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Measuring Soil Hydrologic Properties Using Dielectric Sensors

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Abstract

Knowledge of soil hydrologic properties is essential to many aspects of environmental research. Soil hydrologic properties determined from laboratory analyses often are non-representative of field conditions. In this work, we compare soil hydrologic properties determined in the field with values obtained from soil core laboratory analysis and determine the differences associated with the use of pedotransfer functions to estimate these properties using either field or laboratory data. Double-ring infiltrometers, in combination with tensiometric measurements at three depths, were used to determine soil hydrologic properties in-situ. The studies were conducted on two small watersheds in northeastern Indiana to obtain soil hydraulic conductivity (K) as a function of soil water content and soil moisture as a function of matric potential. After reaching steady-state flow conditions, TDR probes were used to measure the changes in profile soil water content over time during vertical drainage. Soil matric potential was measured with tensiometers placed at 15, 30 and 60 cm depths, concurrent with TDR measurements at 15cm intervals to a depth of 60cm. Coincident with these measurements; we measured 0-5cm soil moisture daily in the inner ring with the Theta Probe to capture changes in near-surface soil moisture to simulate remotely sensed surface soil moisture observations. At the end of the drainage experiment soil cores were collected to determine the relationship between soil moisture and matric potential using the laboratory pressure-plate procedure. The data were used to:1) compare field and laboratory measurements of water retention and estimates of K, 2) to evaluate the use of pedotransfer functions using either field or laboratory data, and 3) investigate the relationship between the 0-5cm soil moisture dynamics and profile soil moisture to a depth of 60cm. The use of TDR and Theta Probes eliminated the need to take numerous gravimetric soil samples normally required for these types of field studies.

Key Words Soil moisture, soil hydraulic conductivity, time-domain reflectometry, water characteristics curve

Introduction

Time domain reflectometry (TDR) is commonly used to measure volumetric water content in soils. It is based on the relationship between the soil dielectric constant (K) measured by TDR, and the soil volumetric water content (θ_v). According to a historical review by Grant et al. (1978[1]) the technique has been in use since 1951. However, the relationship between the dielectric properties of a soil and its water content were the subject of much earlier work by Smith-Rose (1933[2]). Based on a comprehensive laboratory study, Topp et al. (1980[3]) developed an empirical expression relating apparent dielectric constant (K_a) and θ_v. From this general relationship an equation was derived to find θ_v from measured values of K_a:

$$\theta_v = -5.3x10^{-2} + 2.92x10^{-2} K_a - 5.5x10^{-4} K_a^2 + 4.3x10^{-6} K_a^3 \qquad [1]$$

The work of Topp et al. (1980[3]) clearly demonstrated the potential of TDR for the measurement of soil moisture and were fundamental to future studies and many advances in TDR technology.

Volumetric soil water content determined by TDR involves measurement of the propagation velocity (or time delay) and attenuation of an electric step or pulse function applied along a transmission line in the soil. A time domain reflectometer generates a voltage pulse which propagates as an electromagnetic wave through the soil via a transmission line (waveguide). The propagation velocity (v) corresponds to the time it takes for a step pulse to travel a distance to the end of the transmission line and back.
Velocity (v) can be expressed as,

$$v = \frac{2L}{t} \qquad [2]$$

where L is the linear distance traveled, and t is the measured travel time. The time interval is the variable quantity measured by the TDR technique and used to determine soil water content (Hook and Livingston, 1995[4]). As soil water content increases, the time required to traverse the length of the transmission line also increases.

The propagation velocity is usually normalized to the speed of light and expressed in terms of K_a (Topp et al., 1980[1]),

$$K_a = (c/v)^2 \qquad [3]$$

where c is the speed of light (3 x 10^8 m/s) and v is velocity as above. Based on the model of Herkelrath et al. (1991[5]), and using the transmission line theory of Eq. [2] and [3], Hook and Livingston (1996[6]) derived a general formula to obtain soil water content from measured travel time given as,

$$\theta_v = [(T/T_a - T_s/T_a)]/\sqrt{K_w} - 1 \qquad [4]$$

where they express v in terms of time intervals with T being the travel time of an electric pulse in soil and normalized with respect to the theoretical travel time of the transmission line in air (T_a). Travel time in oven-dried soil is T_s, and K_w is the dielectric constant for water equal to 80.32. Using the dielectric constant for water, Eq. [4] has a theoretical slope of 0.1256. An average value for T_s/T_a of 1.55 and an average slope of 0.1193 was obtained by Hook and Livingston (1996[6]) and used to represent all agricultural nonclay soils.

The ESI[1], Model MP917-C TDR instrument used in this study to obtain profile θ_v, measures T and is referred to as measured time delay from which θ_v is calculated according to Eq. [5] (Hook and Livingston, 1995; 1996[4,6]).

$$\theta_v = (T/T_a - 1.55)0.1256 \qquad [5]$$

Thus, Eq. [5] serves as the factory calibration equation, where T/T_a is as described in Eq. [4] and the value of 0.1256 is the theoretical slope for the relationship between θ_v and T/T_a (Hook and Livingston, 1996[6]).

