Murrumbidgee Soil Moisture Monitoring Network Field Calibration

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Introduction

Soil moisture is currently monitored at eighteen stations across the Murrumbidgee River Basin. Four depths (usually 0-7cm, 0-30cm, 30-60cm and 60-90cm) are monitored at each site. Soil temperature and soil suction (the 60-600kPa range) are also measured at the midpoint of these layers. Rainfall is measured using tipping bucket raingauges. Volumetric soil moisture is monitored using Campbell Scientific CS615 sensors (Campbell Scientific Inc., 1996). Of all the sensors installed at these stations, the CS615s are the only ones requiring field calibration. Occasional measurements of volumetric soil moisture are also made with Time Domain Reflectometry and by gravimetric methods. This document outlines preliminary calibration of the CS615 sensors for each site.

Development of Generalised Calibration Approach

The Campbell Scientific CS615 Water Content Reflectometer instrument responds to changes in the dielectric constant of soils and is used to measure volumetric soil moisture. The specific soil moisture calibration curve depends on soil type. By developing a generalized calibrating relationship with only one soil dependent parameter, the task of developing specific calibration relationships for field measured soil moisture data could be expedited while at the same time improving confidence in calibrations developed from a small number of samples.

This section describes the development of such a curve for Campbell Scientific CS615 sensors. The likely errors associated with this approach and the optimal moisture conditions for sampling are discussed. Only one calibration parameter that is unique to each soil type for which measurements are made needs to be set before estimates of soil moisture are possible for future study sites.

Soil moisture data from various sites, each with a different soil type, in the Mahurangi River Catchment in New Zealand, the Tarrawarra Catchment in Australia and three sites in the United States were used for calibrating the CS615 instrument. The New Zealand sites are: *Satellite Station*, *Carran's*, *Clayden's* and *Marine Road*. Two different soil types exist at *Satellite Station*, therefore there is data from two separate sites (covering the two soil types – one from the valley floor (*Satellite Station Flat*) and one from hill slopes (*Satellite Station Hill*). *Tarrawarra* is the one site in Australia from which data were used. Soils from two horizons were used for each of the Australian and New Zealand sites. These data were measured by (Western et al., 2001b). The US data are sampled from *clay, silt* and *summit* sites in the Reynolds Creek watershed (Seyfried and Murdock, 2001).

In total, there were 103 soil moisture measurements across all sample sites used for calibration in this exercise. The mean volumetric soil moisture value across the 103 measurements from each site was 29.6%, with a variance of 151.4 and standard deviation of 12.3. Thus a wide range of moisture conditions were available.

Fitting Procedure

The CS615 sensor produces a square wave, the period of which is related to the volumetric soil moisture via a calibration relationship. (Seyfried and Murdock, 2001) and (Western et al., 2001a; Western et al., 2001b) found that this calibration relationship depends on soil type and is also temperature sensitive. (Western et al., 2001a; Western et al., 2001b) developed a temperature correction procedure that is independent of soil type. Close examination of the data of (Western et al., 2001a; Western et al., 2001b) suggests a family of curves that all pass through a common point equivalent to zero moisture content and the period associated with that (~0.7ms). To collapse all this data onto the one general curve, the period of every CS615 measurement for each site was normalised using the period corresponding to a soil moisture value of 40%. Normalisation calculations were done in Excel using the following equation;

$X = (P_{25}-P_0)/(P_{0.4}-P_0)$ (equation 1)

Where:

P_{25} is the period for CS615 measured soil moisture values, temperature corrected to 25ºC using the procedure of (Western et al., 2001a; Western et al., 2001b));

P_0 is the period corresponding to zero soil moisture – determined graphically by extrapolating a fitted linear relationship from a plot of measured soil moisture v P_{25} data from all sites;

$P_{0.4}$ is the period corresponding to 40% soil moisture – unique to each measurement site.

For P_0, a scatter plot was generated of all soil moisture against P_{25} values from every site. Extrapolating the trend to the Y-intercept (Period) gave an estimate of 0.7 for P_0. This is consistent with the sensor signal when it is placed in air and therefore P_0=0.7ms was used for all calibration calculations.

Initial estimates of $P_{0.4}$ values were made for each site, using as a guide the periods corresponding to the measured soil moisture values closest to 40%. Values of X (using equation 1) for each site were then determined using the estimated $P_{0.4}$ values. A trend line was fitted to the plot with an equation of the form;

$$\theta = 40X^{\beta} \qquad 2$$

relating soil moisture, θ, and the normalised period (X). This was done using a least squares objective function (in the natural domain) and by simultaneously optimising β and the value of $P_{0.4}$ for each soil type. The final value obtained for β was 0.77.

The sum of the minimised differences between measured soil moisture values and values calculated with equation 2 across all sites is 650, equating to an error variance of 7.3 and standard deviation of 2.7. For predicted soil moisture values, the total RMS error value is 2.51.

Figure 1 shows a plot of the optimal normalised period *X*, determined using the above procedure, against measured soil moisture from all sites. Judging from the high R^2 value (0.95) and low RMS error, the fit is acceptable. In fact (Western et al., 2001a; Western et al., 2001b) obtained an average standard error of 2.0 across all the Australian and New Zealand sites by fitting site-specific relationships. This indicates that there is little cost in terms of precision in using the generalised curve developed above. Therefore equation 2 is likely to give good predictions of soil moisture using optimised values of $P_{0.4}$ (determined during the joint optimisation) for each site. The low RMS error value (2.51) between the predicted and measured soil moisture also indicates that fitting optimised X values to equation 2 will lead to accurate predictions.

