Calibration of the Murrumbidgee Monitoring Network CS616 Soil Moisture Sensors

N. Yeoh, J. Walker, R. Young, C. Rüdiger, A. Smith, K. Ellett, R. Pipunic, A. Western

Department of Civil and Environmental Engineering
The University of Melbourne

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Abstract

This document describes the calibration of CS616 water content reflectometers installed in the Murrumbidgee Soil Moisture Monitoring Network. Due to the large number of sensor installations (20 sites with 3 depths each), the difficulty of obtaining reliable soil moisture data at deeper depths in the field, and the time involved for laboratory calibration (up to 2 weeks per sample), it was not realistic to develop site specific calibrations for every sensor installation. Rather, three types of calibrations have been developed with decreasing amounts of ancillary information required: i) site specific optimization; ii) soil texture based; and iii) proximity based. The typical root mean squared error for these three approaches are estimated at 2.1%v/v, 5.1%v/v and 3.1%v/v respectively when applied to available soil moisture data. However, due to the limited amount of data for development and verification of the proximity method, and an assessment with depth integrated field TDR data, it is recommended that the texture based calibration be used in preference to the proximity based calibration. The specific calibration parameters developed for each site are given in Table 3 and Table 4. The equations required for application of these parameters are given in equations (1) to (4).

Introduction

The Murrumbidgee Soil Moisture Monitoring Network was extended in 2003 from an initial 18 monitoring sites to 38 sites (Walker et al. 2008). Due to a change in technology, the CS615 water content reflectometers installed at earlier sites and calibrated for Murrumbidgee soils (Western et al., 2000) were not available at the time of network expansion. The Campbell Scientific CS616 water content reflectometer that replaced the CS615 sensor was therefore used in its place. Consequently, the CS616 sensors required a site-specific calibration for the Murrumbidgee soils as the manufacturer's calibration (Campbell Scientific Inc., 2002) was found to be insufficient, with errors as large as 15%v/v. This document describes the calibration procedure undertaken and the results obtained.

Data

Calibration parameters are required for 20 sites, at 3 depths each (Table 1). To facilitate this, soil moisture data from both the field and laboratory have been used together with ancillary data such as soil texture to calibrate the CS616 sensors. Table 1 shows the sites where: i) soil samples were collected for laboratory analysis, ii) soil texture assessment data is currently available, iii) laboratory measurements of soil moisture have been made, and iv) field measurement of soil moisture have been made. As soil texture data was only available for the surface (0-30cm) and deep (60-90cm) layers, an assumption was made that the soil texture of the central layer (30-60cm) was similar to that of the deep layer. The basis of this assumption is that the soils in the Kyeamba and Yanco areas tend to be duplex with an A horizon depth of approximately 30cm for each of the soil moisture monitoring sites (Northcote, 1960). This was verified by field observations and soil texture analysis.

Table 1: Summary of data available for calibration of the Kyeamba and Yanco sites in the Murrumbidgee network. The texture columns show the clay to silt ratio. The field columns show the number of data points from field measurements with the TDR, while the lab columns show the number of data points from laboratory measurements.

Sites	Depth (cm)	Texture (clay/silt)%	Lab	Field	Sites	Depth (cm)	Texture (clay/silt)%	Lab	Field
K6	0-30	6.51/38.30	0	6	Y4	0-30	19.37/33.24	6	9
	30-60	4.12/31.40	0	0		30-60	24.12/28.67	0	0
	60-90	4.12/31.40	0	0		60-90	24.12/28.67	0	0
K7	0-30	10.19/31.77	0	6	Y5	0-30	11.72/21.35	0	10
	30-60	18.79/45.06	0	0		30-60	24.93/34.41	3	0
	60-90	20.21/48.67	0	0		60-90	16.95/24.13	3	0
K8	0-30	9.26/27.73	0	6	Y6	0-30	N/A	0	7
	30-60	13.59/38.19	0	0		30-60	N/A	0	0
	60-90	13.59/38.19	0	0		60-90	N/A	0	0
K10	0-30	8.12/49.47	3	6	Y7	0-30	25.09/36.30	5	5
	30-60	9.71/45.17	3	0		30-60	22.58/34.74	0	0
	60-90	10.43/49.86	3	0		60-90	22.58/34.74	3	0
K11	0-30	N/A	3	6	Y8	0-30	N/A	0	7
	30-60	N/A	4	0		30-60	N/A	2	0
	60-90	N/A	3	0		60-90	N/A	3	0
K12	0-30	8.44/33.38	0	6	Y9	0-30	13.89/32.77	5	9
	30-60	8.33/36.63	0	0		30-60	10.88/37.74	0	0
	60-90	8.33/36.63	0	0		60-90	10.88/37.74	0	0
K13	0-30	4.03/21.00	5	12	Y10	0-30	N/A	0	7
	30-60	8.82/29.68	5	0		30-60	N/A	0	0
	60-90	6.63/43.08	5	0		60-90	N/A	0	0
K14	0-30	10.19/50.92	6	0	Y11	0-30	N/A	0	18
	30-60	13.03/62.82	0	0		30-60	N/A	0	0
	60-90	13.03/62.82	0	0		60-90	N/A	0	0
Y1	0-30	13.34/32.11	5	8	Y12	0-30	N/A	0	6
	30-60	13.68/47.12	0	0		30-60	N/A	0	0
	60-90	13.68/47.12	4	0		60-90	N/A	0	0
Y2	0-30	17.16/45.79	3	7	Y13	0-30	N/A	0	5
	30-60	29.65/45.29	2	0		30-60	N/A	0	0
	60-90	29.65/45.29	4	0		60-90	N/A	0	0

Figure 1 shows the field setup for soil moisture measurement while Figure 2 shows the setup for laboratory soil moisture measurement. Field measurement of soil moisture relied upon the use of Time Domain Reflectometry (TDR) probes installed vertically over depths of 0-30, 0-60 and 0-90cm. Past experience with this measurement technique has shown that site specific calibration is not typically required for TDR measurements as the general calibration relationships (Topp equation) are quite stable to variations in soil type, with an accuracy of 1.3%v/v (Topp et al., 1980). Moreover, Figure A1 and Figure A2 in the Appendix verified this, showing a good agreement between the TDR measurements and the laboratory data for the 0-30cm measurements of the Kyeamba and Yanco sites. However, measurement accuracy is decreased and measurements are more difficult to make for probe lengths greater than 70cm (Soil Moisture Equipment Corp., 1996), meaning the 0-90cm measurements are not reliable for calibration/verification of the deeper CS616 sensor installations.

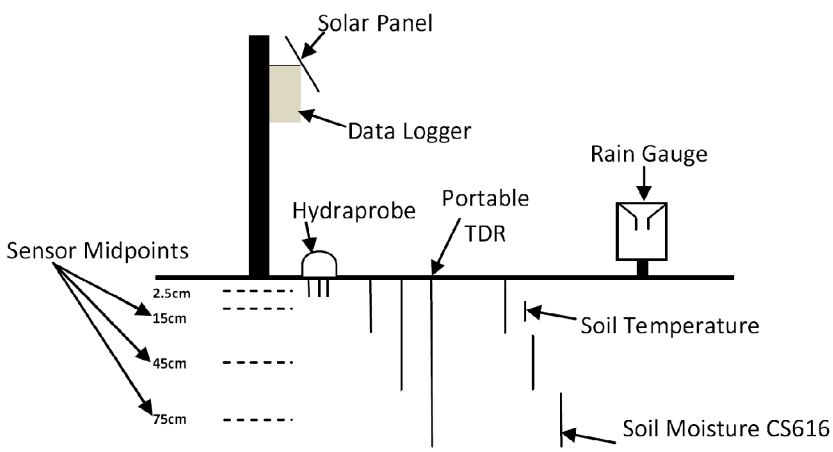

Figure 1: Murrumbidgee monitoring station schematic. Typical setup for field soil measurement (Walker et al. 2008).

