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Field Calibration Accuracy and Utility of Four Down-Hole Water Content Sensors

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Soil water balance studies of profile water content, changes in stored water, crop water use, and spatial variability of water content and use require accurate soil water determinations that are representative across at least field-sized areas. Several capacitance and other electromagnetic (EM) sensors are commercially available for use in access tubes to determine profile water content. Scientists and practitioners need to know if they are suitable replacements for the neutron moisture meter (NMM) in terms of accuracy and utility. In a field calibration of the NMM and three EM sensors in a Panoche clay loam soil in the San Joaquin Valley of California, three access tubes were installed in a site dried by plant water uptake and three were installed in an adjacent plot wetted to saturation and allowed to drain. Sensors were read and volumetric water content samples taken at several depths at each access tube; calibrations of water content vs. sensor reading were calculated for each depth and for appropriate combinations of depths by regression analysis. Calibrations for the EM sensors changed rapidly with depth, often requiring separate calibrations for every 10- or 20-cm depth range, and were relatively inaccurate (RMSE of 0.015–0.063 $m^3\ m^{-3}$). The NMM is the preferred choice for accurate profile water content and change in storage determination. In general, the EM sensors cannot be recommended for profile water content or change in storage determinations due to their relatively less accurate (larger RMSE values) calibrations, strong dependence of calibration slopes and exponents on depth, probable dependence of the calibrations on soil bulk electrical conductivity (BEC), and the likelihood of BEC changes in the field during the irrigation season.

Abbreviations: EM, electromagnetic; ET, evapotranspiration; NMM, neutron moisture meter.

Accurate determinations of soil profile water content are essential for studies of crop water use by soil water balance and are important for irrigation management, environmental studies and management, energy and water balance studies including those involving weather models, and many other fields of study and management objectives. In many of these studies and management efforts, the spatial variability of water use is also important since it affects sensor numbers and management methods and technologies needed for good management. For example, the degree of spatial variability of evapotranspiration (ET) and its response to spatially varying irrigation applications is an important question in irrigation research, with implications for management methods and irrigation system capabilities such as the need for variable-rate irrigation systems. Although weighing lysimeters can provide accurate data on crop water use, they are expensive and are not mobile, limiting the spatial extent, soils, and climates in which water use data can be collected. Alternatively, crop water use or ET can be estimated during a period of time from the soil water balance equation applied to a volume of soil called the control volume by

$$\mathrm{ET} = -\Delta S + P + R_o + F + \varepsilon_{\mathrm{ET}} \quad [1]$$

where P is precipitation (including irrigation), R_o is run-on minus runoff, F is flux (other than infiltration or ET) into or out of the control volume, ΔS is the change in water stored in the control volume, and $\varepsilon_{\mathrm{ET}}$ is an error term incorporating the sum of errors in the other terms on the right-hand side of Eq. [1]. Units are typically those of water depth (e.g., millimeters), and the sign convention for P, R_o, and F is that fluxes into the control volume are positive, resulting in positive values of ΔS. In accordance with common practice, the sign convention for ET is that flux away from the control volume is positive. The control volume is typically taken as a right rectangular prism of given surface area, the top of which begins at the soil surface and which is of depth sufficient to extend well below the soil zone where root water uptake or infiltration fronts cause rapid changes in water content, thus eliminating or minimizing F at the bottom of the volume. Of course, this approach is not suitable when a shallow water table

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is present and upward flux is not negligible, thus preventing easy closure of the water balance.

Early studies of crop water use by soil water balance used soil core sampling and drying to directly measure the profile water content. After the 1950s, the NMM became widely used for the same purpose and had several advantages, including being capable of measurements from within access tubes so that repeated, deep measurements of the same soil profile were possible. The ability to measure the same soil profile repeatedly increased the precision and accuracy of change in storage determinations over what was possible with soil coring, which was affected by the considerable spatial variability of profile water content in many situations (California Department of Water Resources, 1963). In the 1980s, sensors based on capacitance or other EM measurement methods began to be commercially available. Several of these that operate from within plastic or epoxy fiberglass access tubes are currently in use. Although many EM sensors are in the form of probes that may be directly inserted or buried in the soil, sensors that may be used in access tubes are preferred for sensing of soil profile water content for several reasons. Sensors that require burial or insertion usually require the digging of pits that disturb the soil profile, whereas an access tube may be installed with minimal disturbance of the soil around the tube. If many field locations are involved, the cost of sensors deployed in access tubes may be considerably smaller than that of individual sensors inserted or buried to the same depth, particularly if movable sensors are used as is the case for the NMM. Access tubes may be installed to depths considerably below the depth of rooting and penetration of water from irrigation, allowing closure of the water balance and simplifying the use of Eq. [1], whereas installation of individual sensors to such depths may require costly and destructive excavation.

For a given period of time, ΔS determined by a soil water sensor may be represented generally by

$$\Delta S = a_0 + a_1 X_{\mathrm{i}}^{a_2} - a_0 + a_1 X_{\mathrm{f}}^{a_2} = a_1\left(X_{\mathrm{i}}^{a_2} - X_{\mathrm{f}}^{a_2}\right) \quad [2]$$

where the a_i, for i = 0, 1, 2, … are coefficients of a generalized calibration equation in terms of sensor output, X, determined at initial and final times denoted by subscripts i and f. Equation [2] shows that inaccuracy in the intercept term, a_0, of a calibration does not affect the accuracy of ΔS determination. For linear calibrations, the value of a_2 is unity and only the slope term, a_1, affects the accuracy of ΔS. For nonlinear calibrations, both the slope term and the exponent term, a_2, affect accuracy. Other, more complicated calibration models may be required for some sensors but the general consequence that accurate slope and exponent values are needed to determine ΔS accurately remains the same. The coefficient values are commonly obtained by regression analysis of an appropriate model in terms of volumetric water contents, directly measured, vs. sensor output, where water content measurements and corresponding sensor readings are obtained for a range of water contents either in the laboratory or the field.