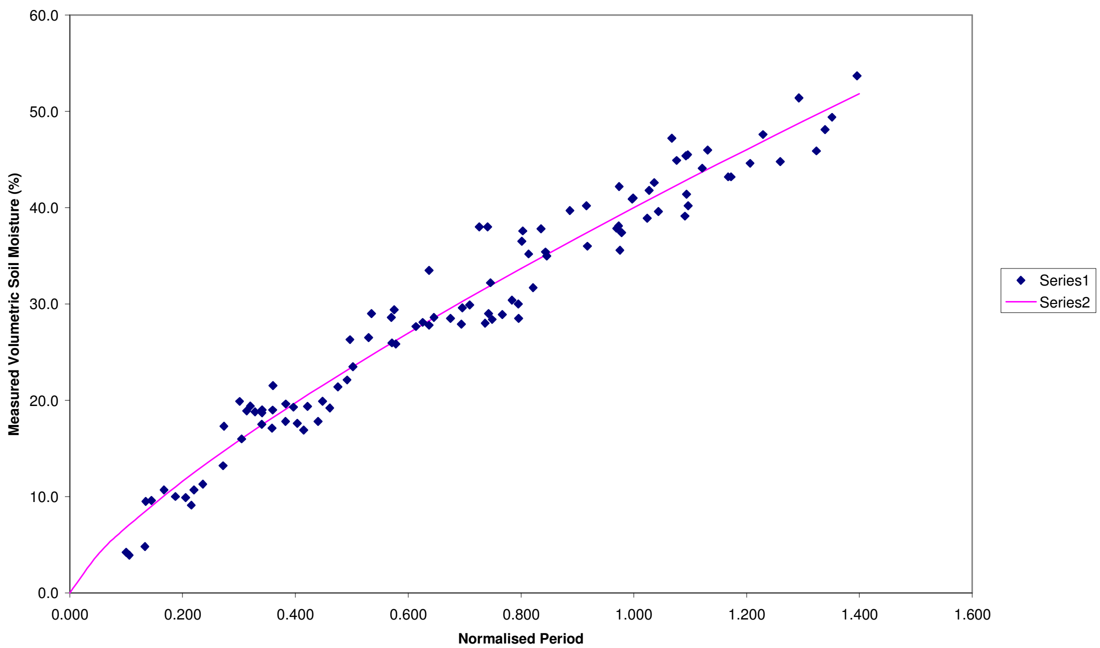

Figure 1: Soil moisture as a function of normalised period. The generalised curve is also shown.

Testing of accuracy achieved

With confidence that the relationship in equation 2 can predict soil moisture with the optimised $P_{0.4}$ values determined for each site, the predictive ability of the relationship was tested using original measured soil moisture and period values.

To do this we assumed we had only one sample and that it was from a relatively wet period. For each site, the measurement with soil closest to 40% was selected. Given that there was now only one sample the optimal value of $P_{0.4}$ could be calculated from Equation 1 and 2 by rearranging themand solving for $P_{0.4}$. Soil moisture predictions were made with this new value of $P_{0.4}$ for all remaining samples at all sites.

The sum of the squared errors between measured and predicted soil moisture is 1436.96, and the RMS error is 4. Figure 2(a) shows all predicted soil moisture values against the measured soil moisture values and figure 2(b) is a similar plot with the same data separated by sample site.

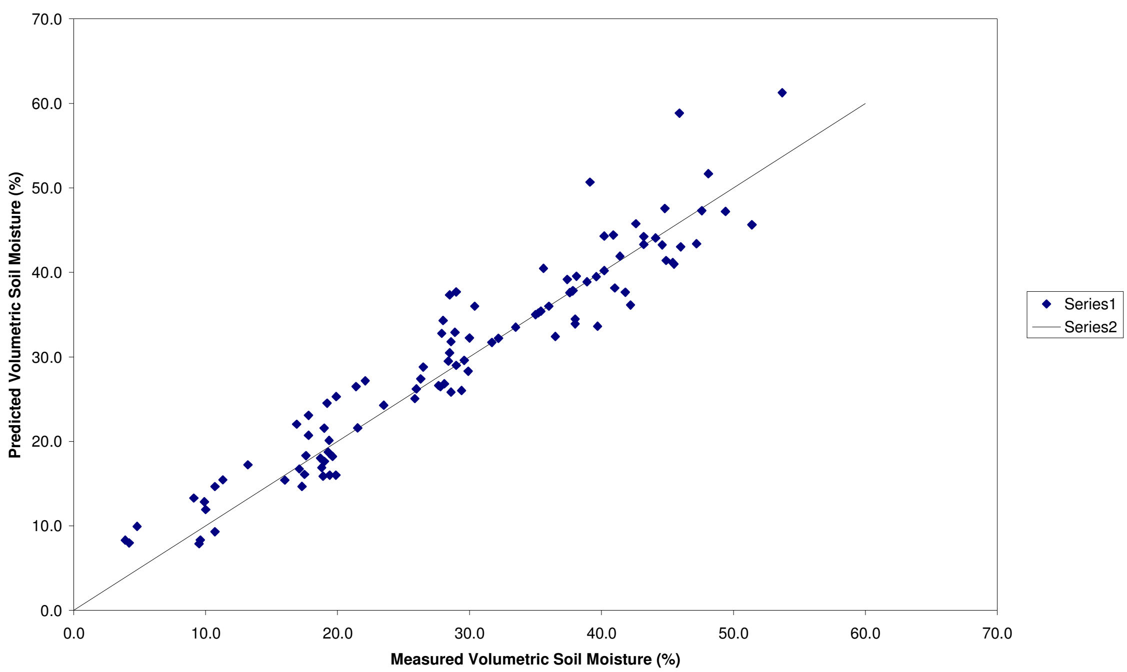

Figure 2(a): Measured Soil Moisture v Predicted Soil Moisture across all sites using a single sample to estimate $P_{0.4}$.