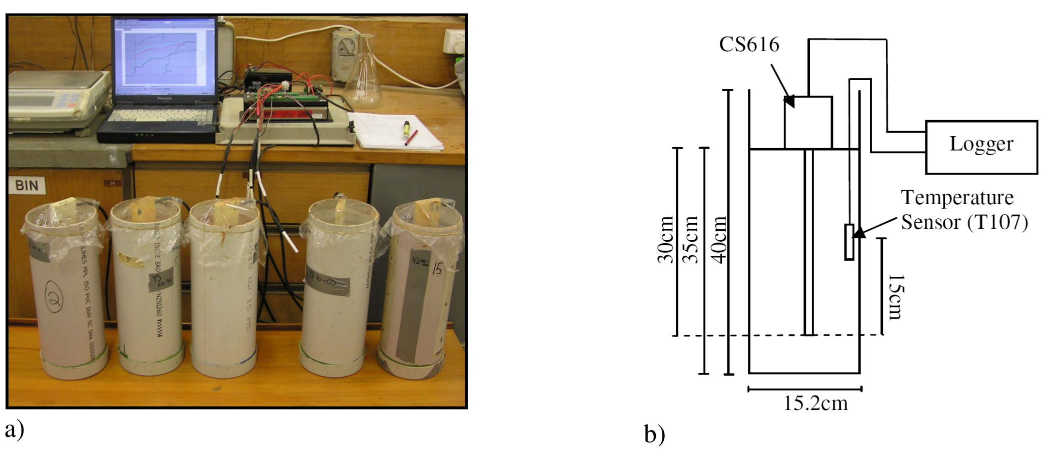

Figure 2: A typical setup for laboratory soil measurement is shown in a) and a schematic of the CS616 and temperature sensor (T107) installations in the sample cylinder is shown in b). Height of sample cylinder is 40cm with a diameter of 15.2cm. Soil depth is 35cm with CS616 probe length of 30cm.

Laboratory measurements were taken from disturbed soil samples which were collected from the monitoring sites by hand auguring. These samples were oven dried to remove existing soil moisture before being re-compacted into a 15.2cm diameter and 40cm long sampling cylinder. A soil temperature sensor and CS616 sensor were installed in the sample, and the samples moisture increased as distilled water was added in known amounts until infiltration from the top ceased (saturation). The volumetric moisture content was determined for each CS616 reading (P_{obs}) by keeping track of the water added and weighing of the sample/cylinder.

Theory

In developing calibration equations for the Murrumbidgee Soil Moisture Monitoring Network, the conversion equations of Rüdiger (2006), developed for the Goulburn River Experimental Catchment soil moisture monitoring stations (Rüdiger et al. 2007), have been used. A brief summary of the equations and approach is reproduced here.

First, the observed CS616 period measurement P_{obs} at temperature *T* is corrected to the equivalent reading that would be made at a temperature of 25°C (Western and Seyfried, 2005) by

$$P_{25} = P_{obs} - C^T(T - 25), \qquad (1)$$

where C^T is a temperature correction coefficient

$$C^T = sP_{25} + o. \qquad (2)$$

The $\boldsymbol{s}$ and $\boldsymbol{o}$ parameters are the slope and offset respectively, which were found to vary with soil type (Rüdiger 2006). The values of $\boldsymbol{s}$ and $\boldsymbol{o}$ were taken from Rüdiger (2006) and are reproduced in Table A1. Using the equations developed by Rüdiger et al. (2008), the temperature corrected period measurement is then converted to soil moisture by

$$\theta = \alpha N \qquad \text{for } N \leq \gamma \qquad (3a)$$

$$\theta = \gamma\alpha + \left(\frac{0.4-\gamma\alpha}{(1-\gamma)^\beta}\right)(N-\gamma)^\beta \qquad \text{for } N > \gamma, \qquad (3b)$$

where *N* is the normalized period of the sensor measurement computed as

$$N = \frac{P_{25}-P_{0.0}}{P_{0.4}-P_{0.0}}, \qquad (4)$$

with $P_{0.4}(\mu s)$ as the (theoretical) period measurement for a moisture content of 0.4v/v at 25°C, $P_{0.0}$ (μs) the period measurement for oven dried soil at a temperature of 25°C, and α, β and γ being shape parameters of the conversion function. In order to estimate soil moisture content using equation (3), parameters $P_{0.4}$, $P_{0.0}$, α, β and γ are required. The values used for these parameters are described below.

Method and Results

Three approaches were used to calibrate for $P_{0.4}$. The first approach was to directly optimize $P_{0.4}$ from the sample data obtained from the combination of field TDR and lab thermograviemtric data. The objective was to obtain a general conversion equation (equation 3) across the network. In achieving this, $P_{0.0}$ and each of the shape parameters, α, β and γ, were constrained to a single value, and then optimized for $P_{0.4}$, where initial values of $P_{0.4}$, $P_{0.0}$, α, β and γ were taken from Rüdiger et al. (2008) based on the analysis of the Goulburn network sites; see Table A2 in the Appendix for these values.

Due to the difficulty of obtaining data for every depth of soil at every site, site specific optimization could not be performed for each sensor installation and therefore, alternate approaches were developed to obtain $P_{0.4}$. The second approach is based on a relationship between $P_{0.4}$ and the soil texture. However, this method could only be used for soil samples where soil texture information (clay, silt and sand proportions) is available.

In the case where neither site specific calibration nor application of the soil texture approach was possible, a proximity based approach was proposed. In this case, a relationship between the $P_{0.4}$ of the 0-30cm layer and the $P_{0.4}$ of the deeper layers was developed. Since a site specific optimization was available for all surface soil layers, this approach could be applied to all sites. However, this is not advisable as discussed later.

Site specific Optimization for $P_{0.4}$

From the field and laboratory data available, a plot of soil moisture content was plotted against *N* after optimization of $P_{0.4}$ for the Kyeamba and Yanco measurements respectively (Figure 3 and Figure 4). Graphs of the data points before the optimization procedure was undertaken are also included in the Appendix in Figure A3 and Figure A4.

