and, hence, the results of the test are not shown here. Nevertheless, the statistical test did suggest that there was no difference in the mean  $K(\Psi)$  values (for all five disk sizes) between the four sites within the plot. This was further confirmed by visual inspection of the soil cracking pattern and vegetation distribution (Fig. 1), which indicated uniformity across the experimental plot. Based on this assumption and observation of spatial homogeneity of soil hydraulic conductivities, we conducted the subsequent infiltration experiments for determining the temporal variability at Site 1 only, as recommended by Sisson and Wierenga (1981). Furthermore, the weather conditions during the 12-d period were more or less uniform with no rainfall event, resulting in a minimum of the shrink–swell phenomenon that is typical in Vertisols.

Table 2 shows the descriptive statistics of  $K(\Psi)$  for the 0.2- and 0.24-m disk sizes. It can be seen that the CVs for both disk sizes were comparable for all  $K(\Psi)$ . The CV rises as the soil water pressure head approaches saturation. The high CV near saturation ( $\Psi = 0, -0.02, \text{ and } -0.05 \text{ m}$ ) could be a result of hitting or missing macropores or cracks in the area below the disk. Lower CV

**Table 2. Descriptive statistics of hydraulic conductivity [ $K(\Psi)$ ] for the two infiltration disk sizes ( $n = 19$  for all pressure head groups).**

$K(\Psi)$	Max.	Min.	Mean	Standard deviation	CV
<b>Disk diameter 0.20 m</b>					
$K(-0.20)$	$8.3 \times 10^{-7}$	$1.5 \times 10^{-7}$	$4.1 \times 10^{-7}$	$2.2 \times 10^{-7}$	53.2
$K(-0.15)$	$6.3 \times 10^{-7}$	$2.4 \times 10^{-7}$	$3.9 \times 10^{-7}$	$1.2 \times 10^{-7}$	31.1
$K(-0.10)$	$1.4 \times 10^{-6}$	$5.4 \times 10^{-7}$	$9.8 \times 10^{-7}$	$2.3 \times 10^{-7}$	23.7
$K(-0.05)$	$2.1 \times 10^{-5}$	$1.4 \times 10^{-6}$	$8.2 \times 10^{-6}$	$6.9 \times 10^{-6}$	85.0
$K(-0.02)$	$3.3 \times 10^{-5}$	$5.6 \times 10^{-7}$	$8.0 \times 10^{-6}$	$1.0 \times 10^{-5}$	128.3
$K(0.00)$	$5.7 \times 10^{-5}$	$8.2 \times 10^{-7}$	$2.2 \times 10^{-5}$	$1.9 \times 10^{-5}$	87.1
<b>Disk diameter 0.24 m</b>					
$K(-0.20)$	$7.6 \times 10^{-7}$	$1.1 \times 10^{-7}$	$4.0 \times 10^{-7}$	$2.3 \times 10^{-7}$	57.6
$K(-0.15)$	$9.5 \times 10^{-7}$	$1.5 \times 10^{-7}$	$4.7 \times 10^{-7}$	$2.6 \times 10^{-7}$	55.2
$K(-0.10)$	$1.8 \times 10^{-6}$	$2.7 \times 10^{-7}$	$9.2 \times 10^{-7}$	$5.1 \times 10^{-7}$	55.8
$K(-0.05)$	$2.5 \times 10^{-5}$	$6.4 \times 10^{-7}$	$7.2 \times 10^{-6}$	$7.6 \times 10^{-6}$	104.7
$K(-0.02)$	$3.3 \times 10^{-5}$	$2.0 \times 10^{-7}$	$7.3 \times 10^{-6}$	$1.0 \times 10^{-5}$	135.8
$K(0.00)$	$5.5 \times 10^{-5}$	$5.7 \times 10^{-7}$	$2.1 \times 10^{-5}$	$1.8 \times 10^{-5}$	85.9

for  $\Psi = 0$  compared with  $\Psi = -0.02$  and  $-0.05 \text{ m}$  for  $d = 0.24 \text{ m}$  and  $\Psi = -0.02 \text{ m}$  for  $d = 0.20 \text{ m}$  may reflect better macropore connectivity at full saturation. We believe this adds to the hydraulic conductivity uncertainty and variability in Vertisols.