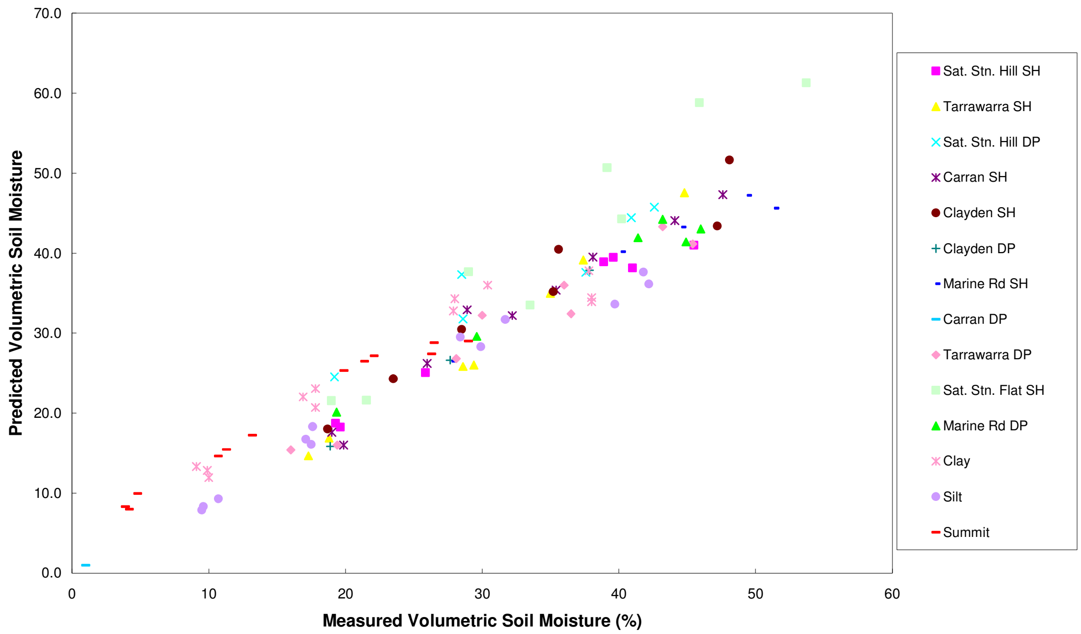

Figure 2(b): As for 2(a) with individual sites distinguished.

The pattern of the data plotted in figures 2(a) and (b), together with the moderately low RMS error value, indicate a good calibration can be obtained using only a single point measurement. From figure 2(b), the Satellite Station Flat SH data splays away slightly from the main trend at a steeper gradient. It should of course be noted that the data used above have been quality controlled primarily by checking for consistency between measurements for each soil. This of course requires multiple samples to be used for any soil, which we would recommend as being standard good practice in any case. Nevertheless it demonstrates the potential for robustly calibrating the Murrumbidgee soil moisture sites using only a small number of soil moisture samples.

Murrumbidgee Network Preliminary Calibration

Time domain reflectometry (TDR) soil moisture measurements from 18 sites across the Murrumbidgee catchment, recorded for three depth ranges – 0-30cm, 30-60cm and 60-90cm – was used for calibrations. Data for a depth range of 0-7cm were also of interest, but unavailable at the time of analysis. Available data for each depth range included corresponding TDR measured soil moisture values, CS615 temperature readings (in degC) and period values (in mSec) from the CS615 instrument. Some gravimetric soil moisture measurements from soil samples were also available, but not used as they were available only for a limited number of sites. More gravimetric data will be collected and they will be used in the final calibration.

The data were first separated according to individual sites, then grouped according to depth ranges for each site. Temperature corrections were applied to the CS615 data to obtain new temperature corrected period values for use in calibration calculations. The following equation from Western et al. (2001) was used for temperature correcting;

$$P_{25} = (P+0.0112(T-25) /(1+0.0128(T-25) \qquad (3)$$

Where P_{25} is the new temperature corrected Period, P is the CS615 measured period and T is the CS615 measured temperature.

A value for $P_{0.4}$ was then estimated for each depth range of every site, using the period corresponding to moisture values close to 40% as a guide. With estimated $P_{0.4}$ values, normalised period values (X) could then be calculated using equation 1, using temperature corrected period values (P_{25}) and 0.7 as the constant P_0. Consequently, predicted soil moisture values could be made using equation 2. Optimised $P_{0.4}$ values ($P_{0.4}$*_fitted)* were then obtained for each depth range at every site by minimising the difference between predicted soil moisture values and measured ones. Table 1 is a summary of the $P_{0.4}$*_fitted* values obtained for depth ranges of every site.

	TDR Depths (cm)										
	0-7			0-30			30-60			60-90	
Sation Site	**P0.4 Fitted**	**RMSE**	**N**	**P0.4 Fitted**	**RMSE**	**N**	**P0.4 Fitted**	**RMSE**	**N**	**P0.4 Fitted**	**RMSE**
SMstn01				2.150	1.103	2	2.222	1.631	3	2.107	2.112
SMstn02				1.704		1	1.668	0.128	2	1.936	0.321
SMstn03				1.909	0.774	2	2.369	0.197	2	2.203	0.735
SMstn04				2.846		1	2.450	2.910	2		
SMstn05				2.599	0.081	2	2.814	1.303	2	2.718	0.461
SMstn06				3.721		1				1.683	
SMstn07				1.803	0.422	2	2.490	0.857	2	2.832	0.560
SMstn08				1.627	3.102	8	2.127	1.959	7	2.546	0.407
SMstn09				1.620	1.892	3	1.803	2.535	3	1.654	1.037

