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Research paper

Field calibration of DFM capacitance probes for continuous soil moisture monitoring

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This study was undertaken to derive textural and lumped site-specific calibration equations for Dirk Friedhelm Mercker (DFM) capacitance probes and evaluate the accuracy levels of the developed calibration equations for continuous soil moisture monitoring in three selected soil types. At each site, 9 probes (3 per plot) were installed in 2 m^2 plots, for continuous soil moisture measurements at 5 different depths (viz. 10, 20, 30, 40 and 60 cm) under dry, moist and wet field conditions. Textural site-specific calibration equations were derived by grouping the same soil textural classes of each site regardless of soil depth, while lumped site-specific calibration equations were derived by grouping all datasets from each site, regardless of soil depth and textural classes. Sensor readings were plotted against gravimetrically measured volumetric soil moisture (θ_v) for different textural classes as a reference. The coefficient of determination (r^2) was used to select the best fit of the regression function. The developed calibration equations were evaluated using an independent dataset. The results indicated that all developed textural and lumped site-specific calibration equations were linear functions, with r^2 values ranging from 0.96 to 0.99. Relationships between the measured and estimated θ_v from calibration equations were reasonable at all sites, with r^2 values greater than 0.91 and root mean square error (RMSE) values ranging from 0.010 to 0.020 $m^3 \cdot m^{-3}$. The results also indicated that textural site-specific calibration equations (RMSE < 0.018 $m^3 \cdot m^{-3}$) should be given preference over lumped site-specific calibrations (RMSE < 0.020 $m^3 \cdot m^{-3}$) to attain more accurate θ_v measurements. The findings of this study suggest that once DFM capacitance probes are calibrated per site, they can be reliably used for accurate in-situ soil moisture measurements. The developed calibration equations can be applied with caution in other sites with similar soil types to attained reliable in-situ soil moisture measurements.

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INTRODUCTION

The need for accurate soil moisture estimates at high temporal and spatial resolution is becoming more urgent to support efficient water management, agricultural productivity, drought management and flood forecasting within the context of climate change modelling and adaptation (Pegram et al., 2010; Seneviratne et al., 2010; Ojo et al., 2015b; Tfwala et al., 2019a). Consequently, there has been a dramatic increase in the number of remote-sensing products and hydrological models to estimate soil moisture instantaneously at high temporal and spatial resolution (e.g. Gruhier et al., 2010; Pegram et al., 2010; Amri et al., 2012). However, their estimates still need to be calibrated and validated using in-situ soil moisture measurements, which are thought to be more accurate (Walker et al., 2004; Dobriyal et al., 2012; Brocca et al., 2017). Therefore, the need for accurate in-situ soil moisture measurements at a high temporal and spatial resolution within the context of evaluation and verification of soil moisture estimates cannot be overemphasized (Zreda et al., 2012; Gruber et al., 2013; Ojo et al., 2015b; Brocca et al., 2017; Holzman et al., 2017).

In recent years, numerous studies have been instituted in various countries to establish in-situ soil moisture monitoring networks (e.g. Dorigo et al., 2011; Albergel et al., 2012; Pan et al., 2012; Zreda et al., 2012; Diamond et al., 2013). Datasets from most of these networks have been merged in the International Soil Moisture Network (ISMN) and are freely available on their website (https://ismn.geo.tuwien.ac.at/) (Dorigo et al., 2011; Albergel et al., 2012; Zreda et al., 2012; Gruber et al., 2013) to support the calibration, validation and improvement of soil moisture estimations. In most of these networks, soil moisture is often measured indirectly with dielectric sensors which are based on time domain reflectometry (TDR) and frequency domain reflectometry (FDR) or capacitance principles (Dorigo et al., 2011; Pan et al., 2012; Gruber et al., 2013; Ojo et al., 2015b; Holzman et al., 2017).

Multi-depth capacitance sensors have become the most popular devices for real-time, continuous and non-destructive soil moisture profile measurements, due to their lower cost compared to TDR (Bello et al., 2019; Dhakal et al., 2019; Hajdu et al., 2019; Kassaye et al., 2019; Tfwala et al., 2019a). Capacitance sensors measure the apparent dielectric permittivity of the soil, which is much lower than that of water, such that the output is related to the volumetric moisture content in the soil (θ_v), via either the manufacturer's default calibration equation or a user's site-specific calibration equation (Cobos and Chambers, 2010; Gabriel et al., 2010; Archer et al., 2016; Parvin and Degré, 2016).

A generalized calibration equation, relating the relative sensor output to θ_v, which is often supplied by the manufacturer, provides an accuracy of ±3% for typical soils, depending on the specific type of sensor (Cobos and Chambers, 2010). However, irrespective of the stipulated accuracy level claimed by the manufacturers, capacitance probes have been reported to require calibration for different soil types to attain accurate soil moisture measurements, with errors being reduced to ±1% (Fares et al., 2011; Kinzli et al., 2011; Paraskevas et al., 2012; Bogena et al., 2017; Bello et al., 2019; Hajdu et al., 2019; Kassaye et al., 2019; Tfwala et al., 2019a). Some of the reasons for this observation are due to differences in electrical conductivity and soil dielectric properties (Gabriel et al., 2010; Kinzli et al., 2011). Capacitance probes can be calibrated in the laboratory or in the field for specific textural classes, irrespective of site (Gabriel et al., 2010; Zerizghy et al., 2013; Bello et al., 2019; Tfwala et al., 2019a). However, capacitance probes have been reported to have required site-specific calibrations to attain more accurate soil moisture measurements (Fares et al., 2011; Kinzli et al., 2011; Paraskevas et al., 2012; Bogena et al., 2017; Bello et al., 2019; Dhakal et al., 2019; Hajdu et al., 2019; Kassaye et al., 2019; Tfwala et al., 2019a).

