Estimating Soil Water Content Using Site-Specific Calibration of Capacitance Measurements from Sentek Enviroscan Systems

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ABSTRACT. *Newly developed sensors, including the EnviroSCAN capacitance system have the potential to monitor and estimate soil moisture content continuously at various depths. A simple site calibration of the sensors is required to obtain accurate soil water content because these sensors are shipped with a default (uncalibrated) equation to the user. Therefore, our research objectives were: 1) to calibrate the EnviroSCAN capacitance system versus soil moisture values estimated by a neutron probe calibrated with gravimetrically measured water contents, then 2) statistically compare the calibrated soil water content results with those estimated by the uncalibrated equation using three years of field data. Both the EnviroSCAN capacitance and the neutron probe were installed in a Warden silt loam soil planted to alfalfa. The average water contents of the soil profile estimated by the EnviroSCAN capacitance was used to develop a site specific calibration equation by comparing the sensors' scaled frequencies for 1998 with the soil water content of the neutron probe. The site calibration equation was then statistically validated using both 1999 and 2000 soil water contents. The statistical analyses indicated that discrepancies existed between soil water contents of the site calibration equation and those estimated by the uncalibrated equation. For instance, the RRMSE values of soil water content produced from the calibrated equation were 7%, 41%, and 40%, compared with uncalibrated RRMSE values of 68%, 59%, and 66%, for 1998, 1999, and 2000, respectively. These results support that the site calibration equation was found to give more accurate estimates of individual values (low RRMSE) of volumetric soil water content compared to those obtained from the uncalibrated equation.*

Keywords. Soil, sensor, Water content, Capacitance, Irrigation, Calibration.

Soil-based irrigation scheduling techniques involve measuring water content directly or indirectly measuring other soil properties related to water content. Soil water content is considered one of the most important and critical properties of the soil for crop production, irrigation scheduling, and environmental management. By measuring water content in the soil, farm managers can better determine when to irrigate and how much water to apply to their field. Many soil water-monitoring devices are currently available to assist farm managers in the scheduling of irrigation. These include: tensiometers, gypsum blocks, neutron probes, and capacitance based sensors. Soil water measurements are usually taken by placing these instruments at various soil depths in the rootzone.

Over the past decade, the sensor industry and computer technology have enormously advanced; motivating a profound increase in the number of soil moisture sensors used to estimate water content. Most of these newly developed sensors continuously measure either the frequency of a capacitance circuit coupled with the soil-water-air medium, or measure the travel time of an electric pulse as influenced by this medium, and then estimate its soil water content using empirical relationships.

Currently, newly developed sensors, including the EnviroSCAN capacitance system were made available to the general research community to measure soil water content as well as to design irrigation scheduling systems. EnviroSCAN sensors have been considered a commonly used and accurate irrigation management tool in Australia and other parts of the world (Sentek, 1995; www.sentek.com.au). These devices involve a permanent installation setup. Sensors are housed in vertical PVC (polyvinyl chloride) access tubes, which are connected via cable to data loggers. Readings are taken using data loggers equipped with computer software at various time and soil depth intervals. The EnviroSCAN system measures a frequency change, which is related to the bulk permittivity of the soil. The system generates continuous trends and information about irrigation management in the rootzone and amount of water consumed by the crop. This technology allows farm managers to make decisions as to when to irrigate and how much water to apply, resulting in economic and environmental benefits.

The EnviroSCAN capacitance system requires soil-specific calibrations to produce accurate estimates of soil water content due to large variability in soils. Several calibration procedures have been conducted under laboratory (Mead et al., 1995; Paltineanu and Starr, 1997) and field (Morgan et al., 1999) conditions. The results from both environments

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support that the accuracy of the capacitance sensors improved when the system was calibrated for specific soil types. Further, the aforementioned research findings suggest that the manufacturer's default equation overestimates soil moisture content in coarse textured soils. Thus, if the uncalibrated equations are used to determine the amount and time of irrigation for crops, there is a strong likelihood that the overestimation can seriously impact crop yields

The EnviroSCAN factory default equation can still be considered an adequate and practical tool for farmers to identify irrigation events based on trend monitoring. In most cases, the EnviroSCAN devices are precise and provide accurate measurements. However, they do not automatically produce an accurate estimate of individual soil water content measurements for all soils.