Although several down-hole EM sensors are now available, there is compelling evidence that most are not well suited for ET determination by soil water balance for efficient irrigation management or for studies of the spatial variability of ET. Indeed, an international study comparing several down-hole EM sensors vs. the NMM and gravimetric methods concluded that the NMM remained the only reliably accurate sensor method for soil water content and change in storage determinations (Evett et al., 2008). Several studies of EM sensors have noted that calibrations are needed for different soil textures and mineralogies, different levels of soil bulk electrical conductivity, and thus different soil temperatures and depths (Baumhardt et al., 2000; Evett et al., 2006; Kelleners et al., 2004a,b; Logsdon, 2007; Schwank and Green, 2007). Other studies have shown that field calibration of EM sensors resulted in relatively small coefficients of determination in the regression relationship and relatively poor accuracy of estimated water contents compared with the NMM or gravimetric measurements (Evett and Steiner, 1995; Heathman, 1993). Calibrations in repacked soil columns have produced calibration equations that would be considered accurate due to their low RMSE of regression (e.g., Paltineanu and Starr, 1997). The uniformity of packing plus the small volume of soil sensed by some EM sensors (Evett et al., 2006; Schwank et al., 2006) brings into question, however, how appropriate such calibrations are for a field soil, which is likely to be much less uniform in bulk density and water content on a small scale. Preliminary studies of the spatial variability of profile water content indicated that some EM sensors were not representative of the spatial variability of water content (Evett and Cepuder, 2008).

All EM sensors generate an electrical signal and measure some property (typically a resonant frequency or travel time) of the response of this signal to changes in the apparent permittivity of the soil, ε_a, which can be affected by the texture and electrical conductivity of the soil. For a signal at a single angular frequency, ω, the effect of direct-current electrical conductivity, σ_{dc}, on the apparent permittivity can be represented by (Robinson et al., 2003)

$$\varepsilon_{\mathrm{a}} = \frac{\mu\varepsilon'}{2}\left(1 + \left\{1 + \left[\left(\varepsilon''_{\mathrm{relax}} + \frac{\sigma_{\mathrm{dc}}}{\omega\varepsilon_{\mathrm{o}}}\right)\Big/\varepsilon'\right]^2\right\}^{0.5}\right) \quad [3]$$

where ε' is the real component of the complex dielectric permittivity, ε''_{relax} is the increase in permittivity due to relaxation losses, and ε_o is the permittivity of free space (8.854×10^{-12} F m^{-1}). The value of ε' is largely dependent on the permittivity of the free water in the soil, but the value of ε_a depends also on the measurement frequency, the value of σ_{dc}, and relaxation effects that increase with soil surface area (texture effect). Thus, the temperature sensitivity of EM methods is due to, among other effects, the temperature sensitivity of the soil bulk electrical conductivity (σ_a, S m^{-1}), the negative temperature dependence of the permittivity of free water (−0.41 to −0.33 °C^{-1} from 0 to 40°C), and the effect of σ_a changes on the effective measurement frequency (Evett et al., 2005, 2006; Kelleners et al., 2005). The apparent permittivity may also increase with the release of bound water from soil particle surfaces as temperature increases (Wraith and Or, 1999), although Evett et al. (2006) concluded that the effect of the loss tangent, $\sigma_a/(\omega\varepsilon_o)$, dominated in the three soils they studied. Numerous studies under irrigated conditions document increasing σ_a with soil depth and water content and the temporal variation of σ_a (e.g., Rhoades, 1972; Rhoades et al., 1981, 1999), raising the question of the suitability of EM sensors for water content determination under these conditions.

In this study, our objectives were to: (i) calibrate three EM sensors and the NMM in the field; (ii) compare the ease and accuracy of calibrations; (iii) discern if, and understand how, varying soil properties affected the calibrations; and (iv) compare the utility of the calibrations and implications for usefulness of the sensors in field studies.

Materials and Methods

Calibrations were conducted in conjunction with a field experiment on spatial variability that was conducted in 2005 at the University of California West Side Research and Extension Center in Fresno County near Five Points in the San Joaquin Valley (formerly known as the West Side Field Station, 36°20′10″ N, 120°6′46″ W). The soil was a Panoche clay loam soil (fine-loamy, mixed, superactive, thermic Typic Haplocambid). Fritschi et al. (2003) described the soil as having a pH of 7.8 in the top 0.6 m and an electrical conductivity (saturation paste extract) of 1.1 dS m^{-1} in the top 0.3 m and 0.7 dS m^{-1} in the 0.3- to 0.6-m depth range. The soil is a clay loam at the surface and to the 91-cm depth, then grades to a silty clay or silty clay loam below that (Table 1). The Panoche soil has three diagnostic horizons: an ochric epipedon from 0 to 18 cm (Ap), a cambic horizon from 18 to 61 cm (Bw), and a zone of redistribution of carbonates or gypsum (from the cambic horizon) from 61 to 152 cm (Bk) (NRCS, 2002). These soils were originally classified as Torriorthents, but were reclassified after heavy irrigation caused redistribution of carbonates or gypsum, thus forming the Bw and Bk horizons. Thus, the depth of the interface between Bw and Bk is somewhat a function of the number of years since irrigation began and the intensity of irrigation.

Sensors used were a NMM (Model 503DR1.5, Campbell Pacific Nuclear International, Concord, CA), and three capacitance sensors (Model PR2/6, Delta-T Devices, Cambridge, UK; Models Diviner 2000 and EnviroSCAN, Sentek Sensor Technologies, Stepney, SA, Australia). These were the same as those used by Evett et al. (2006) in a calibration performed in soil columns of three U.S. Great Plains soils, except that the Delta-T PR1/6 was replaced by a newer model PR2/6, and the Trime T3 tube probe was unavailable for calibration due to failure of its electronics. The NMM was calibrated in the Trime access tubes, however, since it was desired to obtain field readings for other studies in the same access tubes for both the NMM and Trime, and because the Trime access tube was the same size as that normally used for the NMM. All sensors were designed to make readings from within access tubes.

Reading depths were the default depths for the Diviner and PR2/6 sensors (Table 2). The 10-cm uppermost depth and 10-cm increments in depth for the EnviroSCAN were the default for that instrument, but since only 16 sensors can be read on one EnviroSCAN sensor string, a method was devised to obtain 20 readings (to 200-cm total depth). Ten sensors were placed on the sensor string backbone at 20-cm increments, with the uppermost sensor placed so as to read at the 20-cm depth. A set of readings was taken with the sensor string in place in the access tube, and a second set of readings was obtained with the backbone moved upward by 10 cm, thus obtaining readings at every 10-cm depth increment. Reading depths for the NMM were determined by the fact that in this and other field studies the NMM and Trime T3 were read in the same access tubes and at the same depths for purposes of comparison, so readings were taken at depths that would allow the Trime sensor to sense water content throughout the profile without gaps between readings. The depth increment for readings was slightly smaller than the 20-cm increment that we have used in other studies involving the NMM.