Site-specific calibrations that are carried out on specific soil types under specific agro-ecological conditions are more consistent with site measurements (Fares et al., 2011; Kinzli et al., 2011). Site-specific calibrations take into consideration soil properties such as soil texture, mineralogy, bulk density, salinity, temperature and organic matter of the specific site, that are known to vary with depth and affect the accuracy of the capacitance sensors (Huang et al., 2004; Kizito et al., 2008; Fares et al., 2011; Paraskevas et al., 2012; Hajdu et al., 2019). Site-specific calibration equations are generally derived either through textural or lumped site-specific calibration equations (Hajdu et al., 2019). The textural site-specific calibration equations take into consideration the variation of soil properties with depth in a specific soil profile (e.g. Da Silva et al., 2007; Fares et al., 2011; Parvin and Degré, 2016; Dhakal et al., 2019). On the other hand, lumped site-specific calibration equations are derived by grouping all soil textural classes of the specific site regardless of soil depth (Hajdu et al., 2019). Previous studies have indicated that better accuracy of soil moisture measurement can be achieved through textural site-specific calibration of the capacitance probes compared to the lumped site-specific calibration equations (e.g. Da Silva et al., 2007; Parvin and Degré, 2016; Hajdu et al., 2019).

Site-specific calibration equations are generally derived either through laboratory analyses or field techniques, by establishing relationships between the sensor readings and gravimetrically measured θ_v at different moisture levels (Kinzli et al., 2011; Archer et al., 2016; Hajdu et al., 2019). Studies have shown that laboratory calibration equations developed using undisturbed soil samples are more accurate than field calibration equations (e.g., Geesing et al., 2004; Gabriel et al., 2010; Kinzli et al., 2011; Bello et al., 2019; Hajdu et al., 2019; Tfwala et al., 2019a). The high accuracy of laboratory calibration equations over field calibration equations is attributed to the wide range of soil moisture contents, ranging from permanent wilting point to saturation, and a relatively large number of replicates of continuous measurements in the laboratory (Gabriel et al., 2010; Varble and Chávez, 2011; Bello et al., 2019; Tfwala et al., 2019a). Gabriel et al. (2010), Paraskevas et al. (2012) and Tfwala et al. (2019a) calibrated different capacitance probes in the laboratory and were able to use the equation in the field with high accuracy. However, laboratory facilities are costly, and transporting and soil sampling of undisturbed core samples for laboratory studies may alter the soil properties. Furthermore, site-specific calibrations are generally labour-intensive and time-consuming (Gabriel et al., 2010; Tfwala et al., 2019a). Thus, capacitance sensors are often used without proper site-specific calibration in many in-situ soil moisture monitoring networks, which makes the accuracy of their measurements questionable (Gruber et al., 2013; Poltoradnev et al., 2014; Ojo et al., 2015b).

The Agricultural Research Council (ARC) of South Africa is running a project to monitor soil moisture at various sites across the country and to archive the information for potential agricultural use (Moeletsi et al., 2009). Soil moisture monitoring is currently carried out with the use of Dirk Friedhelm Mercker (DFM) capacitance probes (DFM Software Solutions, 2015). However, these probes have been installed without prior textural or site-specific calibrations. To this end, the monitoring network has about 5 years of continuous datasets acquired from 17 stations, distributed across all agro-climatic zones of South Africa. This raises the following questions: how accurate is the output of the probes, and how well can the datasets from these probes be trusted and used as in-situ θ_v?

In South Africa, DFM recently introduced a multifunctional capacitance soil probe, hereafter named DFM capacitance probe, that can measure soil moisture content and temperature simultaneously (DFM Software Solutions, 2015). This device has been widely accepted by farmers and in the past 3 years, 15 000 units were sold in South Africa, with 14 250 going to the agriculture sector and 750 for research purposes (Mjanyelwa et al., 2016). The advantage of this device is that it can measure at multi-depth – normally 6 depths in a soil profile. It is user-friendly, portable, cheap and easy to maintain (Mjanyelwa et al., 2016; Zerizghy et al., 2013). In terms of user-friendliness, the output of the probes is a percentage (%), which farmers can more easily relate to than frequency, millivolts or counts. At this point, it is worth mentioning that calibration and validation of DFM capacitance probe measurements under field conditions has received little scientific attention, although they have been utilized in some scientific studies. For example, Zerizghy et al. (2013) calibrated DFM probes under laboratory conditions using the repacked Bainsvlei topsoil, while in other studies the probes were used directly without reporting their calibration under field conditions (Roets et al., 2013; Tfwala et al., 2019b). Therefore, there is a need to evaluate the performance of DFM capacitance probes in a wide range of soil types, before they can be utilized for reliable and continuous in-situ soil moisture measurements.