Thus, the objectives of this study were: 1) to site specific calibrate the EnviroSCAN soil capacitance measurements using *in situ* water content values estimated with a neutron probe, and 2) to statistically compare the water contents estimated by calibrated equation with those estimated by the manufacturer's default (uncalibrated) equation using three years of field data.

MATERIALS AND METHODS

FIELD TECHNIQUE AND SITE PREPARATION

A study employing EnviroSCAN technology on alfalfa plots was conducted during the 1998, 1999, and 2000 growing seasons at the Washington State University (WSU) Research Station in Prosser, Washington (Leib et al., 2003). The soil is classified as a Warden silt loam (Coarse-silty, mixed, mesic, Xerollic Camborthids); a deep, well drained soil and developed from lacustrine sediments with a mantle of loess parent material. The particle size distribution of the soil is 44% sand, 53% silt, and 3% clay; and average soil bulk density ranges between 1.45 and 1.6 g cm^{-3}. The average annual rainfall at the WSU research station in Prosser is less than 200 mm, average summer temperatures are near 82°F, and average winter temperatures are close to 41°F.

The EnviroSCAN readings were recorded to a depth of 100 cm at 10-cm intervals. The sensor installation process and operational procedures were done according to the manufacturer's recommendations and instructions (Sentek, 1995; www.sentek.com.au). The EnviroSCAN sensors were monitored continually and readings were downloaded to a computer on a weekly or biweekly basis from May to October each growing season. The distance between the EnviroSCAN access tube and the neutron probe access tube in the plot was approximately 2 m.

Micro-sprinklers were used to irrigate the alfalfa plots. The sprinkler system was designed for high uniformity by spacing the sprinklers at 40% of wetted diameter (Leib and Matthews, 1999). Further details regarding the installation process, data collection and manipulation are given in Leib et al. (2003).

NEUTRON PROBE DESCRIPTION

This device consists of a source of fast neutrons and a detector housed in a probe that is lowered into access tube installed permanently in the soil. Fast neutrons emitted from the source collide with hydrogen molecules in the soil water

and are slowed by the collision. The detector counts the slow neutrons that return to the probe. The count of slow neutrons is related linearly to the volumetric moisture content (Gardner, 1986). A PVC access tube (381 mm in diameter with an 862-kPa rating) was installed by augering a hole of the same diameter and inserting the access tube.

FIELD CALIBRATION OF THE NEUTRON PROBE

Field calibration of a neutron probe was done at the research site using a gravimetric soil sampling method. Disturbed soil samples were collected from the auger holes (381-mm diameter) prior to access tube installation at 15-cm intervals to a depth of 1.2 m. This technique seemed to be more accurate, representative, less destructive, and less laborious compared with the method of soil sampling adjacent to the access tube (Leib and Matthews, 1999). Immediately after soil samples were removed, the access tubes were installed, and neutron probe readings were taken at the same depth as soil samples. The soil samples were used to determine water content on a mass basis using the gravimetric method (Gardner, 1986). Water contents by mass were then converted to volumetric values using soil bulk densities at various depths. Finally, the volumetric water contents were used to calibrate the neutron probe readings (Leib et al., 2003).

ENVIROSCAN SYSTEM DESCRIPTION AND OPERATIONAL METHOD

The EnviroSCAN system consists of multiple sensors, which can be installed at various depths to continuously monitor water content in the soil profile. These sensors, which are installed within a vertical PVC access tube, are mounted one above another along the probe length and can be adjusted in 10-cm intervals. Probes are networked via buried cables to a central data logging facility enabling continuous monitoring of soil water content. Data is stored in a logger and downloaded onto a computer for display using Sentek's software. The EnviroSCAN system measures the dielectric constant of the soil and consequently, its water content. The dielectric constant of water is approximately 80, that of air is 1, and that of dry soil is in the range of 4 to 6. Thus, the sensor measures the frequency of a capacitance circuit of the surrounding soil-air-water mixture, and the device converts this reading into a percentage of volumetric water content in the soil.