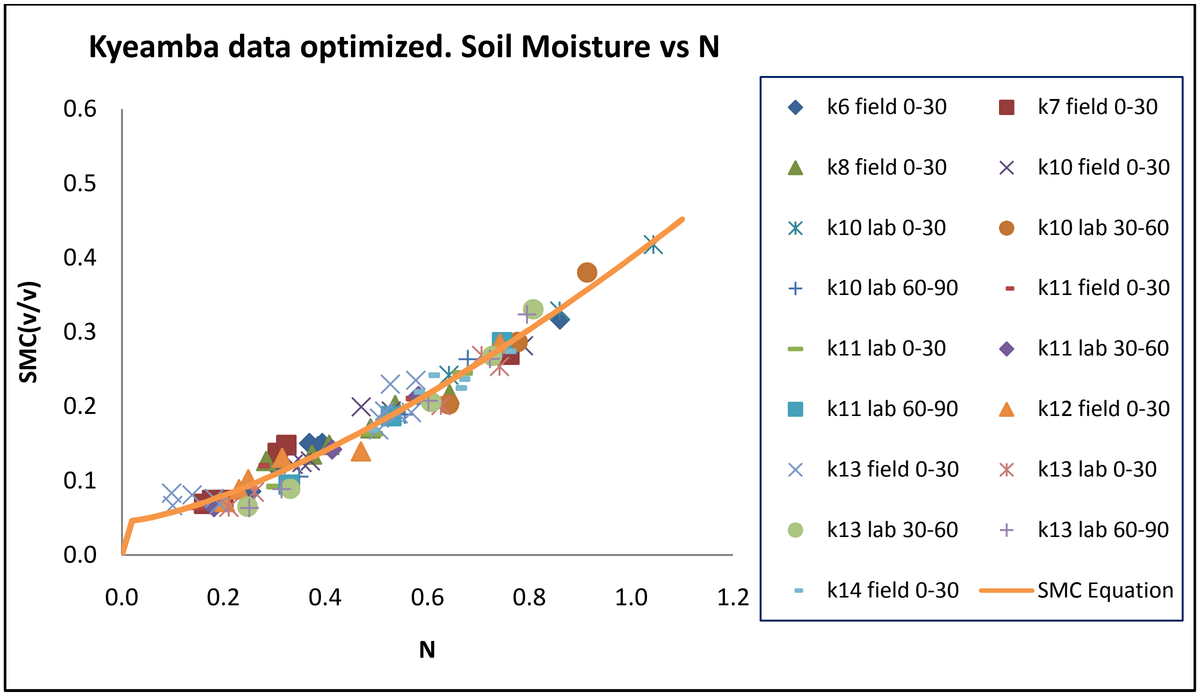

Figure 3: Relationship between soil moisture content (SMC) of the Kyeamba sites and its normalised period (*N*) value after optimizing $P_{0.4}$.

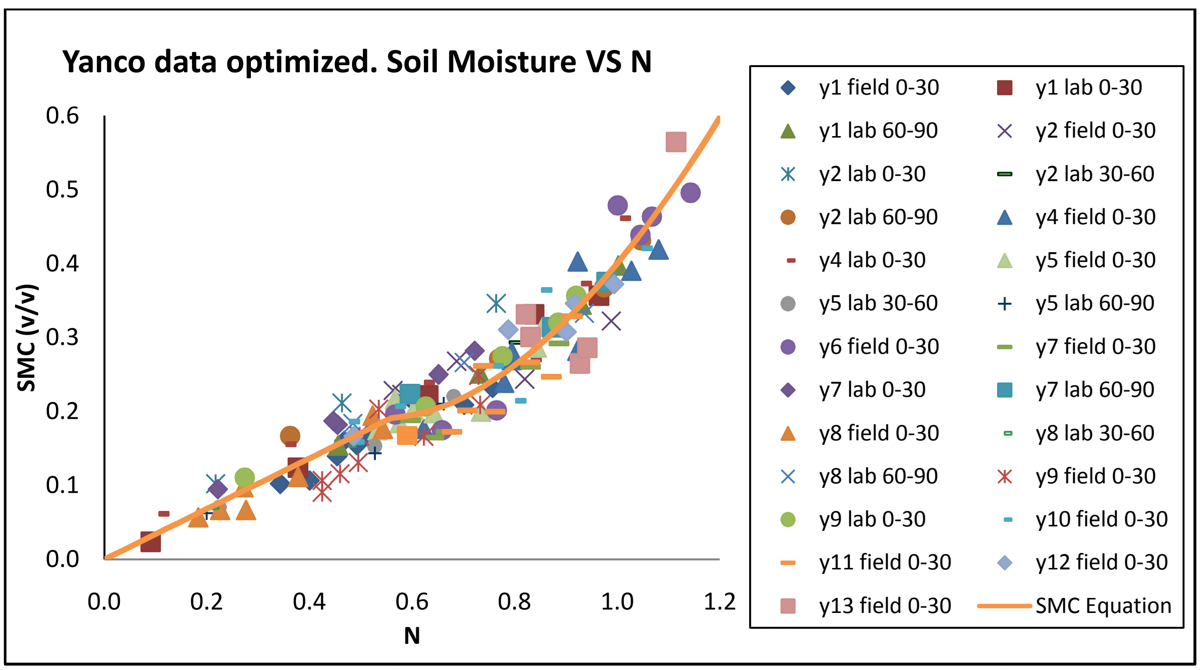

Figure 4: As for Figure 3 but for the Yanco sites.

Table 2: Error comparison before and after global optimization and site specific optimization of $P_{0.4}$.

	Absolute Mean Error (v/v)		Root Mean Squared Error (v/v)		Mean Error (v/v)	
	Kyeamba	Yanco	Kyeamba	Yanco	Kyeamba	Yanco
Before Optimization	0.039	0.093	0.047	0.124	0.016	0.086
Global Optimization	0.023	0.043	0.029	0.066	0.002	-0.002
Site Specific Optimization	0.013	0.025	0.016	0.032	0.000	0.000

Table 2 shows the overall errors for both the Kyeamba and Yanco data where site specific optimization of $P_{0.4}$ was used, holding $P_{0.0}$ fixed at the default values of Table A2; and calibrating for a set of global α, β and γ values as well as $P_{0.4}$ for each sensor installation. The sites used for this approach were those with field and lab data labeled in Table 1. Global optimization was not found to provide sufficiently good results and consequently the site specific approach was preferred. This means that each CS616 installation required one site specific parameter. A more detailed error table for each of the Kyaemba and Yanco sites is given in Table A4 and Table A5 in the Appendix, where results before optimization and with global optimization are included.

Soil Texture Estimation for $P_{0.4}$

Using the ratio of clay to silt in a soil for the samples described above that also have soil texture data available, a relationship with the corresponding $P_{0.4}$ value was found (Figure 5). Other relationships were tested, including the sum of clay and silt proportions proposed by Rüdiger (2006), but the clay to silt ratio was found to give the best results.

The Kyeamba and Yanco information has been combined here because there were not enough data points to confidently estimate individual relationships for each study area. Therefore, using Figure 5, the $P_{0.4}$ values can be estimated for any soil so long as their clay and silt proportion are known. The particle size distribution data is given in Table 1.

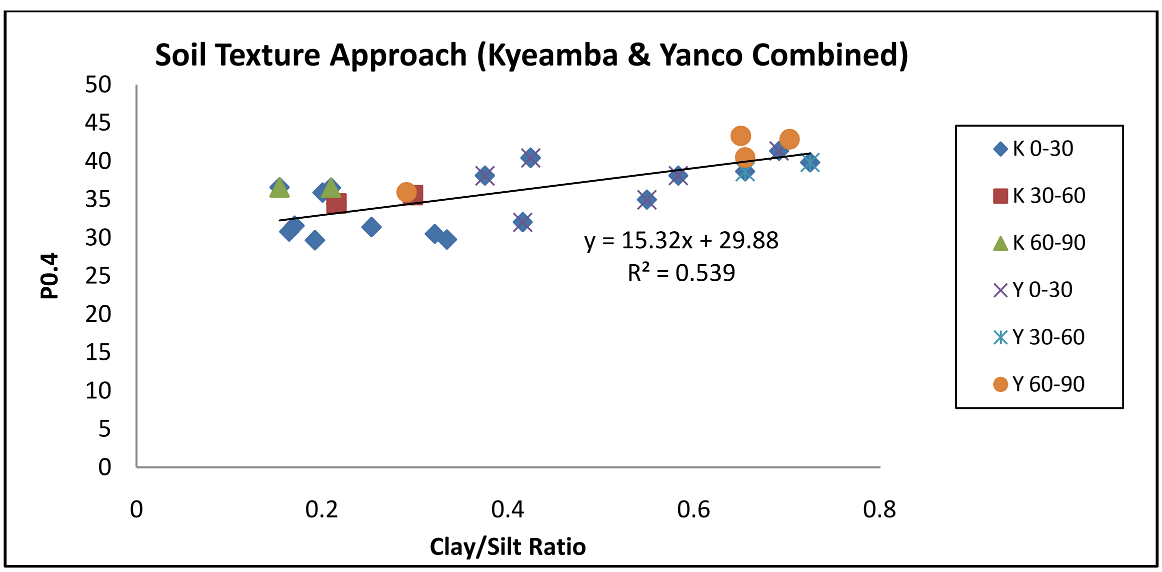

Figure 5: Relationship between $P_{0.4}$ and the clay to silt ratio of the Kyeamba and Yanco sites.