For each type of sensor, three access tubes were installed vertically in each of two 4- by 6-m plots at the northwest corner of a field that was used for a companion study of spatial variability of water content readings from the sensors (reported separately), for a total of six access tubes for each device. Access tubes were placed 1.5 m apart. Access tube installation used factory tools and methods, plus tools and methods developed at the USDA-ARS

Table 1. Soil texture changes with depth in the Panoche soil at the West Side Field Station. Data to 152-cm depth are from Nielsen et al. (1964) and data for depths below 152 cm are from Nielsen et al. (1973). Depths are rounded to the nearest centimeter.

Depth	Sand (>0.05 mm)	Silt (0.002–0.050 mm)	Clay (<0.002 mm)	Texture
cm		%		
0–15	31.3	28.8	39.9	clay loam
15–30	39.7	24.0	36.3	clay loam
30–46	41.3	24.9	33.8	clay loam
46–61	29.5	30.6	39.9	clay loam
61–76	31.7	33.2	35.1	clay loam
76–91	33.2	31.3	35.5	clay loam
91–107	14.8	44.7	40.5	silty clay
107–122	9.6	50.6	39.8	silty clay
122–137	19.4	42.7	37.9	silty clay loam
137–152	13.4	44.3	42.3	silty clay
152–178	21.4	35.6	43	silty clay
178–183	20.7	35.3	44	silty clay

Table 2. Depths of centers of readings in access tubes for the neutron moisture meter (NMM) and three electromagnetic soil water content sensors. Mean soil bulk densities are given for samples taken at the Sentek access tubes (used for EnviroSCAN and Diviner 2000 sensors).

Depth				Bulk density
NMM	PR2/6	EnviroSCAN	Diviner 2000	
		cm		Mg m^{-3}
8.75	10	10	10	1.16
26.25	20	20	20	1.23
43.75	30	30	30	1.31
61.25	40	40	40	1.27
78.75	60	50	50	1.25
96.25	100	60	60	1.23
113.75		70	70	1.25
131.25		80	80	1.18
148.75		90	90	1.19
166.25		100	100	1.16
183.75		110	110	1.13
201.25		120	120	1.15
		130	130	1.18
		140	140	1.20
		150	150	1.22
		160	160	1.19
		170		1.14
		180		1.12
		190		1.14
		200		1.15

laboratory at Bushland, TX (Evett and Cepuder, 2008; Laurent and Evett, 2008). The Diviner 2000 and EnviroSCAN sensors were used in the same polyvinyl chloride access tubes, which were obtained from the manufacturer. The PR2/6 was used in factory-issue fiberglass/epoxy access tubes. The NMM was used in the polycarbonate access tubes normally used with the Trime T3 probe.

To achieve a wide range of water contents, one plot was allowed to dry by drainage and plant water uptake after irrigation was terminated in mid-August. The other plot was bermed and water was ponded on it until the wetting front reached the 2-m depth. Plots were adjacent so that lateral flux from the ponded plot would partially wet the first row of access tubes in the dry plot so that a range of intermediate water contents might be achieved. To avoid rapid changes in water content during sampling, sensor readings and sampling commenced after the wet plot had drained for 3 d after the cessation of ponding.

For the EM sensors, six sensor readings were taken in each access tube at each depth and averaged to one mean reading for each depth in each access tube. Each reading with the PR2/6 was the average of three readings, taken with the probe rotated 120° between readings. Voltage readings from the PR2/6 were converted to electrical permittivity values using the equation given in the user manual. Both voltage readings and permittivity values were used in regression analysis. For the Diviner and EnviroSCAN sensors, reference sensor counts were obtained with the sensors in an access tube surrounded by water (C_w) and in one surrounded by air (C_a) per user manual instructions, and the scaled frequency, SF (unitless), was calculated as

$$\mathrm{SF}=\frac{C_a-C_s}{C_a-C_w} \qquad [4]$$

where C_s is the count in the access tube in the soil. Procedures for NMM operation were described in Evett and Steiner (1995) and Hignett and Evett (2002), including use of a depth control stand (Evett et al., 2003).

After sensor readings were obtained at each access tube, six volumetric soil samples were taken centered at the uppermost depth of sensor reading and four samples were taken at each reading depth below that, all immediately adjacent to the access tube (approximately 2 cm from the tube due to the size of the sampler). Soil samples were taken using a double ring sampler (Model 0200, SoilMoisture, Santa Barbara, CA). Inner rings were brass cylinders (5.4-cm diameter, 6-cm length, 137.4-cm^3 volume). An excavation was made by backhoe alongside each access tube to the 2-m depth and about 30 cm laterally from the access tube. Soil was removed from the side of the excavation to expose the access tube, using a straight shovel to avoid compacting the soil close to the access tube, and soil samples were taken. To minimize the time between sensor readings and soil sampling in the wet plot, sensor readings and soil sampling of the second access tube was not started until the first was completely finished and the excavation refilled with its original soil. This procedure was repeated for the third access tube in the wet plot. Samples were dried for 24 h at 105°C and the mass of water lost on drying converted to volume by dividing by the density of water, which was assumed to be 1.00 g cm^{-3}. Volumetric water content for each sample was calculated as the volume of water lost on drying divided by the volume of the sample. Bulk density was calculated as the dried soil mass divided by the volume of the sample.

Average volumetric water contents (θ, m^3 m^{-3}) and bulk densities (ρ_b, Mg m^{-3}) and the sample SDs of θ and ρ_b were calculated for each depth at each access tube. All data plus the mean and SD values for each depth were plotted to help identify outliers. Since outliers were a mean of data from four or six samples, data for each sample were examined and those that exhibited much larger than average ρ_b and θ, indicating compression of the sample, were discarded and the mean recalculated. For each sensor, linear or nonlinear regressions were calculated for mean measured θ vs. sensor output for each depth of reading and were plotted to help identify outliers and to identify changes of calibration slope with depth. For adjacent depths having nearly identical slopes, data were combined into common calibrations. Regressions were calculated using SigmaPlot software (version 10.0, Systat Software, San Jose, CA).

