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Towards a general equation for frequency domain reflectometers

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SUMMARY

It is well documented that capacitance-based soil moisture sensor measurements are particularly influenced by particle size distribution, density, salinity, and temperature of a soil, in addition to its moisture content. Moreover, the equations provided by manufacturers of soil moisture sensors are often only applicable to a limited number of soil types, thus yielding significant errors when compared with gravimetric measurements for observations in real soils. This limitation makes site-specific calibrations of such sensors necessary. Consequently, development of a general equation provides the possibility to derive the needed parameters from information such as soil type or particle size distribution. This paper describes the development of a general equation for the Campbell Scientific CS616 Water Content Reflectometers using data from sensors installed throughout the Goulburn River experimental catchment. It is subsequently tested using monitoring sites in the Murrumbidgee Soil Moisture Monitoring Network, which were not part of the original development; both monitoring networks are located in south-eastern Australia. Previously developed equations for temperature correction and soil moisture estimation using the Campbell Scientific CS615 Water Content Reflectometer are adapted to the new CS616 sensor. Moreover, relationships between readily available soil properties and the parameters of the general equations are derived. It is shown that the general equations developed here can be applied to data collected in the field using only information on the soil particle size distribution with an RMSE of around 6% m³/m³ (<1% m³/m³ under laboratory conditions; which is a significant improvement in comparison to 14% m³/m³ when using the manufacturer's equations).

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Introduction

Regular and relatively direct information on the actual moisture content within the soil profile can only be obtained from *in situ* observations using automatic measurement techniques. Over the past decade, and with the impending launch of two dedicated soil moisture satellite missions, several countries have recognised the importance of soil moisture information in a range of environmental applications (Robinson et al., 2008). Consequently, these countries now have extensive *in situ* soil moisture monitoring networks. Perhaps the most notable networks are the Oklahoma Mesonet network (Brock et al., 1995) and the nationwide Soil Climate Analyses Network (SCAN) operated by the US Department of Agriculture's National Resources Conservation Service (USDA NRCS). Other relevant networks include the Soil Moisture Observ-

ing System – Meteorological Automatic Network Integrated Application (SMOSMANIA) in France (Albergel et al., 2008), the Soil Moisture Measurement Stations Network of the University of Salamanca (REMEDIUS) near Salamanca in Spain (Martínez-Fernández and Ceballos, 2005), the Canadian Central Saskatchewan and Southern Ontario networks, the Goulburn River experimental catchment (Rüdiger et al., 2007) and Murrumbidgee Soil Moisture Monitoring Network (www.oznet.unimelb.edu.au) in Australia, and the African Monsoon Multidisciplinary Analysis–Coupling the Tropical Atmosphere and the Hydrological Cycle (AMMA–CATCH) soil moisture network in western Africa (Lebel et al., *in press*). These networks have typically used the Delta-T Devices Theta Probe, Stevens Water Hydra Probe, or Campbell Scientific Water Content Reflectometer (CS615 or CS616) as their sensing device.

One of the major tasks in establishing these networks has been the necessity for site-specific calibration of the sensors. While Merlin et al. (2007) have presented a general equation for processing the Hydra Probe data and Western and Seyfried (2005) have developed an empirical approach for the CS615, there are no established procedures for the other sensor types. Consequently, this paper develops a general equation for the CS616, the successor of the

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CS615; both instrument types have been in use for several years at various field sites throughout the world (e.g. Woods et al., 2001; Stenger et al., 2005; Rüdiger et al., 2007).

It is well known that soil moisture sensors typically require a soil type-specific calibration to ensure that their interpretation properly represents the volumetric water content at different field sites (Seyfried and Murdock, 2001; Blonquist et al., 2005; Western and Seyfried, 2005; Kizito et al., 2008). As the equations provided by the manufacturers are generally limited to a specific soil type (often loam) under laboratory conditions, they typically cannot be applied to measurements taken in other types of soil. Consequently, equations for a generic application to soils typically found in the field must be developed, in order for the interpretation of soil moisture data from large networks across diverse soil types to be practically tractable.

Following the work of Western and Seyfried (2005) for the CS615, new equations and parameters for the CS616 are developed, as laboratory results obtained in initial calibration efforts for the Goulburn River catchment instrumentation have shown that these two sensor types have a very different response. This is mostly due to the different frequency ranges used by each sensor type (45–70 MHz in free air for the CS615 and CS616, respectively). While a small number of studies have undertaken the calibration of CS616 sensors (e.g. Blonquist et al., 2005; Plauborg et al., 2005; Kelleners et al., 2005), these studies have not presented a general equation and typically used complex theoretical dielectric models to obtain soil moisture from the raw period measurements, rather than the comparatively simple equations presented here.

While this paper uses similar equations to those of Western and Seyfried (2005), there are two distinct differences: (i) the sensor used here operates in a higher frequency range and (ii) the relationships are generalised to require only soil texture information, making them applicable to a wide range of soil types. Data used for developing the relationships is taken from site-specific calibrations of sensor installations in the Goulburn River experimental catchment in New South Wales, Australia (Rüdiger et al., 2007). Several distinctly different soil types are found in this region, ranging from sandy soils to heavy black clays, with varying soil densities and salinities. The availability of consistent data from such a wide range of soil types allows for the derivation of a generalised relationship with applicability to a range of different soils. This relationship is subsequently applied to independent data from another field site in Australia, the Murrumbidgee Monitoring Network (www.oznet.unimelb.edu.au), where the soils have a higher silt content.

Background

Several studies have investigated frequency domain reflectometry sensor response to changes in soil moisture (e.g. Gong et al., 2003), and for the CS615 in particular (e.g. Seyfried and Murdock, 2001; Quinones et al., 2003; Stenger et al., 2005; Western and Seyfried, 2005), under varying conditions. However, there are comparatively fewer studies that have used the CS616 (e.g. Blonquist et al., 2005; Plauborg et al., 2005; Kelleners et al., 2005). Moreover, those studies have used either a simple linear equation to correct for the bias in calculated soil moisture due to differences in the soil type (Plauborg et al., 2005) or compared the calculated soil electric permittivity of the sensor with dielectric model predictions from the soil moisture data (Blonquist et al., 2005; Kelleners et al., 2005), without providing more accurate inference equations. In contrast, Western and Seyfried (2005) have developed a set of equations that use site-specific parameters for interpretation of CS615 data. As both the CS615 and CS616 sensors are based on the same principles, the equations developed in that study have been extended

for application to the CS616 herein. The equations of Western and Seyfried (2005) are

$$\theta = 0.4N^\beta, \quad (1)$$

where θ is the soil moisture content (m^3/m^3); β is a shape parameter of the function; and N is the dimensionless normalised period measurement of the sensor, defined as

$$N = \frac{P^{25} - P_{0.0}}{P_{0.4} - P_{0.0}}, \quad (2)$$

where P^{25} is the temperature corrected (to 25 °C) period measurement of the sensor at the current soil moisture content (in milliseconds (ms) for the CS615 and microseconds (μs) for the CS616), effectively eliminating the temperature effects on the sensor; $P_{0.0}$ is the period for oven dried soil at 25 °C (ms or μs); and $P_{0.4}$ is the soil type-specific period for a moisture content of $0.4 \text{ m}^3/\text{m}^3$ at 25 °C (ms or μs). $P_{0.0}$ has typically been estimated from laboratory measurements in oven dried soil, with only a small variation between soil types. The remaining parameters were estimated globally for all soil types by jointly optimising the shape parameter β (a single parameter value valid for observations at all sites) of Eq. (1) and the nominally saturated soil period $P_{0.4}$ (a site and soil type-specific parameter) of Eq. (2).

The temperature corrected period measurement P^{25} is obtained through

$$P^{25} = P_{\text{obs}} - C^T(T - 25), \quad (3)$$

where P_{obs} is the uncorrected period (ms or μs) measurement made at the actual soil temperature T (°C); and C^T is a temperature correction coefficient ($\text{ms}/^\circ\text{C}$ or $\mu\text{s}/^\circ\text{C}$) derived from laboratory experiments (see Section 4.1). Western and Seyfried (2005) found that typical root mean square errors (RMSE) from independent validation measurements were $<0.03 \text{ m}^3/\text{m}^3$.

