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In situ measurement of soil moisture: a comparison of techniques

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Abstract

A number of automated techniques for point measurement of soil moisture content have been developed to an operational level over the past few decades. While each of those techniques have been individually evaluated by the thermogravimetric (oven drying and weighing) method, typically under laboratory conditions, there have been few studies which have made a direct comparison between the various techniques, particularly under field conditions. This paper makes an inter-comparison of the Virrib®, Campbell Scientific CS615 reflectometer, Soil Moisture Equipment Corporation TRASE® buriable- and connector-type time domain reflectometry (TDR) soil moisture sensors, and a comparison of the connector-type TDR sensor with thermogravimetric measurements for data collected during a 2-year field study. Both qualitative and quantitative comparisons between the techniques are made, and comparisons made with results from a simple water balance 'bucket' model and a Richards equation based model. It was found that the connector-type TDR sensors produced soil moisture measurements within the ±2.5% v/v accuracy specification of the manufacturer as compared to thermogravimetric data when using the manufacturer's calibration relationship. However, comparisons with the water balance model showed that Virrib and buriable-type TDR sensors yielded soil moisture changes that exceeded rainfall amounts during infiltration events. It was also found that the CS615 reflectometer yielded physically impossible soil moisture measurements (greater than the soil porosity) during periods of saturation. Moreover, the buriable-type TDR measurements of soil moisture content were systematically less than the Virrib measurements by approximately 10% v/v. In addition to the good agreement with thermogravimetric measurements, the connector-type TDR soil moisture measurements yielded the best agreement with Richards equation based model predictions of soil moisture content, with Virrib sensors yielding a poor agreement in the deeper layers. This study suggests that connector-type TDR sensors give the most accurate measurements of soil moisture content out of the sensor types tested.

Keywords: Soil moisture; In situ measurement; Techniques; Comparison

1. Introduction

It has long been recognised that reliable, robust and automated techniques for the measurement of soil moisture content can be extremely useful, if not essential, in hydrologic, environmental and agricultural

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applications. Over the last 70 years, this recognition has fostered the investment of a considerable amount of ingenuity in developing such techniques. The standard method of measuring soil moisture content is the thermogravimetric method, which requires oven drying of a known volume of soil at 105 °C and determining the weight loss. This method is time consuming and destructive to the sampled soil, meaning that it cannot be used for repetitive measurements at the same location. However, it is indispensable as a standard method for calibration and evaluation purposes.

Among the widely used automated soil moisture measurement techniques are neutron scattering, gamma ray attenuation, soil electrical conductivity (including electrical conductivity probes, electrical resistance blocks and electromagnetic induction), tensiometry, hygrometry (including electrical resistance, capacitance, piezoelectric sorption, infra-red absorption and transmission, dimensionally varying element, dew point, and psychometric), and soil dielectric constant (including capacitance and time domain reflectometry). Reviews on the advantages, disadvantages, and basis of these measurement techniques may be found in Wilson, (1971); Schmugge et al. (1980); Zegelin (1996); Topp (2003).

While there is a wide range of point soil moisture measurement techniques commercially available for monitoring of soil moisture content, and each of the techniques have been evaluated using the standard thermogravimetric technique, there has been little in the way of quantitative inter-comparison between the various techniques, or evaluation under field conditions. This paper compares the soil moisture measurements obtained with four different soil moisture sensors during a 2-year field study. A variety of techniques are used in the evaluation, including comparison of a single technique with the standard thermogravimetric method, inter-comparisons between the techniques, and comparisons with predictions from generally accepted models.

2. Field data and soil moisture sensors

The field data used in this study are from the Nerrigundah experimental catchment, located in a temperate region of eastern Australia. The main objective of this rangeland experimental catchment was to enable a soil moisture assimilation study at the catchment scale. A detailed description of the experimental catchment and the entire data set is given in Walker et al. (2001a), so only the pertinent details are given here.

The Nerrigundah catchment was instrumented to monitor evapotranspiration, precipitation and soil moisture from 12 October 1996 to 20 October 1998. The soil moisture instrumentation, contained within a 1×1 m portion of soil located in an area of negligible lateral redistribution, consisted of Virrib® soil moisture sensors (the mention of trade and company names is for the benefit of the reader and does not imply an endorsement of the product), Soil Moisture Equipment Corporation TRASE® buriable- and connector-type time domain reflectometry (TDR) soil moisture sensors, and a Campbell Scientific CS615 water content reflectometer (see Fig. 1). Thermogravimetric measurements were also made. There were no instrument failures during the 2-year period.