SMstn10	2.007	2.353	2	2.026	0.651	2	2.004	0.567
SMstn11	1.746	0.816	3	1.729	0.676	2	2.163	0.585
SMstn12	1.567	1.814	2	1.910	1.425	2	1.624	0.450
SMstn13	1.687	2.026	3	2.033	2.009	3		
SMstn14	1.545	1.103	3	2.094	0.963	3	1.609	0.911
SMstn15	1.726	3.635	4	1.857	0.817	4	2.121	0.955
SMstn16	1.755	2.479	2	1.648	0.879	2	1.559	1.557
SMstn17	1.555	1.747	3	1.824	1.386	3	2.020	2.621
SMstn18	1.536	2.386	3	2.197	0.860	3	2.276	3.021

Table 1

Included in Table 1 are the number of data records (*n*) for each Station site at each depth range, and the RMS error of the minimised difference between predicted and measured soil moisture values across each depth range. Quality control checking of data revealed some erroneous data recordings. An example is for site SMstn06 (Hay) where anomalous data were observed in the form of extreme measured soil moisture values and period values, which lead to anomalous $P_{0.4}$_*fitted* values (the value 3.721 for the 0-30cm depth range is considered very high). Referring to Table 1, there are also missing $P_{0.4}$_*fitted* values for some sites due to a lack of recorded data there. Table 2 below is a revised version of Table 1, and includes estimated $P_{0.4}$_*fitted* values for where there was missing data or where there were anomalous values such as with site SMstn06.

				TDR Depths (cm)		
	0-7			**0-30**	**30-60**	**60-90**
Sation Site	**P0.4 Fitted**	**RMSE**	**N**	**P0.4 Fitted**	**P0.4 Fitted**	**P0.4 Fitted**
SMstn01	2.150			2.150	2.222	2.107
SMstn02	1.704			1.704	1.668	1.936
SMstn03	1.909			1.909	2.369	2.203
SMstn04	2.846			2.846	2.450	2.5
SMstn05	2.599			2.599	2.814	2.718
SMstn06	2.0			2.0	2.0	2.000
SMstn07	1.803			1.803	2.490	2.832
SMstn08	1.627			1.627	2.127	2.546
SMstn09	1.620			1.620	1.803	1.654
SMstn10	2.007			2.007	2.026	2.004

SMstn11	1.746	1.746	1.729	2.163
SMstn12	1.567	1.567	1.910	1.624
SMstn13	1.687	1.687	2.033	2.0
SMstn14	1.545	1.545	2.094	1.609
SMstn15	1.726	1.726	1.857	2.121
SMstn16	1.755	1.755	1.648	1.559
SMstn17	1.555	1.555	1.824	2.020
SMstn18	1.536	1.536	2.197	2.276

Table 2

Table 2 includes revised $P_{0.4}$_*fitted* values, where anomalous or missing values have been replaced with more realistic values (estimated using values from adjacent depth ranges as a guide). Values for the 0-30cm depth range were used for the 0-7cm range, for which no data were available.

Appendix 1 contains graphs for all 18 sites with normalised period (X) plotted against soil moisture values. The generalised calibration relationship is also included, giving a visual perspective of how closely the normalised period values (X) fit the equation.

Finally, the $P_{0.4}$_*fitted* values in Table 2 were used together with CS615 measured temperature and period data to predict soil moisture for the periods of Spring/Summer 2001, and Autumn 2002. Temperature data were used to temperature correct period values, then the temperature corrected periods (P_{25}) were used to calculate normalised period values (X) and the soil moisture from the generalised calibration curve.

Graphical representation of predicted soil moisture v's time enabled a visual perspective of the quality of the data available. Errors were noted for sites SMstn10 and 16 (Adelong Ck, Rochedale and Adelong Ck, Keenans respectively) caused by erroneous temperature values in the data, leading to erroneous moisture predictions. Therefore, better quality temperature data from the closest site, SMstn15 Adelong Ck Weeroona, were used for recalculating soil moisture for sites SMstn10 and 16. Soil temperature data will need to be checked and relationships developed for infilling when a longer record is available in the near future. Problems were also noted for SMstn06, at Hay, where for the deeper moisture predictions (for 30-60cm and 60-90cm) there is a steady increase in moisture over time in the order of 8-10%. This occurrence is not expected and has yet to be explained, although it may be the result of erroneous data or geological conditions.

References

Campbell Scientific Inc., 1996. CS615 Water content reflectometer: Instruction manual. Version 8221-07. Revision 10.96. Campbell Scientific Inc., Logan Utah, 11 pp.

Seyfried, M.S. and 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.