One reason for using the ratio of clay to silt and not the sum of clay and silt was that any different proportions of silt and clay could possibly sum up to the same value, meaning the different proportions of silt and clay could share the same $P_{0.4}$. By substitution of the site specific $P_{0.4}$ with the texture based estimate, the root mean squared error (RMSE) was estimated to increase by around 3%v/v to a total RMSE of 5.1%v/v. The sites used in this error analysis were K10, K13, Y1, Y2, Y5 and Y7 as these were the sites where comparative data was available.

Proximity Estimate of $P_{0.4}$

A relationship was established between the $P_{0.4}$ value of the 0-30cm sensor and the $P_{0.4}$ value at multiple depths at the same site using the site specific optimization values described above for sites with samples at deeper depths. Since site specific calibrations were available for all 0-30cm depths, this relationship could then be applied to all remaining sensor installations.

Figure 6 shows the relationship between $P_{0.4}$ of different sensor depths at the same measurement site. This is again a combination of the Kyeamba and Yanco $P_{0.4}$ values as calibration data was available for deep sensor depths at only a few measurement sites. A linear best fit line was used as there was insufficient data to fit a higher order equation.

By substitution of the site specific $P_{0.4}$ values with the proximity based estimates, the RMSE was estimated to increase by not more than 1%v/v to a total RMSE of 3.1%v/v. However, as was mentioned above these results were obtained from a limited amount of data (sites K10, K13, Y1, Y2, Y5 and Y7). Therefore, it is not possible to definitively say which method of approximation is better among the two (soil texture approach and proximity approach) based on the RMSE results alone. This will be further discussed below when more verification results are shown.

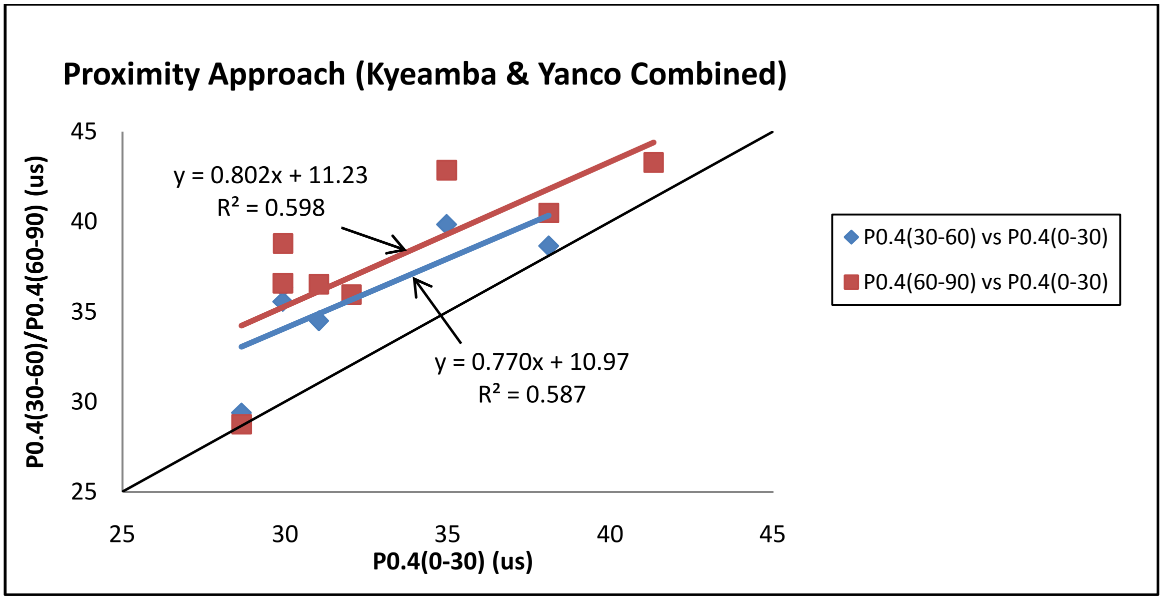

Figure 6: Relationship between $P_{0.4(0-30cm)}$ and both $P_{0.4(30-60cm)}$ and $P_{0.4(60-90cm)}$.

Calibration Results

The calibration results for the Murrumbidgee Monitoring Network are summarized in Table 3 and Table 4. In verifying these results, the average soil moisture for deeper soil depths was calculated for direct comparison with the deeper field TDR measurements by

$$SMC_{0-60} = \frac{SMC_{0-30} + SMC_{30-60}}{2} \quad (5)$$

$$SMC_{0-90} = \frac{SMC_{0-30} + SMC_{30-60} + SMC_{60-90}}{3}, \quad (6)$$

where SMC_{x-y} is the soil moisture of depth *x* to *y* cm.

Table 3: Calibration parameters for the Kyeamba sites. In the source column, the term 'site specific' refers to the site specific optimization method used on each site where data was available; 'texture' refers to the soil texture method which involved soil texture information for $P_{0.4}$ estimation; and 'proximity' is the estimation of $P_{0.4}$ based on the optimized $P_{0.4}$ of the 0-30cm layer.

Sites	Depth(cm)	Soil Classification	$P_{0.4}$	$P_{0.0}$	α	β	γ	Source
K6	0-30	silt loam	31.561	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	31.990	15.990	5.451	1.414	0.008	texture
	60-90	silt loam	31.990	15.990	5.451	1.414	0.008	texture
K7	0-30	silt loam	30.499	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	36.368	15.990	5.451	1.414	0.008	texture
	60-90	silt loam	36.342	15.990	5.451	1.414	0.008	texture
K8	0-30	silt loam	29.764	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	35.432	15.990	5.451	1.414	0.008	texture
	60-90	silt loam	35.432	15.990	5.451	1.414	0.008	texture
K10	0-30	silt loam	30.800	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	34.488	15.990	5.451	1.414	0.008	site specific
	60-90	silt loam	36.534	15.990	5.451	1.414	0.008	site specific
K11	0-30	silt loam	28.112	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	29.397	15.990	5.451	1.414	0.008	site specific
	60-90	silt loam	28.760	15.990	5.451	1.414	0.008	site specific
K12	0-30	silt loam	31.388	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	33.374	15.990	5.451	1.414	0.008	texture
	60-90	silt loam	33.374	15.990	5.451	1.414	0.008	texture
K13	0-30	loamy sand	29.670	16.217	5.451	1.414	0.008	site specific
	30-60	loamy sand	35.562	16.217	5.451	1.414	0.008	site specific
	60-90	loamy sand	36.587	16.217	5.451	1.414	0.008	site specific
K14	0-30	silt loam	35.889	15.990	5.451	1.414	0.008	site specific
	30-60	silt loam	38.634	15.990	5.451	1.414	0.008	[*]proximity
	60-90	silt loam	40.027	15.990	5.451	1.414	0.008	[*]proximity

[*] The proximity approach was used for these sites despite the availability of soil texture information as it provided more realistic values.

Table 4: As for Table 3 but for the Yanco sites.