2.1. Virrib sensors

The Virrib soil moisture sensors consist of two stainless steel concentric circular rings (electrodes of diameters 28 and 20 cm). Measurements of soil moisture content using the Virrib sensors are made by means of an electro-magnetic wave between these two electrodes (Komin, Technical Data). The sensor produces an output between 5 and 55 mA, which corresponds to a soil moisture content range from 5 to 55% v/v. Soil moisture measurements using the Virrib sensors are reported to be independent of the soil's chemical properties (Komin, Technical Data). Due to the diameter of the outer electrode and the layer thickness over which the sensor output responds (approximately 12 cm when installed horizontally), the sensor provides average soil moisture measurements for a 20 l volume of soil (Komin, Technical Data).

A total of five Virrib sensors were installed horizontally at depths of 10, 15, 20, 30, and 40 cm to continuously monitor soil moisture throughout the 46 cm soil profile, with measurements logged every 15 min. The minimum depth at which the Virrib sensor could be installed without having interference from the air layer above was 10 cm (Komin, Technical Data).

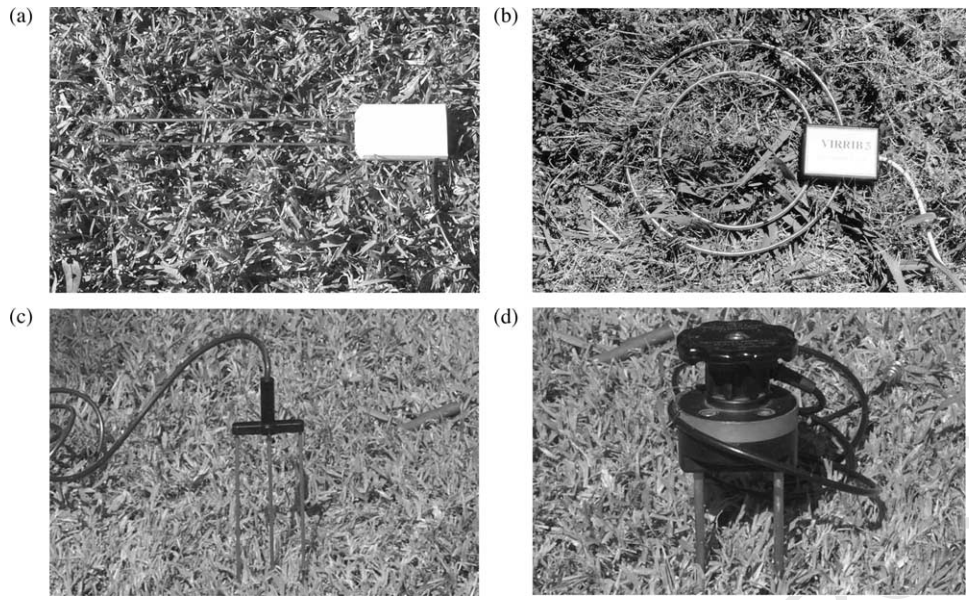

Fig. 1. (a) Campbel Scientific CS615 water content reflectometer; (b) Virrib® soil moisture sensor; (c) Soil Moisture Equipment Corporation TRASE® buriable- and (d) connector-type TDR soil moisture sensor.

Given the design of the Virrib sensors, installation required excavation and recompaction of the soil in which the sensors were placed for measurement of soil moisture content. To minimise the effects of soil disturbance, the soil was replaced in the same order in which it was removed, with as little soil mixing as possible. Due to the disturbance of the soil, these sensors are reported to generally require a few months settling time before representative soil moisture measurements may be made (Komin, Technical Data).

2.2. Buriable-type TDR sensors

The buriable-type TDR sensors consist of three 20 cm long waveguides and the TRASE signal unit. By the TDR technique, measurements of soil moisture content are made through a relationship with the velocity of an electromagnetic wave that is passed along the waveguides, determined by measuring the time-of-travel. These sensors provide an average soil moisture measurement over a layer thickness of approximately 4 cm when installed horizontally, with a specified accuracy of ±2.5% v/v when used in typical mineral soils with the manufacturer's standard calibration relationship (Soil Moisture Equipment Corp., 1989). While this technique can be automated, it was not done in this application.