The EnviroSCAN software interpolates the frequency readings from the data logger and displays the dynamics of soil water content through time. The following equation described by Buss (1993) was used to convert field frequencies into scaled frequencies, SF:

$$\text{Scaled Frequency (SF)} = \frac{\text{air frequency} - \text{field frequency}}{\text{air frequency} - \text{water frequency}} \quad (1)$$

The default manufacturer's equation that converts scaled frequency to volumetric water content is:

$$SF = A\theta_v^B + C \quad (2)$$

where A is 0.1957, B is 0.404, and C is 0.028520, and θ_v is the soil water content by volume.

Equation 2 can also be written in terms of volumetric water content as:

$$\theta_v = \left[\frac{SF - C}{A}\right]^{1/B} \tag{3}$$

STATISTICAL METHODS

Several statistical parameters were used to compare the uncalibrated and calibrated EnviroSCAN estimated results with neutron probe estimated water contents. The mean difference, Md (eq. 4), suggested by Addiscott and Whitmore (1987) and the relative root mean square error, RRMSE (eq. 5), proposed by Loague and Green (1991) were used to assess the degree of coincidence between uncalibrated, calibrated and neutron probe water content estimated values.

The Md measures the average difference between uncalibrated and calibrated EnviroSCAN estimated water content and neutron probe measured values. A Md value equal to zero denotes no difference between EnviroSCAN uncalibrated, calibrated results, and neutron probe measured values. The sign indicates whether the sensor tends to overestimate (+) or underestimate ($-$) the measured neutron probe values. A t-test was used to determine whether Md was significantly different from zero.

The relative root mean square error, RRMSE, provides a percentage for the total difference between uncalibrated and calibrated water contents and the neutron probe measured values based on neutron probe measured mean basis. The RRMSE may be considered as an index of the total error. It is similar to the coefficient of variation and can be used directly to compare relative accuracy in the measurements. A smaller RRMSE indicates better performance. The Md and RRMSE statistical parameters were defined as:

$$Md = \frac{\sum_{i=1}^{n}(E_i - M_i)}{n} \tag{4}$$

$$RRMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)^2\right]^{0.5} \times \left(\frac{100}{\overline{M}}\right) \tag{5}$$

where E is the value of soil moisture content estimated by the EnviroSCAN (uncalibrated or calibrated), M is the corresponding measured neutron probe value, n is the number of measurements, and $\overline{M}$ is the mean of the neutron probe measurements.

Further, linear equations were generated from the regression analysis of sensor uncalibrated and calibrated values on neutron probe measured values (SAS Institute, 2002). The coefficient of determination (r^2), test of the null hypothesis of an intercept of zero, and slope equal to one were used as a measure of 1:1 relationship, and a degree of association between uncalibrated and calibrated EnviroSCAN soil water contents and neutron probe measured values.

RESULTS AND DISCUSSION

NEUTRON PROBE CALIBRATION

The neutron probe was calibrated *in situ* using data at various depths in the soil profile (Leib et al., 2003). A highly

and significantly correlated relationship with $r^2 = 0.98$ was found between the measured gravimetric soil water content and neutron probe count ratio (fig. 1; eq. 6):

$$\theta_v = -0.0758 + 0.348\,C_R \tag{6}$$

where C_R is the neutron probe count ratio and θ_v is the volumetric water content by a gravimetric method (Gardner, 1986). This equation with a high degree of linear association demonstrated that a calibrated neutron probe could be used as the standard to calibrate the EnviroSCAN sensor and/or other sensors. The regression data also contained a large range of soil water content values (10% to 35%), which means that most neutron probe measurements will be an interpolation and not extrapolation of the calibration.

