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In-Situ Soil-Water Retention and Field Water Capacity Measurements in Two Contrasting Soil Textures

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Abstract. The primary objective of this study was to estimate the in-situ field water capacity (FWC) from the soil-water retention curve developed from volumetric water content, ? and water matric potential, ? data collected in the field using soil moisture sensors in two soils. The soils are Lihen sandy loam and Savage clay loam. Six 117 cm × 117 cm metal frames, 30 cm in height were inserted 5- to 1 0 cm into soil. Two Time Domain Reflectrometry (TDR) sensors were installed in the center of the frame and two Watermark (WM) sensors were installed in the SW corner at 15 and 30 cm depths to continuously monitor soil ? and ?, respectively. A neutron probe (NP) access tube was installed in the NE corner of each frame to measure soil ? used for TDR calibration. The soil inside each frame was saturated by applying approximately 18 to 20 cm of water intermittently to saturate the upper 50 to 60 cm of soil. Frames were then covered with plastic tarps. The Campbell and Gardner equations best fit the soil water retention curves for both soils. The field capacity times (t_{FWC}) were reached at approximately 50 and 450 hrs for sandy loam and clay loam soils, respectively . Using soil-water retention curves, ? values at field water capacity ($?_{FWC}$) were approximately 0.228 and 0.344 $m^3 m^{-3}$ for sandy loam and clay loam soils, respectively. The TDR and WM sensors provided accurate in-situ soil water retention data from simulta neous soil ? and ? measurements.

Keywords. Water content, water potential, sensors, irrigation, watermark, time domain reflectrometry.

Introduction

In most soils, optimal irrigation management practices for many crops require estimation of soil water retention data in the field or laboratory to assess both the amount and timing of irrigation. A water retention curve, also called the soil moisture characteristic curve, describes the “functional relationship between the soil water content, ? and soil matric potential, ? in unsaturated soils that is characteristic for different types of soil” (Hanks and Ashcroft, 1980; Taylor and Ashcroft, 1972). The curve is a basic soil property that is affected by soil physical and chemical characteristics; e.g., soil texture, structure, amount and degree of aggregates, amount of colloids, type of clay mineral, and amount of soluble salts (Taylor and Ashcroft, 1972).

In-situ field water capacity (FWC) “is the content of water on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible” (www.soils.org/sssagloss, verified April 23, 2008). After soil infiltration ceases and equilibrium level reaches, water within the wetted portion of the soil profile drains to deeper depths under the influence of soil potential gradients. The downward movement of water in the soil profile is relatively fast at beginning and then decreases rapidly with time (Hillel, 1971; Taylor and Ashcroft, 1972; Hillel, 1980).

Many attempts have been made to relate FWC to soil water retention at a particular soil matric potential, often to the - 33 kPa (- 1/3 bar); thus, the physical definition of field capacity by many agronomists, soil scientists and agricultural engineers is considered the bulk water content retained in the soil at - 33 kPa (- 1/3 bar) of soil matric potential or suction (tension), ? (Hillel, 1971; Jury et al., 1991; Kirkham, 2005). However, FWC is not a unique value but is rather expressed as a range of values of soil water contents (Kirkham, 2005). It is influenced by many factors such as previous soil water content, soil texture and structure, type of clay, organic matter, water table, presence of impeding layer and evapotranspiration (Kirkham, 2005). Nevertheless, the term of FWC is often misunderstood (Warrick, 2002) and little research has been done on estimation of FWC and development of in situ soil water retention curves using newly developed soil moisture sensors.

The newly developed sensors including Watermark (WM) an d Time Domain Reflectrometry (TDR) can be data logged for continuous measurements of soil ? and ? at various depths in the soil profile (Leib et al., 2003). These continuously monitoring sensors have been recently used in soil water content measurements for a variety of agricultural and environmental applications including irrigation management and scheduling (Dane and Hopmans, 2002). Nevertheless, the relationship developed between soil ? measured by WM resistance blocks and soil ? measured by the TDR must be determined before these sensors can be used effectively in irrigation scheduling and management (Morgan et al., 2001).