Results and Discussion

After evaluating outliers, six of 948 volumetric soil samples taken were discarded from the statistical analysis. The six samples were compressed during sampling. Sample dilation (usually shattering), which results in simultaneously smaller θ and ρ_b, was not observed in this data set. Mean ρ_b values were 1.19, 1.20, and 1.21 Mg m^{-3} and mean SDs were 0.05, 0.05, and 0.06 Mg m^{-3} for samples taken around the Sentek (EnviroSCAN and Diviner) access tubes, the Trime (NMM) access tubes, and the PR2/6 access tubes, respectively. Bulk density was smaller at the 10-cm depth (1.16 Mg m^{-3}) than in the 20- to 70-cm depth range (mean of 1.26 Mg m^{-3}) and was again smaller below 70 cm (mean of 1.17 Mg m^{-3}), but did not vary greatly with depth, ranging from 1.12 to 1.31 Mg m^{-3} (Table 2). Bulk densities measured around the NMM and PR2/6 access tubes were similar to those measured around the Sentek access tubes. Mean θ values were 0.253, 0.257, and 0.247 m^3 m^{-3} and mean sample SDs were 0.019, 0.024, and 0.018 m^3 m^{-3} for samples taken around the Sentek, Trime, and PR2/6 access tubes, respectively. There was no pattern of larger SD values associated with access tubes nearest the border between the adjacent dry and wet plots, indicating that the wetting protocol did not result in excessively large heterogeneity of θ at those access tubes. The slightly larger SD of water content for samples taken around the Trime (NMM) access tubes was due to a sand lens that occurred at one of the access tubes. Data from the sand lens were not discarded.

Calibrations for the NMM were typical of those in desert or semiarid soils with a horizon of carbonate or gypsum accumulation in that there was a separation of calibration slopes between that for the cambic horizon (26–114 cm) and that for the Bk horizon (131–201 cm) (Table 3, Fig. 1A). The larger slope for the deeper Bk horizon is the reverse of what is typically seen (Evett et al., 2007), however, probably partially due to the increased clay content below approximately 1-m depth (Table 1), and perhaps indicating that the carbonate or gypsum accumulation was weak and that the effect of soil textural differences exceeded the effect of carbonate or gypsum accumulation. Still, the depth of the separation between calibration slopes may indicate that the cambic horizon here extends to approximately 1.2 m, deeper than typical for the Panoche soil, probably due to intensive irrigation at the field station. The separate calibration equation for the

Table 3. Calibration equations by corresponding depth ranges for the neutron moisture meter (NMM) and three electromagnetic soil water content sensors used in access tubes. The root mean squared error (RMSE) and coefficient of determination (r^2) are shown.

Sensor	Depth	Calibration equation†	RMSE	r^2
	cm		$m^3\ m^{-3}$	
NMM	8.8	$\theta = -0.031 + 0.2839\ C_R$	0.021	0.973
	26–114	$\theta = -0.092 + 0.2440\ C_R$	0.016	0.959
	131–201	$\theta = -0.136 + 0.2827\ C_R$	0.014	0.979
PR2/6	10	$\theta = -0.087 + 0.1080\ \varepsilon^{0.5}$	0.024	0.971
	20	$\theta = 0.093 + 0.0503\ \varepsilon^{0.5}$	0.063	0.600
	30–40	$\theta = 0.101 + 0.0395\ \varepsilon^{0.5}$	0.032	0.774
	60	$\theta = -0.090 + 0.0769\ \varepsilon^{0.5}$	0.030	0.845
	100	$\theta = -0.326 + 0.1001\ \varepsilon^{0.5}$	0.015	0.982
Diviner 2000	10–40	$\theta = 0.3491\ (SF)^{1.526}$	0.029	0.905
	50 and 60	$\theta = 0.3318\ (SF)^{1.829}$	0.018	0.936
	70 and 80	$\theta = 0.2900\ (SF)^{2.876}$	0.023	0.930
	90 and 100	$\theta = 0.2638\ (SF)^{4.621}$	0.040	0.812
	110–160	$\theta = 0.2384\ (SF)^{5.813}$	0.044	0.669
EnviroSCAN	10–40	$\theta = 0.3576\ (SF)^{1.144}$	0.025	0.931
	50 and 60	$\theta = 0.3626\ (SF)^{1.310}$	0.021	0.913
	70 and 80	$\theta = 0.3133\ (SF)^{2.131}$	0.025	0.916
	90 and 100	$\theta = 0.2932\ (SF)^{3.339}$	0.039	0.824
	110 and 120	$\theta = 0.2709\ (SF)^{4.566}$	0.031	0.858
	130–150	$\theta = 0.3058\ (SF)^{7.079}$	0.051	0.511
	160–200	$\theta = 0.3047\ (SF)^{3.390}$	0.039	0.635

† θ, volumetric water content; C_R, count ratio; ε, dielectric permittivity; SF, scaled frequency.

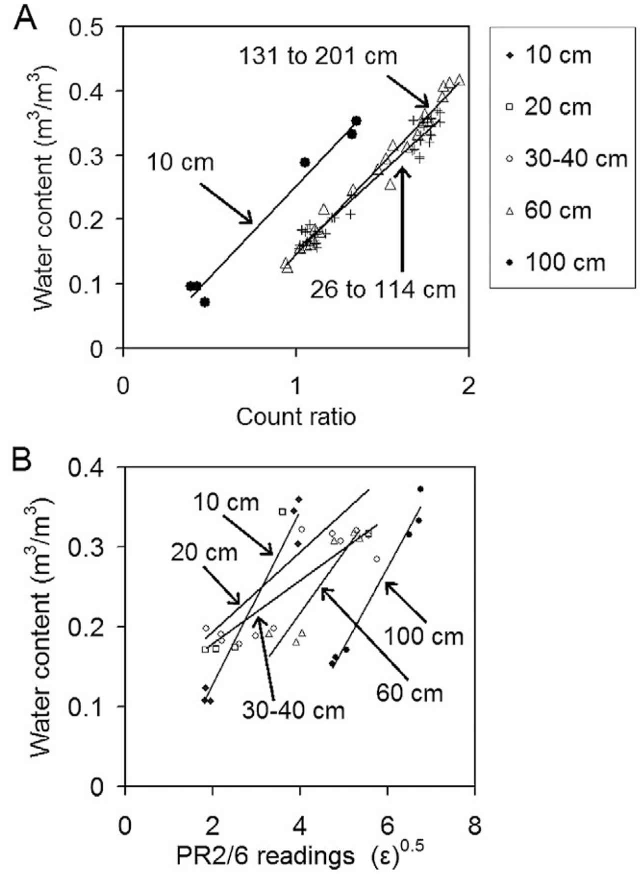

Fig. 1. Measured water content and sensor output: (A) calibrations for the neutron moisture meter in relation to the count ratio; (B) calibrations for the Delta-T PR2/6 in relation to the square root of the reported permittivity, ε.