ENVIROSCAN SYSTEM CALIBRATION

The EnviroSCAN capacitance sensors were calibrated to the site using the 1998 data. The calibration equation (eq. 7) was developed by comparing the sensors' readings of 1998 (Scaled Frequencies, SF) with the soil water contents of calibrated neutron probe.

$$\theta_v = 0.0034\,e^{26.592SF} \tag{7}$$

The exponential calibration equation developed from 1998 data was applied to the 1999 and 2000 sensors' readings. The calibration equation and curves for 1998, 1999, and 2000 as compared with uncalibrated (manufacturer's default equation) results are shown in figures 2, 3, and 4, respectively. Although calibration curves showed similar trends to the default equation curves, large discrepancies existed between the two non-linear curves, as reflected by the Md values that were considerably large and significantly different from zero. The mean differences between uncalibrated and calibrated results for 1998, 1999, and 2000 were 0.1114, 0.1174, and 0.1187 m^3/m^3, respectively. The uncalibrated equation appeared to consistently overestimate soil water content by a magnitude of nearly 0.1 m^{3}m^{-3} and larger for all three years.

TRENDS COMPARISON

Soil moisture contents at various depths were used to calculate the mean soil water content for the soil profile (0 to
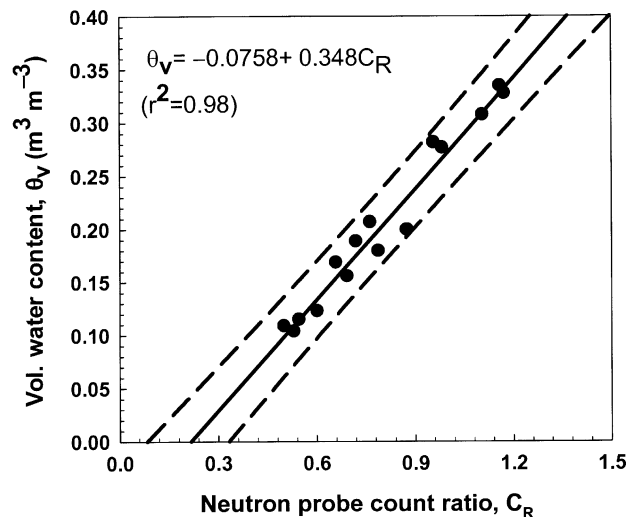

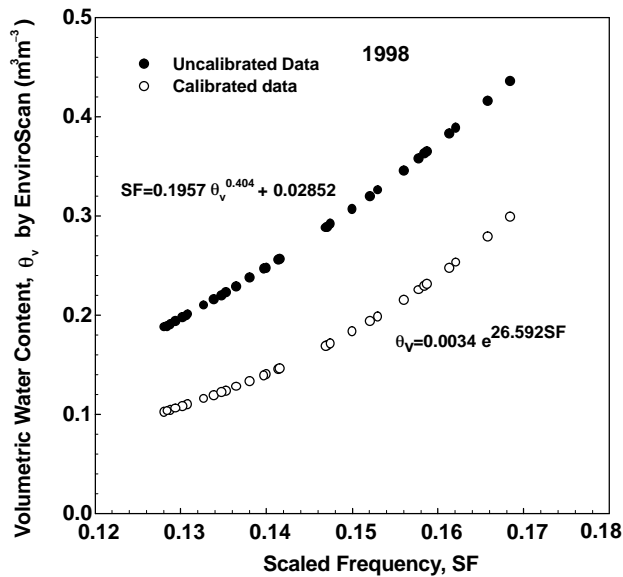**Figure 1. Calibration of neutron probe.**

Figure 2. Relationship between the scaled frequency and water content for 1998 calibrated and uncalibrated data.
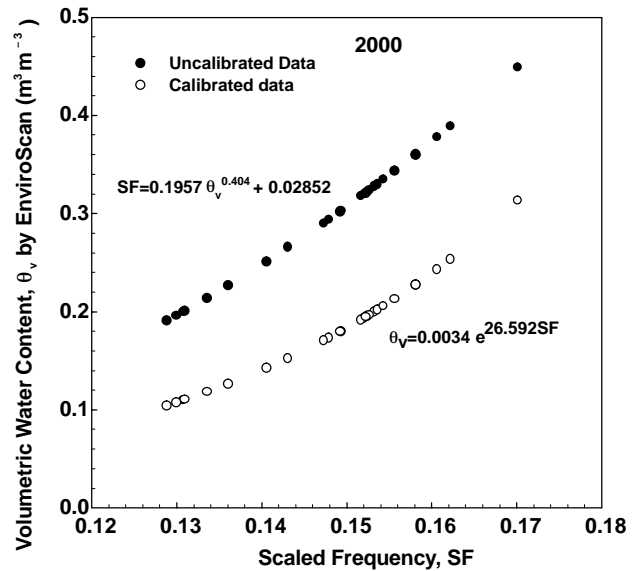

Figure 4. Relationship between the scaled frequency and water content for 2000 calibrated and uncalibrated data.

