Calibration of a frequency-domain reflectometer for determining soil-water content in a clay loam soil

G Lukanu and MJ Savage*

Soil-Plant-Atmosphere Continuum Research Unit, School of Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa

Abstract

A soil-water frequency domain reflectometry sensor, the ThetaProbe, was evaluated for its ability to measure the apparent soil dielectric constant and subsequent estimation of soil-water content. The soil-water content of a clay-loam soil, determined using factory-supplied parameters for the sensor and soil-estimated parameters, was compared to the soil-water content determined in the laboratory. The range in soil-water content was from 0.20 to 0.42 $m^3 \cdot m^{-3}$. A total of 78 soil samples from the 0 to 600 mm depth of a clay loam soil were used for these comparisons. There was a good correlation between sensor soil-water content determined using the factory-supplied parameters and the gravimetric soil-water content. Use of both the factory-supplied and the soil-estimated parameters resulted in more than 20% overestimation of soil-water content compared to the gravimetric soil-water content. However, using a recalibration process, the adjusted soil-water content was within 0.02 $m^3 \cdot m^{-3}$ for both the factory-supplied and the soil-estimated calibration constants. Soil bulk density, clay content and temperature had negligible influence on sensor soil-water contents.

Keywords: soil-water content, ThetaProbe, frequency domain reflectometer

Introduction

Knowledge of soil-water content is important for water management and hydrological studies and for calibration and validation of soil-water balance models. Monitoring soil-water content for irrigation scheduling, based on a measurement and control system, requires fast, precise, non-destructive and *in situ* measurement techniques (Lukangu et al., 1999; Gebregiorgis and Savage, 2006a, b). The laboratory methods for determining soil-water content gravimetrically and pressure plate soil-water potential fail to satisfy this requirement, although they are still used for calibration purposes. The neutron probe field method has the advantage of allowing measurements of soil-water content for a greater soil volume but radioactive hazard, lack of automated data collection methodology, and high cost restrict its use.

Dielectric-based soil-water content techniques are influenced by factors that affect the dielectric constant of the soil other than water. The time domain reflectometry (TDR) method involves measuring the propagation of an electromagnetic pulse along the transmission lines (wave guides). By measuring the travel time, the velocity and hence the apparent dielectric constant of the soil can be estimated. Usually, the TDR method is not soil-specific (Drnevich et al., 2005), and therefore no soil calibration is required. The frequency-domain reflectometer (FDR) method used in the present study makes use of radio frequencies and the electrical capacitance of a capacitor (formed by using the soil and embedded rods as a dielectric) for determining the dielectric constant and thus the soil water content. The signal reflected by soil combines with the generated signal to form a standing wave with amplitude that is a measure of the soil-water content. In the case of capacitance-type sensors, such as that used by Grooves and Rose (2004), the charge time of a capacitor is used to determine the soil-water content. Profile-probe versions using FDR and capacitance methods are now commercially available (Whalley et al., 2004; Czarnomski et al., 2005; Mwale et al., 2005).

The effect of clay, soil organic matter content and soil bulk density on TDR measurements has been reported by Topp et al. (1980), Roth et al. (1990), and Jacobson and Schjonning (1993a, b). A temperature effect has been reported by Topp et al. (1980) while an iron influence on the dielectric constant has been discussed by Robinson et al. (1994). Evett et al. (2005) found that TDR measurements may be affected by soil salinity, soil temperature, clay type and clay content. The TDR technique may overestimate soil-water content in saline soils because the apparent dielectric constant also depends on the electrical conductivity of the soil (Wyseure et al., 1997). For example, Wyseure et al. (1997) used a dielectric-based technique to estimate the electrical conductivity. Miyamoto and Maruyama (2004) found that by coating the TDR rods, more accurate measurements in a heavily fertilised paddy field was possible. Roots, earthworm channels, cracks and stones can also cause small variations in soil-water content estimated using the dielectric-based technique (Jacobson and Schjonning 1993b). Furthermore, old root channels would affect dielectric measurements if these were within the measurement volume of the sensor.

The objective of this work was firstly to calibrate the FDR sensors, for example, the ThetaProbe, for the site and compare the calibration parameters with those supplied by the manufacturer. A second objective was to evaluate the effect of soil bulk density, clay content and temperature on soil-water content measured with these sensors.

* To whom all correspondence should be addressed.
☎ +2733 260 5510; fax: +2733 260 5514;
e-mail: savage@ukzn.ac.za
Received 21 January 2005; accepted in revised form 1 November 2005.

Materials and methods

The ML1 ThetaProbe (Delta-T Devices, Cambridge, England), as well as so-called TDR and other FDR techniques can provide a continual, precise, non-destructive and *in situ* measurement of soil-water content under field conditions.