8.8-cm depth is typical of NMM calibrations at shallow depths in that the intercept was greater than those for the deeper calibrations. The coefficients of determination, >0.9, were typical for a calibration using wet and dry plots, but the RMSEs of regression ranging from 0.014 to 0.021 $m^3\ m^{-3}$ were slightly larger than typical, possibly because of the double ring sampler used, which is not recommended for volumetric water content sampling (Hignett and Evett, 2002).

In contrast, for the PR2/6 there were separate calibration equations for each depth except for the combined calibration for the 30- and 40-cm depths, which plotted together (Table 3, Fig. 1B). Except for the 10-cm depth, calibration lines moved progressively, with depth, to larger values of bulk electrical permittivity, ε_a, for a given value of θ, indicating progressively smaller sensitivity to changes in ε_a as depth increased. This is indicative of an increase in the imaginary component of the permittivity, probably related mostly to an increase in the loss tangent resulting from increasing bulk electrical conductivity with depth, since the soil texture is quite uniform within the top 1 m of soil and thus could not account for the differences in calibrations. Coefficients of determination ranged from 0.600 to 0.982 and RMSE values ranged from 0.015 to 0.063 $m^3\ m^{-3}$, indicating that calibration accuracy was variable and could cause large errors in profile water content determination. Serious errors in θ and ΔS will occur if salinity and its variation with depth are large and vary across the field, rendering this instrument unusable for spatial variability studies in all but very uniform soils. Irrigation management using this sensor would be difficult since the accuracy of water contents would depend on placement of the sensor in the field. Nonlinear regressions of water content vs. PR2/6 voltage output resulted in very similar trends and are not shown here.

Similar to the PR2/6, calibration results for the Diviner 2000 showed a trend with increasing depth of decreasing sensitivity of the scaled frequency, SF, to θ (and thus of ε_a to θ; Table 3, Fig. 2A). While the relationship between the SF and ε_a is complex (Kelleners et al., 2004a,b), it is known that SF increases with ε_a. We postulate that increases of σ_a with depth caused increases in ε_a that were not related to water content per se, thus reducing the sensitivity of the SF to water content, similar to the sensitivity reduction with depth shown for the PR2/6. The smaller r^2 values of calibrations for the 90- to 100- and 110- to 160-cm depth ranges are more a reflection of the lack of sensitivity of the SF to water content than to increased scatter in the data. Five calibration equations were needed for the 160-cm-deep profile sensed by the Diviner 2000. The range of RMSE values from 0.018 to 0.044 $m^3\ m^{-3}$ indicates less accuracy than for the NMM. Calibrations for depths >70 cm plotted to the right (>SF for a given water content) of the calibration of Evett et al. (2006), which itself plotted to the right of the factory calibration (Fig. 2A). Like the calibration of Evett et al. (2006) in a clay loam soil in which σ_a increased with water content to 2 dS m^{-1} near saturation, calibrations in the Panoche soil indicated much smaller

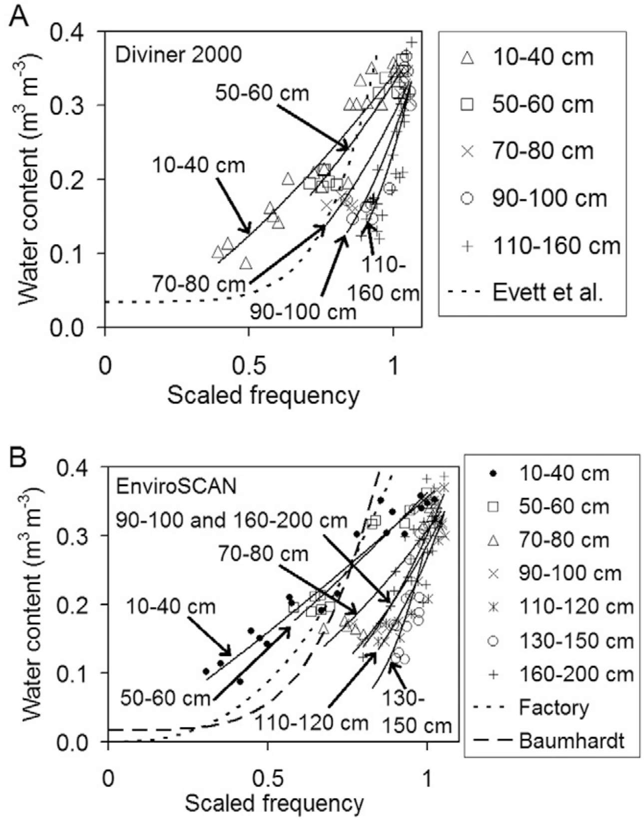

FIG. 2. Directly measured water content vs. sensor output: (A) calibrations for the Diviner 2000 in relation to the scaled frequency compared with the calibration of Evett et al. (2006); (B) calibrations for the EnviroSCAN in relation to scaled frequency compared with both the calibration of Baumhardt et al. (2000) and the factory calibration. The regression for the 160- to 200-cm depth range nearly overlaps that for the combined data from the 90- and 100-cm depths.

sensitivity of the SF to water content changes at the wet end than at the dry end.

EnviroSCAN sensor calibrations were similar to those obtained for the Diviner 2000 (Table 3, Fig. 2B). Sensitivity of the SF to water content decreased uniformly with depth up to 150 cm. The calibration for the 160- to 200-cm depth range was similar to that for the 90- to 100-cm depth range. The range of RMSE values (0.021–0.051 $m^3 m^{-3}$) and r^2 values (0.511–0.931) were similar to those obtained for the Diviner 2000, although RMSE values were slightly smaller for the Diviner, which operates at a greater frequency than does the EnviroSCAN and so should be less sensitive to bulk electrical conductivity. Calibrations were not similar to either the factory calibration or that of Baumhardt et al. (2000), which was similar to that of Evett et al. (2006). Both of the latter calibrations were done in soil columns of similar clay loam soils that exhibited increasing bulk electrical conductivity as they wet due to expanding lattice clays but were not saline. Similar to the results for the Diviner 2000, calibrations for depths >70 cm plotted to the right of the factory calibration and that of Baumhardt et al. (2000).