Periodic measurements of soil moisture using horizontally installed buriable-type TDR sensors at depths of 5, 10, 15, 20, 30 and 40 cm were made on a fortnightly basis, apart from September 1997 when they were made every 2–3 days. The minimum depth at which the sensor could be installed without causing a loss of accuracy was 5 cm (Soil Moisture Equipment Corp., 1989). As the sensors consist of straight waveguides, these sensors could be inserted into undisturbed soil from the side of the excavation. Therefore, measurements made using these sensors should not be affected by disturbance to the soil from excavation to the same extent as the Virrib sensors. However, the disturbance caused by the actual insertion of the waveguide into the soil may be significant for larger waveguide diameters. Rothe et al. (1997)) have shown that merely pushing the TDR waveguides into the soil results in a reduction of the measured soil moisture content of up to 10% v/v, with the effects being strongest close to saturation. Therefore, for waveguide diameters greater than 6 mm, Rothe et al. (1997) suggest that it is necessary to remove soil prior to waveguide installation by drilling. The buriable-type TDR sensors have

a waveguide diameter of 3.2 mm. However, due to the dry state of the soil at the time of installation, the soil was extremely hard and installation was difficult, requiring pilot holes to be formed prior to installation of the sensors. Thus the installation of these types of sensors could be prone to suffer from gaps between the soil and the waveguide.

2.3. Connector-type TDR sensors

The connector-type TDR sensors consist of two stainless steel waveguides of user specified length, a balun and the TRASE signal unit. These sensors are reported to have the same area of influence and accuracy specifications as the buriable-type sensors. The connector-type TDR sensors consist of two 6 mm diameter waveguides that are inserted from the soil surface. Given the design and diameter of these waveguides, they could be inserted from the surface into undisturbed soil without pre-forming holes, even under relatively dry soil conditions.

The vertically inserted connector-type TDR sensors provided an average soil moisture measurement over depths of 0–5, 0–10, 0–15, 0–20, 0–30, and 0–40 cm, being the length of the waveguides used. While this technique can be automated, in this application measurements were made on a fortnightly basis, apart from September 1997 when they were made every 2–3 days. These sensors were not installed until 24 April 1997.

There are upper and lower limitations on the length of TDR waveguides that may be used. The upper limit on waveguide length is governed by the strength-of-arm of the person who inserts the waveguide. However, a more severe limit to waveguide length arises from loss of TDR signal in the soil (Zegelin, 1996). To overcome the arm strength limitations, waveguides of greater than 15 cm length were inserted by hammering employing a waveguide insertion tool. The lower limit on waveguide length is imposed by the accuracy of the time-of-travel measurement of the TDR device, which is currently of order 0.1 ns, limiting waveguide length to greater than 5 cm (Zegelin, 1996). However, Zegelin (1996) has noted that waveguide lengths of 10 cm even have a reduced accuracy because of this timing limit, and Soil Moisture Equipment Corp., 1989) warns against using waveguide lengths of less than 15 cm due to a loss of accuracy. The impact of shorter waveguides on measurement accuracy is discussed further in the section on thermogravimetric measurements.

2.4. Campbell scientific CS615 sensors

The Campbell Scientific CS615 water content reflectometer consists of two 30 cm long stainless steel waveguides connected to a printed circuit board, and measures the soil moisture content using the TDR technique (Campbell Scientific Inc., 1995). The CS615 reflectometer is specified to have an accuracy of $\pm 2.5\%$ v/v when applied to typical mineral soils using the manufacturer's standard calibration relationship. Soils with different dielectric properties show an error that appears as a constant offset (Campbell Scientific Inc., 1995). However, both the accuracy and stability of the sensor are affected by the soil's electrical conductivity. With soil electrical conductivity above 2 dSm^{-1} the sensor output changes and at electrical conductivity values greater than 20 dSm^{-1} the sensor output becomes unstable (Campbell Scientific Inc., 1995). An important consideration with the CS615 reflectometer is its strong dependence on soil temperature. To account for this temperature dependence, a temperature correction polynomial has been supplied (Campbell Scientific Inc., 1995).