In this preliminary study, three types of sensors for measuring soil dielectric properties were used to determine volumetric soil water content based on the principles described above. Only factory supplied calibrations for each sensor were used in this study. TDR segmented probes were installed to measure θ_v in 15 cm depth intervals to a depth of 60 cm during field infiltration studies. ML2 Theta Probes[2] were used to measure daily changes in near-surface θ_v (0-5 cm) during the drainage cycle (Fig 3). Permanently installed Hydra Probes[3] were used to continuously measure θ_v at 5, 20, 40 and 60 cm depths at field-site weather stations. These measurements were necessary to determine, *in situ*, soil hydraulic properties at three locations along the slope in each field and compare the values determined *in situ* with those obtained from soil-core laboratory analysis, as well as hydraulic properties estimated using different pedotransfer functions.

Experimental Procedures

The basic soil hydraulic properties and characteristic functions that govern the flow of water in soils are soil hydraulic conductivity as a function of soil water content K (θ) or matric suction K (*h*) and soil water content as a function of matric suction θ (*h*), commonly referred to as the soil water characteristics curve (Hillel, 1980[7]; Ahuja and Nielsen, 1990[8]). It has been widely recognized that hydraulic properties of field soil are best measured in situ (Ahuja et al., 1976[9]). However, laboratory and field methods for determining soil hydraulic properties are time consuming and expensive.

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[1] Environmental Sensors, Inc., Victoria, BC; [2] Dynamax, Houston, TX; [3] Stevens, Beaverton, OR. Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors or the USDA.

An alternative approach is the use of pedotransfer functions (PTFs) which predict various soil hydraulic properties based on more readily available physical properties. Two different PTFs were used in this study to estimate saturated hydraulic conductivity (Ks) for each experimental site.

Saturated hydraulic conductivity (Ks) was estimated using an empirical function (a modified form of the Kozeny-Carmen equation) describing Ks as a power function of effective porosity (φ_e). The method is based on the experimental studies of Ahuja et al. (1988[10]), in which effective porosity is defined as saturation water content (θs) minus the -33kPa (1/3 bar) water content. The equation is written as,

$$Ks = 764.5\ \varphi_e^{\mathbf{3.29}} \qquad [6]$$

where Ks is in cm hr^{-1}, and φ_e is given in cm^3 of pores per cm^3 of bulk soil. Values used to estimate Ks were obtained from soil core laboratory measurements of the water characteristic curve. Considering the magnitude of errors involved with field-measured Ks due to the presence of macropores and air entrapment, the proposed equation has shown promise.

Rawls et al. (1982[11]) showed that saturated hydraulic conductivity can be determined using the following equation

$$Ks = 1930\ \varphi_e^{(3-\lambda)} \qquad [7]$$

where φ_e is the effective porosity determined from the total porosity minus the water content at -33 kPa and (λ) is the slope of the log transformed water characteristics curve.

Sensor Descriptions

The ESI, TDR probes are constructed of stainless steel, epoxy, and high density plastic that vary in length and are approximately 1cm thick and 2 cm wide. The probes are a segmented device having known distances between segment endpoints. Probe design is based on TDR remote diode shorting technology (Hook et al., 1996[6]) that enables profile measurements of θ_v in layered soils. They are installed using a probe insertion/extraction tool kit. The type of probes used in this study was 4-segment, having 0-15, 15-30, 30-45, and 45-60 cm segments. Data are obtained manually with the ESI datalogger system. The Theta Probe is a hand held instrument consisting of four, 0.3-cm diameter tines and 6 cm in length. The instrument is inserted into the surface soil and readings are taken. Measurements are stored in the unit and later downloaded to a computer. The Hydra Probe consists of a 4-cm diameter cylindrical head which has four, 0.3-cm diameter tines that protrude 5.8 cm. The probes are permanently installed at several real-time weather and soil monitoring stations within the Cedar Creek watershed.

Study Areas

Field and laboratory studies to measure soil physical and hydraulic properties were conducted on two agricultural field sites within the Cedar Creek watershed in north eastern Indiana (Fig. 1 and 2). The field sites were selected based on differences in management practices with one field (AS1) under no-till management, corn/soybean and the second field (AD) in conventional tillage, oats/alfalfa. Soil cores (5 cm dia.) were collected at 5 and 15 cm depth intervals to a depth of 60 cm along transects within each field and used to determine the water characteristics curve in the laboratory. Double-ring infiltrometer studies were conducted at three sites along the slope in each field to determine *in situ* hydraulic properties.

Laboratory Analysis

Selected soil physical (Table 1) and hydraulic properties (Table 2) were determined at each site to a depth of at least 60 cm in 5 and 15 cm intervals. Soil cores were extracted from the site using a soil-core sampling tool having a 15 cm long barrel with a 5 cm inside diameter. Care was taken to minimize compaction during sampling. Each soil core was divided into 5 cm long subsamples. One subsample was used to determine soil texture using the hydrometer method (Day, 1965[12]). The remaining subsample was used to determine the soil water characteristics using the procedure given in Ahuja et al. (1985[13]). Bulk density and θ_v at saturation and at 1, 5, 10, 20, 33, 100, 500, 1000, and 1500 -kPa were determined for each 15 cm interval in the profile.