Data

Goulburn River experimental catchment

CS616 Water Content Reflectometers were installed at 26 soil moisture monitoring sites throughout the Goulburn River experimental catchment (Rüdiger et al., 2007), inserted vertically into the soil over different depths (0–300, 300–600, and 600–900 mm) to monitor the soil moisture profile throughout the root zone. Temperature sensors were placed at the mid-point of the top-most sensors for temperature correction at all locations with two locations having a full soil temperature profile alongside the reflectometers. Soil samples were extracted at the various soil moisture monitoring site near the actual point of installation of the *in situ* sensors by auguring, meaning the soil needed to be re-compacted to its original bulk density for laboratory calibration of the sensors. To avoid overrepresentation of any particular soil type in the calibration, not all available soil samples were used. The soil samples used are shown in Table 1, representing soil types ranging from almost pure sands at M2 to heavy clays at K3. Unfortunately, soil types with an intermediate particle size distribution were not available for this study site, due to the geology in the catchment (Rüdiger et al., 2007). As soils with an intermediate particle size distribution are missing, the analysis of the results is based on either very coarse or very fine material soils. Therefore, to validate the applicability of these equations, data from another field site in Australia were obtained. Those are used to estimate the parameters and then derive a soil moisture content which is then compared to *in situ* soil moisture observations obtained via time-domain reflectometry (TDR) measurements.

Table 1

Site specific particle size distributions and salinities of the soils used in the laboratory experiment, according to the Australian classification system. The soil salinities were obtained using a 5:1 water to soil solution and then converted into corresponding values as would have been obtained with the paste extraction method, using an empirical equation validated for Australian soils (Loveday, 1974).

Station	Station, depth	Clay%	Silt%	Sand%	Salinity (dS/m)
G1	300–600	n/a	n/a	n/a	0.168
	600–900	n/a	n/a	n/a	0.469
G2	0–300	21	56	23	0.520
G3	0–300	64	25	11	0.605
G4	300–600	11	13	76	0.154
G5	0–300	9	17	74	0.254
G6	0–300	33	35	32	0.492
K2	0–300	6.5	8.5	85	0.141
	600–900	n/a	n/a	n/a	0.249
K3	0–300	71	23	6	0.472
K5	0–300	62	26	12	0.368
K6	0–300	35	44	21	3.789
M1	0–300	6.5	21.5	72	0.189
M2	0–300	0	6	94	0.415
M3	0–300	36	43	21	0.590
M4	0–300	25	49.5	25.5	0.398
M5	0–300	69	21	10	0.825
M6	0–300	51	17.5	31.5	0.407
M7	0–300	35	40	25	0.696
	600–900	n/a	n/a	n/a	0.995
S1	0–300	54	40	6	0.454
S2	0–300	39	35	26	0.394
S3	0–300	n/a	n/a	n/a	0.588
S4	0–300	n/a	n/a	n/a	1.096
S6	0–300	41	28	31	n/a

While this paper does not address the effects of salinity on the CS616 measurements, it is acknowledged that soil salinity has a significant effect on the performance of **Water Content Reflectometers**, particularly at high water contents (e.g. Kim and Benson, 2002; Kizito et al., 2008). Salinities of each site were determined (Table 1), to ensure that the soils were within the manufacturer's specifications. Moreover, with one exception, there was no observable impact of salinity on the data used in this paper. The manufacturer's specifications detail that the CS616 is particularly affected by salinity above **1.5 dS/m** (Campbell Scientific Inc., 2002). This threshold is only exceeded by the soil at K6 (and in that case quite significantly with **3.8 d S/m**). While an individual calibration was derived for this particular soil, it was not included in the optimisation of the global parameters, to avoid undesired effects because of the potential bias resulting from the high salinity.

Murrumbidgee **Soil Moisture Monitoring Network**

The Murrumbidgee Soil Moisture Monitoring Network (MSMMN) is located within the **80,000 km²** catchment of the Murrumbidgee River in south-eastern Australia. While the first monitoring sites installed used the CS615 sensor, more recent expansion of the network used the CS616 (as the CS615 was no longer available), bringing the total number of stations to 38. Sensors were installed in a similar configuration to monitoring sites in the Goulburn River catchment. Additionally, **time-domain** reflectometry (TDR) measurements were made on a periodic basis. The soils in the Murrumbidgee River catchment are predominantly silts, with a number of more sandy sites in the western reaches of the catchment. In this study, soil samples and **in situ** data from both TDR and CS616 obtained from sites within the Kyeamba catchment, one of the subcatchments within the MSMMN, are used for the validation of the general equation developed with the soils from the Goulburn River experimental catchment.

Laboratory analysis

The CS616 consists of a printed circuit board and two parallel stainless steel rods. The rods are 3.2 mm in diameter, 300 mm long with a spatial separation of 32 mm (see Western and Seyfried (2005) and Benson and Wang (2006) for detailed descriptions of the sensors' specifications). These two rods act as wave guides for the electrical impulse, and due to their configuration a relatively large quantity of soil is measured, meaning a large sample size was required for the laboratory experiments. The soils used here were placed into a container **150 mm** in diameter and **400 mm** high (**325 mm** filling depth), to allow for the required clearances of at least **25 mm** between the sensor and the container walls as specified by the manufacturer (Campbell Scientific Inc., 2002). Each container was also equipped with a thermocouple placed at **150 mm** in the centre of the container to monitor the soil temperature of the soil column. The containers were vertically suspended from load cells, which were constantly measuring the change in weight of the soil through which the volumetric soil moisture content was calculated. The load cells were recalibrated before each new soil batch was loaded and no discernible changes in the conversion from voltage into weight were observed. In order to avoid losses due to evaporation from the soil surface, the containers were sealed with lids that were only removed for adding water to the soil column and then resealed.

In previous studies (e.g. Quinones et al., 2003; Western and Seyfried, 2005; Kizito et al., 2008) soil moisture content was increased by removing the soil from the containers, oven-drying and adding a known quantity of water. The soil would then be mixed to ensure a homogeneous distribution of the water throughout the soil before repacking the soil into the containers. This procedure was not followed here as it would not be guaranteed that the pore structure or density of the soil would resemble that of the previous measurement. Rather, the soil moisture content was increased by adding water to the top of the container and allowing time for the water to fully infiltrate into the soil column. It was assumed that the water was properly infiltrated and in equilibrium when the sensor measurement did not show any further changes over a period of approximately **4 h**. This ensured that soil density, pore structure, and sensor orientation were not changed throughout the experiment. While it could be argued that this laboratory set up does not ensure that the water is homogeneously distributed over the soil column, the same could be said for measurements made in the field, where infiltration occurs from the soil surface. The bottom of the cylinders contained holes to prevent air from being trapped in the process. Water loss only occurred through these holes when the soil reached its field capacity. This did not pose a problem as the loss was recorded through the load cell measurements.