A single CS615 sensor was installed horizontally into undisturbed soil from the side of an excavation at a depth of 5 cm, providing a soil moisture measurement over a layer thickness of approximately 4 cm (Campbell Scientific Inc., 1995). Thermocouples were installed at depths of 4 and 6 cm to enable the temperature correction to be made. These measurements were logged every 10 min from 8 May 1997. The CS615 reflectometer has a waveguide diameter of 3.2 mm (the same as the buriable-type TDR sensors), but due to the moist state of the soil at the time of installation, the sensor could be easily installed without pre-forming holes.

2.5. Thermogravimetric measurements: sensor calibration

An in-situ calibration of the soil moisture sensor installations described above could not be performed without destroying the soil moisture monitoring site.

Hence, evaluation of soil moisture measurements was performed by making comparisons between the different soil moisture sensor types, and using a calibration of the connector-type TDR sensor to give confidence in those measurements. The calibration of 5, 10 and 15 cm waveguide lengths was evaluated from thermogravimetric field samples (10 cm diameter soil sampling ring of 5 cm depth). The calibration of longer waveguides was not evaluated due to the destructive nature and labour intensiveness of the testing, and the number of calibration data values required to make conclusive statements regarding accuracy, and the good agreement for the shorter waveguides. In addition, literature suggests that longer waveguides should not result in any further loss of accuracy for the waveguide lengths used. Hence, provided satisfactory calibration results were obtained for the shorter waveguides, measurements made with longer waveguides should also be of sufficient accuracy.

The comparison of connector-type TDR and thermogravimetric measurements is given in Fig. 2, where it can be seen that measurements from the 10 and 15 cm waveguides are in good agreement with thermogravimetric measurements when using the manufacturer's calibration relationship with approximately the ±2.5% v/v accuracy stated by the manufacturer. However, the comparison with 5 cm waveguides may be interpreted in one of three ways:

(i) TDR soil moisture measurements follow a 1:1 relationship with the thermogravimetric measurements but have a very low accuracy, approximately ±7% v/v. This interpretation requires the assumption that the lack of spread around the 1:1 line at soil moisture contents below 40% v/v is due to an insufficiently large sample size.
(ii) There is a non-linear or non-continuous relationship between TDR and thermogravimetric soil moisture measurements. Using this interpretation, individual relationships may be fitted to TDR soil moisture measurements above and below 25% v/v.
(iii) For soil moisture content less than 15% v/v the TDR method cannot measure soil moisture content reliably using 5 cm waveguides, with a variation of 20% v/v in the TDR measurements for the same thermogravimetric soil moisture content.