Field Experiments

Soil hydraulic properties at each of the field sites were measured *in situ* using the instantaneous profile method (Hillel, 1980[7]). According to a comparative study by Paige and Hillel (1993[14]), the instantaneous profile method is the most effective method for determining soil hydraulic properties *in situ*. The method involves gravimetric soil sample analysis, double-ring infiltrometry, and tensiometric data analysis. It is based on the Darcian analysis of *in-situ* tensiometric measurements during infiltration and the subsequent drainage, using the water content-matric pressure relationship (Richards et al., 1956[15]; van Bavel et al., 1968[16]). The soil water content-matric pressure relationship can be obtained by periodic measurement of soil water content during the drainage phase by gravimetric, neutron thermalization, TDR, or gamma-ray attenuation techniques.

The instantaneous profile method involves measuring the rate of water entering the soil surface and the changes in soil water potential with depth and over time using tensiometers. A double-ring infiltrometer with two concentric metal rings having diameters of approximately 90 cm and 50 cm, respectively, were co-located with tensiometers placed at depths of 15, 30 and 60 cm in the soil profile located just outside the inner ring (Fig. 3). The rings were driven into the soil approximately 10 cm leaving approximately 20 cm of ring above the soil surface. The rings were completely filled with water to pre-wet the soil the day before infiltration measurements began.

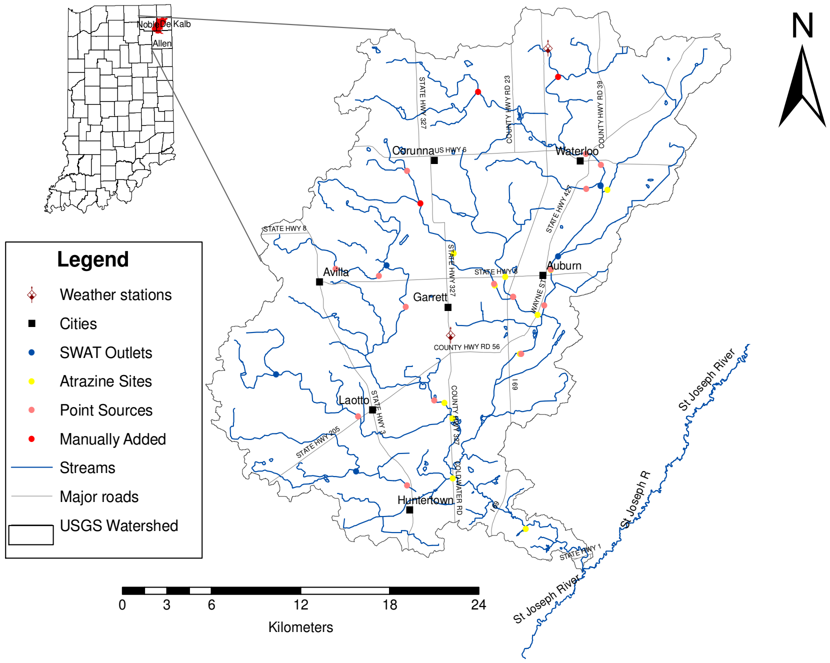


Fig. 1. The Cedar Creek Watershed in northeastern Indiana.

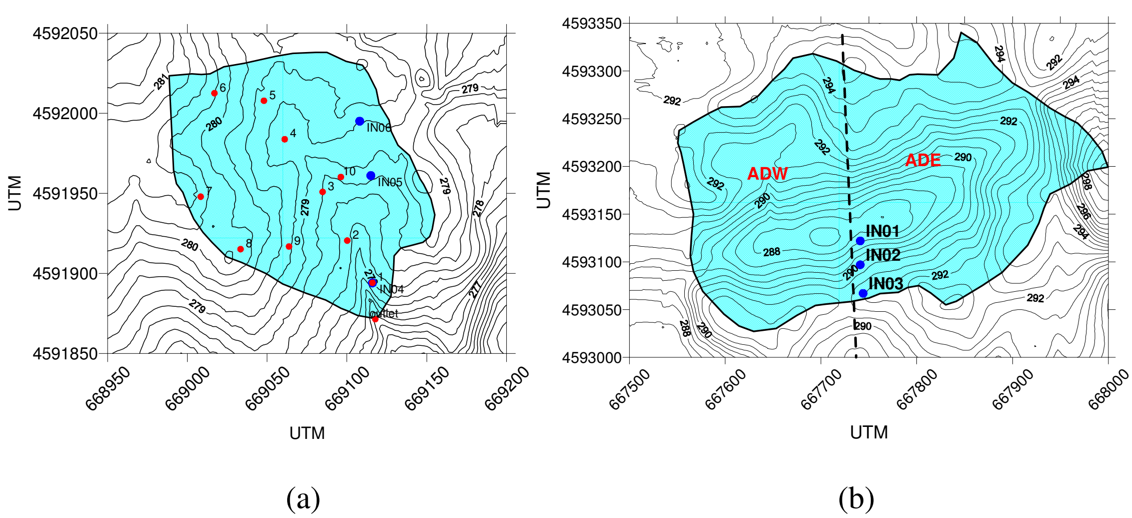
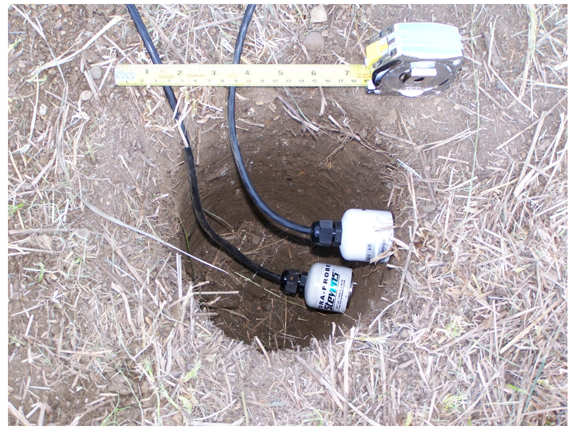