Calibration of the DFM capacitance probes of the ARC is required to improve the confidence with which the soil moisture data can be used. The objectives of this study were to develop textural and lumped site-specific calibration equations for DFM capacitance probes and to evaluate the accuracy levels of the developed calibration equations for continuous soil moisture monitoring in three selected soil types, in different agro-climatic zones of South Africa. Due to the range of soil types used in this study, it is assumed that the derived calibration equations can be applied with caution in other sites with similar soil types to attained reliable in-situ soil moisture measurements.

MATERIALS AND METHODS

Study site description

The study was conducted at three automatic weather stations, located at Bainsvlei (in Free State), Bronkhorstspruit (in Gauteng) and Mandeni (in KwaZulu-Natal), which represent a wide range of soil types and agro-climatic zones found in South Africa (Table 1). The choice of stations was also based on the completeness (< 10% missing data) of the ARC soil moisture dataset. Although all stations were within agricultural cropping areas, the stations were in flat grassland (slope < 2%, data not presented here). Each site had a weather station equipped with a rain gauge, solar radiation, air temperature and relative humidity, wind speed and wind direction sensors as well as a DFM capacitance probe for that location. The soil at the Bainsvlei station was classified as Rhodic Ferralsols (IUSS Working Group, 2014), which is locally known as the Hutton soil form (Soil Classification Working Group, 1991). The soil at the Bronkhorstspruit station was classified as Glossic Leptosols (IUSS Working Group, 2014), which is locally known as the Glenrosa soil form (Soil Classification Working Group, 1991).

Table 1. Characteristics of three sites used

Station name	Latitude (°)	Longitude (°)	Elevation (m amsl)	Soil form	Climate conditions
Bainsvlei	–29.146	26.146	1 290	Hutton	Arid, steppe and cold arid
Bronkhorstspruit	–25.702	28.799	1 500	Glenrosa	Warm temperate, dry winter and warm summer
Mandeni	–29.156	31.344	107	Namib	Warm temperate, fully humid and hot summer

Soil classification was based on the Soil Classification Working Group (1991) and the description of climatic conditions was based on the Köppen-Geiger climate classification of Conradie (2012)

The soil at the Mandeni station was classified as Arenic Arenosols (IUSS Working Group, 2014), which is locally known as the Namib soil form (Soil Classification Working Group, 1991).

Description of the DFM capacitance probe

DFM capacitance probes are multi-depth sensors that measure soil moisture and temperature continuously and simultaneously at 6 depths in a soil profile (Fig. 1). The sensing radius of the DFM capacitance probe is 10 cm (DFM Software Solutions, 2015). DFM capacitance probes are equipped with small solar panels and rechargeable batteries, and have PVC caps that protect the electronics, and hence are suitable for continuous soil moisture monitoring under severe weather conditions (DFM Software Solutions, 2015). The DFM capacitance probe is a stand-alone sensor with a datalogger that can store data at different time intervals for more than 60 days. Stored data can be displayed and downloaded onto a computer, either in the field or in the office, using DFM software (DFM Software Solutions, 2015).

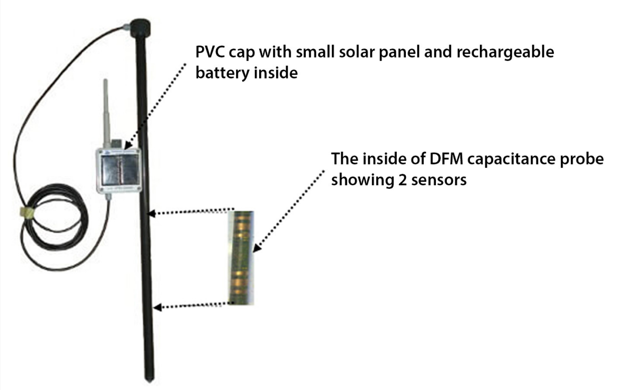

Figure 1. DFM capacitance probe with 6 sensors inside a tube 80 cm long (adapted from DFM Software Solutions, 2015)

Calibration procedure

Experimental layout and moisture regimes

At each site, three sampling plots of 2 m^2 were demarcated approximately 2 m away from the ARC's existing DFM capacitance probe, to prevent any possible damage to their sensors (Fig. 2a). The soil, vegetation and slope characteristics at the pits were the same as the existing ARC probe sites (Fig. 2b). These plots were constructed by forming soil ridges around the plot boundaries to allow ponding of water on the surface during the wetting process. Within each plot, three DFM capacitance probes were installed approximately 1 m apart in a triangular configuration (Fig. 2c) for continuous soil moisture measurements at 5 different depths (viz. 10, 20, 30, 40 and 60 cm), following the manufacturer's installation recommendations (DFM Software Solutions, 2015). Two pits of approximately 0.4 m wide and 0.8 m deep were dug between the three plots for soil dry bulk density (ρ_d) core sampling at different moisture levels (Fig. 2d). Although these pits were at the fringes of the plots, they represent soil moisture levels within the plots.

The surfaces of wet and moist plots were uniformly filled with water using water tanks to near saturation while the moist plot was filled with half the total volume of water used in the wet plot. All plots were then covered immediately by sackcloth bags to minimize evaporation, and left for about 2 weeks to allow water to infiltrate and redistribute within the soil profile in both the moist and wet plots while allowing the dry plot to remain un-watered (Fig. 2a). A 2-week period allowed the probes to stabilize within the soil for reliable soil moisture measurements.