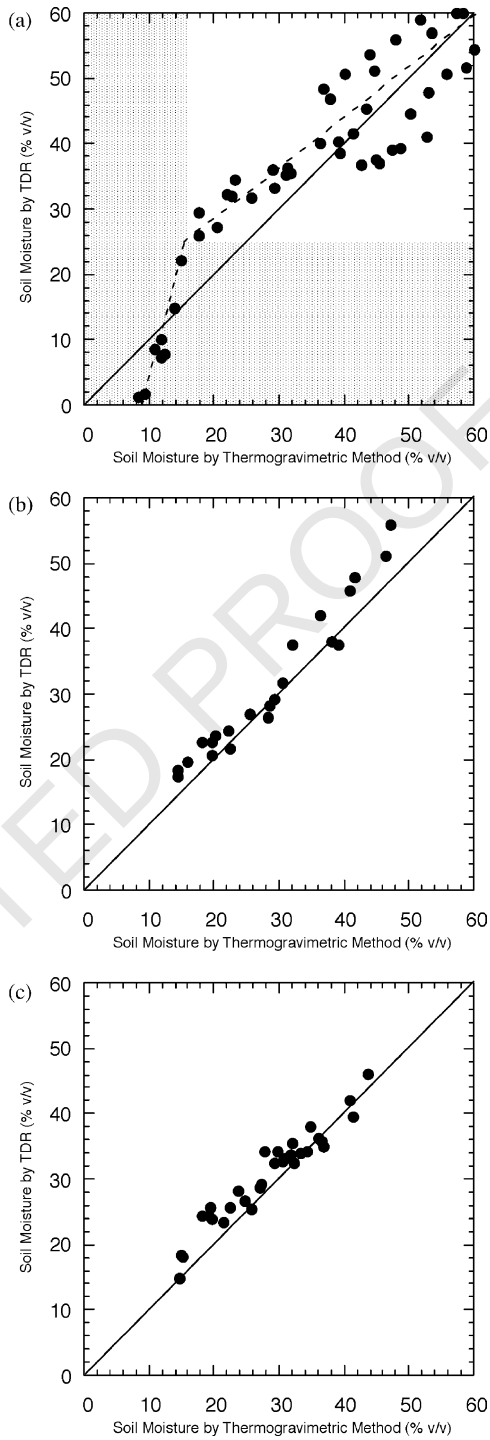

Fig. 2. Comparison of thermogravimetric and connector-type TDR soil moisture measurements for varying waveguide lengths: (a) 5 cm; (b) 10 cm; and (c) 15 cm.

A reason to support (iii) is that as soil becomes drier, the dielectric constant of the soil is reduced, and hence the velocity of the electromagnetic wave is increased. The effect of this increase in velocity would be to make determination of the travel time along the waveguide more difficult due to the shortness of the waveguide. Timing errors will also have a greater influence on the soil moisture content measurement with shorter waveguides. From this third interpretation, a linear relationship may be fitted to TDR measurements above 25% v/v, and any TDR soil moisture measurements below 25% v/v regarded as erroneous. Because of the uncertainty associated with 5 cm waveguide measurements, this data is only used in the qualitative comparison section of this paper.

3. Qualitative comparison of techniques: sensor intercomparison

An intercomparison of soil moisture as measured by the various electronic techniques described above is given in Fig. 3 for depth variation at discrete times, and Fig. 4 for temporal variation in the near-surface measurements. Fig. 5a shows an intercomparison of the temporal variation of soil moisture in the top 40 cm of the soil profile.

The intercomparisons in Fig. 3 show that the Virrib sensors continually gave soil moisture measurements that were approximately 10% v/v higher than the buriable-type TDR sensors, while the connector-type TDR sensors gave mid-range soil moisture contents. Moreover, plotting of the soil moisture profile measurements at discrete times revealed that the soil moisture measurements did not yield a smooth variation of soil moisture content with depth, and that disaggregation of the connector-type TDR measurements for the soil moisture profile was sometimes difficult (e.g. 1 October), as small differences in soil moisture measurements yielded large differences in the layer estimates when performing the disaggregation. Thus, aggregated rather than disaggregated comparisons are made in the remainder of this paper. The non-smooth variation of soil moisture with depth for Virrib and buriable-type TDR may be a result of: (i) inaccurate measurement of soil moisture content by