Fig. 2. Field study sites (a) AS1, no-till corn soybean rotation and (b) AD, conventional tillage, oats and alfalfa. The red dots indicate soil-core sampling sites used for laboratory water characteristics analysis. The blue dots are infiltration study sites in each field. Coordinate are in Universal Transverse Mercator (UTM).



(a) (b)

Fig. 3. (a) Double-ring infiltrometer with TDR probe (blue cap), Theta Probe, and tensiometers (red caps) and (b) Hydra Probes at 5 and 20 cm depths during installation.

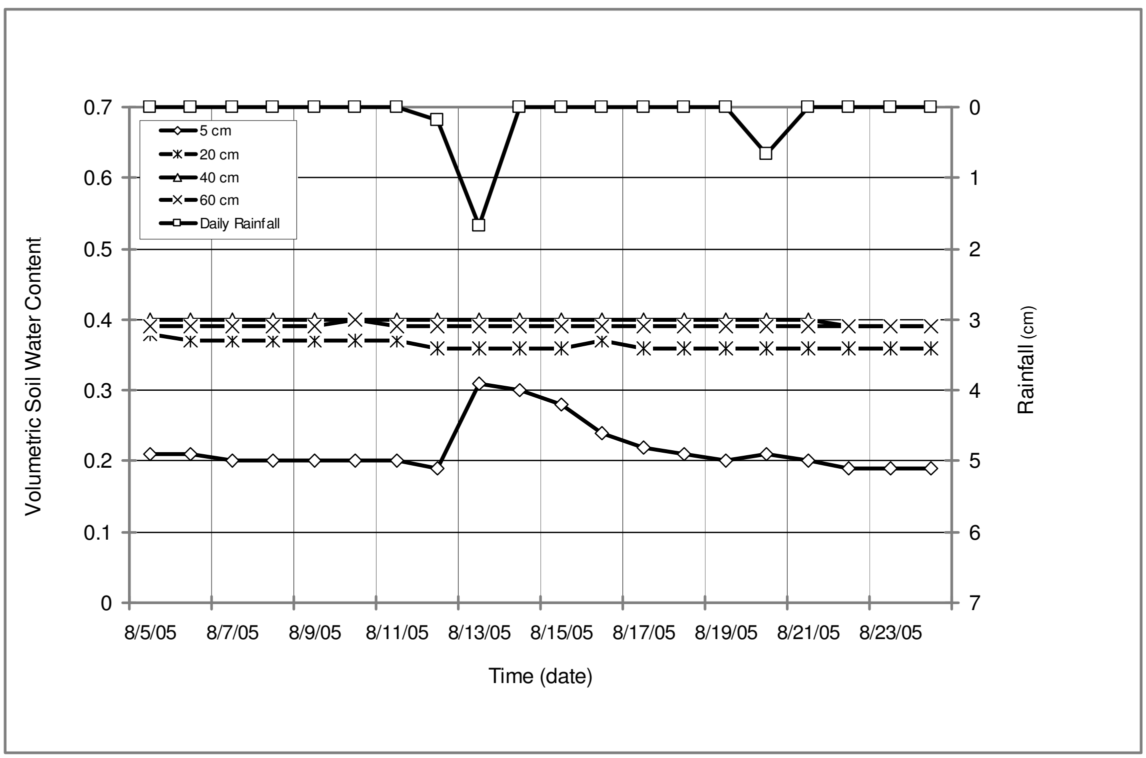


Fig. 4. Volumetric soil water content at four depths and rainfall during the study period obtained from Hydra Probes installed at the AS1 weather and soil monitoring site.

Pre-wetting the soil allows for sufficient wetting to a depth of 1 meter on the day measurements begin. On the day of measurement, water was carefully ponded in the rings with the change in water level over time observed. Once the rate of change became constant, the vertical flux of water in the profile was assumed to be at steady state. At this time the hydraulic conductivity in the zone of constant matric potential is said to be numerically equal to the flux density of water and thus a value of saturated conductivity (Ks) was obtained. Tensiometric readings were taken at this time as a check on unit gradient conditions and saturated water content. The rings were then covered to minimize evaporation and protect the area from rainfall. In this data set, tensiometric data and gravimetric soil samples were obtained from each site to determine matric potential and soil water content, respectively, 4 to 8 days during the drainage phase.