Theoretical considerations

The ThetaProbe (type ML1) is essentially an FDR sensor that detects the ratio between the oscillator voltage (for 100 MHz signal) and that reflected by rods installed in soil. The ratio of the two voltages is dependent essentially on the apparent dielectric constant of the soil (ε) which is determined by the soil-water content. A 5[th] order polynomial of the sensor analogue output voltage V (in volts), is used to estimate the square root of the dielectric constant of the soil ($\sqrt{\varepsilon}$) as (Delta-T Devices, 1999):

$$\sqrt{\varepsilon} = 1 + 6.19V - 9.72V^2 + 24.35V^3 - 30.84V^4 + 14.73V^5 \quad (1)$$

The volumetric soil-water content θ_v ($m^3 \cdot m^{-3}$) is calculated from the dielectric constant by using the soil calibration constants a_o and a_1:

$$\theta_v = (\sqrt{\varepsilon} - a_o)/a_1 \quad (2)$$

where:

a_o is the square root of the dielectric constant of dry soil ($\sqrt{\varepsilon_0}$) where ε_0 is the dielectric constant for dry soil) calculated using the corresponding measured voltage output and Eq. (1)

a_1 is the difference between the square root of the dielectric constant of saturated ($\sqrt{\varepsilon_w}$) and that for dry soil divided by soil-water content at saturation (θ_{vs}):

$$a_1 = (\sqrt{\varepsilon_w} - \sqrt{\varepsilon_0} -)/\theta_{vs}. \quad (3)$$

The square root of the dielectric constant of the soil at saturation is also calculated using Eq. (1) for the corresponding measured voltage output. Factory values for a_o and a_1 of 1.6 and 8.4 for mineral soils and 1.3 and 7.8 for organic soils are used, respectively. These values were derived from measurements in many different soil types.

The calibration process is a tool to minimise the error that an inaccurate sensor would cause in the observed data. Statistical equations by Snedecor and Cochran (1980) provide a method for estimating an independent variable X (laboratory soil-water content) from dependent variable Y (sensor soil-water content), referred to as a prediction of X from Y, from a Y *vs.* X relationship having a slope b and intercept I:

$$X = [(Y - I)/b]/(1 - c^2) \quad (4)$$

where:

$$c^2 = (1/\sum x^2)(t\, S_{y.x}/b)^2$$

is a factor that accounts for the error in estimating X using the dependent variable Y, slope b and intercept I (where $x = X - \overline{X}$), t is the Student t statistic $S_{y.x}$ is the standard error of Y on X). For perfect agreement between the laboratory (X) and sensor soil-water contents (Y), $c^2 = 0$ and hence $X = (Y - I)/b$.

Experimental procedure

Five ThetaProbe sensors were calibrated in the laboratory using clay loam soil from Vita Farm, Tala Valley, KwaZulu-Natal, South Africa (latitude ≈ 29°50'S, longitude ≈ 30°30'E and altitude ≈ 900 m). The sensor is 125 mm long and 40 mm in diameter with a cylinder housing the electronics, with four sensing rods 60 mm in length, with three of the rods distributed uniformly around a circumference of 26.5 mm and one rod at the centre.

Soil bulk density was determined using a core method (Blake and Hartge, 1986). Undisturbed soil cores, with a diameter of 100 mm and a thickness of 80 mm were taken from each of four 150-mm layers at the field site (Table 1). The soil samples were covered, transported to the laboratory, and soil-water content measured using a sensor inserted into the soil sample. The sensor was then removed and the samples were weighed. The samples were then oven-dried for 24 h at 105°C and the gravimetric soil-water content calculated. The volumetric soil-water content (θ_v) of the core was calculated from the gravimetric soil-water content and soil bulk density. This procedure was repeated for all 78 soil samples. Particle size distribution was determined using the pipette method reported by Gee and Bauder (1986).

Sensors were connected to a CR7X data-logger (Campbell Scientific Inc., Logan, Utah) and sensed using a differential voltage instruction. Volumetric soil-water content was estimated from the measured voltages using Eq. (2). The a_o and a_1 values therefore allowed the real-time estimation of soil-water content (using the data-logger 5[th] order polynomial instruction). The soil sensors were calibrated using undisturbed soil cores removed from the site. In the laboratory, the soil cores were saturated and the sensor voltage and the corresponding gravimetric soil-water

TABLE 1
Physical characteristics of four strata of the soil studied (Lukangu et al., 1999)

Depth mm	Bulk density kg m^{-3}	Soil-water content ($m^3 \cdot m^{-3}$) for various depths and matric potentials			Particle size distribution			Gravel %	Organic matter %
		Saturation 0 kPa	Field capacity -10 kPa	Refill point -100 kPa	Clay %	Silt %	Sand %		
0-150	1508	0.402	0.292	0.233	36	23	41	2.1	3.3
150-300	1595	0.412	0.289	0.230	35	24	41	3.4	3.3
300-450	1604	0.394	0.294	0.241	33	27	40	15.3	2.9
450-600	1476	0.414	0.291	0.253	46	15	39	8.7	2.8
Mean	1546	0.406	0.292	0.239	38	22	40	7.4	3.1