90 cm). Variations of the mean in soil profile water contents for 1998, 1999, and 2000 from both uncalibrated and calibrated equations of the EnviroSCAN system and neutron probe measurements following irrigation events were compared and displayed in figures 5, 6, and 7, respectively.

Overall, the trends in soil moisture content results appear to be similar and virtually the same in all three years. The calibrated equation consistently produced lower values than soil water content estimated by the default equation (figs. 5, 6, and 7). These variations indicated that there was a sharp, rapid increase in soil water content values after each irrigation event, followed by a gradual decrease after several weeks. This decrease was due to depletion of water by alfalfa roots and evapotranspiration, which caused the soil to dry. Calculations of soil water content resulting from the calibrated equations were very close to those measured by the neutron probe compared to results estimated by the uncalibrated equation for all three years.
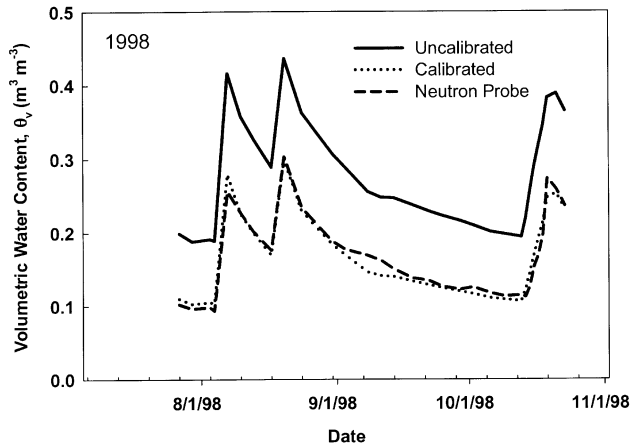

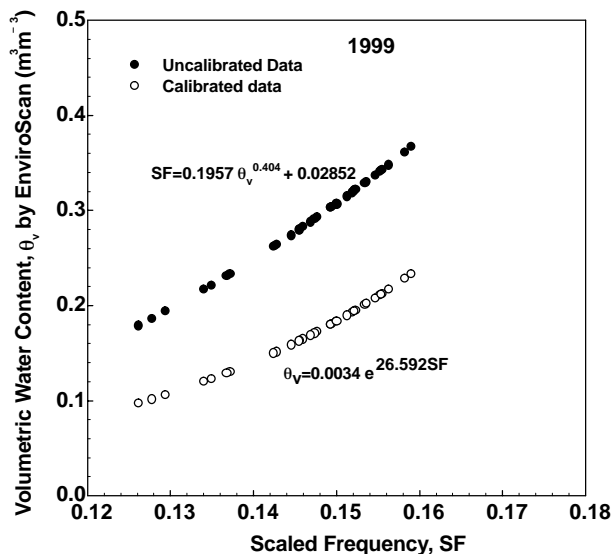**Figure 5. Distribution of soil water content with time throughout 1998 growing season.**

Figure 3. Relationship between the scaled frequency and water content for 1999 calibrated and uncalibrated data.
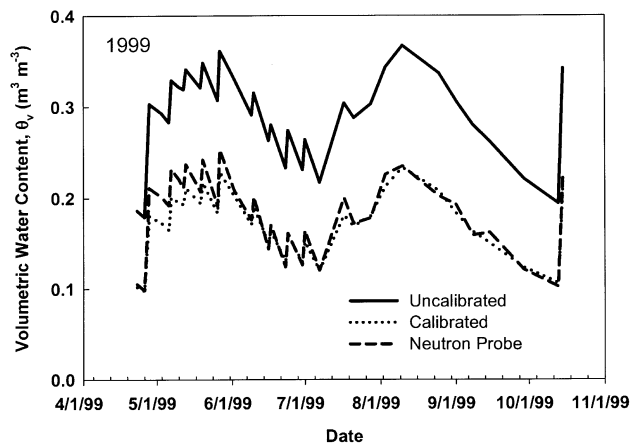