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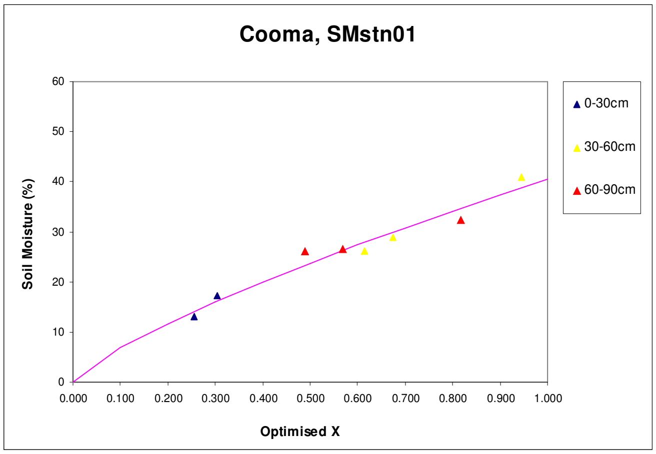
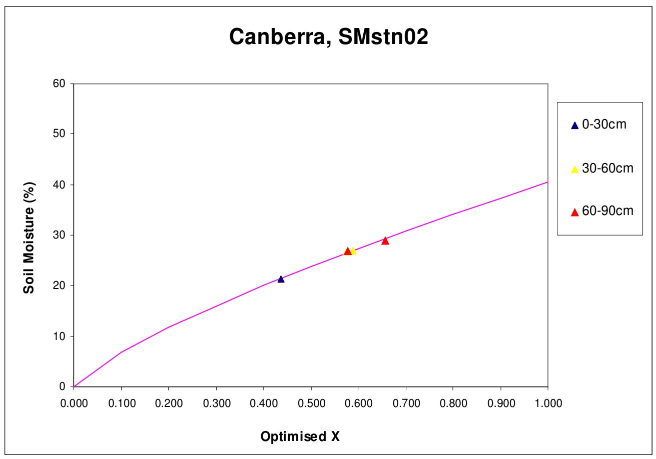
Western, A.W. et al., 2001b. Soil Moisture Instrument Calibration and Reliability Assessment for MaRVEX, Tarrawarra and Point Nepean Experimental Sites. 04/01, Centre for Environmental Applied Hydrology, The University of Melbourne, Melbourne.

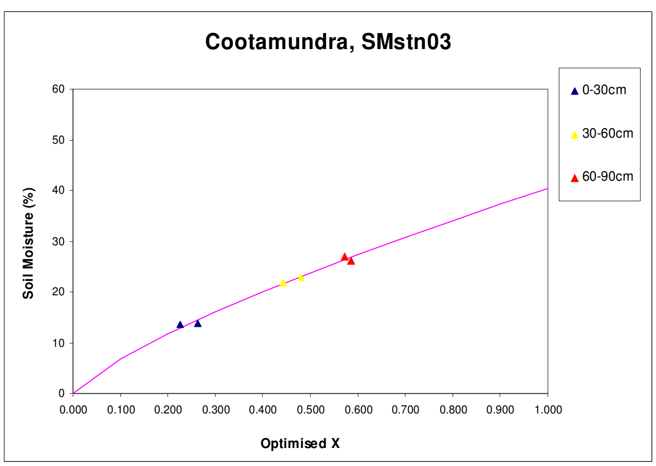
Appendix 1



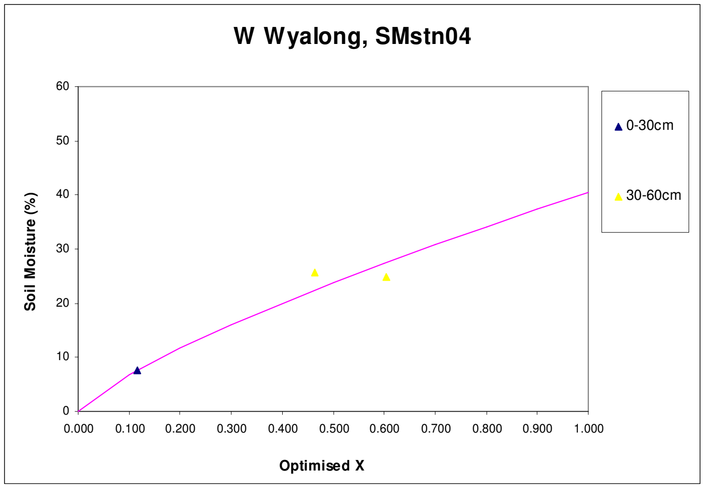
Cooma, SMstn01
Soil Moisture (%)
60
50
40
30
20
10
0
0.000 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
Optimised X
0-30cm
30-60cm
60-90cm

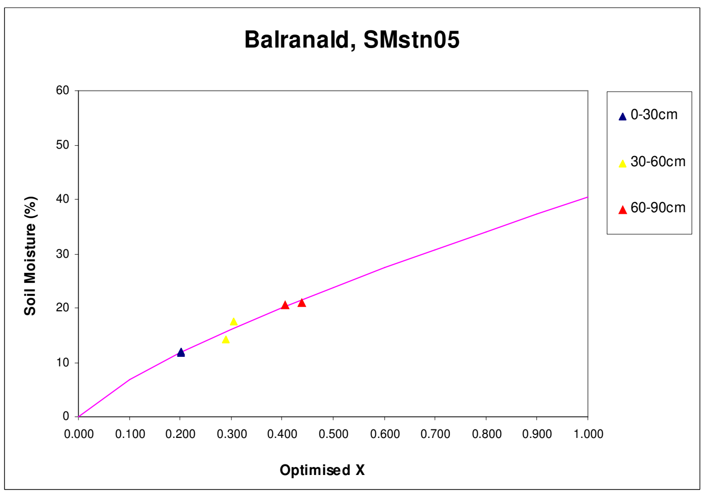


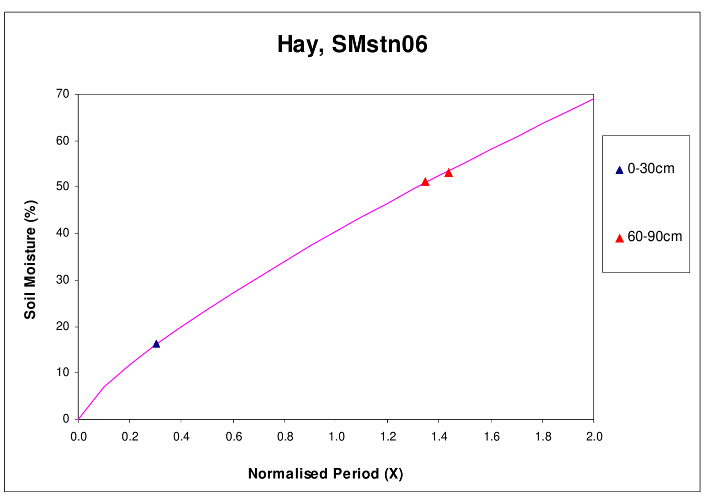
Canberra, SMstn02
Soil Moisture (%)
60
50
40
30
20
10
0
0.000 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
Optimised X
0-30cm
30-60cm
60-90cm