Available on website **http://www.wrc.org.za**
ISSN 0378-4738 = Water SA Vol. 32 No. 1 January 2006
ISSN 1816-7950 = Water SA (on-line)

content determined between saturation and air-dry conditions. Measurements were taken every two days to encompass a range of water contents while the samples were allowed to dry. After each voltage and soil-water content determination, the mass of the soil core was determined and the gravimetric soil-water content calculated. Linear regression was used to compare volumetric soil-water content estimated using the factory-supplied and soil-estimated parameters a_o and a_1 (Eqs. (2) and (3)) with the soil-water content determined in the laboratory.

The temperature dependence of the sensor voltage was determined by inserting the sensor and a close-contact thermocouple into a soil core of known soil-water content. The soil containers were covered with aluminium foil to reduce evaporation of water. The experiment was repeated for several soil cores for a range of known volumetric water contents prepared in the laboratory: 0.15, 0.34 and 0.42 $m^3 \cdot m^{-3}$. Each sensor was artificially heated using a heater wire. Chromel-constantan thermocouples, in contact with the body of the sensors inserted into the soil, were used to measure the temperature variation of the sensor and soil.

To develop retentivity relationships for the field soil cores, the soil cores were saturated in the laboratory and subjected to various suctions on a porous tension table with a hanging column of water to study characteristics for matric potentials of 0 and -10 kPa (Avery and Bascomb, 1974). Retentivity characteristics at a matric potential of -100 kPa was determined using undisturbed soil cores and the pressure-plate apparatus (Soil Moisture Equipment Corp., Santa Barbara, California). The volumetric water contents for each soil-water potential was determined using the ThetaProbe. When necessary, soil cores were dried in an oven. Before replacing the cores on the porous plate for the next pressure equilibrium step, the plate was made wet to ensure good contact between ceramic plate, filter paper and soil. A detailed description of the equipment and procedures are found in Klute (1986). The matric potentials corresponding to field capacity and wilting point for these soils (Table 1) were those recommended by Schulze et al. (1985).

Results and discussion

Selected physical characteristics of the soil from the site are shown in Table 1. Soil bulk density ranged from 1 476 $kg \cdot m^{-3}$ (for the 400 to 500 mm soil layer) to 1 604 $kg \cdot m^{-3}$ (300 to 450 mm layer) with an average of 1 546 $kg \cdot m^{-3}$. Mean soil-water content at saturation measured using the pressure plate laboratory method was 0.406 $m^3 \cdot m^{-3}$ and at -10 kPa was 0.292 $m^3 \cdot m^{-3}$. Particle size distribution showed the soil to have a clay loam texture. The soil had a high gravel content of iron and manganese concretions in the 300 to 450 mm layer. The organic matter content averaged 3.1%.

Factory calibration *vs.* soil calibration

The factory-supplied parameters for mineral soil, $a_o = 1.6$ and $a_1 = 8.4$, were used to estimate soil-water content (Eq. (2)). The average soil-estimated parameters of $a_o = 1.411$ and $a_1 = 11.09$ were used to estimate the soil-calibrated soil-water content. These parameters were calculated using Eqs. (1) and (3). The sensor output voltage under soil air-dry conditions was 0.074 V and under saturated conditions was 0.882 V, while the soil-water content at saturation was 0.406 $m^3 \cdot m^{-3}$. The dielectric constant of the dry and saturated soil was 2.1 and 23.1 (Eq. (3)), respectively.

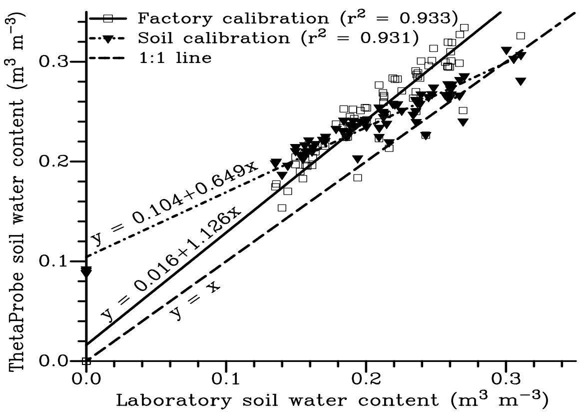

Figure 1
Laboratory calibration of the sensor soil-water content using the factory-supplied and the soil-estimated parameters vs. the laboratory soil-water content