Table 3 shows the results of the (parametric)  $t$ -test and the (nonparametric) Wilcoxon signed rank test for comparison of mean  $\log_e K(\Psi)$  values between the 0.2- and 0.24-m disk sizes during the entire experiment. Statistical tests suggest that there were no significant differences between the  $\log_e K(\Psi)$  values of the 0.2- and 0.24-m disk sizes for all pressure head groups using a 95% confidence interval. This finding implies that variations between 0.2 and 0.24 m in disk diameter (measurement support) for conducting infiltration experiments do not affect soil hydraulic responses in the experimental plot. It is noteworthy that the statistical  $t$ -test comparing the mean  $K(\Psi)$  values between the five different disk sizes for experiments conducted during May 2003 at all four sites indicated no significant difference. Although these results are somewhat qualitative because of the low statistical power of the test (only four data points in each group), they somewhat reaffirm the findings obtained by comparing the results for the 0.2- and 0.24-m disk sizes for the entire 21-mo period. Thus, it appears that variations in disk diameters (between 0.2 and 0.24 m) encompassing different macroporosities do not influence temporal variations in soil hydraulic properties within soil water pressure heads ranging from  $\Psi = -0.2 \text{ m}$  up to saturation.

**Table 3. Student's  $t$ -test and Wilcoxon signed rank test for comparison of mean  $\log_e$  hydraulic conductivity [ $K(\Psi)$ ] between the 0.20- and 0.24-m disk sizes.**

Hydraulic conductivity	Statistic ( $t$ or $Z$ )	Significance (two-tailed), $P$
<b>Student's <math>t</math>-test</b>		
$\log_e K(-0.20)$	-0.19	0.85
$\log_e K(-0.05)$	-0.78	0.44
$\log_e K(-0.02)$	-0.73	0.47
<b>Wilcoxon signed rank test</b>		
$\log_e K(-0.15)$	-0.85	0.39
$\log_e K(-0.10)$	-0.66	0.50
$\log_e K(0.00)$	-0.53	0.59

Figure 4A shows the long-term temporal variations of  $K(\Psi)$  and AMC from 12 May 2003 to 29 Jan. 2005 for the soil water pressure head groups  $\Psi = -0.2, -0.15,$  and  $-0.1$  m. The average  $K(\Psi)$  values for both 0.2 and 0.24 m disk diameters are presented, together with 10% error bars, because the means for both disk sizes were statistically similar (discussed above). Although the  $K(\Psi)$  values demonstrated strong temporal variations for both disk sizes, it was difficult to identify a common seasonal trend among  $K(\Psi)$  values at the given pressure

heads ( $\Psi = -0.2, -0.15,$  and  $-0.1$  m). Additionally,  $K(\Psi)$  showed correlations with AMC, albeit weak with the exception of  $\Psi = 0.2$  m (Fig. 4B). Similar to Fig. 4A, Fig. 5A shows the seasonal pattern of  $K(\Psi)$  values at  $\Psi = -0.05, -0.02,$  and  $0$  m. The correlations between  $K(\Psi)$  and antecedent moisture content for these three pressure head groups are illustrated in Fig. 5B. Apparently the  $K(\Psi)$  values for the  $\Psi = -0.05$  to  $0$  m soil water pressure head range have a stronger positive correlation with antecedent moisture contents when com-