Figure 2. Experimental layout at the Bainsvlei site during the calibration process of DFM capacitance probes (a), soil, vegetation and slope characteristics at the plots were the same as for the existing ARC probe (b), 3 probes installed in a wet plot (c), 0.4 m wide and 0.8 m deep pit for bulk density sampling (d)

Soil sampling

After 2 weeks, three gravimetric samples, at each of the depths corresponding to the depths of sensors on the DFM capacitance probes installed within the plots, were collected using a soil auger. Although the sampling radius (approximately 30 cm) was beyond the sphere of influence of the probe (10 cm) to prevent any possible damage to the sensor and cables, it could still be regarded as a representative measurement of the soil moisture (Kinzli et al., 2011). The time of sampling and probe numbers were recorded. After sampling, the wet plot was then uniformly refilled with water to near saturation while the moist plot was filled with half the total volume of water used in the wet plot, following the procedure of Hajdu et al. (2019). After the ponded water had infiltrated, the wet and moist plots were covered immediately to minimize evaporation. Approximately 2 h was allowed for the water to infiltrate and redistribute within the soil profile, while the dry plot was left open to air dry throughout the calibration process. Once the sensor outputs were stable, three gravimetric soil samples at each of the depths corresponding to the sensors on the installed DFM capacitance probes were collected using a soil auger. Undisturbed soil samples for ρ_d were collected from the pits using 98 cm^3 steel cylinders, and the time of sampling was recorded. All plots were then allowed to air dry further and the sampling process was repeated every 2 h while drying took place. This cycle of wetting, taking gravimetric and ρ_d samples while recording time of sampling as the plots were air-dried, was repeated for 3 days to get a wide range of soil moisture statuses for calibration. All the collected soil samples were immediately weighed in the field to determine their initial weights and re-weighed after oven-drying at 105°C for 48 h to determine gravimetric soil moisture content (θ_g). In addition, 3 replicates of bulk soil samples were also collected from the same depths at each site using a soil auger and mixed thoroughly to make a composite sample of 5 kg for each depth. Composite soil samples were transported to the ARC laboratory to determine particle size distribution, electric conductivity (EC) and organic carbon content (OC) for each depth. The textural triangle of the United States Department of Agriculture (USDA) classification scheme of Gee and Bauder (1986) was then used to determine the soil textural class for each depth.

Data collection and processing

Sensor outputs during the calibration period from each probe were extracted from the ARC databank. The recorded time of sampling and probe numbers were then used to match θ_g and the corresponding sensor reading. The bulk density of each soil depth was used to convert the corresponding θ_g to θ_v. All data underwent a quality control routine to identify errors to ensure that the data were consistent. For example, an average of either 2 or 3 replicates that had less than a 10% difference was used as a single data point. Unreasonable θ_v measurements and sensor readings (%) were discarded, resulting in a relatively low number of observations. Errors in θ_v measurements were attributed to the non-uniform distribution of water within the sampling plots and the presence of stones in some samples. On the other hand, errors in sensor readings were due to either non-response or response with inconsistent values amongst replicates that were attributed to the sensor production process, as also noted by Bello et al. (2019).

Calibration and validation of DFM capacitance probes

For each site, the same soil textural classes were grouped, regardless of soil depth, and then divided in half, with one half used for the development of a textural site-specific calibration equation and the other for validation of the developed equation. In addition, all datasets from each site were grouped, regardless of soil depth and textural class, and then divided in half, with one half used for the development of a lumped site-specific calibration equation and the other for validation of the developed equation. All calibration equations were developed by plotting sensor outputs against corresponding θ_v measurements. The accuracy of the developed calibration equations was evaluated using an independent dataset, by comparing gravimetrically measured and estimated θ_v from calibration equations using corresponding sensor outputs.

Statistical analysis

The coefficient of determination (r^2) was used to select the best fit of the regression function during the development of calibration equations (Bello et al., 2019; Hajdu et al., 2019; Tfwala et al., 2019a). The root mean square error (RMSE), mean bias error (MBE) and index of agreement (d) were used to evaluate the performance of the calibration equations and were calculated based on Willmott et al. (1985) as:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(\theta_{\mathrm{ve}\,i}-\theta_{\mathrm{v}\,i}\right)^2}{n}} \tag{1}$$

$$\mathrm{MBE}=\frac{\sum_{i=1}^{n}\left(\theta_{\mathrm{ve}\,i}-\theta_{\mathrm{v}\,i}\right)}{n} \tag{2}$$

$$d=1-[\frac{\sum_{i=1}^{n}\left(\theta_{\mathrm{ve}\,i}-\theta_{\mathrm{v}\,i}\right)^2}{\sum_{i=1}^{n}\left(\theta_{\mathrm{ve}\,i}-\overline{\theta}_{\mathrm{v}}\,|+|\,\theta_{v\,i}-\overline{\theta}_{\mathrm{v}}\,|\right)^2} \tag{3}$$

where i is the data pair index, θ_ve is the estimated volumetric moisture content from the DFM probes, θ_v is the observed volumetric moisture content, $\overline{\theta}_\mathrm{v}$ is the mean of all observations of θ_v and n is the number of observations. A linear regression between θ_ve and θ_v values was also computed:

$$\theta_\mathrm{ve}=m\theta_\mathrm{v}+c \tag{4}$$

where the slope (m) was used as a measure of accuracy and c is the y-intercept. The coefficient of determination (r^2) was used as a measure of precision. According to Willmott et al. (1985) for the best model performances, RMSE, MBE and c values should approach zero whilst d, r^2 and m values should approach 1.