The linear sensor calibration relationship for all soil depths is shown in Fig. 1 for soil samples removed from the study site. The linear regression statistics for θ_v determined using the factory-supplied or soil-estimated parameters *vs.* θ_v determined gravimetrically at the various matric potentials for individual depths and total depth are shown in Table 2. Unfortunately there was difficulty in measuring soil-water content between 0 and 0.15 $m^3 \cdot m^{-3}$ because the sensor, in spite of its sharp rods, could not be forced into the hard soil without damage to the rods for these low soil-water contents. The 300 to 450 mm layer had the lowest coefficient of determination r^2 (Table 2) probably due to the presence of the coarse lateritic material. Iron-rich minerals have been reported by Robinson et al. (1994) to affect the apparent dielectric constant measurement using the TDR technique for soil-water measurement. However, analysis of the 95% confidence limits showed that there were no significant differences in the slope and intercept values between different layers. It was therefore decided to pool the data from all depths between 0 and 600 mm and use one regression relationship.

There was a somewhat improved correlation of soil-water content estimates when the factory-supplied parameters were used compared to when using the soil-estimated parameters. There was a significant difference between the slope values as judged by the confidence interval for the various depths (Table 2). Soil variability with depth and sampling error may be the main causes for this discrepancy. These causes may also explain the difference between the calibration parameters for the different depths. On average, θ_v could be estimated to within 0.036 $m^3 \cdot m^{-3}$ when using the soil-estimated parameters and 0.034 $m^3 \cdot m^{-3}$ when using the factory-supplied parameters. Both the soil and the factory calibrations gave smaller errors compared to the maximum error of 0.050 $m^3 \cdot m^{-3}$ specified by the manufacturer. The standard deviation for volumetric water content of 0.021 $m^3 \cdot m^{-3}$ (factory-calibration) and 0.013 $m^3 \cdot m^{-3}$ (soil-calibration) was within the range of 0.005 to 0.023 $m^3 \cdot m^{-3}$ found by Jacobson and Schjonning (1993a) using a TDR technique. The soil calibration was determined from the ThetaProbe voltage with the probe inserted into dry soil so as to determine $a_o = \sqrt{\varepsilon_0}$ and then inserted into wet soil so as to determine the square root of the dielectric constant for saturated soil $\sqrt{\varepsilon_w}$ (Eq. 1). The a_1 value was then determined using Eq. (3). The estimated parameters were $a_o = 1.411$ and $a_1 = 11.09$ for the Tala Valley soil.

TABLE 2
Regression analysis between the laboratory soil-water content (*X*) and the estimated soil-water content (*X*) using the factory-supplied (*Y*) or the soil-estimated parameters (*Y*) for individual layers and the entire soil layer

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	column 12	column 13
Depths (mm)	0 -150		150 - 300		300 - 450		450 - 600		0 - 600		0 - 600	
	factory	soil	factory	soil	factory	soil	factory	soil	factory	soil	factory	soil
	------------------------		----------------------		------------------------		------------------------		------------------------		---Recalibration -----	
N	24	24	24	24	23	23	7	7	78	78	78	78
r^2	0.955	0.952	0.98	0.976	0.85	0.851	0.993	0.988	0.933	0.931	0.933	0.931
t statistic	21.563	20.96	32.608	29.613	10.897	10.968	27.139	20.47	32.498	32.046	32.498	32.046
Students's t test value	2.06	2.06	2.06	2.06	2.06	2.06	2.31	2.31	1.98	1.98	1.98	1.98
Slope	1.145	0.655	1.159	0.666	1.047	0.596	1.239	0.737	1.126	0.649	1.004	1.004
Intercept ($m^3 \cdot m^{-3}$)	0.013	0.104	0.01	0.101	0.028	0.113	0.007	0.094	0.016	0.104	0	0
Standard error of y on x (S_{yx}) ($m^3 \cdot m^{-3}$)	0.016	0.009	0.011	0.007	0.029	0.017	0.01	0.008	0.019	0.011	0.017	0.018
Sum X^2	1.072	1.072	1.075	1.075	1.075	1.075	0.271	0.271	3.493	3.493	3.493	3.493
SE slope	0.053	0.031	0.036	0.022	0.096	0.054	0.046	0.036	0.035	0.02	0.031	0.031
Slope confidence limit 99%	0.995, 1.294	0.567, 0.743	1.059, 1.259	0.603, 0.73	0.775, 1.319	0.442, 0.75	1.055, 1.423	0.592, 0.882	1.034, 1.218	0.595, 0.702	0.922, 1.085	0.921, 1.087
Slope confidence limit 95%	1.035, 1.255	0.59, 0.72	1.085, 1.233	0.62, 0.713	0.847, 1.246	0.483, 0.709	1.122, 1.357	0.644, 0.83	1.057, 1.195	0.609, 0.689	0.942, 1.065	0.942, 1.066
SE intercept	0.011	0.007	0.008	0.005	0.474	0.045	0.009	0.007	0.007	0.004	0.007	0.007
Intercept confidence limit 99%	-0.018, 0.045	0.085, 0.122	-0.012, 0.031	0.087, 0.114	-1.315, 1.372	-0.015, 0.241	-0.029, 0.044	0.066, 0.123	-0.003, 0.036	0.093, 0.116	-0.017, 0.017	-0.018, 0.018
Intercept confidence limit 95%	-0.01, 0.037	0.09, 0.117	-0.006, 0.025	0.091, 0.111	-0.959, 1.015	0.019, 0.207	-0.016, 0.031	0.076, 0.112	0.002, 0.031	0.096, 0.113	-0.013, 0.013	-0.013, 0.013
Mean square error (unsystematic)	0.005	0.002	0.002	65.892	0.018	132.375	0	1.452	0.026	0.009	0.158	0.147
Mean square error (systematic)	0.045	0.038	0.044	1.556	0.033	0	0.02	0	0.143	0.128	0.141	0.32
%Unsystematic error	10.521	4.672	5.313	97.693	97.416	100	46.736	100	15.477	6.491	52.794	31.485
%Systematic error	89.479	95.328	94.687	2.307	2.584	0	53.264	0	84.523	93.509	47.206	68.515
Bias b of the regression relationship = $\Sigma(X_i - Y_i)/N$	-0.043	-0.034	-11.631	-9.274	-19.729	-0.435	-0.417	-0.68	-0.042	-0.034	-0.001	-0.001
Mean X ($m^3 \cdot m^{-3}$)	0.203	0.203	0.203	0.203	0.207	0.207	0.180	0.180	0.202	0.202	0.202	0.202
Mean Y ($m^3 \cdot m^{-3}$)	0.245	0.237	0.244	0.236	0.245	0.236	0.230	0.227	0.243	0.235	0.203	0.203
Sum x^2 (- see Eq. (4))	0.086	0.086	0.089	0.002	0.092	0.018	0.045	0.308	0.312	0.312	0.312	0.312
c^2 (- see Eq. (4))	0.009	0.010	0.004	0.175	0.036	0.183	0.007	0.002	0.004	0.004	0.004	0.004
1-c^2 (- see Eq. (4))	0.991	0.990	0.996	0.825	0.964	0.817	0.993	0.998	0.996	0.996	0.996	0.996