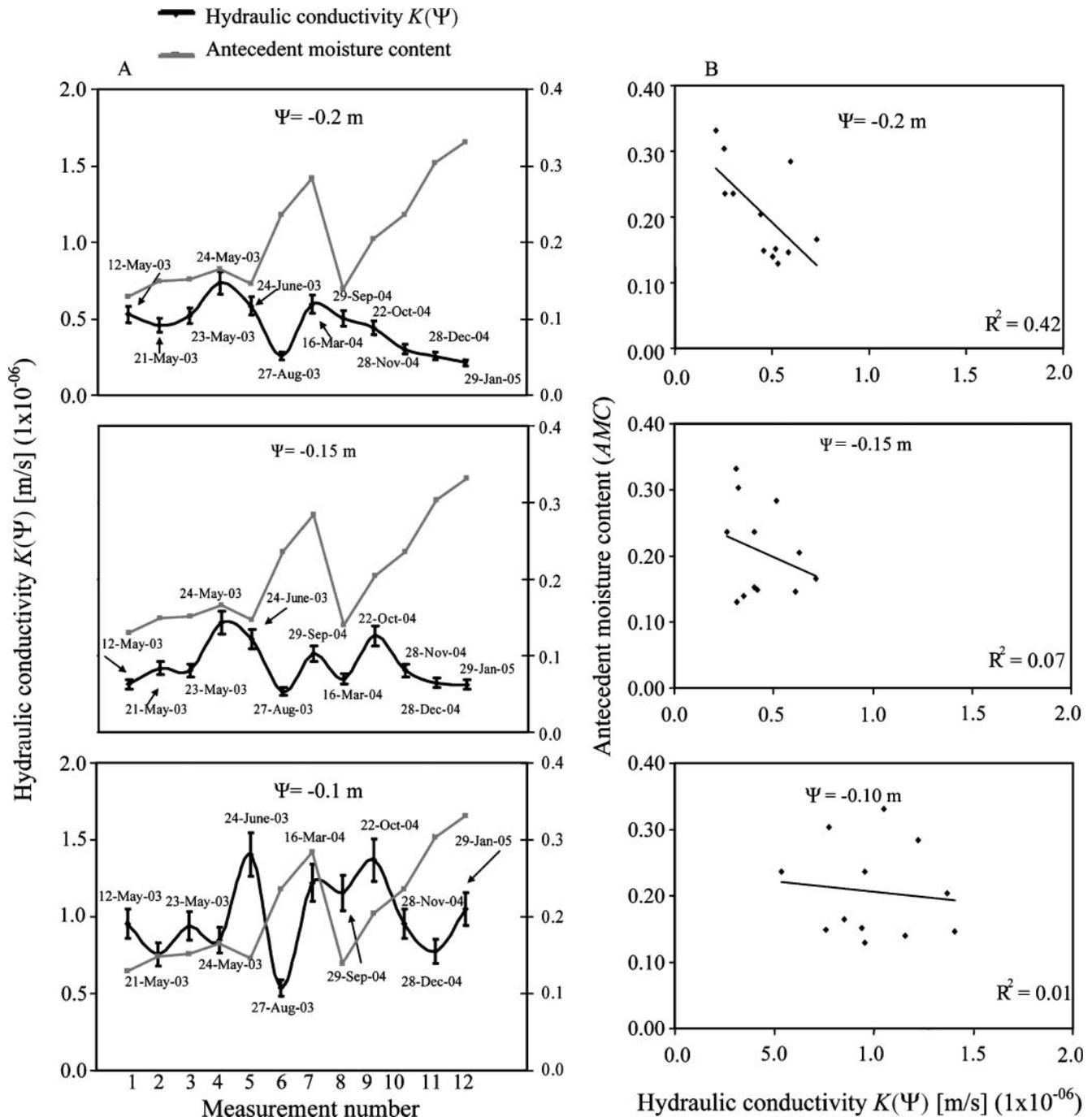


Fig. 4. (A) The temporal variability of hydraulic conductivity [ $K(\Psi)$ ] values and antecedent moisture content (AMC) at varying pressure heads ( $\Psi = -0.2, -0.15,$  and  $-0.1$  m), and (B) the correlation between  $K(\Psi)$  and AMC for the same pressure heads.

pared with those in Fig. 4B for the  $-0.2$   $-0.1$  m soil water pressure head range. The low (or negative) correlation between  $K(\Psi)$  and AMC at low soil water pressure heads (for  $\Psi = -0.15$  and  $-0.1$  m) could be because the macropores, which conduct most of the water, were not active at this pressure range. When  $\Psi$  is close to saturation, the macropores start to conduct water, which can explain the stronger correlation between  $K(\Psi)$  and AMC closer to saturation. An additional explanation for this behavior could be slight hydrophobicity at low soil water

pressure head, which would be overcome as the soil wets up (near saturation). We believe that at soil water pressure heads close to saturation (for  $\Psi = -0.05$  to  $0$  m), high antecedent moisture conditions causes greater cohesion between liquid water particles and bridges of water films across different cracking beds, and the gravitational force causes more water to be conducted via structural cracks and biological macropores. We suggest that the negative correlation between AMC and  $K(\Psi)$  at low soil water pressure head and the positive correlation near saturation