Scaled frequencies from both the EnviroSCAN and Diviner 2000 exceeded unity at the wet end for all depths and even at intermediate water contents for deeper depths. In theory, SF should be less than unity since SF = 1 for pure water surrounding the access tube. Values of unity or greater indicate that bulk electrical conductivity influenced sensor soil counts, C_s, decreasing them to values smaller than the pure water count, C_w.

Relative Utility of the Calibrations

With its relatively better accuracy (i.e., smaller RMSE values) and only three equations needed for the entire 200-cm-deep profile, the NMM is the sensor most likely to provide accurate profile water contents and change in storage values. Due to the similarity of the calibrations for the cambic horizon (26–114 cm) and the Bk horizon (131–201 cm), lack of knowledge across the field about the depth to the interface between these horizons will not have large effects on the accuracy of profile water contents from the NMM. In contrast, the numerous calibration equations needed for the EM sensors, and the fact that calibration slopes and exponents changed greatly with depth, combine to make the use of these calibrations across the field problematic. If soil properties change spatially (texture or σ_a at any depth) or temporally (e.g., σ_a changes during the irrigation season), the relative inaccuracy of the calibration equations obtained for the EM sensors will be compounded by inaccuracies caused by those changes. For example, in irrigated soils of California, variations of σ_a of as much as 12 dS m^{-1} can occur across distances of <1 m (Burt et al., 2003), and differences equally as large can occur from year to year or even within an irrigation season in one location in a field (Hanson et al., 2003). Corwin and Lesch (2005), citing numerous studies in California, explained how σ_a could vary vertically and horizontally according to irrigation practices, position within a crop bed, texture, bulk density, organic matter content, soil temperature, salt content, and water content. Nielsen et al. (1973) noted considerable spatial variability of several soil properties at the West Side Field Station. While we conjecture that σ_a increased with depth in this study, there is no other reasonable explanation for the results obtained; there are many observations in other studies of increasing σ_a with depth under irrigation in arid and semiarid environments. The bulk density changes with depth that we observed were not sufficient to explain the differences in EM sensor calibrations with depth.

Although not directly related to the calibrations, the relatively shallow depth of measurement possible with the PR2/6 (1 m), Diviner 2000 (1.6 m), and EnviroSCAN (normally limited to 1.6 m unless gaps are allowed between sensors) makes them inappropriate for water use studies of deep-rooted crops. For example, Phene et al. (1991) measured corn (*Zea mays* L.) roots extending to depths >2 m in the Panoche soil at the West Side Field Station under drip irrigation. Also, Musick et al. (1994) reported winter wheat (*Triticum aestivum* L.) water uptake to depths of 2.4 m in a Pullman clay loam and increased the depth of sampling accordingly; Cai et al. (2000) observed winter wheat water uptake to depths of 2.5 m in a deep silt loam soil in the southern Chinese loess plateau. Grimes et al. (1975) observed cotton (*Gossypium hirsutum* L.) rooting to depths of 1.83 m in the Panoche soil at the West Side Field Station, with root length densities of 1.12 and 0.49 m m^{-3} at that depth for cotton and corn, respectively. Sugarbeet (*Beta vulgaris* L. subsp. *vulgaris*) water uptake occurred to 2.25 m on the Panoche soil at the West Side Field Station (Howell et al., 1987) and to as deep as 3.0 m on the Pullman clay loam at Bushland, TX (Winters, 1980).

There were large differences in profile water contents estimated using factory calibrations and those that were directly measured around each access tube (Fig. 3). To compare differences in the soil water storage as estimated using both factory calibrations and the soil-specific calibrations developed in this study, we calculated the water content of the soil in the profile from 0- to 105-cm depth (Table 4). This depth range was chosen to accommodate the PR2/6, which measures only to the 100-cm depth and slightly below. Using factory calibrations, the differences in storage between the wet site and dry site were most accurately estimated by the NMM (Table 4). The three EM sensors all showed depth-dependent bias in estimated water contents using factory calibrations, while the NMM did not (Fig. 3). It should be noted that even though errors in water content estimation were large, it could still happen that in a particular situation the change in storage might (accidentally) be estimated well. But in general this is not likely.