The primary objective of this work was to estimate in-situ FWC from a soil-water retention curve developed from soil ? and ? data collected in the field using WM and TDR sensors, respectively, in two contrasting textured soils.

Materials and Methods

Experimental sites and soils

Soil water content, ? and soil matric potentials, ? were measured at two sites of different soil texture, one in North Dakota and the other in Montana **. The North Dakota site (Nesson) is located at the Nesson Valley Research farm, approximately 37 km east of Williston, ND (48.1640 N, 103.0986 W). The soil is mapped as Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll) and consists of very deep, somewhat excessively or well drained, nearly level soil that formed in sandy alluvium, glacio-fluvial, and eolian deposits. www.soils.usda.gov/technical/classification/osd/index.html .**

The Montana site at the Montana State University Eastern Agricultural Research Center (EARC) is **located approximately 2 km north of Sidney, MT (47.7255 N, 104.1514 W)** . **The soil at the** EARC site is classified as Savage clay loam (fine, smectitic, frigid Vertic Argiustolls) **and consists of deep, drained, nearly level soils formed in alluvium parent material www.soils.usda.gov/technical/classification/osd/index.html .** Selected soil physical properties for both soils are given in Table 1.

Table 1. Selected soil physical properties.

Soil	depth	Sand	Silt	Clay	Bulk density
	cm	g kg $^{-1}$	g kg $^{-1}$	g kg $^{-1}$	Mg m $^{-3}$
Sandy loam					
	0 - 15	660	170	170	1.56
	15 -30	670	150	180	1.51
Clayey loam					
	0 - 15	210	410	380	1.43
	15 -30	200	430	370	1.39

Field methods

Using a tractor front loader **,** six 117 cm × 117 cm metal frames, 30 cm in height were inserted 5 to 10 cm into the soil to prevent lateral water movement (Fig. 1). The frames were spaced at approximately 40 m intervals on a 200 m transect to account for soil variability across the field. Two TDR sensors (CS625, Campbell Scientific Inc., Logan, UT) were installed in the center of the frame and two WM sensors (Irrometer company, Riverside, CA) were installed in the south west (SW) corner at 15 and 30 cm depths to continuously monitor changes in volumetric soil water content and soil water matric potential, respectively (Fig. 1). Sensor installation processes and operational procedures were carried out according to the manufacturer's recommendations and instructions (www.campbellsci.com; www.irrometer.com). Data from both sensors were recorded hourly.

A NP access tube was installed in the NE corner of each frame to measure soil water content to be used for calibration of TDR measurements (Fig. 1). The NP readings were taken every 6 hours in sandy loam and daily in clay loam soil. The soil profile in the framed area was thoroughly saturated by applying approximately 18-20 cm of water intermittently to saturate the soil profile to a 50 to 60 cm depth. The remaining ponded water on the soil surface was allowed to infiltrate. After all water was infiltrated the frames were then covered with plastic tarps that were secured to the frames with duct tape to avoid any evaporation fr om the soil. Measurements of soil ? and ? were continuously monitored at two depths using WM and TDR sensors, respectively, for approximately 50 hrs in sandy loam and 19 days in clay loam soil under redistribution. Neutron probe measurements were also taken at two depths in each framed area during the redistribution process and at the end of the experiment.

At the end of the experiment nine soil cores were taken at the 0 to 10 cm, 10 to 20 cm and 20 to 30 cm depths around the center of each framed area to determine soil gravimetric water content.

Figure 1. Schematic of the experimental set up. The sensors are installed in the soil inside the metal frame.

Results and Discussion

The in-situ soil water retention data from simulta neous soil ? and volumetric ? measurements recorded with the WM and TDR sensors for both sandy loam and clay loam soils are presented in Figures 2 and 3, respectively. The mean values of soil ? and volumetric ? at the 0 to 15 and 15 to 20 cm depths were used to develop soil water retention curves for both soils as soils at these two layers were nearly homogeneous and uniform in texture and structure properties (Table 1).