Results and Discussion

Although we consider this work a preliminary investigation, the results are quite interesting nonetheless, and certainly bring into question the general assumption that a soil matric potential value of approximately -33kPa is obtained after two days drainage in an initially saturated profile. The value of -33kPa is commonly referred to in the literature as field capacity, the point at which the flow of water in the soil due to gravity or free drainage discontinues (Hillel, 1980). It is apparent from the results of this study that these conditions were never achieved in either field during the course of a thirteen day drainage cycle. For each field the results are very consistent in showing minimal changes in soil water content after steady-state infiltration conditions were achieved with saturated flow. An important point to highlight is the fact that we used factory calibrations for all dielectric sensors and the soil water content values obtained using the sensors show consistency and show relatively good agreement with soil sampling water content measurements. However, we will use site-specific calibrations for all sensors in future work though for this study we did not have the data necessary for calibrations.

Table 1 shows the soil physical properties for each of the four infiltration study sites in the two fields. The soils in this area are predominately clay as determined in the texture analyses. Bulk density values increase slightly with depth and are within the expected range of values for these texture classes. Table 2 gives values of effective porosity (φ_e) and estimates of Ks using two different PTFs developed by Ahuja et al. (1985[13]) and Rawls et al. (1982[11]), respectively, as well as average profile Ks measured *in situ*. The estimates of Ks using the approach of Ahuja et al. (1985[13]) compare quite well with those measured *in situ*. Comparing average profile Ks values from each field, measured values for AD and AS1 were 1.8 and 0.7 cm hr^{-1}, respectively, as compared to 1.32 and 0.86 cm hr^{-1} estimated by Ahuja's PTF. Estimated Ks values using Rawl's PTF were approximately four times higher than measured values. It appears that the use of total porosity in Rawl's PTF rather than effective porosity as in Ahuja's method, results in overestimation of Ks values for all depths. We were only able to use soil parameters in each PTF based on laboratory soil-core analysis due to the lack of sufficient drainage in the fields, thus preventing a test of the PTFs using parameters measured *in situ*.

Table 1. Soil physical properties at four infiltration study sites, fields AD and AS1.

Site ID	Depth	Sand	Silt	Clay	Texture [a] Name	Bulk Density
	(cm)	--------------%---------------------				----g/cm^3--
AD IN-1	00-15	22.5	52.5	25.0	SiL	1.32
	15-30	20.0	44.2	35.8	CL	1.51
	30-45	5.0	48.8	46.2	SiC	1.52
	45-60	55.0	33.7	11.2	SL	1.84
AD IN-3	00-15	32.5	49.3	18.2	L	1.36
	15-30	30.0	42.5	27.5	CL	1.44
	30-45	27.5	34.3	38.2	CL	1.67
	45-60	36.3	40.0	23.7	CL	1.85
AS1 IN-4	00-15	23.1	37.5	39.4	CL	1.48
	15-30	23.1	40.0	36.9	CL	1.67
	30-45	20.0	27.5	52.5	C	1.56
	45-60	--	--	--	--	-----
AS1 IN-6	00-15	28.1	37.5	34.4	CL	1.50
	15-30	27.5	35.0	37.5	CL	1.56
	30-45	35.6	30.0	34.4	CL	1.72
	45-60	--	--	--	--	-----

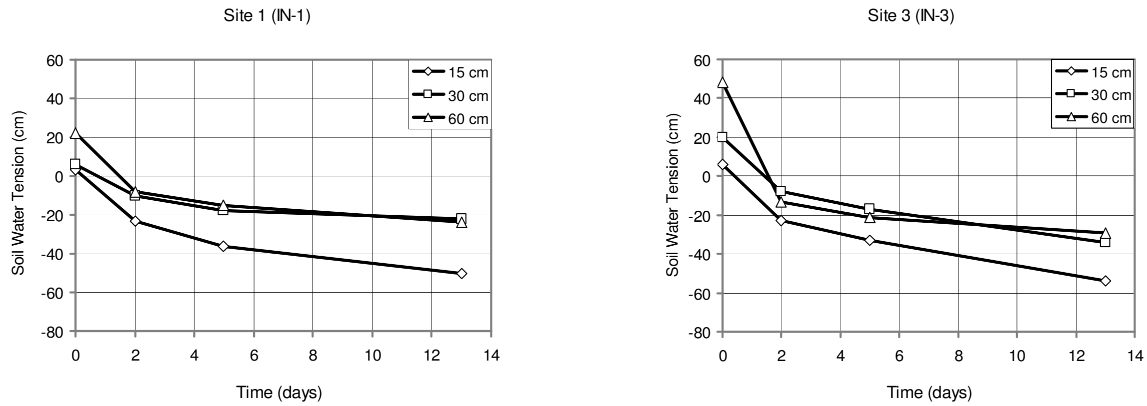
[a] Texture names: S–Sand, Si–Silt, C–Clay, L–Loam.

Table 2. Estimated and measured saturated conductivity values for infiltration sites at AD and AS1.