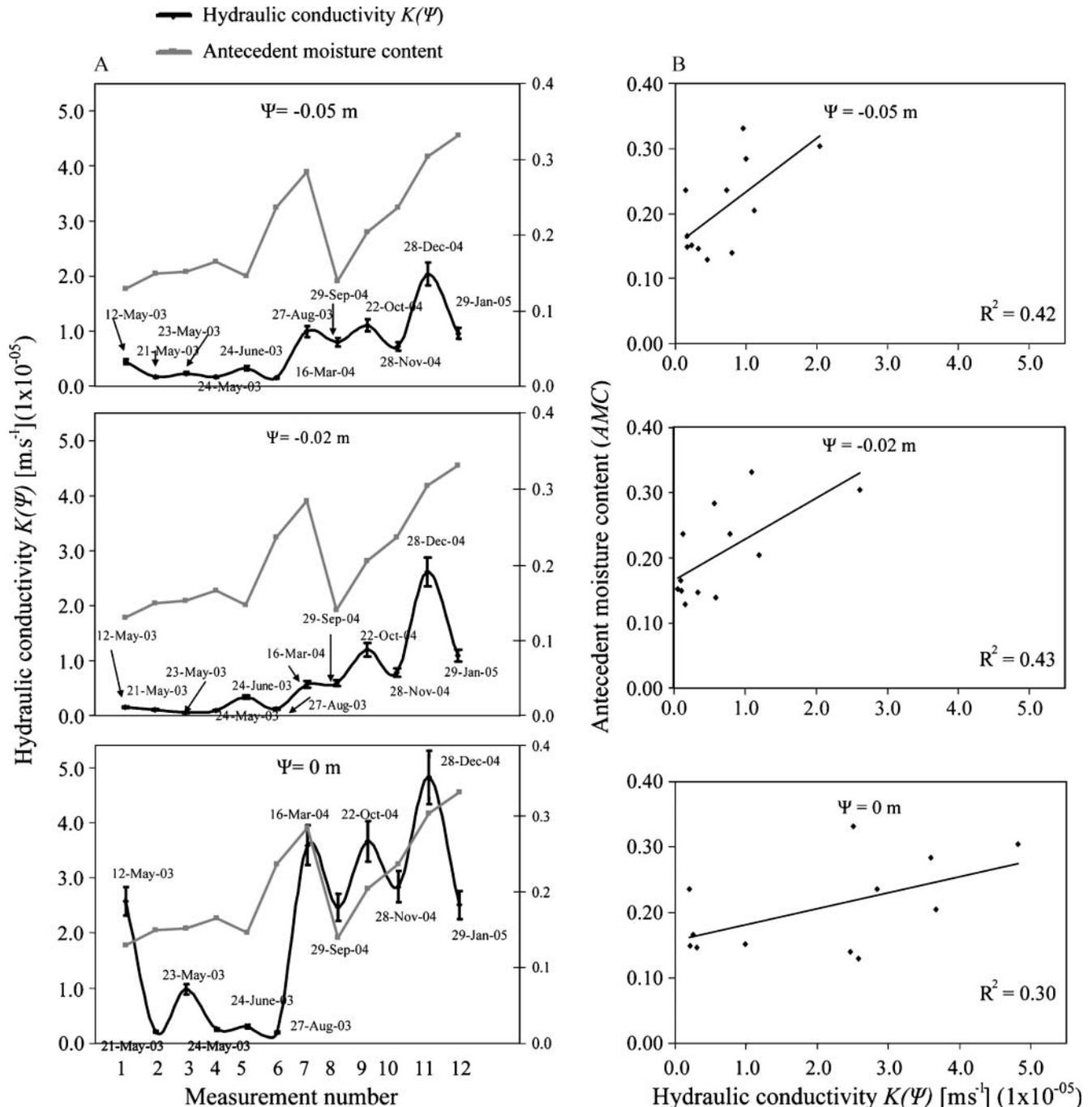


Fig. 5. (A) The temporal variability of hydraulic conductivity [ $K(\Psi)$ ] values and antecedent moisture content (AMC) at varying pressure heads ( $\Psi = -0.05, -0.02,$  and  $0$  m), and (B) the correlation between  $K(\Psi)$  and AMC for the same pressure heads.

is a general response when macropore flow is prominent in the system. In other words, at a particular location when flow occurs as a combination of macropore and matrix flow, macropore flow (reflected in  $K$  near saturation) and matrix flow (reflected in  $K$  at low soil water pressure) are somewhat negatively related (see Fig. 6). Because of this phenomenon, we observed an increase in hydraulic conductivity with the increase in antecedent moisture content near saturation. Furthermore, this behavior near saturation suggests that AMC (on different dates) relates to the activation of flow in biological and structural macroporosity in the biporous system, leading to higher near-saturated hydraulic conductivity, as demonstrated by Or et al. (2000) and Nimmo (1997) in their pore-space evolution modeling frameworks.