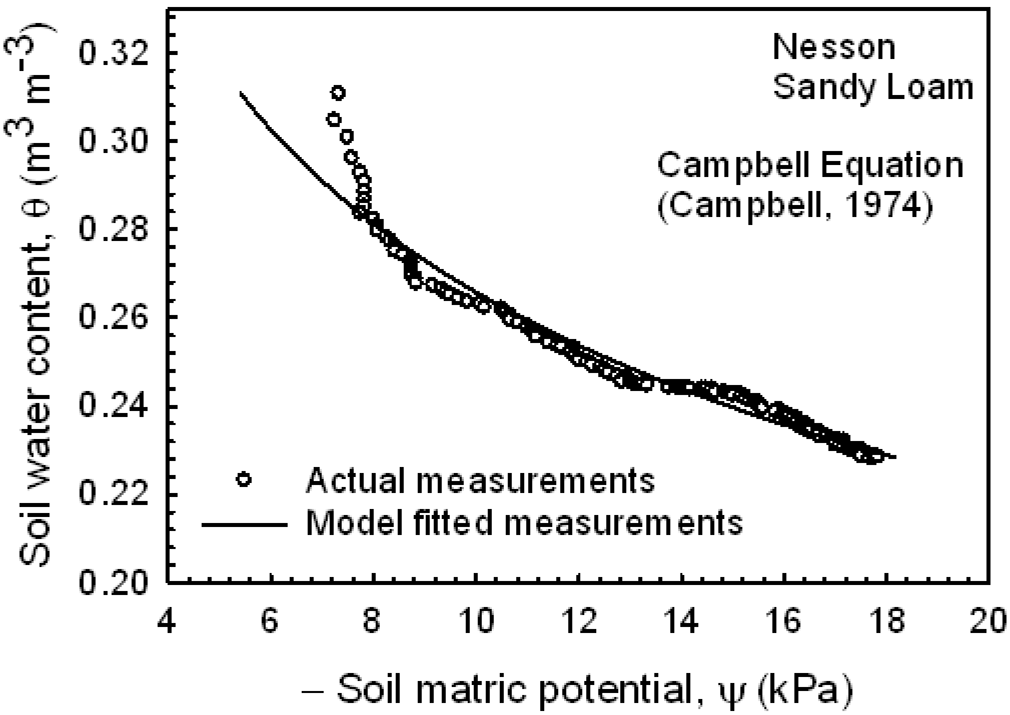

Figure 2. Soil water retention curve for sandy loam soil at Nesson location.

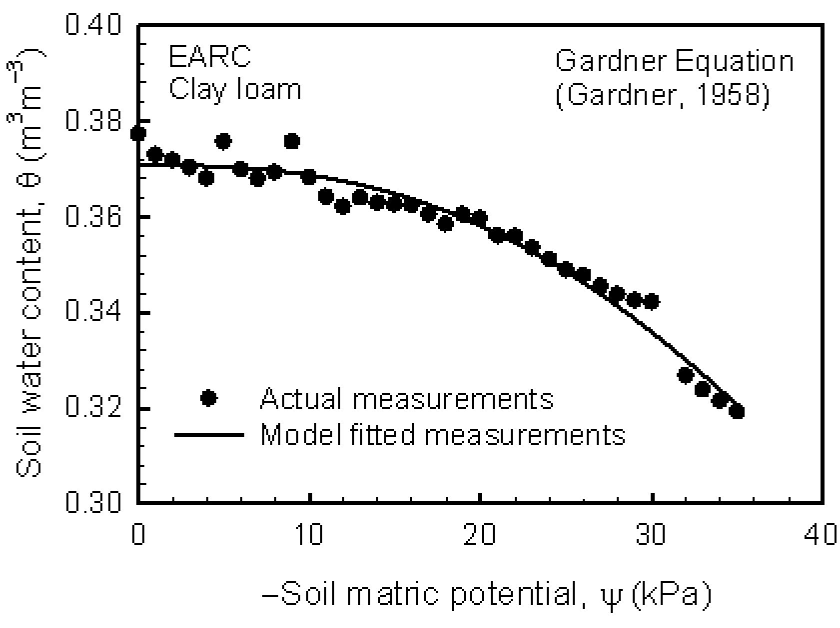

Figure 3. Soil water retention curve for clay loam soil at the EARC location.