Figure 6. Distribution of soil water content with time throughout 1999 growing season.
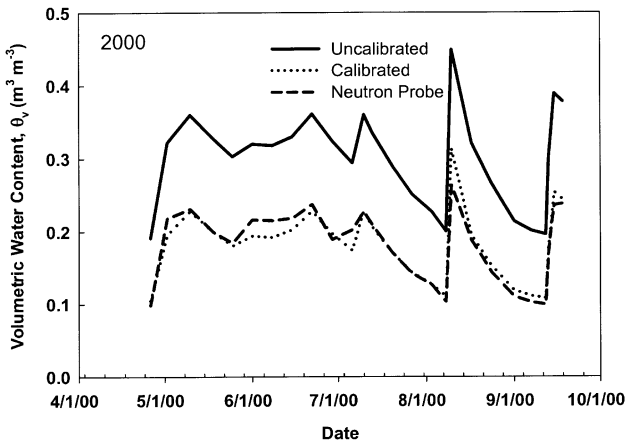
Figure 7. Distribution of soil water content with time throughout 2000 growing season.

STATISTICAL ACCURACY ASSESSMENT AND COMPARISON

The average soil water contents obtained from both the uncalibrated and calibrated equations were compared with those of neutron probe measured values. Results were plotted on 1:1 line and displayed in figures 8, 9, and 10 for 1998, 1999, and 2000, respectively, to compare and assess the EnviroSCAN capacitance equation's accuracy.

In the 1998 calibration year, soil water content estimated by both uncalibrated and calibrated equations were compared with those of neutron probe (table 1). The positive Md value for the uncalibrated equation results suggest that EnviroSCAN considerably overestimated the neutron probe values (fig. 8) when compared with the results estimated by the calibrated equation (eq. 7). The Md value for uncalibrated water contents was large, positive, and significantly different from zero (Md = 0.111 m^3/m^3; t = 27.7; p < 0.0001). However, the Md for calibrated equation results (Md = -0.00081 m^3/m^3; t = -0.36; p = 0.7196) were very small and not significantly different from zero (table 1).

Figure 9. Comparison of calibrated and uncalibrated water contents of EnviroSCAN with those of neutron probe in 1999.