Only data of the equilibrium soil water state were included in the analysis. All other data collected during the advancement of the wetting front and any data artefacts were removed. A scatterplot showing the uncorrected laboratory measurements at ambient temperature for the various soils is presented in Fig. 1. In this figure three distinct groups of data are identified. The first group (near the dashed line representing the manufacturer's equation) are the coarse sandy soils. This is followed by the clayey (and higher electrical conductivity) soils displaying a shift to the higher period measurements. The third group consists only of the measurements within the soil from site K6, which displays a significant shift in the period measurements, due to the soil's high salinity/electrical conductivity (consequently increasing the apparent soil moisture). These data show that both salinity and soil type may play significant roles in the retrieval of the soil moisture content. It is also concluded that the equation provided by the manufacturer can only be applied to coarse material soils, as the conversion from voltage to soil moisture will otherwise result in

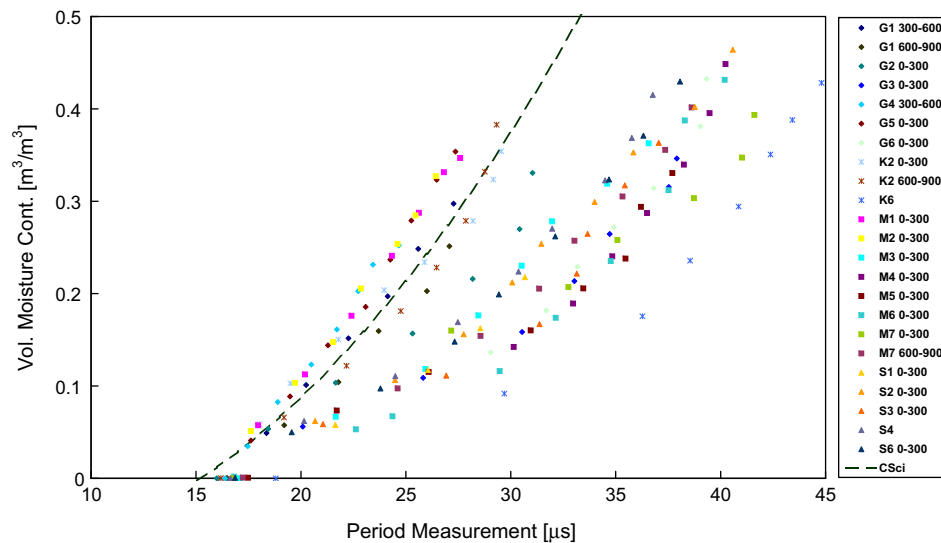


Fig. 1. Scatterplot showing the Water Content Reflectometer measurements (oscillation period) and the corresponding soil moisture content (gravimetric measurement), as well as the soil moisture calculated with the manufacturer's calibration equation (dotted line).

a significant overestimation of the soil moisture content for fine material soils.

General equation

Temperature correction

To determine the effect of variations in soil temperature on the sensor response, eight soil samples, representative of the different soils throughout the Goulburn River experimental catchment, were chosen. These samples were then subjected to a range of temperatures at different levels of soil moisture content in order to derive parameters for the temperature correction of Eq. (3). The temperatures ranged from ambient ($\sim 20^\circ\text{C}$) to 45°C . Other studies (e.g. Western and Seyfried, 2005; Benson and Wang, 2006) have shown that the temperature effects are generally linear for temperatures above 4°C and constant soil moisture content. This is confirmed in Fig. 2. The (apparent) hysteresis effect in the cool-down phase of the soil is due to the peripheral soil cooling down more quickly than the temperature sensor located in the centre of the cylinder. Because of the above results, it was not considered critical to consider hysteresis or temperatures lower than ambient in deriving

the temperature correction relationship. Consequently, the equations provided in this paper should only be used for soil temperatures above 4°C .

Following Western and Seyfried (2005), the temperature correction coefficient C^T of Eq. (3) was found to be a function of the soil moisture content, with the temperature effect increasing with increasing soil moisture content (Fig. 3). Western and Seyfried (2005) developed a single temperature correction equation with fixed parameters valid for all soil types that was dependent on P^{25} . Because P^{25} varied with soil type for a given soil moisture content, their approach implicitly captured both soil moisture and soil type effects. However, this was found to be insufficient for the CS616 because the slope of the C^T and P^{25} regression lines (s) were observed to vary as a function of the soil type (Fig. 4). The reason for this difference between the two instruments is not fully understood but is likely to be related, at least in part, to differences in complex dielectric behaviour at the different measurement frequencies of the two instruments. This is consistent with the findings published by Benson and Wang (2006), which showed a distinct difference in the temperature correction coefficient from sandy to clayey soils. Similarly, Escorihuela et al. (2007) observed an increase in the relationship between the temperature correction

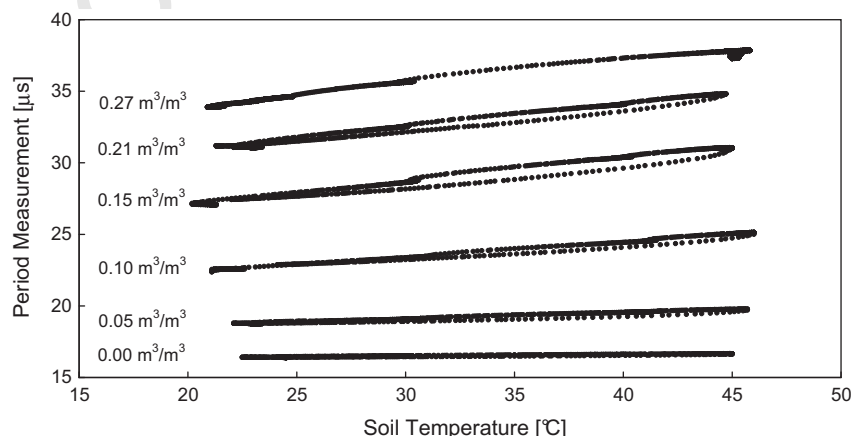


Fig. 2. Influence of temperature variability on the period measurement of a typical soil within the Goulburn River experimental catchment (G2) at different soil moisture levels. The hysteresis occurs clockwise (as does the heating and cooling effect).

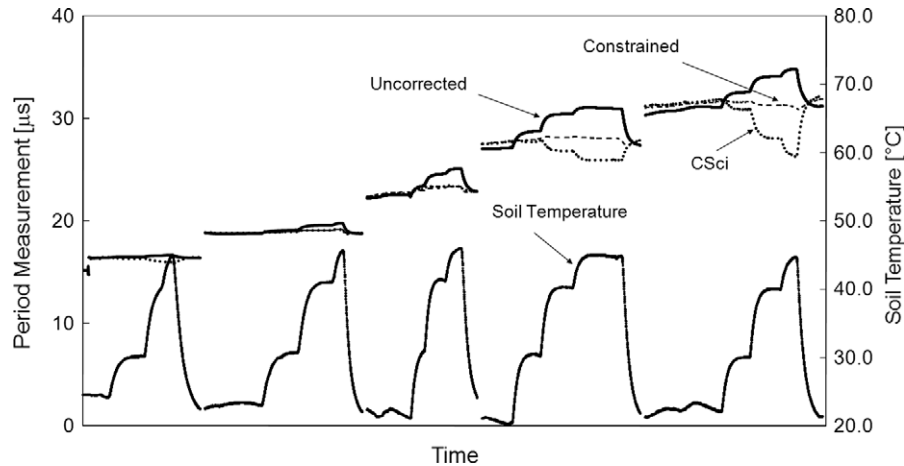


Fig. 3. Example of temperature effects in the sensor response for a silty soil (G2), with the wetting phase removed from the time series. The temperature was varied from 20 °C to 45 °C for different soil moisture levels; the uncorrected response (solid line) shows significant temperature effects, increasing the apparent soil moisture content as compared to the response corrected with the constrained approach ($P_{0,0}$ set to 16.81 μs) (dashed line) with the parameters derived herein. The manufacturer's temperature correction (CSci, dotted line) is shown for reference.

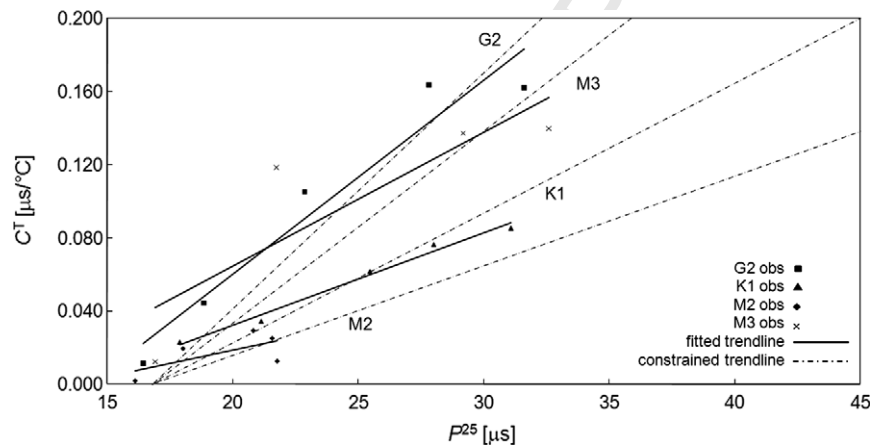


Fig. 4. Correlation between soil specific temperature correction (C^T) and temperature corrected period (P^{25}) values for four of the eight soil types tested. The measurements are represented by symbols, best fit trend lines are shown as solid lines, and fitted lines with an intercept at 16.81 μs (the average of all observed $P_{0,0}$ values) are shown as dashed-dotted lines.

and the dielectric constant for a sensor operating at 100 MHz. They also found that the slope of the correction function reduced at elevated soil moisture levels.