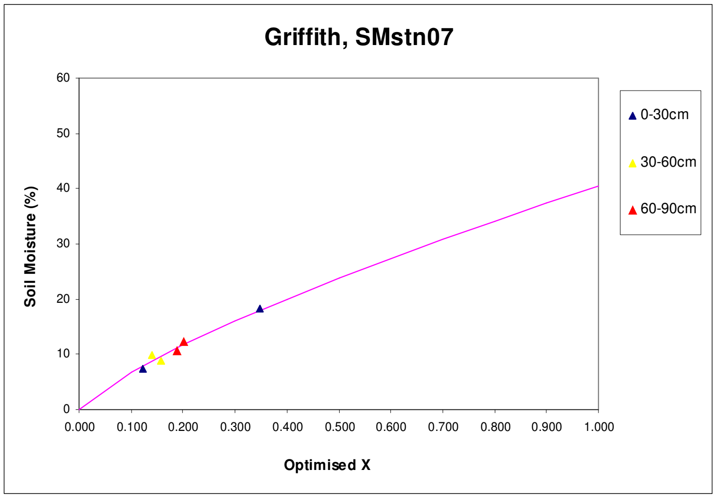


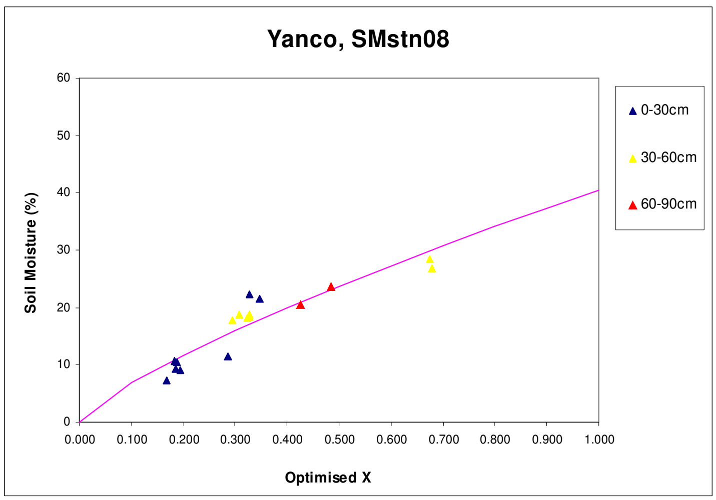
Cootamundra, SMstn03
Soil Moisture (%)
60
50
40
30
20
10
0
0.000 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
Optimised X
0-30cm
30-60cm
60-90cm

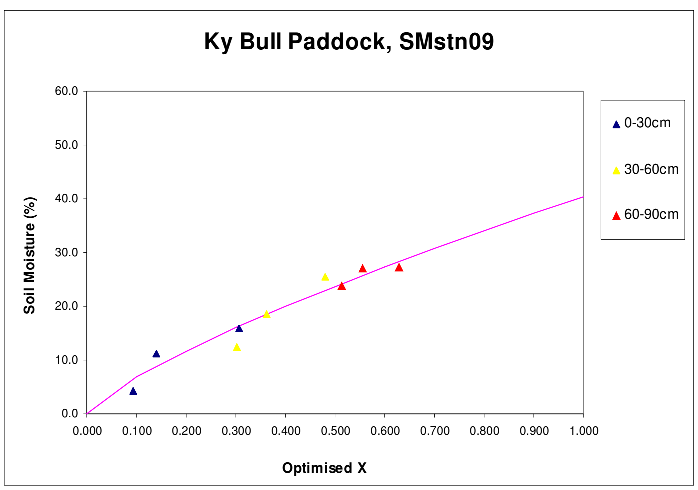

W Wyalong, SMstn04
Soil Moisture (%)
60
50
40
30
20
10
0
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
Optimised X
0-30cm
30-60cm

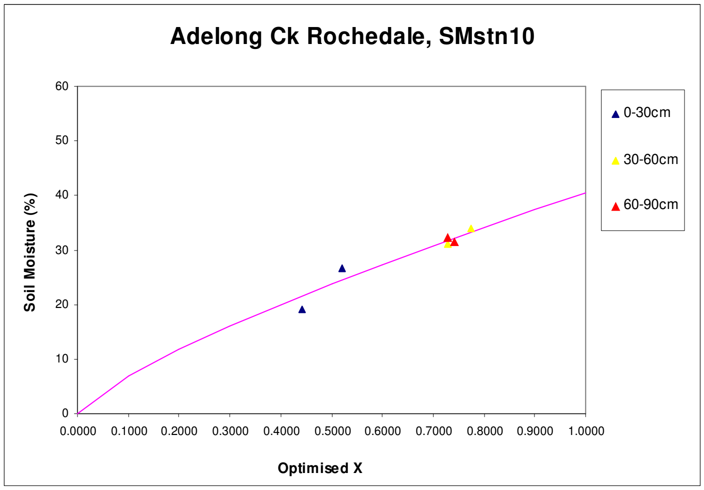

Balranald, SMstn05
Soil Moisture (%)
60
50
40
30
20
10
0
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
Optimised X
0-30cm
30-60cm
60-90cm