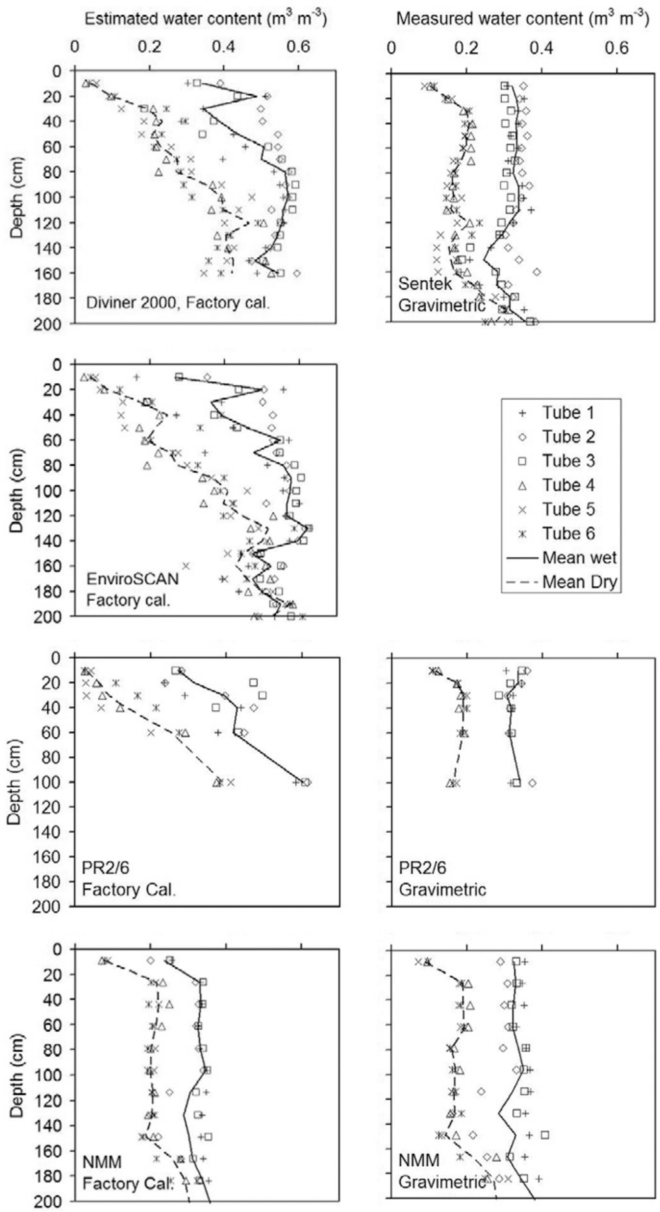

Fig. 3. Profile water contents as estimated using factory calibrations (left column) and as directly measured by soil coring around each access tube (right column). Mean values for the wet site are shown by solid lines and for the dry site by broken lines. The same access tubes were used for both of the Sentek sensors (Diviner 2000 and EnviroSCAN). Separate access tubes were used for the neutron moisture meter and Delta-T PR2/6 sensors, which have different diameters.

Although soil-specific calibrations improved the depth-dependent bias (figure not shown), the improvement in estimates of both the soil water storage and the difference in storage between the wet and dry sites was modest for the EM sensors compared with the improvement for the NMM (Table 4). Using soil-specific calibrations, the absolute error in difference in storage between wet and dry sites was 2 mm for the NMM, 18 mm for the PR2/6, 23 mm for the Diviner 2000, and 28 mm for the EnviroSCAN. The implications for determination of the change in soil water storage for plant water use studies are (i) that using factory calibrations can result in large errors even when calculating differences in water content, and (ii) that soil-specific calibration of EM sensors may not improve the change in storage estimates enough in some soils to be useful for plant water use determination. Finally, we point out that laboratory calibrations (e.g., Paltineanu and Starr, 1997; Baumhardt et al., 2000; Evett et al., 2006) typically have combined soils from layers that appeared to be similar, often considering that the soil profile was represented by only one or two soil types. A laboratory calibration of the soil studied here might easily have focused only on the difference in texture (clay loam above 1-m depth and silty clay below 1 m) and thus would have produced two calibration

Table 4. Mean profile water contents in depth of water from 0- to 105-cm depth for the wet site, dry site, and the difference in storage between the wet and dry sites (ΔS) as directly measured by soil coring (DM) around each access tube for the neutron moisture meter (NMM), the Sentek sensors, and the Delta-T PR2/6 sensor. Also shown are mean profile water contents estimated using the factory and soil-specific calibrations for the NMM, Sentek sensors (EnviroSCAN and Diviner 2000, which used the same access tubes), and the PR2/6. Numbers in parentheses are standard deviations for the three access tubes in the wet site and three in the dry site.

Method	Wet site	Dry site	ΔS	Difference from DM ΔS
	mm			
NMM DM	347 (24.7)	173 (10.8)	174	
NMM factory calibration	333 (10.7)	198 (10.8)	135	−39
NMM soil-specific calibration	349 (14.6)	173 (13.5)	176	2
Sentek DM	348 (20.2)	182 (5.0)	166	
EnviroSCAN factory calibration	494 (44.8)	258 (38.0)	236	70
EnviroSCAN soil-specific calibration	330 (23.6)	191 (4.4)	138	−28
Diviner 2000 factory calibration	494 (50.3)	241 (8.6)	253	87
Diviner 2000 soil-specific calibration	330 (21.8)	187 (7.2)	143	−23
PR2/6 DM	340 (10.2)	180 (2.9)	160	
PR2/6 factory calibration	453 (34.8)	239 (29.0)	214	54
PR2/6 soil-specific calibration	332 (17.3)	190 (11.2)	142	−18

equations for the sensors studied here, a result that would have been completely inadequate to characterize the depth-dependent changes in calibration found here.

Conclusions

Because of spatial changes in soil properties and relatively large calibration inaccuracy, the EM sensor calibrations would have limited utility in the field studied. Compared with the EM sensors, the NMM was more accurate, was insensitive to soil property changes with depth, and required only three calibrations for the entire 200-cm profile, including the requisite calibration for shallow depth measurements. Also, the difference in calibrations for the Bw and Bk horizons was small, making overall accuracy relatively insensitive to the depth of the interface between these horizons. In general, the EM sensors cannot be recommended for profile water content or change in storage determinations due to their relatively less accurate (larger RMSE values) calibrations, strong dependence of calibration slopes and exponents on depth, probable dependence of the calibrations on soil σ_a, and the likelihood of σ_a changes in the field during the irrigation season. Indeed, since σ_a affects calibration so strongly, the simple act of wetting a profile to provide a wet site for calibration may affect the calibration appreciably due to the strong dependence of σ_a on water content. The relatively greater accuracy of the NMM calibrations and its relative lack of sensitivity to spatial changes in soil properties other than water content make the NMM the preferred choice for accurate profile water content and change in storage determinations, particularly in studies of the spatial variability of the soil water balance and crop water use.

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References

Baumhardt, R.L., R.J. Lascano, and S.R. Evett. 2000. Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes. Soil Sci. Soc. Am. J. 64:1940–1946.

Burt, C.M., B. Isbell, and L. Burt. 2003. Long-term salinity buildup on drip/micro irrigated trees in California. p. 46–56. *In* Understanding and Addressing Conservation and Recycled Water Irrigation: Proc. Int. Irrig. Assoc. Tech. Conf., San Diego, CA. November 2003 [CD-ROM]. Irrig. Assoc., Falls Church, VA.

Cai, G., T. Dang, S. Guo, and M. Hao. 2000. Effect of nutrient and soil management on the efficiency of nitrogen and water use in rainfed wheat in China. p. 196–202. *In* Nuclear Techniques in Integrated Plant Nutrient, Water and Soil Management: Proc. Int. Symp. Vienna. 16–20 Oct. 2000. C&S Pap. Ser. 11/P. Int. Atomic Energy Agency, Vienna.

California Department of Water Resources. 1963. Vegetative water use studies 1954–1960. Bull. 113. Calif. Dep. of Water Resources, Sacramento.