The Campbell equation (Eq. 1) provides the best fit the water retention curve for sandy loam soil (Fig. 2).

$$\psi = \psi_e \left(\frac{\theta}{\theta_s} \right)^{-b} \qquad [1]$$

where ? $_e$ is the air-entry water potential, *?* is the volumetric soil water content, ? $_s$ is water content at saturation, and *b* is empirically determined from the soil-water retention curve (Campbell, 1974).

Equation (1) can also be rearranged in terms of soil *?* as:

$$\theta = \theta_s \left(\frac{\psi}{\psi_e} \right)^{-1/b} \qquad [2]$$

Equation (2) converts the soil matric potential directly to soil volumetric water content.

Figure 3 shows an in-situ soil water retention curve for a sandy loam soil that is best described using the Gardner equation (Eq. 3) (Gardner, 1958).

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{1 + \left(\frac{\psi}{a} \right)^b} \qquad [3]$$

where ? $_r$ is the residual water content, ? $_s$ is the saturated water content, a and b are empirically determined parameters estimated from the soil-water retention curve (Gardner, 1958). The preceding equation is more commonly referred to as a logistic four parameter curve (Seber and Wild, 1989). The estimated ? $_r$ for this data set was too small because of the wet soil conditions used in this study and was therefore set to zero. Equation [3] was then rearranged using ? $_r$ = 0 and simplified as:

$$\theta = \frac{\theta_s}{1 + \left(\frac{\psi}{a} \right)^b} \qquad [4]$$

Equation [4] c an be used to estimate ? at any given value of ? using soil water retention data. The fitting parameters for Eqs. 1, 2, 3 and 4 are listed in Table 2.

Field water capacity, FWC estimation

The change of soil ? over elapsed time following cessation of infilt ration for both sandy loam and clay loam soils are plotted in Figures 4 and 5, respectively. Figures 4 shows a data set of water potential for a sandy loam that is best fit by a 3-parameter sigmoid model (R^2 = 0.997) as is given in Eq. 5:

$$\psi = \frac{a}{1 + e^{\frac{-(t - t_0)}{b}}} \qquad [5]$$

Table 2. Models' fitting parameters

Equation	Fitting parameters			
Eqs. 1 and 2				

(Campbell, 1974)	? e	? s	b	
	1.637	0.421	3.934	
Eqs. 3 and 4 (Gardner, 1958)	? r	? s	a	b
	1.86 × 10 - 10 ~ 0	0.371	70.1	2.667
Eq. 5	a	t 0	b	
	18.71	13.32	12.67	
Eq. 6	a	t 0	b	
	57.47	614	- 0.80	