Sites	Depth(cm)	Soil classification	$P_{0.4}$	$P_{0.0}$	α	β	γ	Source
Y1	0-30	silt loam	32.035	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	34.338	15.990	0.342	1.773	0.563	texture
	60-90	silt loam	35.959	15.990	0.342	1.773	0.563	site specific
Y2	0-30	silt loam	38.103	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	38.646	15.990	0.342	1.773	0.563	site specific
	60-90	silt loam	40.486	15.990	0.342	1.773	0.563	site specific
Y4	0-30	silt loam	38.115	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	42.783	15.990	0.342	1.773	0.563	texture
	60-90	silt loam	42.783	15.990	0.342	1.773	0.563	texture
Y5	0-30	loamy sand	34.965	16.217	0.342	1.773	0.563	site specific
	30-60	loamy sand	39.836	16.217	0.342	1.773	0.563	site specific
	60-90	silt loam	42.858	15.990	0.342	1.773	0.563	site specific
Y6	0-30	silt loam	37.327	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	39.743	15.990	0.342	1.773	0.563	proximity
	60-90	silt loam	41.182	15.990	0.342	1.773	0.563	proximity
Y7	0-30	silt loam	41.324	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	39.850	15.990	0.342	1.773	0.563	texture
	60-90	silt loam	43.287	15.990	0.342	1.773	0.563	site specific
Y8	0-30	silt loam	29.931	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	36.369	15.990	0.342	1.773	0.563	site specific
	60-90	silt loam	38.789	15.990	0.342	1.773	0.563	site specific
Y9	0-30	silt loam	40.426	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	42.130	15.990	0.342	1.773	0.563	*proximity
	60-90	silt loam	43.667	15.990	0.342	1.773	0.563	*proximity
Y10	0-30	silt loam	37.207	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	39.650	15.990	0.342	1.773	0.563	proximity
	60-90	silt loam	41.085	15.990	0.342	1.773	0.563	proximity
Y11	0-30	silt loam	34.909	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	37.879	15.990	0.342	1.773	0.563	proximity
	60-90	silt loam	39.241	15.990	0.342	1.773	0.563	proximity
Y12	0-30	silt loam	39.806	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	41.653	15.990	0.342	1.773	0.563	proximity
	60-90	silt loam	43.170	15.990	0.342	1.773	0.563	proximity
Y13	0-30	silt loam	39.857	15.990	0.342	1.773	0.563	site specific
	30-60	silt loam	41.692	15.990	0.342	1.773	0.563	proximity
	60-90	silt loam	43.211	15.990	0.342	1.773	0.563	proximity

* The proximity approach was used for these sites despite the availability of soil texture information as it provided more realistic values.

Table 5: Errors obtained from TDR verification. Shows the RMSE between the integrated CS616 value and the TDR values from the field measurements. The i) 'proximity' columns show the RMSE from using the proximity approach, ii) 'soil texture' columns show the RMSE from the soil texture approach and iii) 'combination' columns shows the overall error expected from the network using the combination of site specific optimization, soil texture and proximity approaches given in Table 3 and Table 4.

	Overall RMSE for 0-60cm TDR			Overall RMSE for 0-90cm TDR		
	Proximity (v/v)	Soil Texture (v/v)	Combination (v/v)	Proximity (v/v)	Soil Texture (v/v)	Combination (v/v)
Kyeamba	0.028	0.024	0.023	0.037	0.040	0.040
Yanco	0.112	0.193	0.105	0.144	0.126	0.125

Notice that errors from the Yanco sites shown in Table 5 were found to be significantly larger than those at Kyeamba. As no bias was observed when the TDR field measurements were verified against the lab data for the Yanco sites (Figure A4), it is possible that these errors are due to errors from using the longer TDR probes in the Yanco soils and/or physical conditions of the soil. Surface cracks as a result of dry soils and higher clay content at the Yanco locations were observed, thus making air gaps possible; air gaps have a detrimental effect on TDR measurement of soil moisture (Schmugge et al., 1980; Zegelin, 1996). Furthermore, from the observation of high salt tolerant vegetation, it was believed that salinity at these sites were higher relative to those at the Kyeamba location. Salinity also reduces the TDR measurement accuracy (Soil Moisture Equipment Corp., 1996).

Earlier results from the substitution verification have suggested that the proximity based $P_{0.4}$ is more reliable than that of the soil texture approach. However, the TDR verification results given here show only marginal differences between the two approaches. Consequently, our final recommendation on which approach to adopt in the absence of site specific calibration is based on the quantity and quality of data available for developing the $P_{0.4}$ relationship. We therefore recommend that use of the soil texture based approach take precedence to the proximity based approach.

Example plots of soil moisture data from the Murrumbidgee Monitoring Network are given in Figure 7 and Figure 8 for the K3 and Y3 sites during autumn in 2006. Both plots show the dry conditions that existed across the Murrumbidgee sites during that period, with small amounts of rainfall recorded.

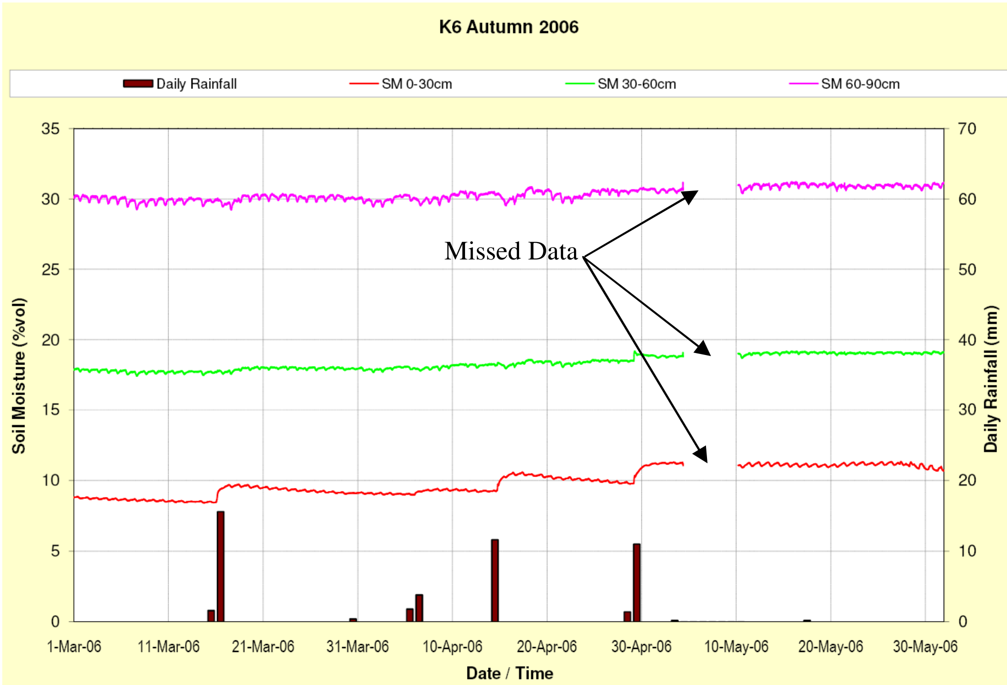

Figure 7: Time series soil moisture plot of site K6 at Kyeamba during autumn 2006 for all 3 depths, 0-30cm, 30-60cm and 60-90cm. Diurnal variations are believed to be a combination of temperature artifact and physical change in soil moisture.