The results of Fig. 4 shows that C^T in soils with predominantly fine particles has a more significant influence on the sensor response (increased C^T) with increasing period measurements (i.e. higher soil moisture) than in more sandy soils. This observation is consistent with findings in other studies (e.g. Benson and Wang, 2006). While a non-linear equation for C^T as a function of the period measurement results in a better fit for the data shown in Fig. 4, it did not significantly improve the temperature correction of the observations. Consequently, it was decided to define linear best fit functions with a constant intercept of 16.81 μs , which is the average period measurement of oven dried soil (with a standard deviation of 0.47 μs) for the full range of soil types used in this study, and which was found to be almost soil temperature independent. The standardised equation for C^T as a function of P^{25} is then defined as

$$C^T = sP^{25} + o, \quad (4)$$

where s is the slope of the regression line and o is the y-intercept of the intersection point through the y-axis (1/°C and $\mu\text{s}/^\circ\text{C}$, respectively), as shown in Fig. 4.

Substituting Eq. (4) into Eq. (3) and rearranging the new equation to solve for P^{25} yields the equation for temperature corrected period measurement

$$P^{25} = \frac{P_{\text{obs}} - o(T - 25)}{1 + s(T - 25)}, \quad (5a)$$

with s and o being soil type-specific parameters. Rearranging Eq. (4) and assuming that the temperature correction coefficient for oven-dry soils is $C^T(P_{0,0}) = 0$ (where $P_{0,0}$ is the above 16.81 μs for oven-dry soils), Eq. (4) becomes $o = sP_{0,0}$. Consequently, Eq. (5a) simplifies to:

$$P^{25} = \frac{P_{\text{obs}} + (sP_{0,0})(T - 25)}{1 + s(T - 25)}, \quad (5b)$$

where by P^{25} is now only dependent on the selection of s , as T and P_{obs} are observed and $P_{0,0}$ is set at 16.81 μs . The difference here from Eqs. (1)–(3) is therefore the inclusion of a soil type dependency of C^T through the new parameters s (and implicitly o). The values for s for the different soil types are presented in Table 2, where s is shown to increase with an increase in the fraction of fine particles.

The validity of the temperature correction is shown in Fig. 3, where the derived temperature correction equation is applied to the original temperature effected sensor response. In this case, a soil sample (G2) was subjected to different temperatures, while

Table 2
Soil type-specific temperature calibration parameters for the slope (s) and the offset (o) of Eq. (5a) for soils with a forced intercept. Soil types here are defined according to the Australian soil texture classification (AS 1289.0–2000).

Soil type	Slope (s) (1/°C)	Offset (o) (μs/°C)
Sand	0.00257	−0.04318
Sandy loam	0.00393	−0.06602
Loam	0.00805	−0.13542
Silt loam	0.00825	−0.13860
Clay loam	0.00841	−0.14129
Clay	0.00757	−0.12718

simultaneously observing the soil temperature in the samples centre and the period measurement of the CS616. This was undertaken by first placing the oven-dry sample in the container and raising the air temperature in steps from ambient to 45 °C. At each step the temperature would only be raised further, after the observed soil temperature had reached its target temperature. This was then repeated for temperatures at 30 °C, 40 °C and 45 °C, respectively. After reaching 45 °C, the heating was turned off and the soil temperature would slowly return to ambient. Water was then added before the temperature cycle was repeated for another level of soil moisture within the sample. A total of five moisture levels were tested from dry through to wet. Also shown for comparison on Fig. 3 is the manufacturers temperature correction equation, which significantly overcompensates for the effect of temperature for this

soil type. These results show the poor response of the manufacturers correction equation especially for soil temperatures above 30 °C, which are frequent for many parts of the world.

Soil moisture calculation

As discussed previously, three groups of soil type-specific sensor responses were identified in Fig. 1, with soil type and salinity playing an important role in the sensor response. When plotting the data as a normalised period response according to Eq. (2), it was found that the normalised period measurements below a certain threshold were linearly related to the soil moisture observations (Fig. 5a and b). Moreover, the non-linear two-parameter relationship of Western and Seyfried (2005) resulted in a consistently underestimated soil moisture content for very dry or very wet conditions (mean bias of 0.01 m³/m³), which is particularly significant for dominantly dry environments. Conversely, the soil moisture content of moderately humid conditions (between 0.12 and 0.3 m³/m³) was found to be overestimated by 0.01 m³/m³. The overall RMSE of this non-linear equation was 0.025 m³/m³. A linear fit to the data was also tested, but found to be significantly biased for all soil moisture conditions (−0.012/−0.016/0.027 m³/m³). Moreover, several derived $P_{0.4}$ values were found to be outside of the operational range of the instruments, and consequently were not acceptable as parameters for a soil moisture content of 0.4 m³/m³.

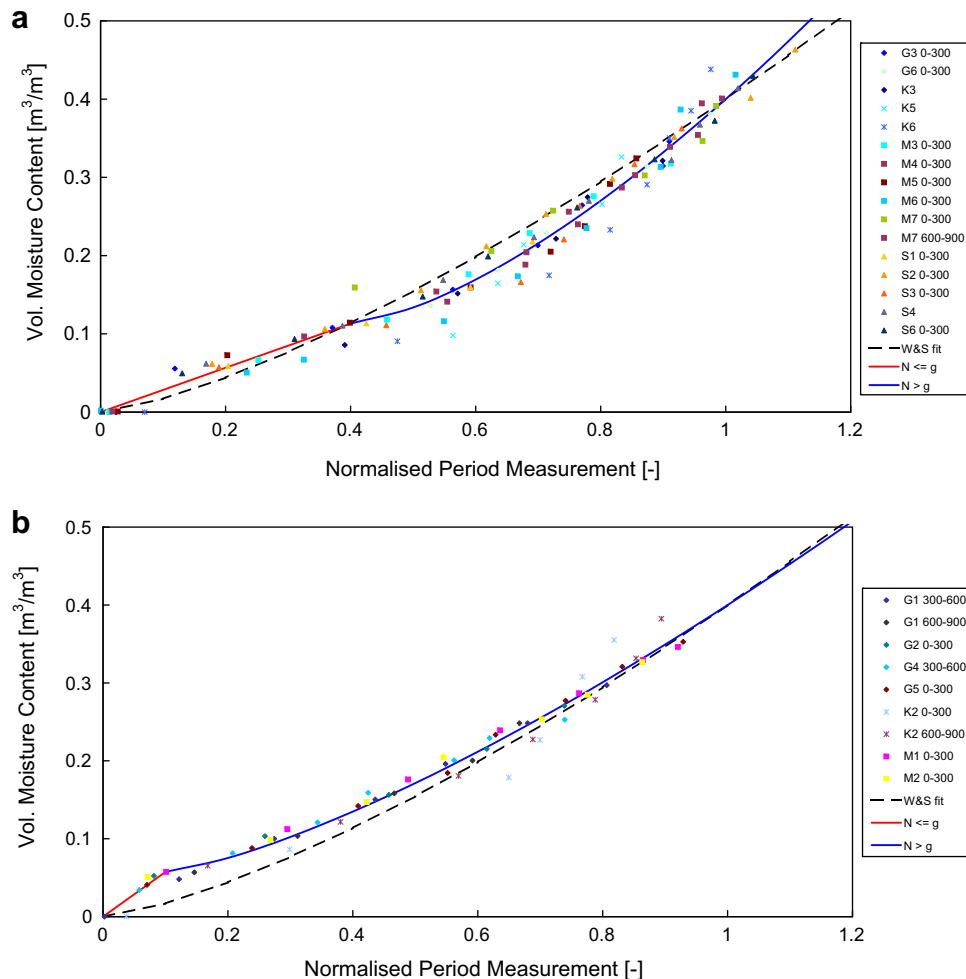


Fig. 5. Calibration curves for (a) fine and (b) coarse material soils. Both plots also show the results from the new soil specific calibration equations (solid line) with linear and non-linear response components and the result from applying the original equation in Eq. (1) (dashed line).