## CONCLUSIONS

Spatial and temporal variability of soil hydraulic conductivities near saturation are important for estimating water, energy, and chemical fluxes across the land–atmosphere boundary and in the vadose zone. A Texas Vertisol, characterized by its biporosity and pore space dynamics, was studied for spatiotemporal variability of hydraulic conductivity near saturation. Overall, the 21-mo-long infiltration experiments demonstrated that infiltration in this region occurred in a bimodal fashion consisting of preferential flow through biological and structural macropores and matrix flow through textural micropores. The preferential flow occurred at soil water pressure heads near saturation (ranging from  $\Psi = -0.05$  m to saturation) and matrix flow occurred below  $\Psi = -0.1$  m. Preferential flow was characterized by high  $K(\Psi)$  values with greater variability and matrix flow was characterized by low  $K(\Psi)$  values and less variability. The macropores resulted in gravity-dominated preferential infiltration of water at pressure heads ranging from  $-0.05$  m to 0 m and caused substantial variability of the  $K(\Psi)$  values at these pressure heads, compared with the lower soil water pressure heads. No significant differences in hydraulic conductivities were observed by altering the size of infiltration disks while conducting the infiltration experiments. Strong temporal variations were observed for the  $K(\Psi)$  values from May 2003 to January 2005. It was also observed that hydraulic

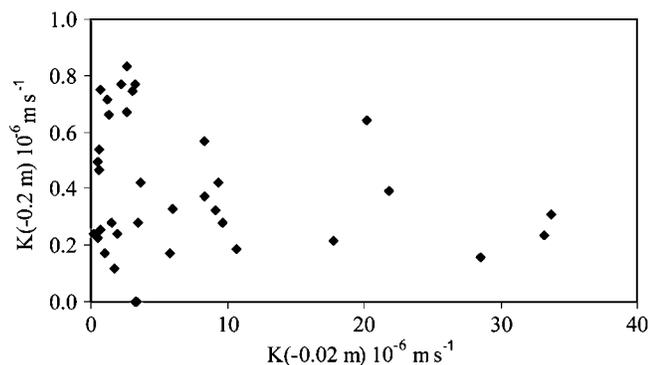


Fig. 6. Scatter plot of macropore flow near saturation (soil water pressure head  $\Psi = -0.02$  m) and matrix flow at a low  $\Psi$  ( $-0.2$  m) for the combined data sets of the 0.2- and 0.24-m disks.

conductivities were positively correlated with antecedent moisture contents at soil water pressure heads close to saturation, reflecting liquid cohesion, water films bridging across different crack-separated peds, and activation of flow in structural and biological macropores in the biporous soil system. At a particular location when flow occurred as a combination of macropore and matrix flow, macropore flow (reflected in  $K$  near saturation) and matrix flow (reflected in  $K$  at low soil water pressure) were somewhat negatively related. These temporal variations in soil hydraulic properties would ultimately help in improving the long-term hydrologic, environmental, land–atmosphere feedback, and climate and weather prediction models.

## ACKNOWLEDGMENTS

We acknowledge the partial support of NASA Terrestrial Hydrology grants (NAG5-11702, NNG04GM35G), NSF Hydrologic Sciences Grant EAR 0296158, and NSF Water Cycle Research Grant 459741.