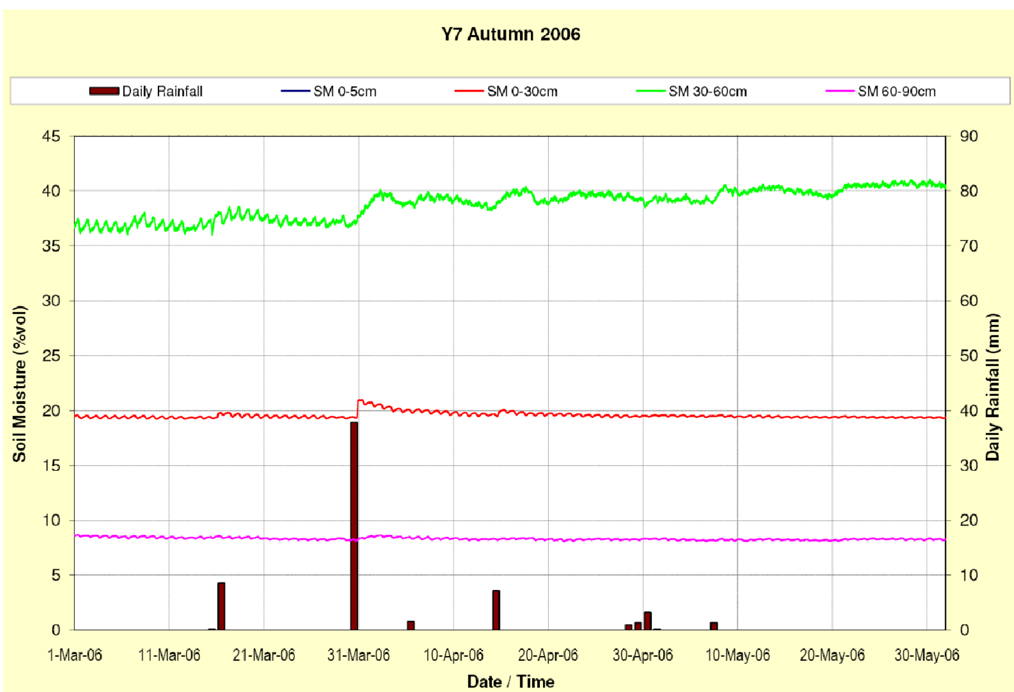

Figure 8: As for Figure 7 but for Y7 at Yanco.

Conclusion

Each monitoring site has had the necessary CS616 soil moisture sensor parameters derived from a combination of methods, including site specific optimization, soil texture based approximations, and proximity based approximations for sites where soil texture data is not available. From our analysis of these methods we found the RMSE for these individual methods to be 2.1%v/v, 5.1%v/v and 3.1%v/v. However, due to the small amount of data available for the development and testing of texture and proximity based approaches, it is our recommendation to use the soil texture approximation in preference to the proximity approach.

With these calibration parameters, soil moisture can be estimated for all soil sensor installations within the Murrumbidgee Monitoring Network without undertaking laboratory analyses of soil samples for every site at every depth. The error estimates derived serve to provide confidence in the resulting soil moisture data to within better than 5%v/v.

Acknowledgements

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References

Campbell Scientific Inc., 2002. *CS616 and CS625 Water Content Reflectometer.* Campbell Scientific Inc., Logan, USA. pp.25-30.

Northcote, KH, 1960. *Atlas of Australian Soils.* Sheet 3, CSIRO and Melbourne University Press.

Rüdiger, C, 2006. *Streamflow Data Assimilation for Soil Moisture Prediction*, Ph. D. Thesis, The Department of Civil and Environmental Engineering. The University of Melbourne. ch 3 pp.21-27.

Rüdiger, C, Hancock, GR, Hemakumara, HM, Jacobs, B, Kalma, JD, Martinez, C, Thyer, M, Walker, JP, Wells, T and Willgoose, GR, 2007. *The* Goulbourn River Experimental Catchment Data Set. *Water Resources Research*, 43, W10403, doi: 10.1029/2006WR005837.

Rüdiger, C, Western, AW, Walker, JP, Smith, AB, Kalma, JD, Willgoose, GR, 2008. The Role of Soil Temperature and Soil Texture on the Calibration of Time Domain Reflectometers. *Journal of Hydrology*, In review.

Schmugge, TJ, Jackson, TJ and McKim, HL, 1980. Survey of Methods for Soil Moisture Determination. *Water Resources Research*, 16(6): 961-979.

Soil Moisture Equipment Corp., 1996. *6050X1 Trase System, Operating Instructions.* Soil Moisture Equipment Corp., ch7, pp.4.

Topp, GC, Davis, JL, Annan, AP, 1980. Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines.*Water Resource Research*, 16, pp.574-582.

Walker, JP, 1999, *Estimating Soil Moisture Profile Dynamics from Near-Surface Soil Moisture Measurements and Standard Meteorological Data,* Ph. D. Thesis, The Department of Civil, Surveying and Environmental Engineering. The University of Newcastle. New South Wales, Australia, ch 9, pp.24 – 30.

Walker, JP, Young, RI, Yeoh, N, Smith, AB, Ellet, KM, Merlin, O, Western, AW. 2008. *Soil Moisture and Meteorological Observations from the Murrumbidgee Catchment.* Department of Civil and Environmental Engineering. The University of Melbourne.

Western AW, Young, RI, Chiew, F., 2000, *Murrumbidgee Soil Moisture Monitoring Network Field Calibration.* Cooperative Research Centre for Catchment Hydrology.

Western, AW and Seyfried, MS, 2005. A Calibration and Temperature Correction Procedure for the Water Content Reflectometer. *Hydrological Process,* 19, 3785-3793.

Zegelin, S, 1996. *Soil Moisture Measurement. In: Field Measurement Techniques in Hydrology-Workshop Notes.* Cooperative Research centre for the Catchment Hydrology, Corpus Christi College, Clayton, C1-C22.

Appendix

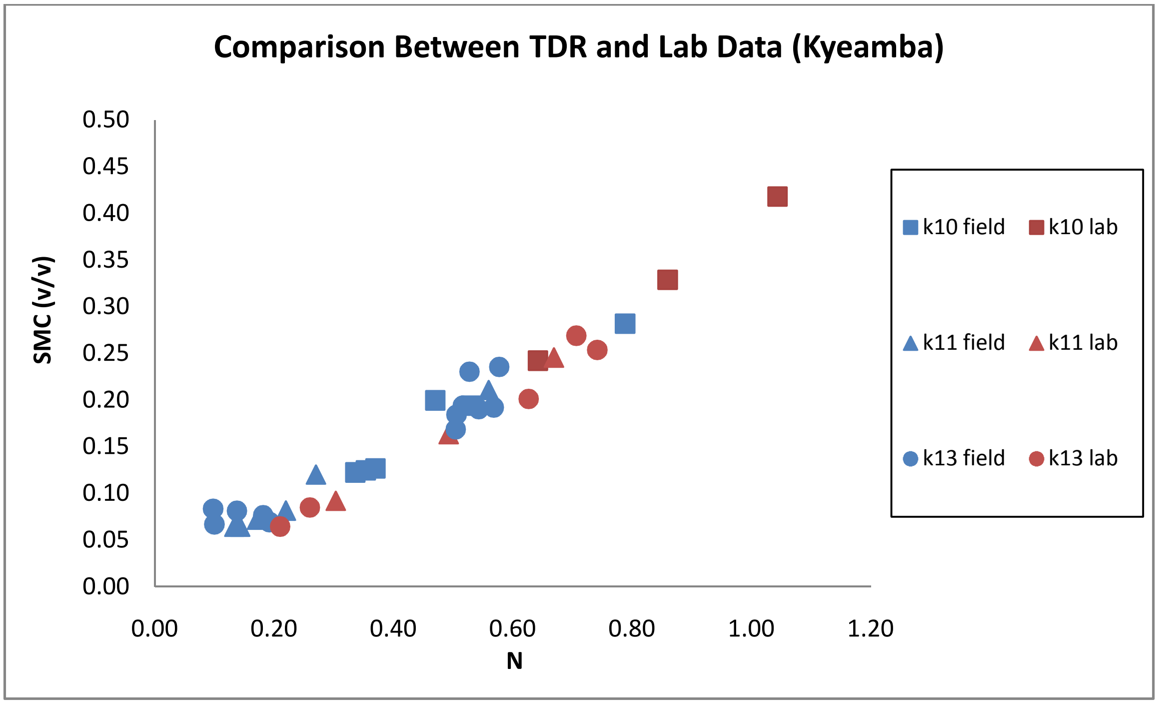

Figure A1: Comparison between TDR and Lab measurements for the Kyeamba sites. The TDR measurements are distinguished from the lab data by colour.