As the linear relationship between N and the observed soil moisture content was only observed for relatively dry conditions, it required a new formulation of Eq. (1) to allow for both wet and dry soil moisture conditions. Consequently, Eq. (1) was extended to allow its application to different soil types and soil moisture ranges, while still maintaining a similar structure. Consequently Eq. (1) becomes

$$\theta = \alpha N \quad \text{for } N \leq \gamma \quad (6a)$$

and

$$\theta = \alpha\gamma + \left(\frac{0.4 - \alpha\gamma}{(1 - \gamma)^\beta} \right) (N - \gamma)^\beta \quad \text{for } N > \gamma, \quad (6b)$$

where α is the slope of the linear part of the function (m^3/m^3); and γ is the scaled soil moisture content at the point of transition from linear to non-linear sensor response (-). For γ equal to zero Eq. (6b) reverts back to Eq. (1). It is proposed that the same optimisation procedure as in Western and Seyfried (2005) be used to jointly optimise the parameters $P_{0.4}$ and β , together with the new parameters α and γ , where $P_{0.4}$ is a site-specific parameter and α , β and γ are general parameters, applicable to all sites. As it was found that the linear behaviour within sandy soils was limited to much lower soil moisture conditions than in fine material soils, α , β and γ were optimised independently for coarse and fine material soils, resulting in a parameter data set for each of the two soil categories. This separation of the soils into fine and coarse material soils improved the RMSE from $0.023 \text{ m}^3/\text{m}^3$ for a joint optimisation of all parameters

to $0.019 \text{ m}^3/\text{m}^3$ and $0.014 \text{ m}^3/\text{m}^3$ for fine and coarse material soils, respectively. The most significant correction was achieved in the dry and moderately humid range of the soil moisture conditions, with an almost complete removal of the biases. The values found for α , β and γ are shown in Table 3, presenting the distinctly different parameters for γ , underlining the importance to separate the soils into two categories. With the γ parameters obtained through the optimisation procedure, the different thresholds of the soil moisture content above which the sensor response appears to be non-linear is then calculated using 6a, resulting in $0.12 \text{ m}^3/\text{m}^3$ and $0.06 \text{ m}^3/\text{m}^3$, for fine or coarse material soils respectively (see Table 4).

Generalised parameters

The foregoing results show that several of the calibration parameters are correlated with soil type, particularly s , γ and $P_{0.4}$; as $P_{0.0}$ is defined as independent of soil type, a constant value of $16.81 \mu\text{s}$ is used. This provides an opportunity to estimate the parameters from commonly available soil properties alone, such as the soil particle size distribution and consequently the soil type. Application of the general equations using the generalised parameters developed here is summarised in Box 1.

Table 3

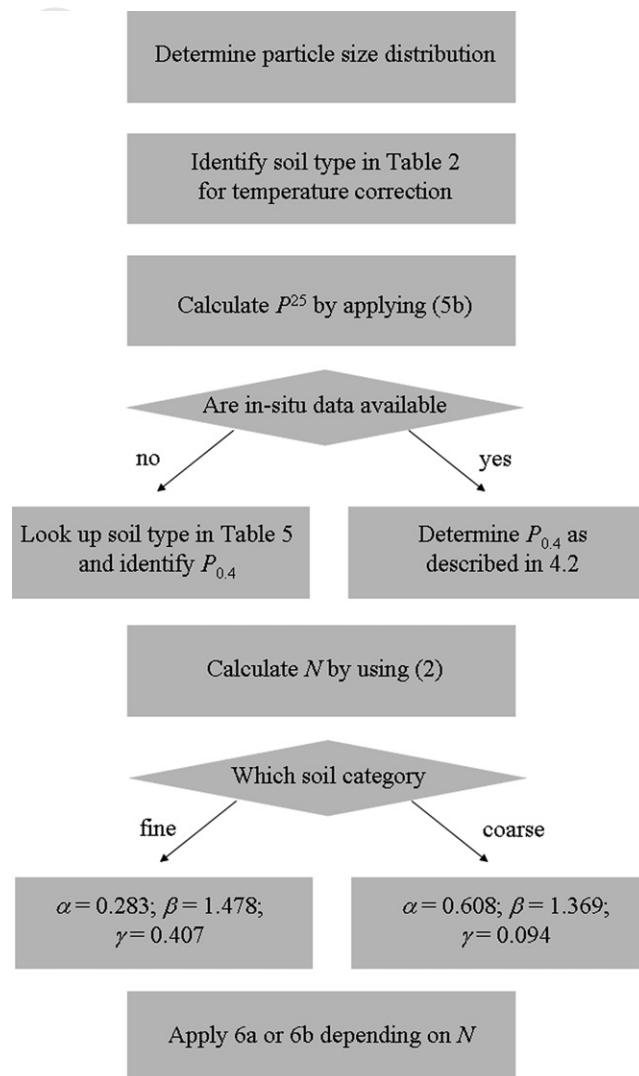
Curve parameters α , β , and γ for the two presented optimisation approaches, obtained through the use of the measurements from all sites to derive one general parameter set (A), or sites with fine particle soils (B_f) and sites with coarse particle soils (B_c), respectively.

Approach	α	β	γ
A	0.334	1.588	0.288
B_f	0.283	1.478	0.407
B_c	0.608	1.369	0.094

Table 4

Site-specific optimised $P_{0.4}$ (μs) calibration parameters, obtained from the soil classification into fine (B_f) and coarse materials (B_c) or using all available soil samples (A), as defined in Table 3.

Station, depth	Approach	$P_{0.4}$ (B_c or B_f) (μs)	$P_{0.4}$ (A) (μs)
G1 300–600	B_c	29.79	28.81
G1 600–900	B_c	32.87	31.07
G2 0–300	B_f	38.72	39.19
G3 0–300	B_f	39.99	40.19
G4 300–600	B_c	27.75	26.76
G5 0–300	B_c	28.12	27.54
G6 0–300	B_f	39.73	39.90
K2 0–300	B_c	33.09	31.89
K2 600–900	B_c	30.82	30.06
K6	B_f	44.98	45.15
M1 0–300	B_c	28.55	28.04
M2 0–300	B_c	27.97	27.31
M3 0–300	B_f	37.18	37.44
M4 0–300	B_f	40.42	40.59
M5 0–300	B_f	41.10	41.38
M6 0–300	B_f	40.01	40.14
M7 0–300	B_f	42.01	42.13
M7 600–900	B_f	39.01	39.14
S1 0–300	B_f	37.64	38.19
S2 0–300	B_f	38.37	38.42
S3 0–300	B_f	38.67	38.89
S4 0–300	B_f	36.53	36.64
S6 0–300	B_f	37.25	37.33



Box 1. Schematic of the recommended conversion path from P_{obs} to θ , as described in this paper.

It is important to note that the soil types discussed in this paper are based on the Australian soil texture classification in AS 1289.0 (Standards Australia, 2000). This classification differs from the USDA classification, which is often used in the USA and Europe. The detailed ranges of the particle sizes are (USDA definition in brackets): clay $< 2 \mu\text{m}$, $2 \mu\text{m} < \text{silt} < 20(50) \mu\text{m}$, and $20(50) \mu\text{m} < \text{sand} < 2000 \mu\text{m}$. In the following sections, the fraction of the fine particles is defined as the sum of the clay and silt fractions (CS; %) of the respective soil types, whereas coarse materials are represented by the fraction of sand. This classification may be important, as Western and Seyfried (2005) found that the correlation between soil particle distribution and the derived calibration parameters was negligible in the case of the CS615. However, their particle size distribution was based on the USDA and New Zealand classifications, while the soils in the present study were entirely analysed according to Australian standards only.