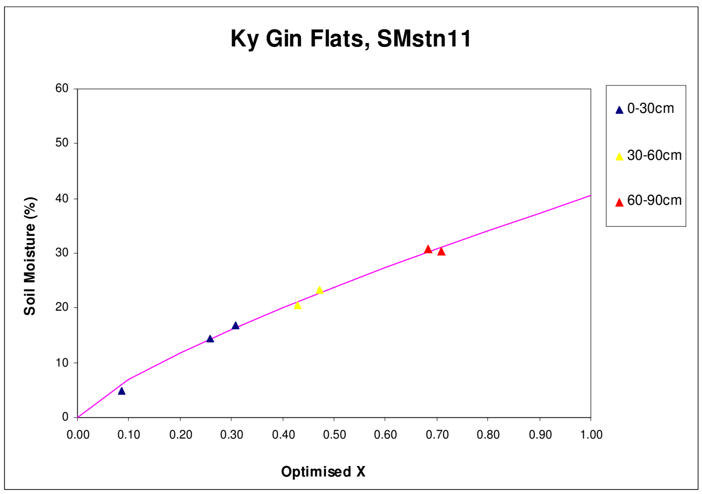

Hay, SMstn06
Soil Moisture (%)
70
60
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Normalised Period (X)
0-30cm
60-90cm

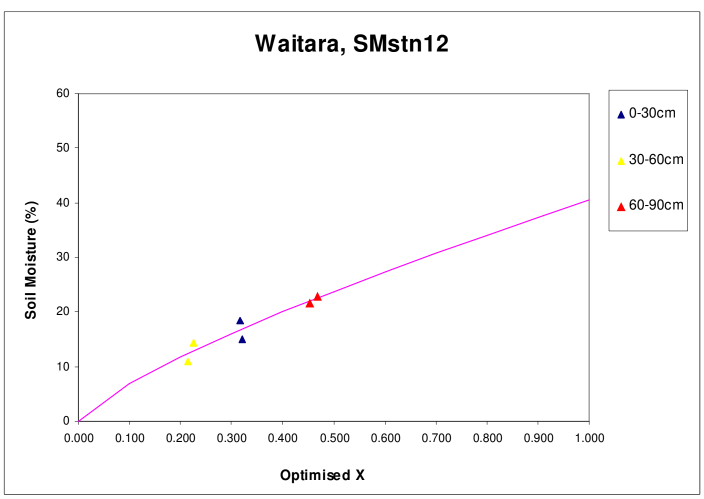

Griffith, SMstn07
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000

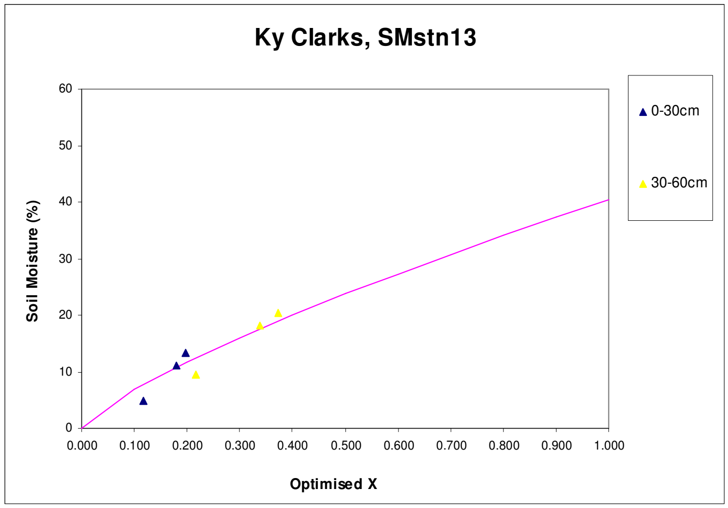

Yanco, SMstn08
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000

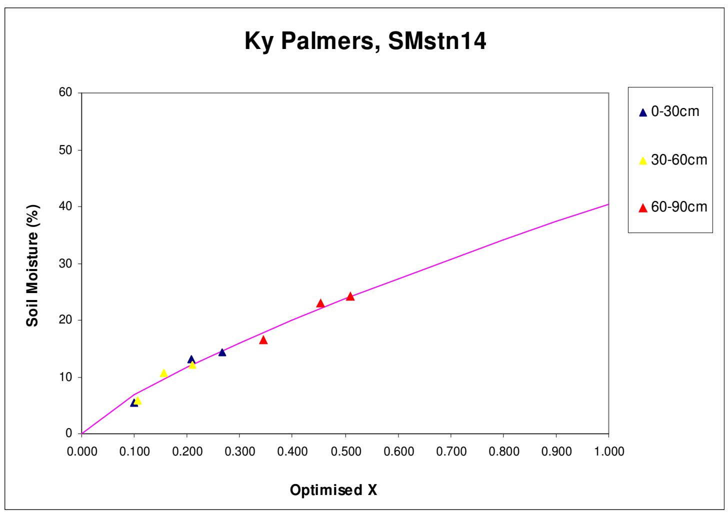

Ky Bull Paddock, SMstn09
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0.0
10.0
20.0
30.0
40.0
50.0
60.0
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000