Corwin, D.L., and S.M. Lesch. 2005. Characterizing soil spatial variability with apparent soil electrical conductivity: I. Survey protocols. Comput. Electron. Agric. 46:103–133.

Evett, S.R., and P. Cepuder. 2008. Capacitance sensors for use in access tubes. p. 73–90. *In* S.R. Evett et al. (ed.) Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology. Int. Atomic Energy Agency, Vienna.

Evett, S.R., L.K. Heng, and P. Moutonnet (ed.) 2008. Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology. Int. Atomic Energy Agency, Vienna.

Evett, S., N. Ibragimov, B. Kamilov, Y. Esanbekov, M. Sarimsakov, J. Shadmanov, R. Mirhashimov, R. Musaev, T. Radjabov, and B. Muhammadiev. 2007. Neutron moisture meter calibration in six soils of Uzbekistan affected by carbonate content. Vadose Zone J. 6:406–412.

Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59:961–968.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2003. A depth control stand for improved accuracy with the neutron probe. Vadose Zone J. 2:642–649.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2005. Time domain reflectometry laboratory calibration in travel time, bulk electrical conductivity, and effective frequency. Vadose Zone J. 4:1020–1029.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2006. Soil profile water content determination: Sensor accuracy, axial response, calibration, temperature dependence and precision. Vadose Zone J. 5:894–907.

Fritschi, F.B., B.A. Roberts, R.L. Travis, D.W. Rains, and R.B. Hutmacher. 2003. Response of irrigated Acala and Pima cotton to nitrogen fertilization growth, dry matter partitioning, and yield. Agron. J. 95:133–146.

Grimes, D.W., R.J. Miller, and P.L. Wiley. 1975. Cotton and corn root development in two field soils of different strength characteristics. Agron. J. 67:519–523.

Hanson, B., D. May, and W. Bendixen. 2003. Drip irrigation in salt affected soil. p. 57–65. *In* Understanding and Addressing Conservation and Recycled Water Irrigation: Proc. Int. Irrig. Assoc. Tech. Conf., San Diego, CA. November 2003 [CD-ROM]. Irrig. Assoc., Falls Church, VA.

Heathman, G.C. 1993. Soil moisture determination using a resonant frequency capacitance probe. Paper no. 931053. Am. Soc. Agric. Eng., St. Joseph, MI.

Hignett, C., and S.R. Evett. 2002. Neutron thermalization. p. 501–521. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Howell, T.A., L.H. Ziska, R.L. McCormick, L.M. Burtch, and B.B. Fisher. 1987. Response of sugarbeets to irrigation frequency and cutoff on a clay loam soil. Irrig. Sci. 8:1–11.

Kelleners, T.J., D.A. Robinson, P.J. Shouse, J.E. Ayars, and T.H. Skaggs. 2005. Frequency dependence of the complex permittivity and its impact on dielectric sensor calibration in soils. Soil Sci. Soc. Am. J. 69:67–76.

Kelleners, T.J., R.W.G. Soppe, J.E. Ayars, and T.H. Skaggs. 2004a. Calibration of capacitance probe sensors in a saline silty clay soil. Soil Sci. Soc. Am. J. 68:770–778.

Kelleners, T.J., R.W.G. Soppe, D.A. Robinson, M.G. Schaap, J.E. Ayars, and T.H. Skaggs. 2004b. Calibration of capacitance probe sensors using electric circuit theory. Soil Sci. Soc. Am. J. 68:430–439.

Laurent, J.-P., and S.R. Evett. 2008. TRIME FM3 moisture meter and T3 access tube probe. p. 91–100. *In* S.R. Evett et al. (ed.) Field estimation of soil water content: A practical guide to methods, instrumentation, and sensor technology. Int. Atomic Energy Agency, Vienna.

Logsdon, S.D. 2007. Water content reflectometer calibration and field use. *In* Abstracts, ASA–CSSA–SSSA Annu. Int. Meet., New Orleans, LA. 4–8 Nov. 2007 [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Musick, J.T., O.R. Jones, B.A. Stewart, and D.A. Dusek. 1994. Water–yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. 86:980–986.

Nielsen, D.R., J.W. Biggar, and K.T. Erh. 1973. Spatial variability of field measured soil water properties. Hilgardia 42:215–259.

Nielsen, D.R., J.M. Davidson, J.W. Biggar, and R.J. Miller. 1964. Water movement through Panoche clay loam soil. Hilgardia 35:491–498.

NRCS. 2002. Official series description– Panoche series. Established Series, Rev. GWH/LCL/RCH/TDC/KDA, 10/2002. Available at www2.ftw.nrcs.usda.gov/osd/dat/P/PANOCHE.html (verified 18 June 2008). NRCS Soil Survey Div., Washington, DC.

Paltineanu, I.C., and J.L. Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Sci. Soc. Am. J. 61:1576–1585.

Phene, C.J., K.R. Davis, R.B. Hutmacher, B. Bar-Yosef, D.W. Meek, and J. Misaki. 1991. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. Irrig. Sci. 12:135–140.

Rhoades, J.D. 1972. Quality of water for irrigation. Soil Sci. 113:227–284.

Rhoades, J.D., F. Chanduvi, and S. Lesch. 1999. Soil salinity assessment: Methods and interpretation of electrical conductivity measurements. Irrig. Drain. Pap. 57. FAO, Rome.

Rhoades, J.D., D.L. Corwin, and G.J. Hoffman. 1981. Scheduling and controlling irrigation from measurements of soil electrical conductivity. p. 106–115. *In* Proc. ASAE Irrig. Scheduling Conf., Chicago, IL. 14 Dec. 1981. Am. Soc. Agric. Eng., St. Joseph, MI.

Robinson, D.A., S.B. Jones, J.M. Wraith, D. Or, and S.P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone J. 2:444–475.

Schwank, M., and T.R. Green. 2007. Simulated effects of soil temperature and salinity on capacitance sensor measurements. Sensors 7:548–577.

Schwank, M., T.R. Green, C. Mätzler, H. Benedickter, and H. Flühler. 2006. Laboratory characterization of a commercial capacitance sensor for estimating permittivity and inferring soil water content. Vadose Zone J. 5:1048–1064.

Winters, S.R. 1980. Suitability of sugarbeets for limited irrigation in a semi-arid climate. Agron. J. 72:118–123.

Wraith, J.M., and D. Or. 1999. Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development. Water Resour. Res. 35:361–369.