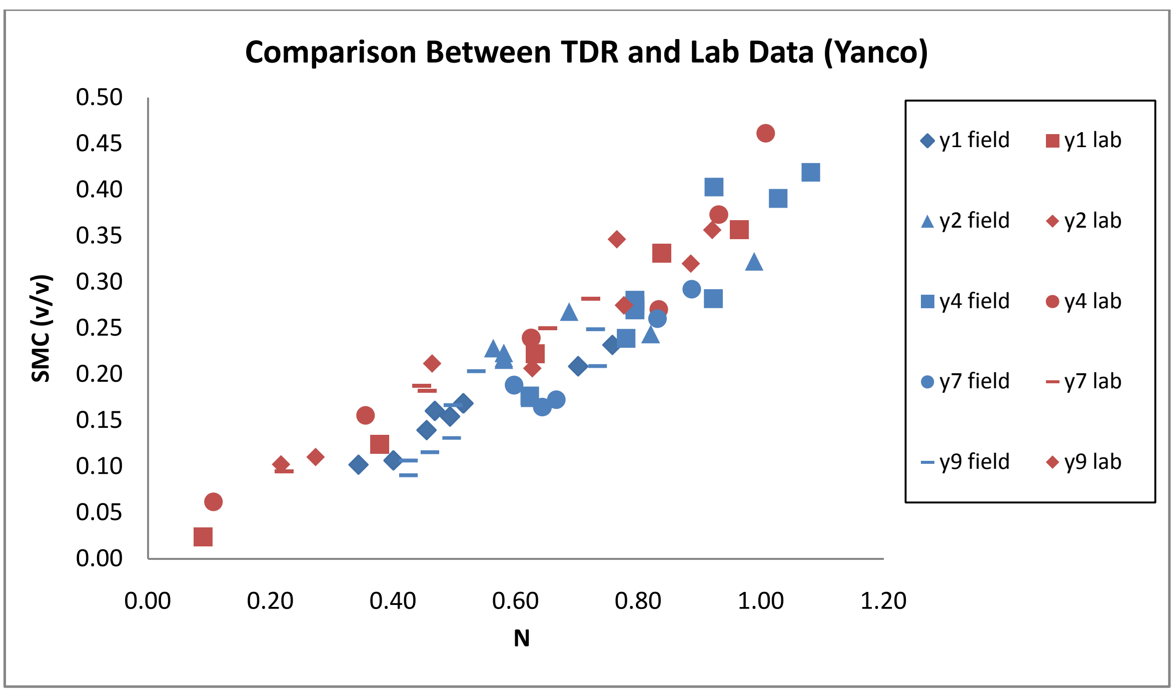

Figure A2: As for Figure A1 but for the Yanco sites.

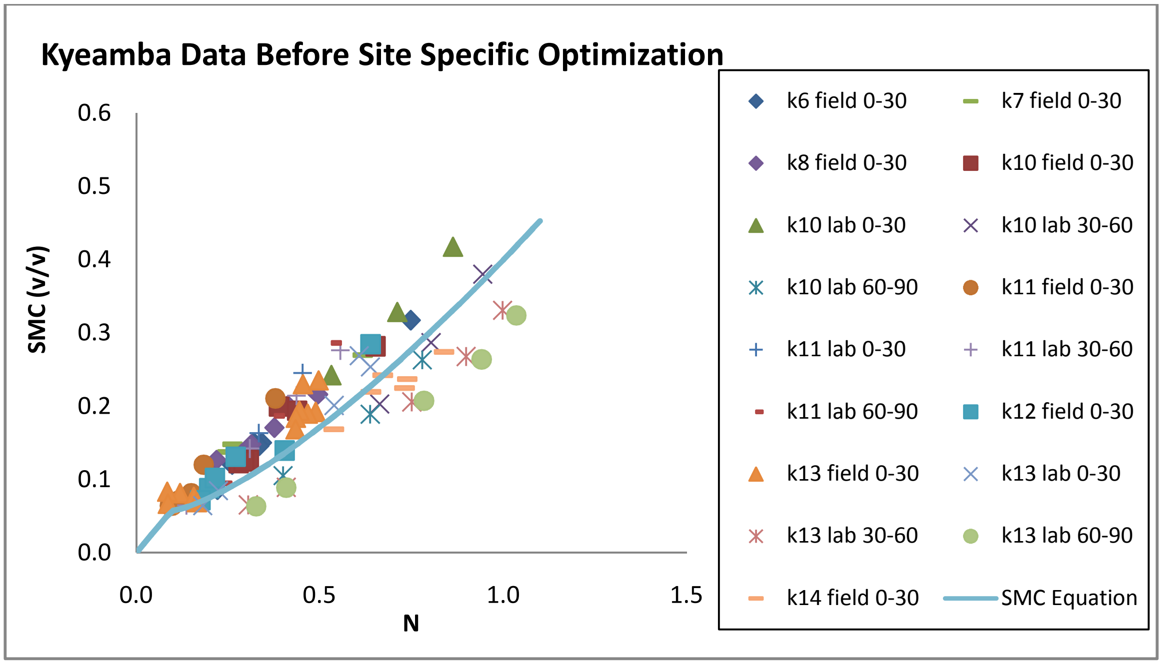

Figure A3: Relationship between SMC of the Kyeamba sites and its *N* value BEFORE optimization.

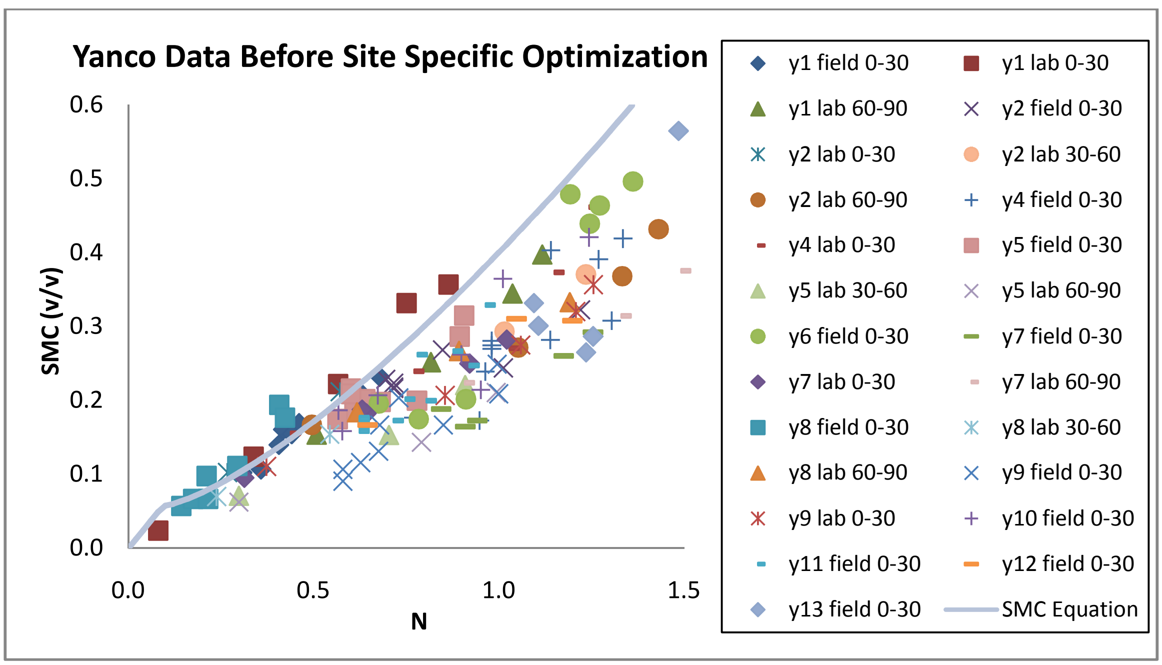

Figure A4: As Figure A3 but for the Yanco sites.