## REFERENCES

- Ankeny, M.D., M. Ahmed, T.C. Kaspar, and R. Horton. 1991. Simple field method for determining unsaturated hydraulic conductivity. *Soil Sci. Soc. Am. J.* 55:467–470.
- Cassel, D.K., and L.A. Nelson. 1985. Spatial and temporal variability of soil physical properties. *Soil Tillage Res.* 5:5–17.
- Clothier, B.E., and K.R.J. Smettem. 1990. Combining laboratory and field measurements to define the hydraulic properties of soil. *Soil Sci. Soc. Am. J.* 54:299–304.
- Clothier, B.E., and I. White. 1981. Measurement of sorptivity and soil water diffusivity in the field. *Soil Sci. Soc. Am. J.* 45:241–245.
- Gardner, W.R. 1958. Some steady-state solutions of the unsaturated moisture flow equation with applications to evaporation from a water table. *Soil Sci.* 85:228–232.
- Lin, H.S. 1995. Hydraulic properties and macropore flow of water in relation to soil morphology. Ph.D. diss. Texas A&M Univ, College Station (Diss. Abstr. 9534383).
- Lin, H.S., K.J. McInnes, L.P. Wilding, and C.T. Hallmark. 1997. Low tension water flow in structured soils. *Can. J. Soil Sci.* 77:649–654.
- Lin, H.S., K.J. McInnes, L.P. Wilding, and C.T. Hallmark. 1998. Macroporosity and initial moisture effects on infiltration rates in Vertisols and vertic intergrades. *Soil Sci.* 163:2–8.
- Logsdon, S.D., and D.B. Jaynes. 1993. Methodology for determining hydraulic conductivity with tension infiltrometers. *Soil Sci. Soc. Am. J.* 57:1426–1431.
- Logsdon, S.D., and D.B. Jaynes. 1996. Spatial variability of hydraulic conductivity in a cultivated field at different times. *Soil Sci. Soc. Am. J.* 60:703–709.
- Messing, I., and N.J. Jarvis. 1993. Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. *J. Soil Sci.* 44:11–24.
- Mohanty, B.P. 1999. Scaling hydraulic properties of a macroporous soil. *Water Resour. Res.* 35:1927–1931.
- Mohanty, B.P., M.D. Ankeny, R. Horton, and R.S. Kanwar. 1994a. Spatial analysis of hydraulic conductivity measured using disc infiltrometers. *Water Resour. Res.* 30:2489–2498.
- Mohanty, B.P., R.S. Bowman, J.M.H. Hendrickx, and M.Th. van Genuchten. 1997. New piecewise-continuous hydraulic functions for modeling preferential flow in an intermittent flood-irrigated field. *Water Resour. Res.* 33:2049–2063.
- Mohanty, B.P., R.S. Kanwar, and C.J. Everts. 1994b. Comparison of saturated hydraulic conductivity measurement methods for a glacial-till soil. *Soil Sci. Soc. Am. J.* 58:672–677.
- Mohanty, B.P., T.H. Skaggs, and M.Th. van Genuchten. 1998. Impact of saturated hydraulic conductivity on the prediction of tile flow. *Soil Sci. Soc. Am. J.* 62:1522–1529.
- Nimmo, J.R. 1997. Modeling structural influences on soil water retention. *Soil Sci. Soc. Am. J.* 61:712–719.

- Or, D., F.J. Leij, V. Snyder, and T.A. Ghezzehei. 2000. Stochastic model for post-tillage soil pore space evolution. *Water Resour. Res.* 36:1641–1652.
- Ott, R.L., and M.T. Longnecker. 2001. *An introduction to statistical methods and data analysis*. 5th ed. Duxbury Press, Belmont, CA.
- Perroux, K.M., and I. White. 1988. Designs for disc permeameters. *Soil Sci. Soc. Am. J.* 52:1205–1215.
- Reynolds, W.D., and D.E. Elrick. 1991. Determination of hydraulic conductivity using a tension infiltrometer. *Soil Sci. Soc. Am. J.* 55: 633–639.
- Shouse, P.J., and B.P. Mohanty. 1998. Scaling of near-saturated hydraulic conductivity measured using disc infiltrometers. *Water Resour. Res.* 34:1195–1205.
- Sisson, J.B., and P.J. Wierenga. 1981. Spatial variability of steady-state infiltration rates as a stochastic process. *Soil Sci. Soc. Am. J.* 45: 699–704.
- Starr, J.L. 1990. Spatial and temporal variation of ponded infiltration. *Soil Sci. Soc. Am. J.* 54:629–636.
- Wang, D., S.R. Yates, and F.F. Ernst. 1998. Determining soil hydraulic properties using tension infiltrometers, time domain reflectometry, and tensiometers. *Soil Sci. Soc. Am. J.* 62:318–325.
- White, I., and M.J. Sully. 1987. Macroscopic and microscopic capillary length and time scales from field infiltration. *Water Resour. Res.* 23: 1514–1522.
- Wilson, G.V., P.M. Jardine, and J.P. Gwo. 1992. Modeling the hydraulic properties of a multiregion soil. *Soil Sci. Soc. Am. J.* 56:1731–1737.
- Wooding, R.A. 1968. Steady infiltration from a shallow circular pond. *Water Resour. Res.* 4:1259–1273.