Site	Depth	Estimates from Soil Cores @ -33 kPa			Measured in-situ
		EP [a] (m^3 m^{-3})	K_{S1} [b] (cm hr^{-1})	K_{S2} [c] (cm hr^{-1})	K_S [d] (cm hr^{-1})
AD IN-1	00-15	0.185	2.976	12.23	2.8
	15-30	0.086	0.241	1.238	
	30-45	0.015	0.001	0.006	
	45-60	0.104	0.449	2.181	
AD IN-3	00-15	0.217	5.026	19.73	0.8
	15-30	0.148	1.418	6.220	
	30-45	0.046	0.031	0.191	
	45-60	0.100	0.397	1.948	
AS1 IN-4	00-15	0.135	1.043	3.999	1.2
	15-30	0.073	0.140	0.675	
	30-45	0.061	0.079	0.403	
	45-60	-----	-----	-------	
AS1 IN-6	00-15	0.179	2.682	9.522	0.2
	15-30	0.132	0.989	3.888	
	30-45	0.086	0.238	1.088	
	45-60	-----	-----	-------	

[a] Effective porosity calculated as the difference between Saturated Theta-V and -33 kPa Theta-V.
[b] Saturated conductivity estimated using Ahuja's approach.
[c] Saturated conductivity estimated using Rawl's approach.
[d] Average profile saturated conductivity from double-ring Infiltrometers.

a) AD



b) AS1

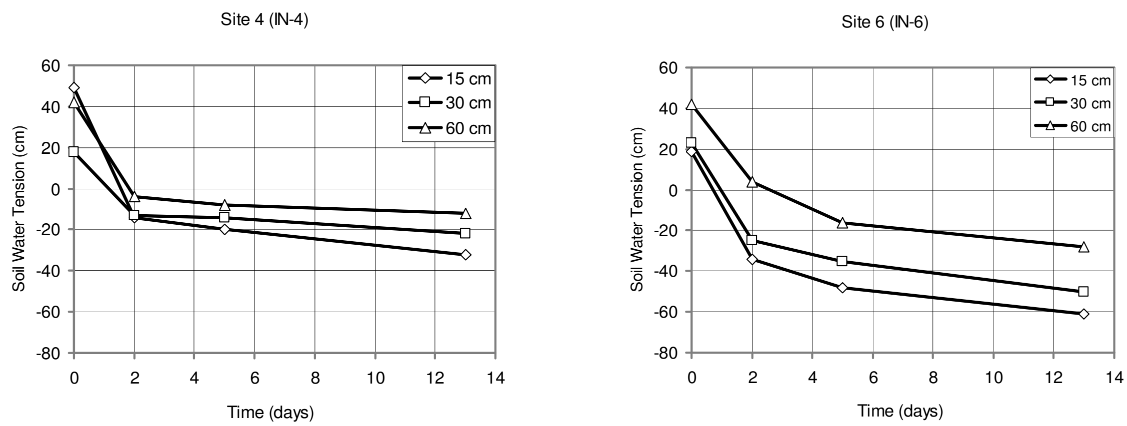


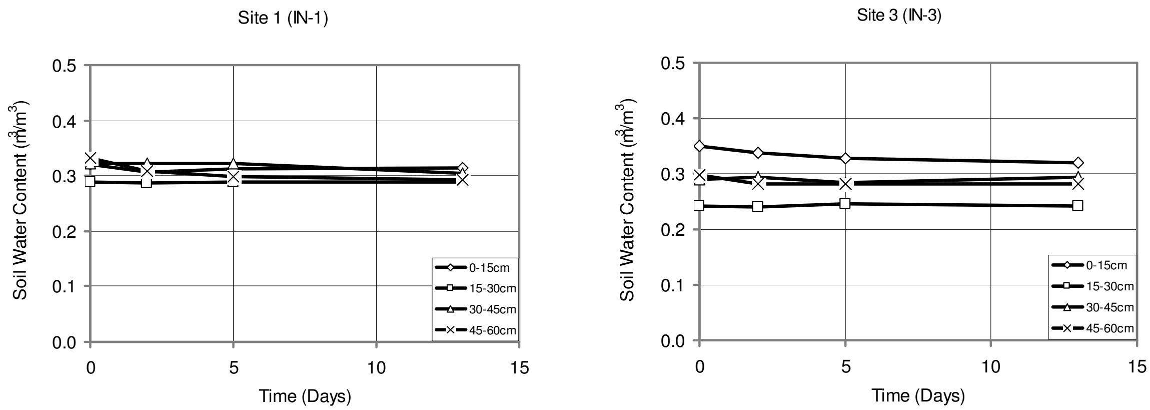
Fig. 5. Soil water tension (matric potential) versus time at four sites during the drainage cycle.

Longer periods of study in the future should provide the data necessary for extending these methods.

The data plotted in Figure 5 show soil water tension (matric potential) as a function of time at three depths per site in each field. The data trends are quite similar with soil water tensions ranging from 50 to -60 cm, or a total of -110 cm in pressure change, on average, over a 13 day period. This is a rather surprising result in that on day 13 of the drainage cycle the soil water tension was only -6 kPa (-60 cm), on average, which is much lower than the value of -33 kPa usually assumed after 2 days drainage. Indeed, further study is warranted to explore the reasoning for such a deviation.