There was a slight overestimation of soil-water content when using the factory-supplied calibration factors compared to the laboratory-determined soil-water content. Little et al. (1998) found that soil-water content was underestimated for a ThetaProbe in a clay soil. Standard deviations for the slope and intercept for the present study were smaller that those obtained in the mentioned reference. In the present study an r^2 of 0.92 was obtained compared to an r^2 of 0.76 in an Inanda soil (clay texture) and 0.92 in a Hutton soil (sandy texture) obtained in KwaZulu-Natal by Little et al. (1998).

The estimate of the soil-water content indices (saturation, air entry, field capacity, refill point and wilting point) using the sensor and related percentage errors for the factory-supplied and soil-estimated parameters is shown in Fig. 2. For each depth, the sample water contents were averaged but for Case 5 in Fig. 2, the average was for all samples at all depths. The soil-water content at air entry (-5 kPa) was determined as reported by Gregson et al. (1987), Williams et al. (1992) and Williams and Ahuja (1993). Other soil-water content indices were measured on undisturbed soil using the porous tensions table or pressure plate laboratory methods. Both the factory-supplied and the soil-estimated parameters resulted in an average error of more than 20%.

Recalibration of the sensor

An attempt was made to recalibrate the sensors (see Eq. (4) and the statistics from Table 2 (Columns 10 and 11)) in order to improve the regression (Columns 12 and 13). The regression line was forced through the (0, 0) origin based on the assumption that if the soil-water content is 0 $m^3 \cdot m^{-3}$, then the measured value would also be 0 $m^3 \cdot m^{-3}$. The range of soil-water contents was limited to greater than about 0.150 $m^3 \cdot m^{-3}$ since below this value, as mentioned previously, the soil was too hard to insert the sensor. The slope, y-intercept and bias of the recalibrated sensors were closer to the ideal slope of 1, and y-intercept and bias of 0. The r^2 was much the same, while the standard error of the predicted Y values for each X value increased for both the factory and the soil calibration. Using the recalibration procedure, soil-water con-

Available on website **http://www.wrc.org.za**
ISSN 0378-4738 = Water SA Vol. 32 No. 1 January 2006
ISSN 1816-7950 = Water SA (on-line)