RESULTS AND DISCUSSION

Soil physical and chemical properties

A summary of the physical and chemical properties that affect soil moisture measurement accuracy illustrated the wide range of textural classes across the study sites (Table 2). The results of the soil analysis showed that the Bainsvlei site was dominated by sand (0–40 cm), while sandy loam was found only from 40 cm depth, indicating homogeneity of the soil profile. The Bronkhorstspruit site had sandy topsoil (0–10 cm) and was dominated by loamy sand (20–40 cm), while sandy loam was only found from 40 cm, indicating heterogeneity of the soil profile. The Mandeni site had only sand (0–60 cm), indicating homogeneity of the soil profile. The clay content, ρ_d and OC of the soils increased with depth at all sites as expected (Bello et al., 2019; Hajdu et al., 2019). The results further showed that the Bronkhorstspruit site had the highest bulk densities compared to the other sites. Soil properties such as ρ_d, EC, pH and OC were within the expected range for each soil textural class (Ersahin et al., 2006; Bello et al., 2019).

Table 2. Selected physical and chemical properties of the study sites

Site	Textural class	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	ρ_d (g·cm^{-3})	EC (mS·m^{-1})	pH (KCl)	OC (%)
Bainsvlei	Sand	0–40	95	2	3	1.64	5.53	5.01	0.76
	Sandy loam	40–60	81	2	17	1.78	8.36	5.70	0.75
Bronkhorstspruit	Sand	0–10	89	6	5	1.58	7.73	4.30	1.29
	Loamy sand	20–40	84	4	12	1.80	7.03	4.43	0.87
	Sandy loam	40–60	77	15	8	1.84	3.82	4.60	0.27
Mandeni	Sand	0–60	96	4	0	1.57	7.79	5.51	0.84

where ρ_d *is the soil dry bulk density, EC is the electric conductivity and OC is the organic carbon content*

Table 3. Textural and lumped site-specific calibration equations for DFM capacitance probes with their statistical indicators

Site	Textural class	*n*	Regression type	Calibration equation	r^2	*p*
Bainsvlei	Sand	42	Linear	$\theta_v = 0.0053x - 0.0153$	0.97	<0.001
	Sandy loam	23	Linear	$\theta_v = 0.0056x - 0.0221$	0.96	<0.001
	Lumped site-specific	65	Linear	$\theta_v = 0.0054x - 0.0155$	0.96	<00001
Bronkhorstspruit	Sand	12	Linear	$\theta_v = 0.004x + 0.0743$	0.97	<0.001
	Loamy sand	12	Linear	$\theta_v = 0.0034x + 0.0878$	0.99	<0.001
	Sandy loam	12	Linear	$\theta_v = 0.0035x + 0.0834$	0.98	<0.001
	Lumped site-specific	36	Linear	$\theta_v = 0.0035x + 0.084$	0.96	<0.001
Mandeni	Sand	40	Linear	$\theta_v = 0.0038x - 0.0615$	0.99	<0.001
	Lumped site-specific	40	Linear	$\theta_v = 0.0038x - 0.0615$	0.99	<0.001