Further, the RRMSE values of soil water content produced from a calibration equation (eq. 7) was very small (7%) compared to the RRMSE of the uncalibrated equation results (68%) (table 1), which reflects a large scatter in the data. These results indicated that the calibration equation reduced RRMSE value of soil water content by approximately ten-fold. The RRMSE suggested that the individual values of soil water content resulting from the calibration equation in 1998 were much more accurate than those estimated using the uncalibrated equation. Thus, the Md and RRMSE results support the calibration equation (eq. 7) as it provided an accurate estimate of individual volumetric soil water contents.
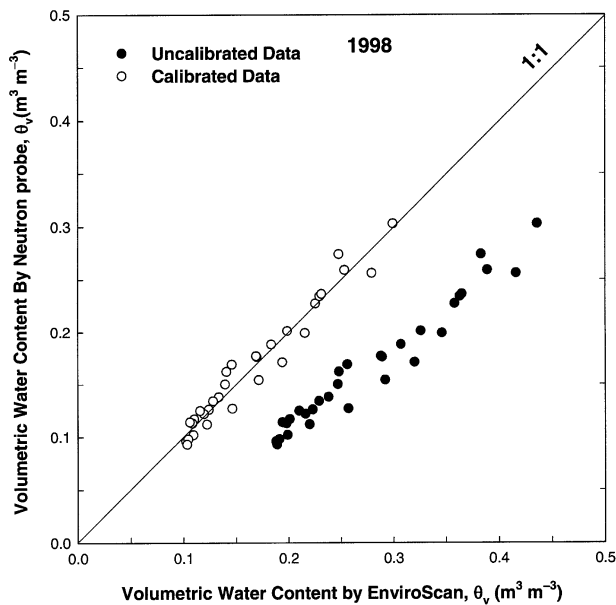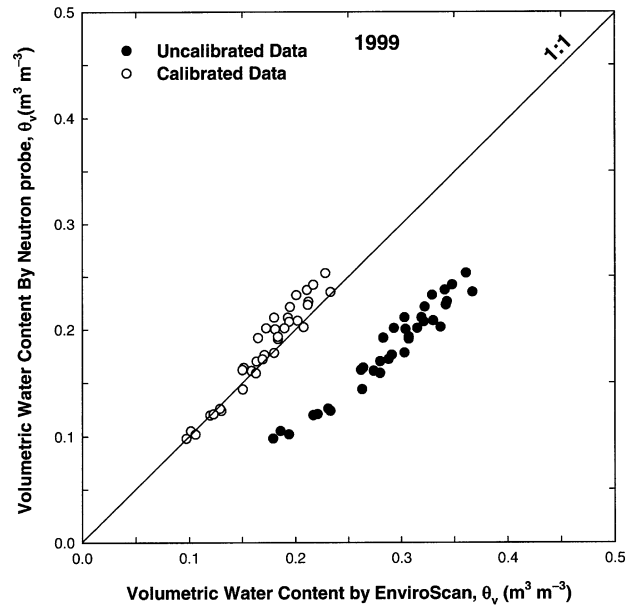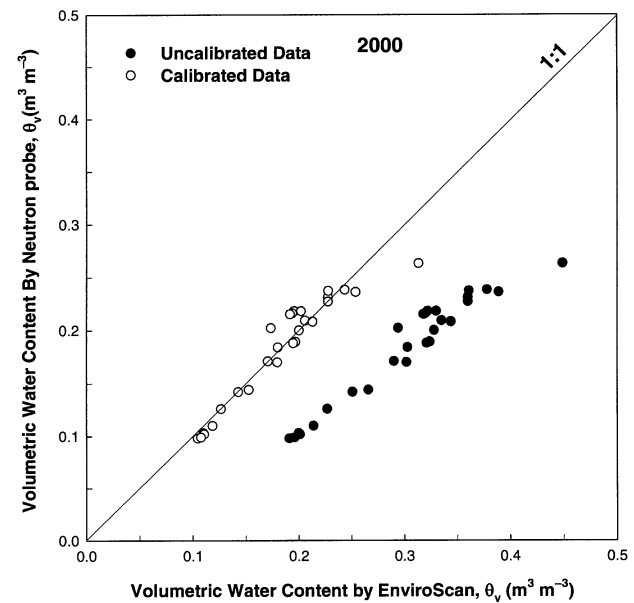

Figure 8. Comparison of calibrated and uncalibrated water contents of EnviroSCAN with those of neutron probe in 1998.

Figure 10. Comparison of calibrated and uncalibrated water contents of EnviroSCAN with those of neutron probe in 2000.

Table 1. Statistical summary.

Year	Equation	n[a]	Md	Std Err	t value	Pr > |t|
1998	Default	31	0.111[b]	0.0040	27.72	<0.0001
	Calibrated	31	-0.0008	0.0022	-0.36	0.7196
1999	Default	35	0.1070[b]	0.0022	49.44	<0.0001
	Calibrated	35	-0.0098[b]	0.0020	-4.92	<0.0001
2000	Default	27	0.1196[b]	0.0041	29.40	<0.0001
	Calibrated	27	0.0009	0.0031	0.30	<0.7656

[a] Denotes the number of observations.
[b] Significantly different from zero at 5% probability level.

Soil water content values of the neutron probe were regressed against both the EnviroSCAN calibrated and uncalibrated results (SAS Institute, 2002). Regression analyses indicated that the intercept and slope of calibrated results were not significantly different from zero and one respectively, compared with the regression parameters of uncalibrated results (table 2). These statistical results suggest that calibrated sensors better predicted the measured neutron probe values and were more accurate than uncalibrated sensors or equations in measuring the actual individual values of water content in the soil.