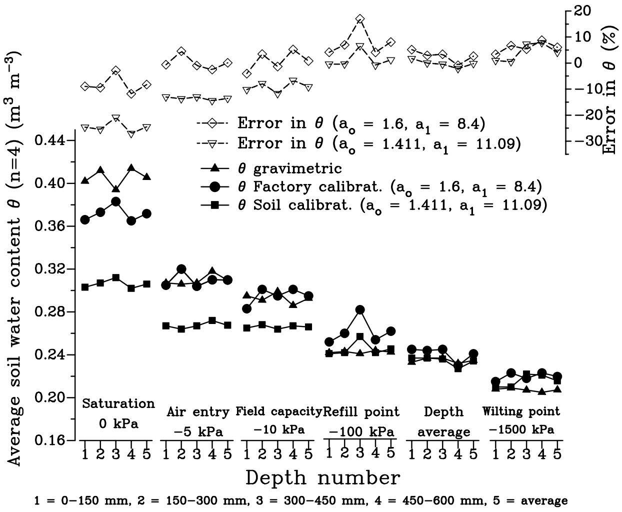

Figure 2

The estimated soil-water content indices using the sensor with the factory-supplied (a_o =1.6 and a_1 = 8.4) and soil-estimated (a_o = 1.411 and a_1 = 11.09) parameters, and the corresponding error

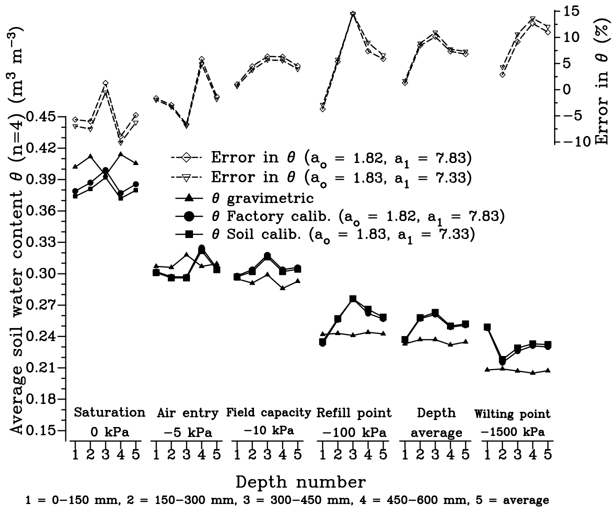

Figure 3

The estimated soil-water content indices using the recalibration of the sensor

tent could be estimated to within 0.020 $m^3 \cdot m^{-3}$ for both the soil-estimated and the factory-supplied parameters. There was an improvement for the soil-estimated parameters. The estimated percentage errors for different soil-water content indices after the recalibration process are presented in Fig. 3 with the adjustment of the factory-supplied parameters (a_o = 1.82 and a_1 = 7.83) and adjustment of the soil-estimated parameters (a_o = 1.83 and a_1 = 7.33) and the corresponding error. Compared to the percentage error shown in Fig. 2, the errors for both the factory-supplied and the soil-estimated parameters decreased.

The "best fit" expression for estimating soil-water content using the sensor was obtained using a recalibration procedure (Snedecor and Cochran, 1980). This procedure, based on Eq. (4), allowed the laboratory soil-water content to be estimated ($\theta_{v\text{-adjust}}$, the *X*-value) using:

- The estimated θ_v determined using the sensor (*Y*-value)
- The slope b = 0.872 and the intercept I = 0.037 $m^3 \cdot m^{-3}$ (Eq. 4) obtained from the regression between soil-water content determined using the sensor- and laboratory-measured soil-water content (Table 2, Column 10)
- A factor $c^2 = (1/x^2)(t\ S_{yx}/b)^2 = 0.0046$ (Table 2, Column 10) which takes into account the standard error of *Y* on *X*, the Student *t* statistic and the sum of the deviation squared (x^2) of the laboratory soil-water content from the average (Eq. (4)), where:

$$\theta_{v\text{-adjust}} = [(\theta_v - I)/b]/(1 - c^2).$$

A regression between the $\theta_{v\text{-adjust}}$ (*X*) and $\sqrt{\varepsilon}$ (*Y*) gave a *y*-intercept of 1.83 and a slope of 7.82. The *y*-intercept and slope of the regression between $\theta_{v\text{-adjust}}$ (*X*) and $\sqrt{\varepsilon}$ (*Y*) corresponded to a_o = 1.83 and a_1 = 7.82 for the calibration constants (see Eq. (2)) compared to the values a_o = 1.6 and a_1 = 8.4 provided by the manufacturer. The values a_o = 1.83 and a_1 = 7.33 were obtained for the $\theta_{v\text{-adjust}}$ adjusted for the soil-estimated parameters. Use of calibration constants a_o = 1.83 and a_1 = 7.82 or a_o = 1.83 and a_1 = 7.33 would produce the statistics shown in Table 2 (Columns 12 and 13). Comparison of $\theta_{v\text{-adjust}}$ and θ_v values determined in the laboratory is shown in Fig. 4. The $\theta_{v\text{-adjust}}$ approached the 1:1 line when using a_o = 1.83 and a_1 = 7.82 than when using factory-supplied parameters for which a_o = 1.6 and a_1 = 8.4 (Fig. 1).