where n *is the number of observations and* x *(%) is the sensor output*

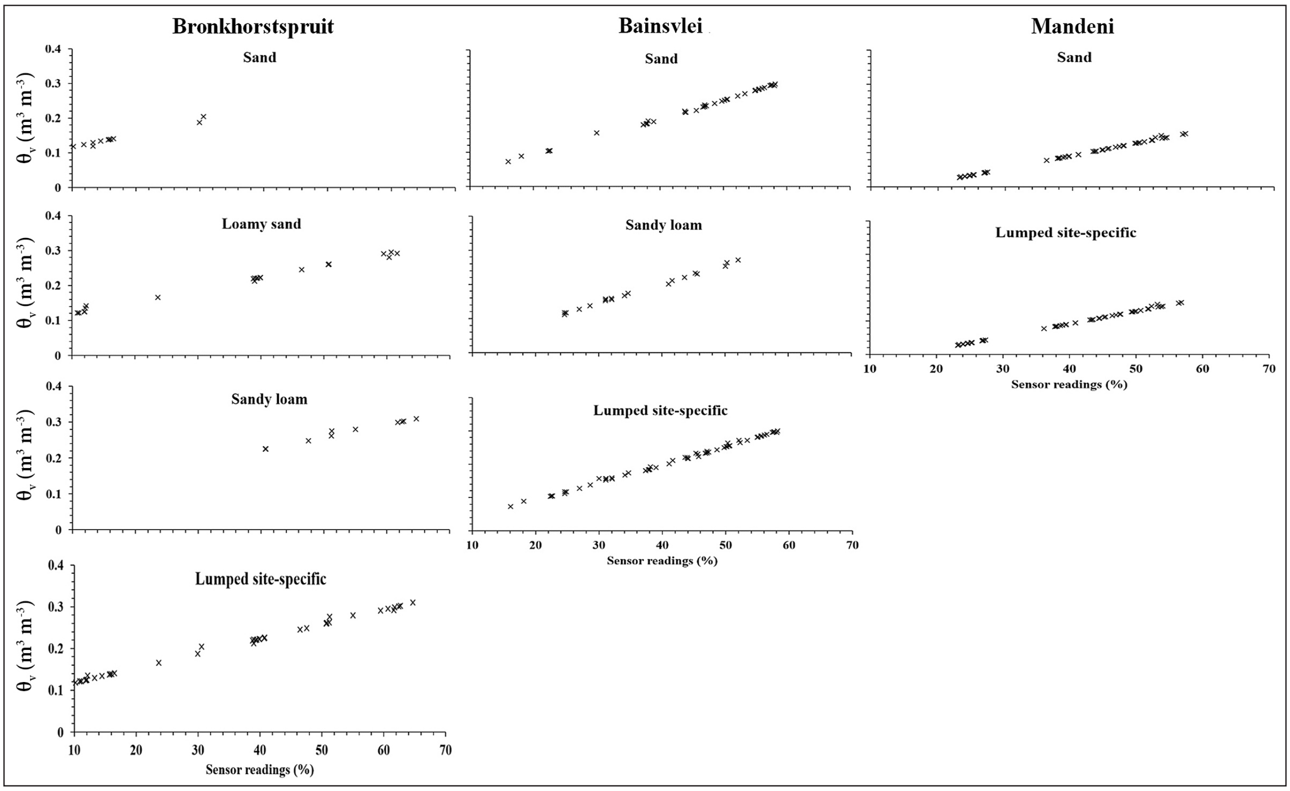

Figure 3. Relationships between sensor outputs of the DFM capacitance probes and volumetric water content for different soil textural classes and sites

Calibration of DFM capacitance probes

At the Bronkhorstspruit site, measured θ_v ranged from 0.11 to 0.20 m^3·m^{-3} (sand), 0.12 to 0.29 m^3·m^{-3} (loamy sand), 0.23 to 0.31 m^3·m^{-3} (sandy loam) and 0.11 to 0.31 m^3·m^{-3} for all collected samples (Fig. 3). At the Bainsvlei site, measured θ_v ranged from 0.04 to 0.30 m^3·m^{-3} (sand), 0.11 to 0.27 m^3·m^{-3} (sandy loam), and 0.04 to 0.30 m^3·m^{-3} for all collected samples. At the Mandeni site, measured θ_v ranged from 0.03 to 0.15 m^3·m^{-3} for all collected samples. Despite attempts made in this study to fill the soil profile uniformly with water to near saturation, measurements of θ_v were not greater than 0.31 m^3·m^{-3} at any of the sites and the lowest θ_v values were observed at the Mandeni site. The relatively low θ_v could be attributed to the low water-holding capacity of sandy soils, which dominated all the sites (Ojo et al., 2015a; Bello et al., 2019; Tfwala et al., 2019a). Therefore, measured θ_v results are typical for the range expected for the site soil textural class, as was also noted by Ojo et al. (2015a). Linear relationships were found between sensor outputs (%) and measured θ_v for all textural classes at all sites and were statistically significant ($p < 0.0001$), with r^2 values ranging from 0.96 to 0.99 (Table 3).

Validation of DFM capacitance probes

The results indicate that relationships between measured θ_v and θ_v estimated from calibration equations were reasonable at all sites, with r^2 values greater than 0.91 and c values less than 0.051 m^3·m^{-3} for all calibration equations (Fig. 4; Table 4). The RMSE values ranged from 0.010 to 0.018 m^3·m^{-3} with MBE values ranging from −0.003 to 0.016 m^3·m^{-3}, indicating that all developed calibration equations estimated θ_v reasonably. The d values greater than 0.93 indicated good similarity between measured θ_v and estimated θ_v at all sites. The results showed that the best estimates of θ_v were observed at the Bainsvlei and Mandeni sites, with r^2 values ranging from 0.96 to 0.98 and d-values ranging from 0.98 to 0.99, respectively. There was a relatively lower precision at the Bronkhorstspruit site, with r^2 values ranging from 0.91 to 0.96 and RMSE values ranging from 0.012 to 0.021 m^3·m^{-3}. The relatively lower accuracy at Bronkhorstspruit could be attributed to the presence of stones at depths greater than 20 cm, which could have resulted in voids and air gaps between the sensor and the soil, resulting in errors, as was also noted by Huang et al. (2004). Moreover, the presence of stones in core samples could have resulted in errors in θ_v derived through the gravimetric technique which was used as a reference in this study, as also noted by Kassaye et al. (2019). The sensing radius of the DFM capacitance probe is 10 cm (DFM Software Solutions, 2015). Consequently, gravimetric samples taken beyond the sphere of influence of the probe (approximately 30 cm) might not have truly represented the soil moisture content at the probe as a result of high spatial variability of soil moisture, particularly in heterogeneous soils.

Previous studies showed that the accuracy of capacitance-based sensors is influenced by soil properties such as soil texture, ρ_d, mineralogy, salinity, temperature and OC (Huang et al., 2004; Kizito et al., 2008; Fares et al., 2011; Ojo et al., 2015a; Matula et al., 2016; Bello et al., 2019; Dhakal et al., 2019; Hajdu et al., 2019). Among these soil properties, ρ_d and clay content were the most relevant to the findings of this study. The results of this study showed that relatively lower precisions were observed when ρ_d values were greater than 1.8 g·cm^{-3} at the Bronkhorstspruit site. Consequently, the accuracy of θ_v estimation decreased with soil depth as ρd values increased with depth at Bronkhorstspruit. These findings are in agreement with the study of Huang et al. (2004), who reported that θ_v estimated using capacitance-based sensors deviated from θ_v measurements at greater bulk densities. The accuracy of θ_v estimation decreased with soil depth as clay content increased at all sites, as also noted by Hajdu et al. (2019).