In both validation years (1999 and 2000), the positive Md values with the uncalibrated equation suggested that the EnviroSCAN sensors significantly overestimated the neutron probe measured values (figs. 8 and 9; table 1), compared with the results estimated by the calibration equation (eq. 7). In both years, the calibrated equation generally produced more accurate values of soil water contents than those estimated by the uncalibrated equation (tables 1 and 2).

In 1999, the Md values for both calibrated and uncalibrated equation results were significantly different from zero; however, the Md value for calibrated soil water contents was much smaller than that of uncalibrated results (table 1). The calibrated equation also reduced the RRMSE of uncalibrated soil water content from 59% to 41% reflecting a small scatter in the data and better accuracy. Further, the calibrated equation slightly underestimated (Md = -0.0098) the neutron probe measured water contents. However, variations were small and the vast majority of the data were closely scattered around the 1:1 line (fig. 9) regardless of the regression parameters of calibrated results, which were not significantly different from zero and one, respectively (table 2).

Based on these statistical results, the calibrated equation reduced discrepancies considerably in uncalibrated results.

Table 2. Statistical Summary.

Year	Equation	n[a]	RRMSE	Intercept	Slope	r^2
1998	Default	31	68	0.068[b]	1.26[c]	0.95
	Calibrated	31	7	0.005	0.97	0.96
1999	Default	35	59	0.086[b]	1.12[c]	0.94
	Calibrated	35	41	0.025[b]	0.81[c]	0.95
2000	Default	27	66	0.069[b]	1.28[c]	0.94
	Calibrated	27	40	0.007	0.97	0.91

[a] Denotes the number of observations.
[b] Significantly different from 0 at 5% probability level.
[c] Significantly different from 1 at 5% probability level.

Further, the results suggested that the actual values of soil water content from the calibrated sensors in 1999 were more accurate than uncalibrated sensors.

In the 2000 validation year, the scenario was slightly different from the 1999 data, but more similar to the calibration year (1998). Site calibrated water content in 2000 resulted in a very small Md that was not significantly different from zero (Md = 0.00089; t = 0.30; p < 0.7656) compared to the statistical results of soil water content estimated by the default equation (table l). The calibration equation also improved the accuracy of sensors as indicated by a smaller RRMSE value, which was reduced from 66% for uncalibrated results to 40% (table 2). The regression parameters indicated that calibrated soil water contents were highly coincided with those of neutron probe values as compared to uncalibrated results that were scattered far away from 1:1 line. The intercept and slope of the regression line of calibrated results were not significantly different from zero and one, respectively (table 2; fig. 10). The calibration equation (eq. 7) was able to estimate soil water content in 2000 as accurate as in the calibration year (1998) as indicated by statistical results reported in tables 1 and 2.

Based on the statistical analysis used in this study, the developed site calibration equation was able to accurately estimate soil water contents for all three years, compared to those estimated by the uncalibrated equation. Therefore, a site calibration is needed if users require the most accurate individual measurements on their specific site or soil. Additionally, the EnviroSCAN sensors have the ability for users to modify the uncalibrated equation and enter their own site/soil calibration equations. However, if the user requires a trend analysis in soil moisture content for irrigation scheduling, most of these sensors are successfully able to produce accurate trend variations in soil water content over a period of time following irrigation events.

SUMMARY AND CONCLUSIONS

Average water content values of the soil profile estimated by the EnviroSCAN capacitance system were used to develop a site-specific calibration equation (eq. 7). A calibration equation was developed using the 1998 soil water content and sensors' scaled frequencies. The calibration equation was then statistically validated using both 1999 and 2000 soil water contents. The statistical analysis also supports considerable discrepancies between soil water contents estimated by the site-calibration and uncalibrated equations. The developed site calibration equation accurately estimated volumetric soil water content values for all three years, compared to those estimated by the manufacturer's uncalibrated equation.

Therefore, site-specific calibration is essential for the most precise soil moisture content measurements as well as to improve the sensor's accuracy and performance.

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