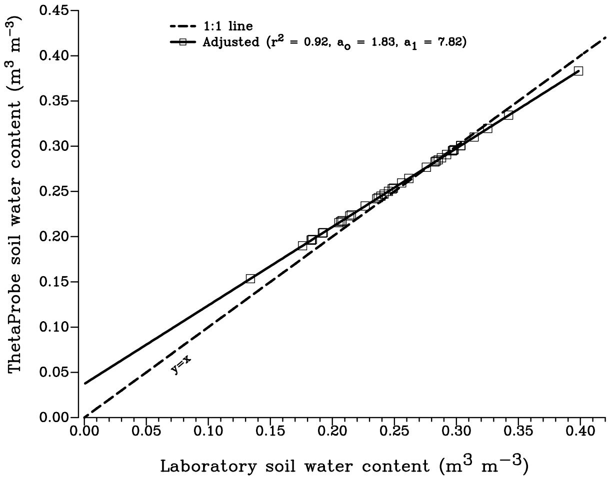

Figure 4

Comparison of $\theta_{v\text{-adjus}}$ (y-axis) and θ_v (x-axis) determined in the laboratory

Effect of soil temperature, bulk density and texture on sensor measurements

The error in soil-water content due to a temperature variation of between 12 and 18°C was not more than 0.015 $m^3 \cdot m^{-3}$ for the surface soil layers and not more than 0.005 $m^3 \cdot m^{-3}$ for the deeper layers. Topp et al. (1980) also had satisfactory results for temperatures between 10 and 30°C. In this experiment, soil-water contents were estimated accurately for soil layers with a high clay content and relatively low soil bulk density (Tables 1 and 2). The r^2 of the linear regression between the sensor-estimated soil-water content (*Y*) and the laboratory soil-water content (*X*) was 0.920 for the adjusted calibrations (Fig. 4). Combining bulk density or clay content with the laboratory soil-water content (X_1 and X_2) increased r^2 to 0.921 (data not shown). Combining the bulk density and clay content with the laboratory soil-water content (X_1, X_2 and X_3) increased r^2 to 0.927. The change in the soil bulk density and clay content of different layers therefore had a very small effect on the sensor-determined soil-water content. In the present study, the range of soil bulk density and clay content were relatively narrow and the results are therefore not sufficiently conclusive. Thus, the possibility of including bulk density and clay content into the calibration (Eqs. (1) and (2)) was not pursued further for these soils. Similar conclusions were reached by Topp et al. (1980) and Jacobson and Schjonning (1993b) for a TDR method using soil samples that included a wider textural and bulk density range than those used in this experiment. However, it is recommended that more research be done on the effect of the bulk density, texture, temperature and other soil physical characteristics on the estimates of the dielectric constant of the soil.

Conclusions

There was a relatively better performance of the FDR sensor used in estimating soil-water content when using the factory-supplied parameters than when using the soil-estimated parameters. A slope of 1, and an intercept and bias of zero were obtained for both the factory-supplied and the soil-estimated parameters when a recalibration process was used. Therefore the sensor could be used with confidence to monitor soil-water content for irrigation or hydrological purposes. For the clay loam soil used, the clay content, soil bulk density and temperature effects on the sensor voltage showed a negligible influence on the measured soil-water content. As judged by the increased variation in the measured soil-water content in the 300 to 450mm layer, the coarse structure and the presence of iron in a laterite layer affected sensor performance. Volumetric soil-water content could be measured to within 0.020 $m^3 \cdot m^{-3}$.

Acknowledgments

We acknowledge the assistance of the late Professor MA Johnston (Soil Science, University of Natal) in the initial phases of this work. The co-operation of Mr ME Wild and his son Alex of the Vita Fresh Farm (Tala Valley) and use of facilities is gratefully acknowledged. We acknowledge the financial support of the Deutscher Akademischer Austauschdienst (DAAD) (Germany), National Research Foundation, Water Research Commission and the University of KwaZulu-Natal. The authors also acknowledge the A. Neto University (Angola) for encouragement. We express our gratitude to the following scientists and technicians for their co-operation and assistance: Dr CS Everson, Professor EA Ripley, Mr PN Dovey and Ms J Manickum. Our thanks go to Mrs MA Savage for editorial assistance.

References

AVERY BW and BASCOMB CL (1982) *Soil Survey Laboratory Methods.* Soil Survey. Technical Monograph No. 6. Harpenden, UK. 83 pp.

BLAKE GR and HARTGE KH (1986) Bulk density. In: Campbell, GS, Jackson RD, Mortland MM, Nielsen DR and Klute A (eds.) *Methods of Soil Analysis. Part 1:Physical and Mineralogical Methods. Agronomy Monograph No. 9* (2nd edn.) Am. Soc. Agron. Inc., Madison, Wisconsin, USA. 363-376.