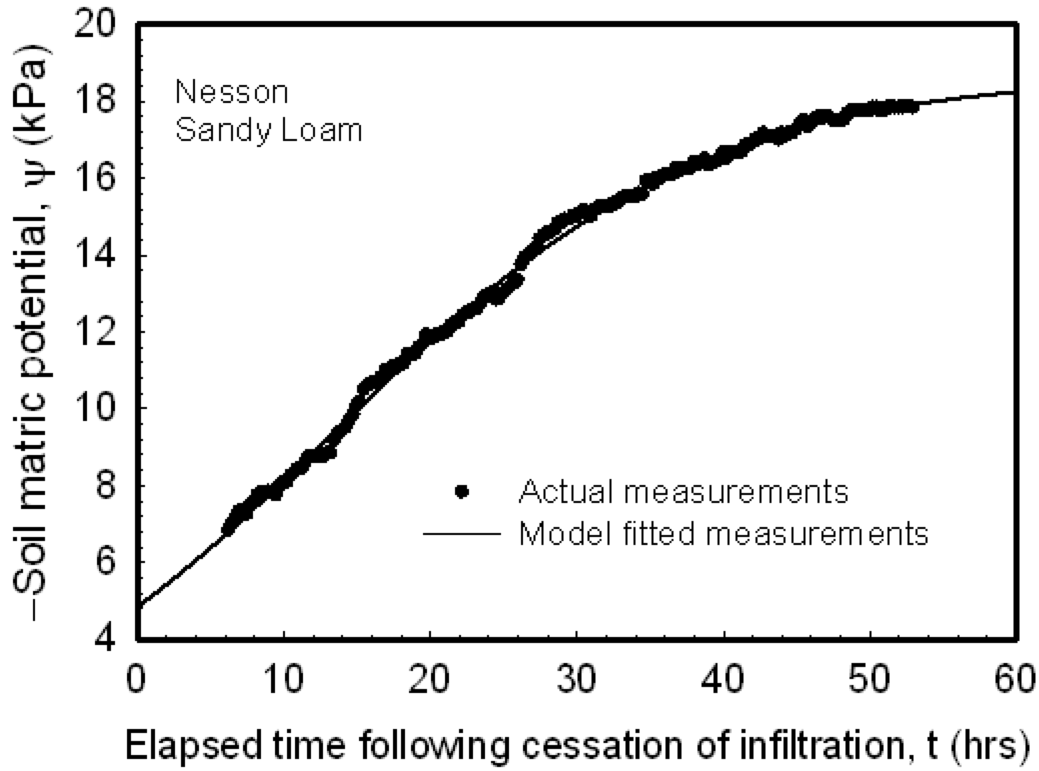

Figure 4. Soil matric potential as a function of time for sandy loam soil at the Nesson location.

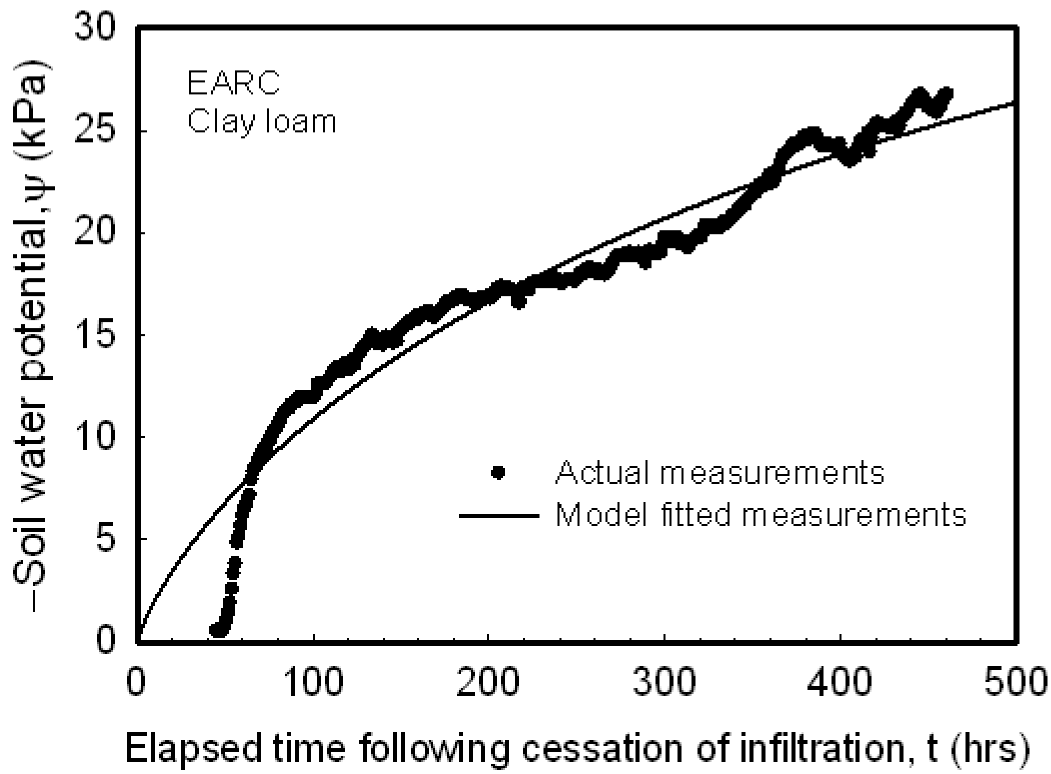

Figure 5. Soil matric potential as a function of time for clay loam soil at the EARC location.