In Figures 6, 7 and 8 soil water content at different depths versus time for each field site. Figure 6 shows TDR measured profile data; Figure 7 is profile soil-core water content; and Figure 8 is a comparison between near-surface Theta Probe measurements and soil-core water content. In all cases it is apparent that there were only small changes in soil water content, at all depths, during the 13 day period.

a) AD



b) AS1

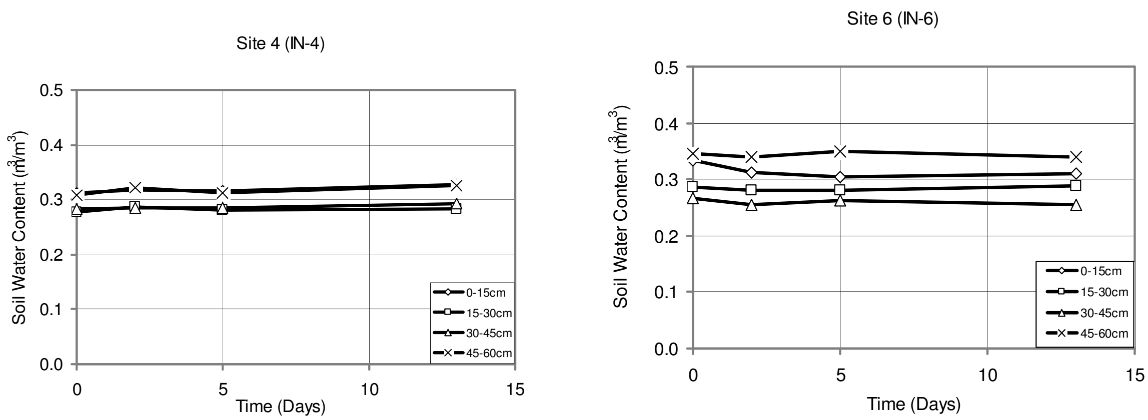
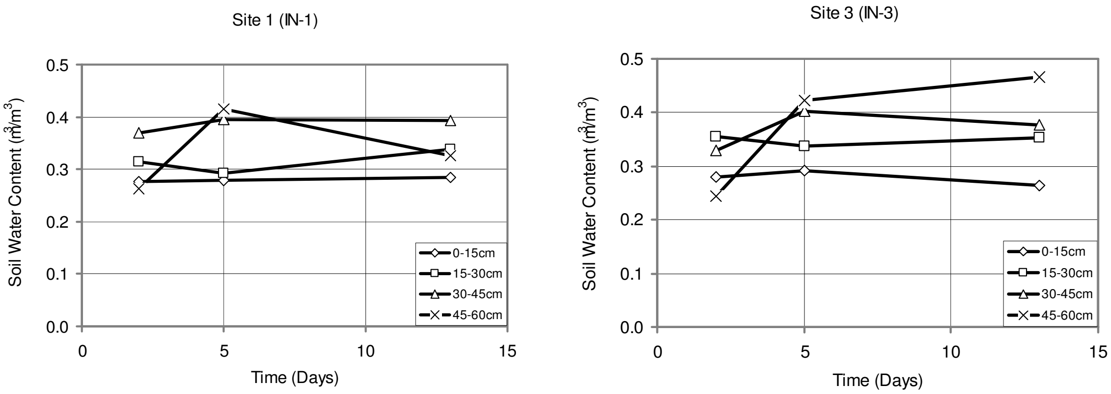


Fig. 6. TDR profile soil water content versus time at four sites during the drainage cycle.

The relative range in soil water content values among Figures 6-8 is small indicating consistency in the measurements, although the measurements using the factory calibrated dielectric sensors are not considered absolute. The graph of soil-core water content (Fig. 7) seems to indicate that saturated conditions during infiltration may not have occurred at deeper depths for sites 1 and 3 in field AD since there was an increase in water content at the 45-60 cm depth with time. The graph in Figure 4 shows that the rainfall event that occurred during the study period did not affect the lower profile so we must assume no contribution by rainfall. In future infiltration experiments we will pre-wet the ring areas for two days prior to beginning the study rather than one day, to ensure uniform saturated profile conditions.