Temperature correction

Fig. 6a shows the slope parameter of the temperature correction equation plotted against the sum of the clay and silt fractions (CS) for each of the eight soil types analysed in the laboratory experiments. Here it can be seen that the slope parameter increased with fine particle content of the soil according to

$$s = 0.00009\text{CS} + 0.00284, \quad (7)$$

with an R^2 of 0.75.

As an example, the RMSE of the temperature corrected period measurements in a sandy and a clayey soil are shown in Table 5

Table 5

RMSE of the estimated P^{25} and soil moisture results from the temperature correction and soil moisture estimation experiment, respectively, for two contrasting soil types (G2 – silty loam; M2 – sand) and three different approaches (CSci – Campbell Scientific standard correction equation; site-specific – individually derived parameter s for 5b; general – parameter s derived from Eq. (7)) and also the RMSE, if no correction is performed. .

Approach	Temperature correction (μs)		Soil moisture estimation (m^3/m^3)	
	G2	M2	G2	M2
Uncorrected	1.769	0.338	–	–
CSci	3.151	0.297	0.079	0.044
Site-specific	0.355	0.102	0.019	0.016
General	0.375	0.185	0.038	0.014

for the uncorrected period measurement and three different correction approaches: (i) manufacturer's correction, (ii) soil type-specific individually derived correction to be used with Eq. (5b), and (iii) the use of Eq. (7) to calculate s . The two soils chosen from the laboratory experiment are a sand (M2; 0% clay, 6% silt, and 94% sand) and a silty loam (G2; 21%/56%/23%). There is an insignificant difference between the performance of (ii) and (iii), whereas the manufacturer's correction significantly overcompensated for the temperature in wet soils (see also Fig. 3). In the case of the silty loam (G2), the error in the period measurement is actually increased when using the manufacturer's relationship, suggesting that no correction would be preferable to the one supplied.

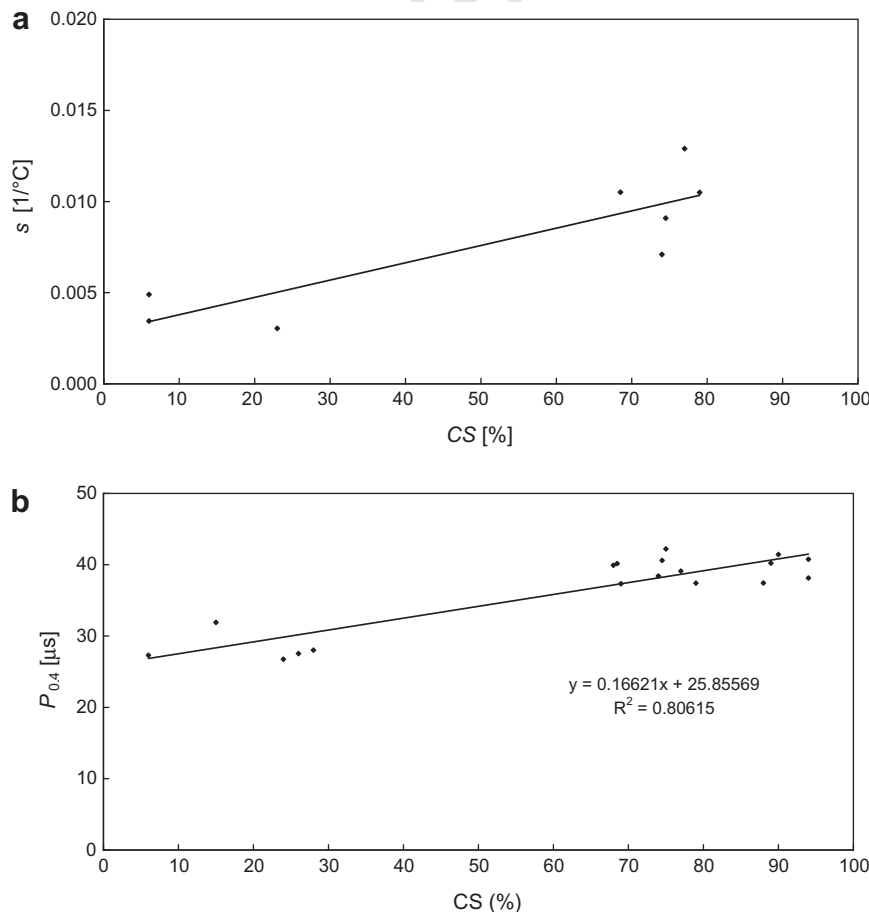


Fig. 6. (a) Correlation between slope (s) of the C^T function with forced intersect (\circ) as a function of clay plus silt fraction of the soil samples (CS); the symbols represent the different soil types from all eight temperature experiments, with a best fit trend line shown. (b) Relationship between the clay and silt content and the optimised $P_{0.4}$ values (symbols) and the best fit line (solid line).

While the above linear function is based on a limited amount of data points, the consistency of this finding with results from other studies suggests that a linear increase of C^T as a function of the particle size distribution is valid. However, a larger number of data are required to confirm Eq. (7). Nevertheless, a significant departure from the proposed function is not expected, as a non-linear function is expected to be between the either of the data clouds of Fig. 6a and the resulting error in the estimation of C^T would be negligible. The maximum error to be expected from the uncertainty due to the spread between the highest and lowest C^T values for clayey soils is to be found for wet and warm conditions. Using the minimum and maximum values of s found for clayey soils and calculating the soil moisture for such conditions ($37 \mu\text{s}$, 30°C) results in a difference of $0.014 \text{ m}^3/\text{m}^3$. As this is the expected maximum difference between two extreme values, any error will be smaller. This example also supports the previous assumption for defining a linear function for the relationship between C^T and P_{25} , as the resulting errors will be small.

Soil moisture calculation

As already noted, soils consisting of coarse material generally had a lower $P_{0.4}$ value than soil of fine material, as shown in Fig. 6b. The $P_{0.4}$ value was found to vary with particle size distribution according to

$$P_{0.4} = 0.16621 * CS + 25.85569, \quad (8)$$

with an R^2 value of 0.81. Using this approximation the RMSE in soil moisture for the same two soils and the different approaches used in the temperature correction example are presented in Table 5. Similar to the temperature correction, it shows that the newly developed equations reduce the initial error by more than half when compared to the soil moisture obtained with the manufacturer's equation with the general approach performing slightly less well, than the site-specific parameters.

Evaluation

Fig. 7 shows the soil moisture content estimated using the approach developed herein with soil type-specific (α , β , and γ) and site-specific ($P_{0.4}$) parameters, plotted against the laboratory soil moisture content observations. This plot shows a good relationship between the gravimetric and CS616 moisture contents (RMSE = $0.017 \text{ m}^3/\text{m}^3$ and $R^2 = 0.981$). As these results were obtained with soils used in derivation of the general equation and its parameters, this does not constitute an independent assessment. Consequently, *in situ* and laboratory CS616 and TDR obser-

ventions obtained for several sites of the Murrumbidgee Soil Moisture Monitoring Network (the Kyeamba Catchment specifically) have been used as an independent evaluation. The Kyeamba Creek catchment contains soils that are generally silty, a soil type rarely found in the Goulburn network. Consequently these observations are very suitable for an independent evaluation of the general equation and recommended parameters.

Results are presented for three approaches, using *in situ* data from five stations across the Murrumbidgee catchment area and various depths, for which a sufficient number of TDR readings were available (Fig. 8). The approaches are: (i) the equations provided by Campbell Scientific; (ii) site-specific value of $P_{0.4}$ by estimating the soil classification from the observed time series (Fig. 8a); and (iii) $P_{0.4}$ value derived from the empirical function given in Eq. (8) (Fig. 8b). As laboratory calibrations for three of the five soils are available, they can be compared to the empirical function derived from Fig. 6b. The combined clay and silt fraction of those three soil types is 25%, 38.5% and 49.7%. Applying Eq. (8), values of 30.01, 32.25, and $34.12 \mu\text{s}$ are estimated for $P_{0.4}$. Those values correspond well with the values found in the laboratory experiment performed for a number of soils of the MSMMN, being 29.65, 34.82, and $35.81 \mu\text{s}$, respectively. The RMSE of using the estimated $P_{0.4}$ parameters for these soils was found to be $0.034 \text{ m}^3/\text{m}^3$, while the application of the parameters obtained in laboratory yielded an RMSE of $0.012 \text{ m}^3/\text{m}^3$.