The data for clay loam soil at the EARC location (Fig. 5) was, on the other hand, well described by a 3-parameter sigmoid logistic model (R^2 = 0.936) as follows:

$$\psi = \frac{a}{1+\left(\frac{t}{t_0}\right)^b} \quad [6]$$

where ? is the soil matric potential, t is the elapsed time following cessation of infiltration, and *a*, t_0 and *b* are model fitting parameters. The fitting parameters for Eqs. 5 and 6 are listed in

Table 2.

Equations [5] and [6] were fitted to the measured data using a non-linear least squares optimization approach that minimized the sum of squared deviations between measured and fitted soil water potentials (Seber and Wild, 1989).

Figures 4 and 5 show the rate of water redistribution as the ? gradients decrease and the hydraulic conductivity of the desorbing zone falls off (Hillel, 1971; Taylor and Ashcroft, 1972). In both soils, ? diminished exponentially with time reaching approximately equilibrium conditions (Figs. 4 and 5).

The time at which soil internal drainage becomes nearly negligible at the gradient of water content approaches zero is the field capacity time, t_{FWC} (Hillel, 1971; Taylor and Ashcroft, 1972; Romano and Santini, 2002). Based on our results, the t_{FWC} for both sandy loam and clay loam soils used in this study were reached at approximately 50 and 450 hrs following cessation of soil infiltration, respectively (Figs. 4 and 5). Using relationships presented in Figs. 4 and 5, the s oil ? values at the field water capacity level, $?_{FWC}$, at t_{FWC} of 50 and 450 hours were approximately 18 and 27 kPa for sandy loam and clay loam soils, respectively. Based on soil water retention curves presented in Figs. 2 and 3, the equivalent ? values at field water capacity, ? $_{FWC}$, were approximately 0.228 and 0.344 m ^{3} m $^{-3}$ for sandy loam (Nesson) and clay loam (EARC) soils, respectively. The ? $_{FWC}$ acquired from the gravimetric and NP measurements at the end of the experiment are given in Table 3. Results r eported in Table 3 show that the estimated ? $_{FWC}$ values were within the range of the measured ? $_{FWC}$ values from the NP and gravimetric water content methods. These results indicate that WM and TDR sensors were useful for estimating ? $_{FWC}$ and provided accurate in-situ soil water retention data that can be used in agricultural, environmental and modeling applications including irrigation management and scheduling.

Table 3. Measured and estimated soil water contents, ? at field water capacity, ? $_{FWC}$.

		Soil water content at the field water capacity, ? $_{FWC}$ (m ^{3} m - ^{3})		
Location	Soil	Gravimetric method	Neutron probe	Estimated from the sensors
		Mean ± 2 standard errors		
Nesson	Sandy loam	0.213 ± 0.011	0.222 ± 0.013	0.228
EARC	Clay loam	0.315 ± 0.021	0.351 ± 0.014	0.344

Conclusions

The in-situ soil water retention curves from simultaneous soil ? and volumetric ? measurements obtained from the WM and TDR sensors were developed for both sandy loam and clay loam soils. The Campbell and Gardner equations provided the best fit for the soil water retention curves with R^2 = 0.97 and 0.96 for sandy loam and clay loam soils, respectively. The changes of soil ? with time following cessation of infiltration were well described by 3-parameter sigmoid models with R^2 = 0.997 and 0.936 for sandy loam and clay loam soils respectively. Based on these relationships, the t $_{FWC}$ were reached at approximately 50 and 450 hrs following cessation of infiltration and soil ? $_{FWC}$ values at thes e two elapsed times were approximately 18 and 27 kPa for sandy loam and clay loam soils, respectively. Using soil water retention curves, the corresponding ? $_{FWC}$ values at 50 and 450 hours were approximately 0.228 and 0.344 m ^{3} m $^{-3}$ for sandy loam (Nesson) and clay loam (EARC) soils, respectively.

The estimated ? $_{FWC}$ values were within the range of the measured ? $_{FWC}$ values obtained from the NP probe and gravimetric measurements. These results indicated that WM and TDR sensors can provide accurate in-situ soil water retention data that can be used in agricultural and environmental applications including irrigation management and scheduling.

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