a) AD



b) AS1

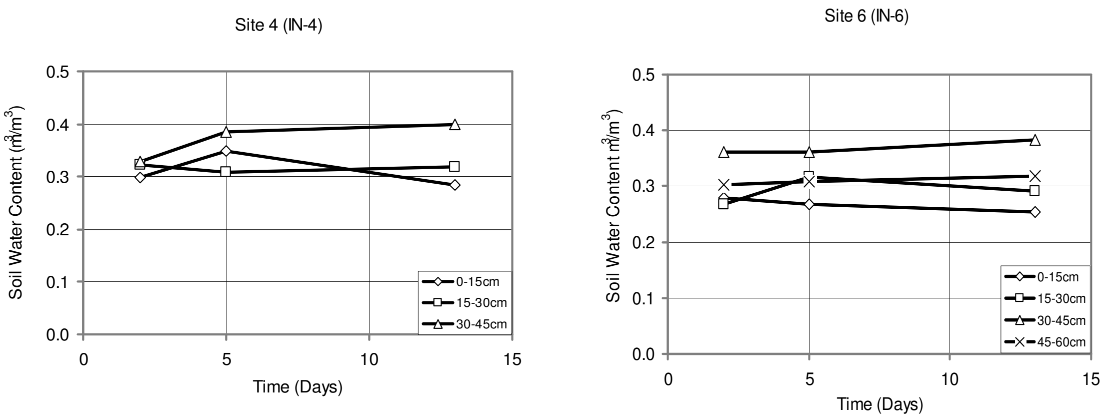


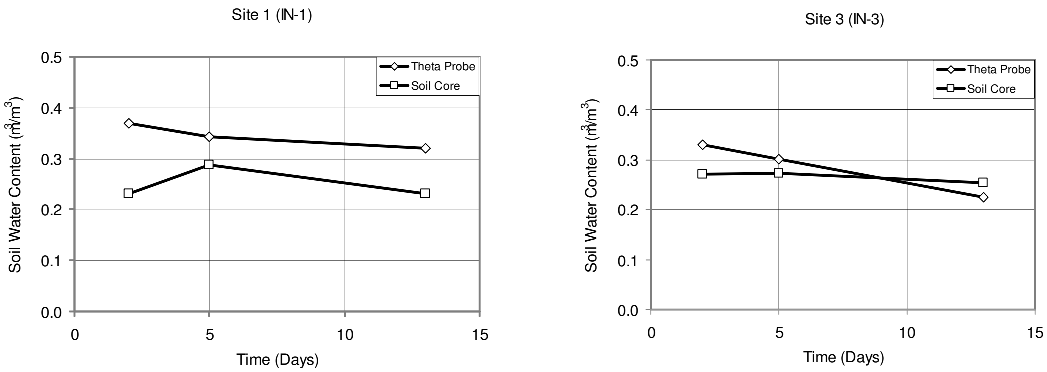
Fig. 7. Profile soil-core water content versus time at four sites during the drainage cycle.

Overall, the soil in both fields at all sites remained very wet during the 13 day drainage cycle. This in turn limited our ability to satisfy our objective to obtain *in situ* water characteristic data. On the other hand, the knowledge gained from this preliminary work has provided considerable insight for future work, along with important questions that our continued research will address in the area of soil hydrology.

Conclusions and Summary

The objective of this work was to determine *in situ* soil hydraulic properties using dielectric measurements of soil water content (θ_v) and compare the field measured values with those estimated by pedotransfer functions based on soil-core laboratory analysis. The use of three types of dielectric sensors proved adequate to their purpose in measuring the change in θ_v during field infiltration and drainage experiments.

a) AD



b) AS1

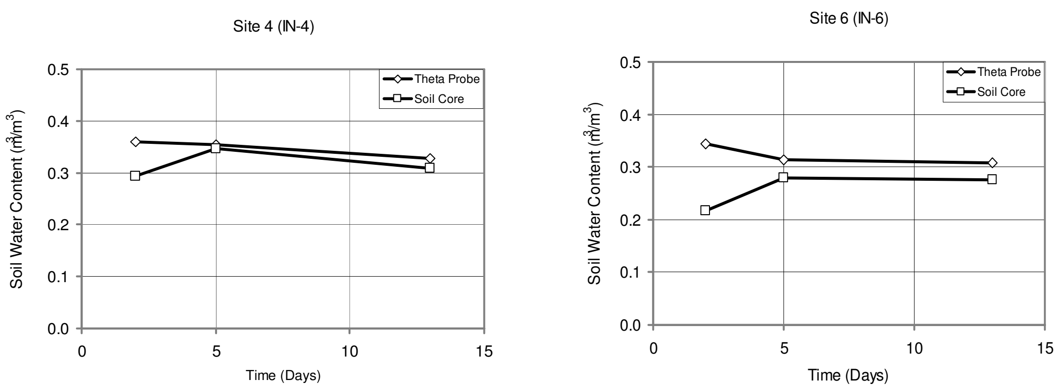


Fig. 8. Comparisons of 0-5 cm Theta Probe and soil-core water content at four sites during drainage cycle.

Although the conditions necessary to determine the water characteristic function *in situ* were not achieved, the use of TDR profiling probes proved successful in measuring daily profile θ_v, thus eliminating the need to take daily gravimetric soil water samples throughout the 15 day study period. However, gravimetric samples should be taken at the beginning and end of the experiment for calibration or validation of the TDR data.

Measurements of near-surface θ_v soil water content using the Theta Probes indicate that these types of measurements may provide the data necessary to test the concept that changes in near-surface θ_v soil water content two days after a sufficient wetting are related to the average profile Ks. Comparisons between the Theta Probes and Hydra Probes for the 0-5 cm depth interval in our ongoing research should offer insight into expanded applications for remotely sensed near-surface θ_v such as those onboard the NASA Earth-Observing System (EOS) satellite mission AQUA . It is interesting to note that the microwave radar sensors onboard AQUA are also based on the measurements of soil dielectric properties.

Based on the results of this study, our ongoing field experiments have been modified and expanded in an effort to obtain sufficient data during the drainage cycle to fully define the water characteristics function, *in situ*, and further test the applicability of pedotransfer functions for estimating soil hydraulic properties. In particular, our future work will focus on quantifying the time at which free drainage ceases and at what pressure potential, and how this knowledge may effect the application of PTFs based on the concepts of field capacity and effective porosity. Nonetheless, the dielectric sensors described in this study should continue to provide the θ_v measurements that are necessary to achieve our ongoing research objectives.

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