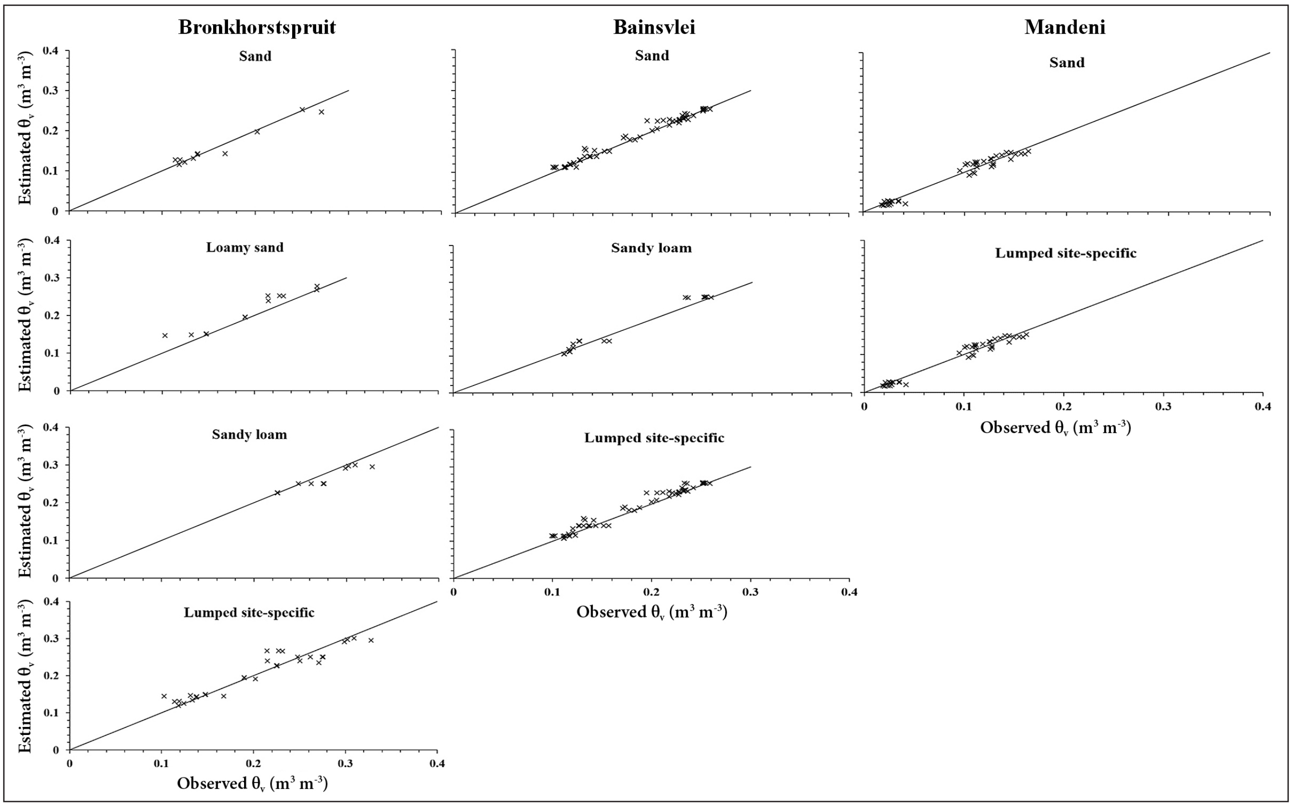

Figure 4. Validation of textural and lumped site-specific calibration equations of DFM capacitance probes at all three study sites

Table 4. Statistical results for the validation of the textural and lumped site-specific calibration equations of DFM capacitance probes at all three sites

Site	Textural class	n	RMSE (m^3·m^{-3})	MBE (m^3·m^{-3})	m (m^3·m^{-3})	C (m^3·m^{-3})	r^2	d
Bainsvlei	Sand	42	0.011	0.004	0.951	0.014	0.97	0.98
	Sandy loam	23	0.012	0.005	1.050	0.003	0.98	0.99
	Lumped site-specific	65	0.020	0.012	0.992	0.008	0.97	0.99
Bronkhorstspruit	Sand	12	0.012	−0.003	0.880	0.017	0.96	0.98
	Loamy sand	12	0.018	0.016	0.934	0.029	0.93	0.93
	Sandy loam	12	0.015	−0.010	0.774	0.051	0.91	0.95
	Lumped site-specific	36	0.020	0.002	0.8642	0.030	0.91	0.98
Mandeni	Sand	40	0.010	−0.001	1.020	0.003	0.96	0.99
	Lumped site-specific	40	0.010	−0.001	1.020	0.003	0.96	0.99

Furthermore, results confirmed that lumped site-specific calibration equations result in lower accuracy when compared to the textural site-specific calibration equations (Da Silva et al., 2007; Dhakal et al., 2019). However, the performance of the lumped site-specific calibration equations was satisfactory, with r^2 values ranging from 0.91 to 0.97 and RMSE values ranging from 0.010 to 0.020 $m^3 \cdot m^{-3}$. The d values greater than 0.98 indicated a very good similarity between measured and estimated θ_v from lumped site-specific calibration equations at all sites. The findings of this study suggest that textural site-specific calibration equations should be given preference over lumped site-specific calibrations for accurate monitoring of θ_v using DFM capacitance probes. The findings of this study are in agreement with the previous studies which demonstrated the need for textural-specific calibration to attain more accurate soil moisture measurements when using multi-depth capacitance sensors (Huang et al., 2004; Evett et al., 2006; Dhakal et al., 2019; Hajdu et al., 2019).