The overall RMSE values for the field data are $0.053 \text{ m}^3/\text{m}^3$, and $0.066 \text{ m}^3/\text{m}^3$ for approaches (ii) and (iii), respectively (the Campbell Scientific equation yielded an RMSE of $0.144 \text{ m}^3/\text{m}^3$ for the same data set). As expected, the RMSEs degraded when compared with the results for the Goulburn catchment soils from the study in the controlled experimental environment in the laboratory, as a result of being both independent sites and field measurements. Because observation inaccuracies of the sensors are additive, and the TDR measurements are assumed to be "true" in this study, i.e. without error, the overall RMSE may be smaller, if high quality gravimetric measurements had been obtained at the same time and used as a basis for comparison. However, the gravimetric measurements would have meant a destruction of the measuring volume in the field. A more detailed analysis revealed that sites with coarse material soils had smaller errors than sites with fine material soils, which is generally due to the coarse material soils reaching a lower soil moisture content than fine material soils. While an RMSE of $0.053\text{--}0.066 \text{ m}^3/\text{m}^3$ is slightly larger than what is typically desirable, these results are still acceptable and even better than other calibration efforts for the CS615 using site-specific, rather than general calibrations (Czarnomski et al., 2005;

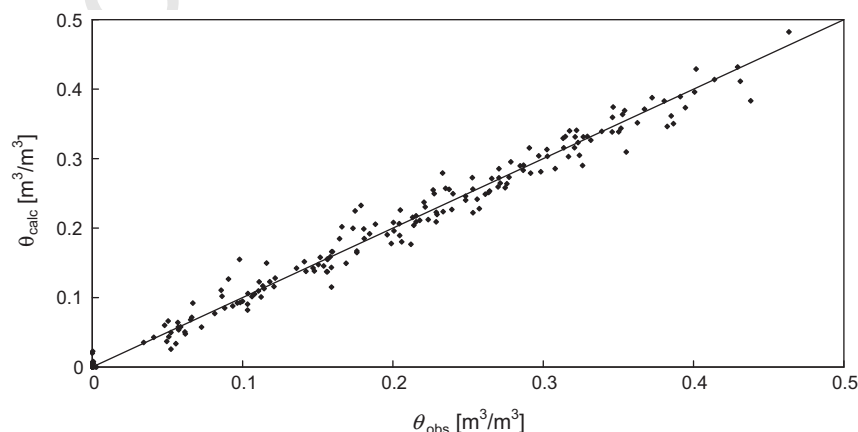


Fig. 7. Relationship between estimated (θ_{calc} ; based on soil type-specific (α , β , and γ) and site-specific ($P_{0.4}$) parameters) and laboratory-based soil type-specific observations of soil moisture content (θ_{obs}) for the Goulburn River soils.

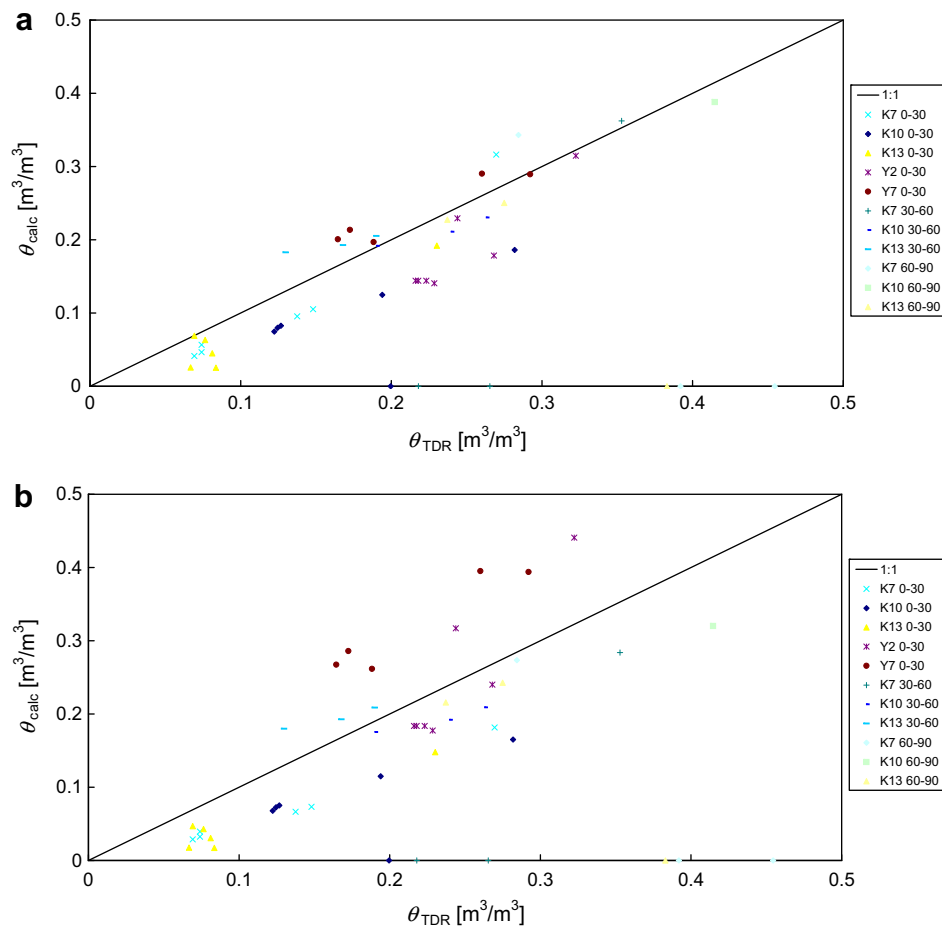


Fig. 8. Evaluation of general equation using independent data from the Murrumbidgee Catchment. Comparison of soil moisture calculated from in situ CS616 observations (θ_{calc}) and TDR measurements (θ_{TDR}) for (a) soil specific parameters (coarse and fine soils), and (b) s and $P_{0.4}$ derived from the soil particle size distribution. The overall RMSE values are $0.053 \text{ m}^3/\text{m}^3$, and $0.066 \text{ m}^3/\text{m}^3$, respectively (the Campbell Scientific equation yielded an RMSE of $0.144 \text{ m}^3/\text{m}^3$ for the same data set).

Stenger et al., 2005). These results are encouraging, especially when considering that both soil moisture estimates were obtained from field measurements and that the errors in TDR soil moisture measurements are also uncertain, especially for the deeper depths. The results on Fig. 8a and b shows that there appears to be a consistent bias in the results, with soil moisture values for a specific site being either over- or underestimated. If this bias were found to be truly consistent for each different soil type, it could be used to reduce the overall RMSE. However, it will require a larger amount of different soil samples from various soil types than were available for this study to assess the possibility of soil type-specific biases.

It was suggested by Western and Seyfried (2005) that if a single well-calibrated TDR or gravimetric measurement was taken near the installed sensor, the sensor results may be improved by using it to constrain the parameters. This was tested by keeping α , β , and γ constant and optimising only the site-specific $P_{0.4}$ of the five aforementioned sites with one randomly chosen TDR field observation. It was found that this additional information resulted in an overall reduction of the RMSE to $0.039 \text{ m}^3/\text{m}^3$, and that the best results are obtained when the single observation was taken under humid conditions. This result is not surprising when studying Eq. (6b), which is linear below a certain threshold (γ). Given that α and γ are not being optimised, any value below this threshold would have no impact on the shape parameter β and consequently on the shape of the non-linear part of the equation.

To identify the potential of this approach to improve the measurement accuracy with one known soil moisture observation,

the same approach was also applied to a sample of three independent soil samples from a field site near the Kyeamba sites. In this case the field TDR observations were replaced with gravimetric soil moisture content directly measured in the laboratory. The laboratory approach was chosen, because it is possible to determine the soil moisture content with a higher accuracy than with a TDR probe under field conditions. All three samples were subjected to six different levels of soil moisture content. The resulting RMSE was $0.008 \text{ m}^3/\text{m}^3$ for the combined sample size, by jointly optimising the $P_{0.4}$ values of the three samples. This result underlines the possibility to improve the calibrations, if a single soil moisture value is well known, together with the corresponding period measurement.