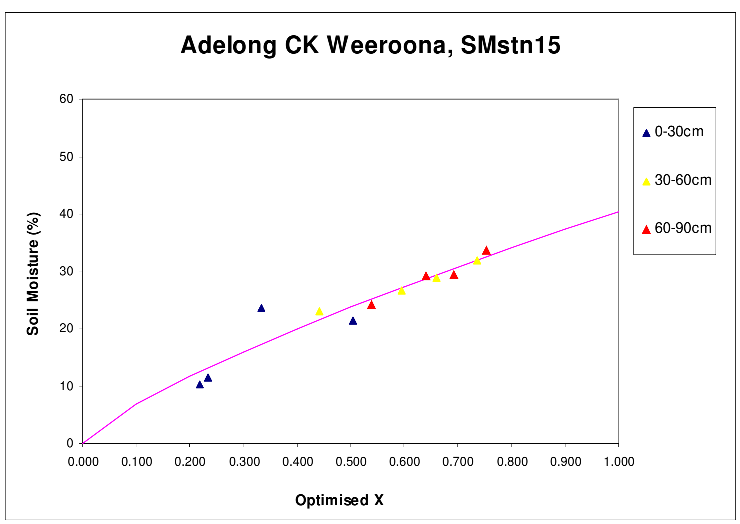

Adelong Ck Rochedale, SMstn10
Soil Moisture (%)
0
10
20
30
40
50
60
0.0000
0.1000
0.2000
0.3000
0.4000
0.5000
0.6000
0.7000
0.8000
0.9000
1.0000
Optimised X
0-30cm
30-60cm
60-90cm

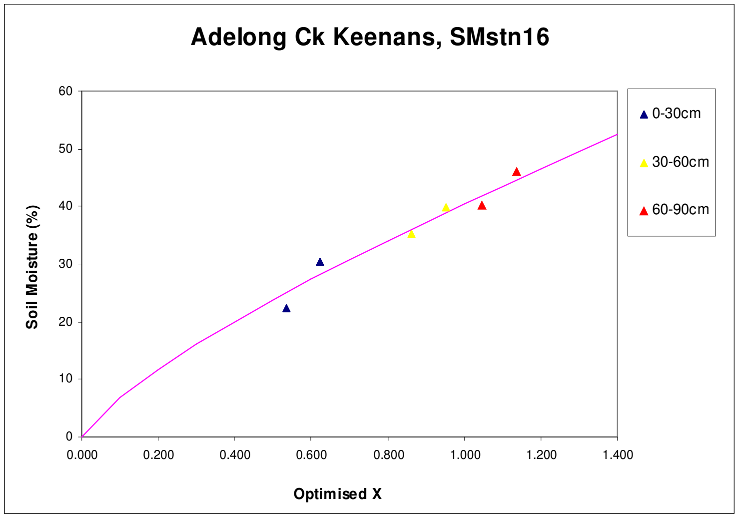

Ky Gin Flats, SMstn11
Soil Moisture (%)
0
10
20
30
40
50
60
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Optimised X
0-30cm
30-60cm
60-90cm

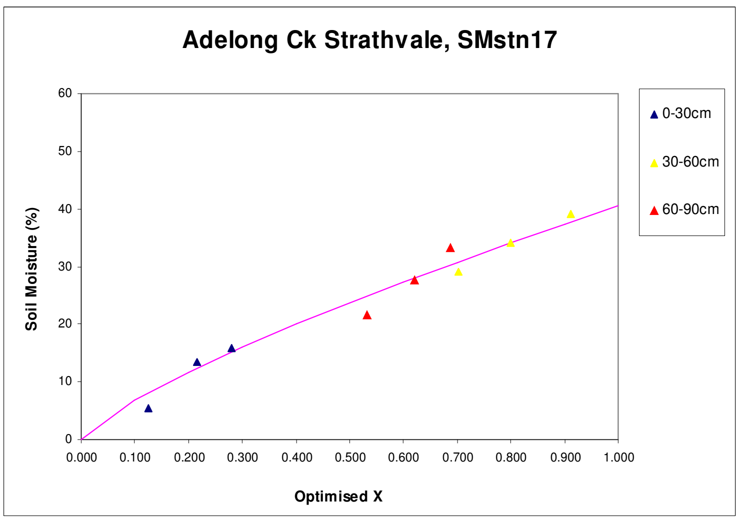

Waitara, SMstn12
Soil Moisture (%)
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
Optimised X
0-30cm
30-60cm
60-90cm

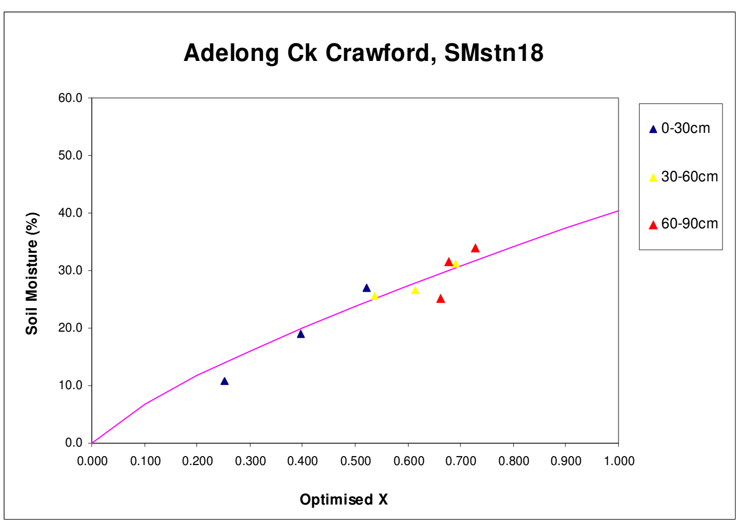

Ky Clarks, SMstn13
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000


Ky Palmers, SMstn14
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000


Adelong CK Weeroona, SMstn15
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000


Adelong Ck Keenans, SMstn16
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0
10
20
30
40
50
60
0.000
0.200
0.400
0.600
0.800
1.000
1.200
1.400


Adelong Ck Strathvale, SMstn17
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0
10
20
30
40
50
60
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000


Adelong Ck Crawford, SMstn18
Soil Moisture (%)
Optimised X
0-30cm
30-60cm
60-90cm
0.0
10.0
20.0
30.0
40.0
50.0
60.0
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000