Field calibration, such as that undertaken in this study, had a limited number of measurements, was labour-intensive and exhibited some errors in heterogeneous soils as gravimetric samples were taken beyond the sphere of influence of the probes. However, previous research has shown that the accuracy of any calibration equation increases with the number of observations and the accuracy of the gravimetric samples as the reference (Kinzli et al., 2011; Bello et al., 2019; Tfwala et al., 2019a). Geesing et al. (2004), Kinzli et al. (2011), Bello et al. (2019) and Tfwala et al. (2019a) showed that laboratory equations developed using undisturbed soil samples through evaporative desorption procedure and continuous measurements of weight loss of the soil cores were more accurate than field calibrations. Some of these observations were due to the colocation, as the sensor readings were recorded on the same soil volume that was weighed for θ_g. Therefore, laboratory equations developed using undisturbed soil samples may provide a suitable alternative methodology that is more reliable, with lower labour requirements for calibration of capacitance-based sensors (Bello et al., 2019; Hajdu et al., 2019; Tfwala et al., 2019a). However, laboratory facilities are costly, and transporting and soil sampling of undisturbed core samples for laboratory studies may alter the soil properties (Tfwala et al., 2019a).

The findings of our study indicated that the RMSE values of all developed textural and lumped site-specific calibration equations were within the acceptable levels of accuracy (< 0.04 $m^3 \cdot m^{-3}$) required for calibration and validation of soil moisture estimates from remote sensing and hydrological models (Rowlandson et al., 2013; Ojo et al., 2015b). Therefore, the results of this study indicated that the field calibration methodology undertaken in this study, which is cheaper and less time-consuming, is adequate for calibration of DFM capacitance probes. Furthermore, the findings of this study suggest that once DFM capacitance probes are calibrated per site, they can be reliably used for accurate in-situ soil moisture measurements in different agro-climatic conditions of South Africa, to support validation and verification of soil moisture estimates. The findings of this study are in agreement with previous studies which demonstrated that field calibration equations developed with numerous gravimetric samples at different soil moisture contents give acceptable levels of accuracy (Kaleita et al., 2005; Qi and Helmers, 2008; Ojo et al., 2015a; Poltoradnev et al., 2014; Hajdu et al., 2019).

The lack of site-specific calibration equations as the result of financial constraints limits the use of collected data for verification of remote-sensing products and hydrological models in this region (Myeni et al., 2019). The proposed field calibration methodology can be reliably used to correct datasets that have been collected over years by soil moisture sensors that have been deployed in monitoring networks without prior site-specific calibrations in this region.

CONCLUSIONS

This study aimed to optimize the accuracy of DFM capacitance probes within the framework of the ARC monitoring network to ensure high-quality soil moisture measurements. The study was undertaken to develop textural and lumped site-specific calibration equations for DFM capacitance probes, and to evaluate the accuracy levels of the developed calibration equations for continuous soil moisture monitoring in three selected soil types, under different agro-climatic conditions of South Africa. The results indicated that all developed textural and lumped site-specific calibration equations were linear functions. They also indicated that all developed calibration equations estimated θ_v reasonably, although a relatively lower precision was observed at the Bronkhorstspruit site as a result of the presence of stones, which resulted in voids and air gaps between the sensor and the soil. The best estimations of θ_v were observed at the Mandeni and Bainsvlei sites. The results also showed that lumped site-specific calibration equations resulted in a lower accuracy compared to the textural site-specific calibration equations. However, the performance of lumped site-specific calibrations was satisfactory at all sites. The results indicated that textural site-specific calibration equations should be given preference over lumped site-specific calibrations to attain more accurate θ_v measurements when using DFM capacitance probes.

This study showed that the DFM capacitance probes require calibration for different soil types to attain accurate soil moisture measurements. Therefore, this study is expected to raise awareness among probe users regarding the potential errors and implications attributed to the use of the DFM capacitance probes without any calibrations. The results of this study indicated that the field calibration methodology undertaken in this study, which is cheaper and less time-consuming than traditional field calibration techniques is adequate for calibration of DFM capacitance probes. Furthermore, the findings of this study suggest that once DFM capacitance probes have been calibrated per site, they can be reliably used for accurate in-situ soil moisture measurements in different agro-ecological conditions of South Africa, to support validation and verification of soil moisture estimates.

AUTHOR CONTRIBUTIONS

Conceptualization, L Myeni and ME Moeletsi; methodology, L Myeni, AD Clulow and ME Moeletsi; data analysis L Myeni, original draft preparation and writing, L Myeni; review and editing, L Myeni, AD Clulow and ME Moeletsi; supervision, ME Moeletsi and AD Clulow.

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