CZARNOMSKI NM, MOORE GW, PYPKER TG, LICATA J and BOND BJ (2005) Precision and accuracy of three alternative instruments for measuring soil water content in two forest soils of the Pacific Northwest. *Can. J. For. Res.* **35** 1867-1876.

DELTA-T DEVICES (1999) *ThetaProbe Soil Moisture Sensor User Manual.* Delta-T Devices, Cambridge, UK.

DRNEVICH VP, ASHMAWY AK, YU X and SALLAM AM (2005) Time domain reflectometry for water content and density of soils: study of soil-dependent calibration constants. *Can. Geotech. J.* **42** 1053-1065.

EVETT SR, HOWELL TA and TOLK JA (2005) Time domain reflectometry laboratory calibration in travel time, bulk electrical conductivity, and effective frequency. *Vadose Zone J.* **4** 1020-1029.

GEE GW and BAUDER JW (1986) Particle-size analysis. In: Campbell GS, Jackson RD, Mortland MM, Nielsen DR and Klute A (eds.) *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Agronomy Monograph No. 9* (2nd edn.) Madison, Wisconsin, USA. 383-409.

GEBREGIORGIS MF and SAVAGE MJ (2006a) Determination of the timing and amount of irrigation of winter cover crops with the use of dielectric constant and capacitance soil water content profile methods. *S. Afr. J. Plant Soil* **23** (In press).

GEBREGIORGIS MF and SAVAGE MJ (2006b) Field, laboratory and estimated soil-water content limits. *Water SA* (In press).

GREGSON K, HECTOR DJ and McGOWAN M (1987) A one-parameter model for the soil water characteristic. *J. Soil Sci.* **38** 483-486.

GROVES SJ, ROSE SC (2004) Calibration equations for Diviner 2000 capacitance measurements of volumetric soil water content of six soils. *Soil Use Mgt.* **20** 96-97.

JACOBSON OH and SCHJONNING P (1993a) A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. *J. Hydrol.* **151** 147-157.

JACOBSON OH and SCHJONNING P (1993b) Field evaluation of time domain reflectometry for soil-water measurements. *J. Hydrol.* **151** 159-172.

KLUTE A (1986) Water retention: Laboratory methods. In Campbell GS, Jackson RD, Mortland MM, Nielsen DR and Klute A (eds.) *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Agronomy Monograph No. 9* (2nd edn.). Am. Soc. Agron. Inc., Madison, Wisconsin, USA. 383-409.

LITTLE KM, METELERKAMP B and SMITH CW (1998) A comparison of three methods of soil-water content determination. *S. Afr. J. Plant Soil* **15** 80-89.

LUKANGU G, SAVAGE MJ and JOHNSTON MA (1999) Use of sub-hourly soil water content measured with a frequency-domain reflectometer to schedule irrigation of cabbages. *Irrig. Sci.* **19** 7-13.

MIYAMOTO T and MARUYAMA A (2004) Dielectric coated water content reflectometer for improved monitoring of near surface soil moisture in heavily fertilized paddy field. *Agric. Water Mgt.* **64** 161-168.

MWALE SS, AZAM-ALI SN and SPARKES DL (2005) Can the PR1 capacitance probe replace the neutron probe for routine soil-water measurement? *Soil Use Mgt.* **21** 340-347.

ROBINSON DA, BELL JP and BATCHELOR CH (1994) Influence of iron minerals on the determinations of soil water content using dielectric techniques. *J. Hydrol.* **161** 169-180.

ROTH K, SCHULIN R, FLUHER H and ATTINGER W (1990) Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. *Water Resour. Res.* **26** 2267-2273.

SCHULZE RE, HUTSON JL and CASS A (1985) Hydrological characteristics and properties of soil in Southern Africa 2. Soil water retention models. *Water SA* **11** 129-136.

SNEDECOR GW and COCHRAN WG (1980) *Statistical Methods* (7th edn.). The Iowa State University Press, Ames, Iowa, USA.

TOPP GC, DAVIS JL and ANNAN AP (1980) Electromagnetic determination of soil water content measurement in coaxial transmission lines. *Water Resour. Res.* **16** 574-582.

WHALLEY WR, COPE RE, NICHOLL CJ and WHITMORE AP (2004) In-field calibration of a dielectric soil moisture meter designed for use in an access tube. *Soil Use Mgt.* **20** 203-206.

WILLIAMS RD and AHUJA LR (1993) Using available water content with the one-parameter model to estimate soil water retention. *Soil Sci.* **156** 380-388.

WILLIAMS RD, AHUJA LR and NANEY JW (1992) Comparison of method to estimate soil water characteristic from soil texture, bulk density, and limited data. *Soil Sci.* **153** 172-184.

WYSEURE GCL, MOJID MA and MALIK MA (1997) Measurement of volumetric water content by TDR in saline soils. *Euro. J. Soil Sci.* **48** 347-354.