Table A1: Soil specific temperature correction parameters (Rüdiger 2006).

Soil Type	Slope	Offset
Sand	0.00257	-0.04318
Sandy Loam	0.00393	-0.06602
Loam	0.00805	-0.13542
Clay	0.00757	-0.12718
Silt Loam	0.00825	-0.13860
Clay Loam	0.00841	-0.14129

Table A2: $P_{0.4}$ and $P_{0.0}$ values from the Goulburn sites (Rüdiger 2006).

Soil type	$P_{0.0}$	$P_{0.4}$
Clay	17.011	39.325
Clay loam	17.063	39.470
Loam	16.542	40.582
Loamy sand	16.217	31.873
Sand	15.995	27.296
Sandy Loam	16.503	27.438
Silt loam	15.990	33.904

Table A3: α, β, and γ values from the Goulburn sites.

Soil Material	α	β	γ
Coarse	0.608	1.369	0.094
Fine	0.027	1.453	0.407

Table A4: Error table for data before optimization (No Opt), global optimization (Global Opt) and site specific optimization (Specific Opt) for the Kyeamba sites. Site specific optimization was the final optimization approach adopted by this report. Results of the optimization are shown in Figure 3.

	Absolute Mean Error			Root Mean Squared Error			Mean Error			
SITE/DEPTH	No Opt(v/v)	Global Opt(v/v)	Specific Opt(v/v)	No Opt(v/v)	Global Opt(v/v)	Specific Opt(v/v)	No Opt(v/v)	Global Opt(v/v)	Specific Opt(v/v)	Soil Type
k6 field 0-30	0.031	0.009	0.013	0.033	0.012	0.013	0.031	-0.006	0.030	silt loam
k7 field 0-30	0.031	0.016	0.014	0.038	0.019	0.019	0.031	0.095	0.036	silt loam
k8 field 0-30	0.047	0.009	0.010	0.047	0.012	0.013	0.047	0.039	0.022	silt loam
k10 field 0-30	0.039	0.014	0.011	0.043	0.016	0.016	0.039	0.012	0.022	silt loam
k10 lab 0-30	0.072	0.043	0.005	0.073	0.046	0.006	0.072	0.128	0.002	silt loam
k10 lab 30-60	0.020	0.019	0.020	0.023	0.024	0.022	-0.014	-0.021	-0.013	silt loam
k10 lab 60-90	0.031	0.036	0.014	0.032	0.042	0.014	-0.031	-0.109	-0.013	silt loam
k11 field 0-30	0.030	0.024	0.007	0.041	0.026	0.010	0.030	0.146	0.023	silt loam
k11 lab 0-30	0.053	0.016	0.009	0.061	0.022	0.012	0.053	0.045	-0.028	silt loam
k11 lab 30-60	0.047	0.026	0.005	0.056	0.032	0.006	0.047	0.104	-0.010	silt loam
k11 lab 60-90	0.058	0.033	0.010	0.069	0.043	0.013	0.058	0.098	-0.015	silt loam
k12 field 0-30	0.023	0.017	0.012	0.030	0.024	0.014	0.023	-0.011	0.000	silt loam
k13 field 0-30	0.032	0.020	0.014	0.038	0.023	0.019	0.032	0.065	0.105	loam sand
k13 lab 0-30	0.021	0.019	0.017	0.028	0.021	0.019	0.019	-0.009	-0.072	loam sand
k13 lab 30-60	0.061	0.031	0.019	0.063	0.035	0.022	-0.061	-0.073	-0.048	loam sand
k13 lab 60-90	0.076	0.029	0.018	0.080	0.033	0.020	-0.076	-0.073	-0.045	loam sand
k14 field 0-30	0.025	0.048	0.012	0.030	0.051	0.014	-0.025	-0.290	0.006	silt loam

Table A5: As for Table A4 but for the Yanco sites. Site specific optimization was the final optimization approach adopted by this report. Results of the optimization are shown in Figure 4.

	Absolute Mean Error			Root Mean Squared Error			Mean Error			
SITE/DEPTH	**No Opt(v/v)**	**Global Opt(v/v)**	**Specific Opt(v/v)**	**No Opt(v/v)**	**Global Opt(v/v)**	**Specific Opt (v/v)**	**No Opt(v/v)**	**Global Opt(v/v)**	**Specific Opt(v/v)**	**Soil Type**
y1 field 0-30	0.010	0.028	0.013	0.012	0.030	0.015	0.001	-0.220	0.013	silt loam
y1 lab 0-30	0.028	0.064	0.019	0.031	0.078	0.025	-0.018	-0.318	-0.009	silt loam
y1 lab 60-90	0.054	0.049	0.007	0.058	0.057	0.010	0.054	-0.196	-0.003	silt loam
y2 field 0-30	0.081	0.025	0.038	0.103	0.027	0.041	0.081	-0.031	-0.010	silt loam
y2 lab 0-30	0.020	0.050	0.061	0.022	0.061	0.068	-0.007	-0.249	-0.061	silt loam
y2 lab 30-60	0.136	0.025	0.006	0.137	0.006	0.022	0.136	0.001	-0.010	silt loam
y2 lab 60-90	0.146	0.023	0.022	0.169	0.027	0.026	0.146	-0.059	-0.012	silt loam
y4 field 0-30	0.149	0.040	0.032	0.158	0.050	0.038	0.149	0.157	0.008	silt loam
y4 lab 0-30	0.063	0.041	0.032	0.081	0.051	0.035	0.061	-0.202	-0.029	silt loam
y5 field 0-30	0.033	0.017	0.012	0.042	0.022	0.017	0.032	-0.003	-0.003	loam sand
y5 lab 30-60	0.089	0.004	0.015	0.099	0.004	0.016	0.089	-0.001	0.008	loam sand
y5 lab 60-90	0.126	0.141	0.013	0.141	0.141	0.022	0.126	0.141	0.013	silt loam
y6 field 0-30	0.108	0.084	0.029	0.124	0.093	0.039	0.108	-0.197	0.004	silt loam
y7 field 0-30	0.212	0.091	0.024	0.217	0.097	0.027	0.212	0.545	0.024	silt loam
y7 lab 0-30	0.067	0.007	0.036	0.081	0.008	0.039	0.067	0.014	-0.036	silt loam
y7 lab 60-90	0.233	0.036	0.015	0.245	0.037	0.018	0.233	0.107	-0.010	silt loam
y8 field 0-30	0.020	0.034	0.013	0.027	0.041	0.015	-0.014	-0.239	0.007	silt loam
y8 lab 30-60	0.025	0.077	0.020	0.027	0.109	0.007	0.025	-0.077	0.006	silt loam
y8 lab 60-90	0.095	0.015	0.027	0.110	0.016	0.031	0.095	-0.045	-0.016	silt loam
y9 field 0-30	0.119	0.053	0.030	0.125	0.058	0.033	0.119	0.475	0.021	silt loam
y9 lab 0-30	0.133	0.019	0.015	0.148	0.023	0.016	0.133	0.087	-0.015	silt loam
y10 field 0-30	0.070	0.036	0.030	0.085	0.045	0.037	0.070	-0.124	-0.007	silt loam
y11 field 0-30	0.066	0.034	0.027	0.071	0.081	0.030	0.051	-0.275	0.019	silt loam
y12 field 0-30	0.225	0.072	0.034	0.261	0.127	0.028	0.225	0.479	-0.005	silt loam
y13 field 0-30	0.166	0.078	0.045	0.179	0.092	0.059	0.133	-0.118	0.002	silt loam