Discussion and conclusion

This paper has developed a general equation for deriving the soil moisture content from Campbell Scientific CS616 period measurements, using only information on the soil texture. The new equations for the soil moisture conversion and for the correction for soil temperature effects and the parameters required for the application the proposed equations to different soil types were derived from laboratory experiments using a number of different soil types from the Goulburn River catchment of south-eastern Australia. Soil samples were subjected to a wide range of soil moisture and soil temperature conditions to develop and test the equations. Key developments of this general equation for the CS616 include

(i) a soil type dependency on the temperature effects of the sensor and (ii) that the period measurement relationship with soil moisture was best described by a curvilinear relationship, with a linear response up to about the soil wilting point. Moreover, it was found that the calibration parameters correlated well with the soil particle distribution, particularly of fine materials soils. This in turn allows the derivation of calibration parameters from the particle size distribution and the generalisation of the calibration equations so that future installations of this instrument may not require site-specific calibration, but only knowledge of the soil particle size distribution. The RMSE obtained using laboratory observations are in the order of $0.014\text{--}0.038\text{ m}^3/\text{m}^3$. The application of the manufacturer's equations to the same observations showed that these latter inference equations work reasonably well for coarse soils, but not for finer soils.

Applying the new equations and parameters to sensors installed at five independent field sites from the Murrumbidgee monitoring network in south-eastern Australia, the resulting RMSE estimated from TDR measurements were found to be between $0.053\text{ m}^3/\text{m}^3$ and $0.066\text{ m}^3/\text{m}^3$. Moreover, if accurate wet *in situ* observations are available, this error can be reduced to $0.008\text{ m}^3/\text{m}^3$, by further optimising the $P_{0.4}$ parameter. Conversely, soil moisture values obtained with the manufacturer's equation resulted in a significantly higher RMSE ($0.144\text{ m}^3/\text{m}^3$). In conclusion, any of the approaches may be applied to coarse textured soils. However, one of the newly approaches presented here must be used to obtain adequate errors for fine texture soils.

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References

- Albergel, C., Rüdiger, C., Pellarin, T., Calvet, J.-C., Fritz, N., Froissard, F., Suquia, D., Petitpa, A., Pignat, D., Martin, E., 2008. From near-surface to root-zone soil moisture using an exponential filter: an assessment of the method based on *in situ* observations and model simulations. *Hydrology and Earth System Sciences* 12, 1323–1337.
- Benson, C.H., Wang, X., 2006. Temperature-compensating calibration procedure for Water Content Reflectometers. In: Proc. TDR 2006, Purdue University, West Lafayette, USA, September 2006, Paper ID 50.
- Blonquist, J., Jones, S., Robinson, D., 2005. Standardizing characterization of electromagnetic water content sensors: part 2. Evaluation of seven sensing systems. *Vadose Zone Journal* 4, 1059–1069.
- Brock, F.V., Crawford, K.C., Elliott, R.L., Cuperus, G.W., Stadler, S.J., Johnson, H.L., Eilts, M.D., 1995. The Oklahoma Mesonet: a technical overview. *Journal of Atmospheric and Oceanic Technology* 12, 5–19.

- Campbell Scientific Inc. 2002. CS616 Water Content Reflectometer Instruction Manual. Campbell Scientific Inc., Logan, USA.
- Czarnomski, N.M., Moore, G.W., Pypker, T.G., Licata, J., Bond, B.J., 2005. Precision and accuracy of three alternative instruments for measuring soil water content in two forest soils of the Pacific Northwest. *Canadian Journal of Forest Research* 35, 1867–1876.
- Escorihuela, M.J., de Rosnay, P., Kerr, Y.H., Calvet, J.-C., 2007. Influence of bound-water relaxation frequency on soil moisture measurements. *IEEE Transactions on Geoscience and Remote Sensing* 45, 4067–4076. doi:10.1109/TGRS.2007.906090.
- Gong, Y., Cao, Q., Sun, Z., 2003. The effects of soil bulk density, clay content and temperature on soil water content measurement using time-domain reflectometry. *Hydrological Processes* 17, 3601–3614.
- Kelleners, T., Seyfried, M., Blonquist, J., Bilskie, J., Chandler, D., 2005. Improved interpretation of water content reflectometer measurements in soils. *Soil Science Society of America Journal* 69, 1684–1690.
- Kim, K., Benson, C., 2002. Water content calibrations for final cover soils. *Geo-Engineering Report 02-12*, Geo-Engineering Program, Univ. of Wisconsin.
- Kizito, F., Campbell, C.S., Campbell, G.S., Cobos, D.R., Teare, B.L., Carter, B., et al., 2008. Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. *Journal of Hydrology* 352, 367–378. doi:10.1016/j.jhydrol.2008.01.021.
- Lebel, T., Cappelaere, B., Galle, S., Hanan, N., Kergoat, L., Levis, S., Vieux, B., Descroix, L., Gosset, M., Mougin, E., Peugeot, C., Seguis, L., in press. AMMA-CATCH studies in the Sahelian region of West-Africa: an overview. *Journal of Hydrology*, doi:10.1016/j.jhydrol.2009.03.020.
- Loveday, J., 1974. Methods for Analysis of Irrigated Soils. Commonwealth Agricultural Bureau, Farnham Royal, UK.
- Martínez-Fernández, J., Ceballos, A., 2005. Mean soil moisture estimation using temporal stability analysis. *Journal of Hydrology* 312, 28–38.
- Merlin, O., Walker, J.P., Panciera, R., Young, R., Kalma, J.D., Kim, E.J., 2007. Calibration of a soil moisture sensor in heterogeneous terrain with the National Airborne Field Experiment (NAFE) data. In: Proc. MODSIM 2007 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand, December 2007, pp. 2604–2610.
- Plauborg, F., Iversen, B., Laerke, P., 2005. In-situ comparison of three dielectric soil moisture sensors in drip irrigated sandy soils. *Vadose Zone Journal* 4, 1037–1047.
- Quinones, H., Ruelle, P., Nemeth, I., 2003. Comparison of three calibration procedures for TDR soil moisture sensors. *Irrigation and Drainage* 52, 203–217.
- Robinson, D.A., Campbell, C.S., Hopmans, J.W., Hornbuckle, B.K., Jones, S.B., Knight, R., et al., 2008. Soil moisture measurements for ecological and hydrological watershed-scale observatories: a review. *Vadose Zone Journal* 7, 358–389. doi:10.2136/vzj2007.0143.
- Rüdiger, C., Hancock, G., Hemakumara, H.M., Jacobs, B., Kalma, J.D., Martinez, C., Thyer, M., Walker, J.P., Wells, T., Willgoose, G., 2007. The Goulburn River experimental catchment data set. *Water Resources Research* 43, W10403. doi:10.1029/2006WR005837.
- Seyfried, M.S., Murdock, M.D., 2001. Response of a new soil water sensor to variable soil, water content, and temperature. *Soil Science Society of America Journal* 65, 28–34.
- Standards Australia, 2000. Australian Standard: Methods of Testing Soils for Engineering Purposes – General Requirements and List of Methods (AS 1289.0-2000), Sydney, Australia.
- Stenger, R., Barkle, G., Burgess, C., 2005. Laboratory calibrations of Water Content Reflectometers and their in-situ verification. *Australian Journal of Soil Research* 43 (5), 607–615.
- Western, A.W., Seyfried, M.S., 2005. A calibration and temperature correction procedure for the water-content reflectometer. *Hydrological Processes* 19, 3785–3793.
- Woods, R.A. et al., 2001. Experimental design and initial results from the mahurangi river variability experiment: MARVEX. In: V. Lakshmi, J.D. Albertson, J. Schaake (Eds.), *Observations and Modeling of Land Surface Hydrological Processes*. Water Resources Monograph. American Geophysical Union.