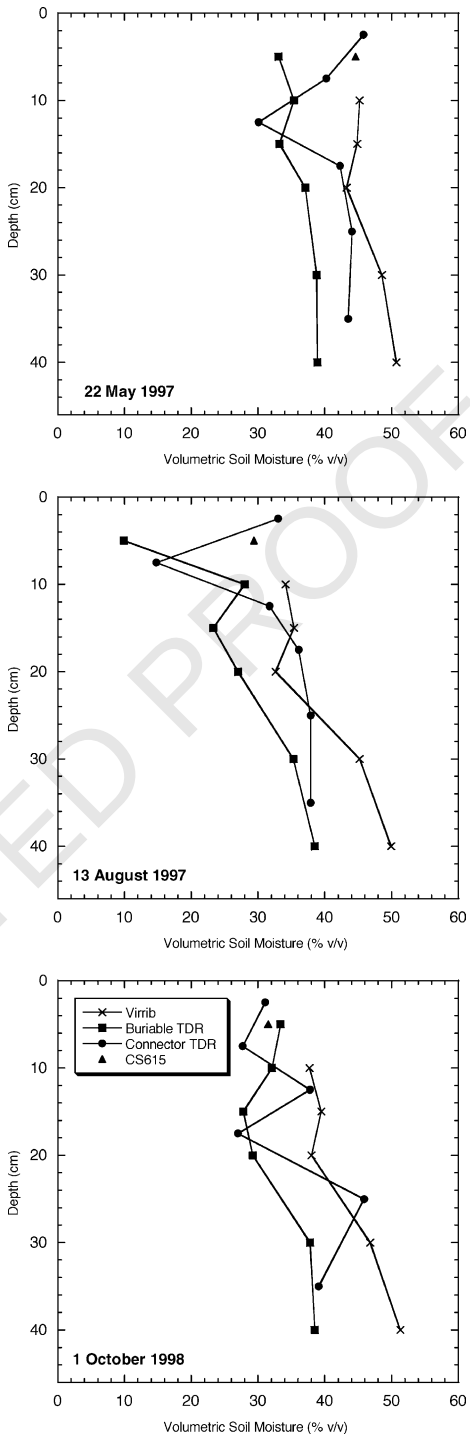

Fig. 3. Depth comparison of Virrib, CS615, buriable- and connector-type TDR soil moisture sensor measurements for various dates.

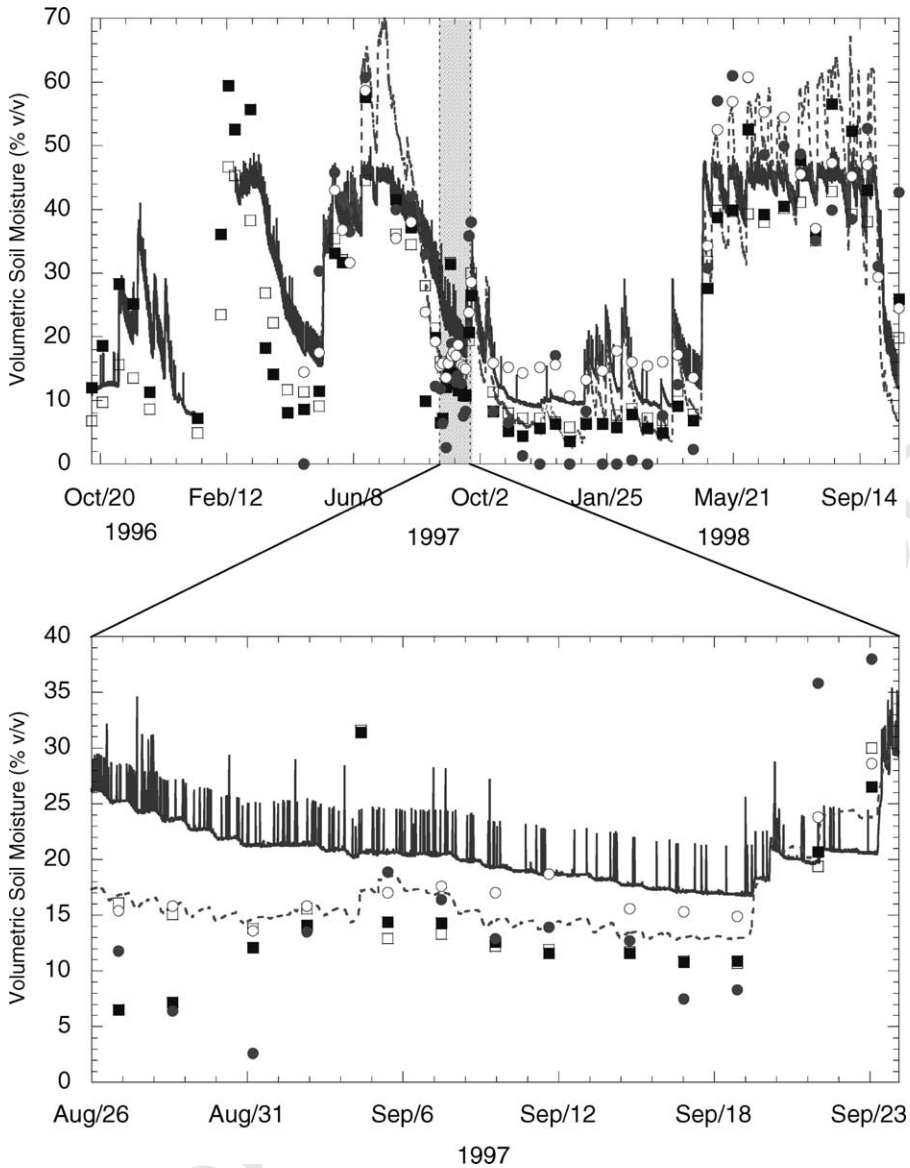

Fig. 4. Temporal comparison of soil moisture measurements: Virrib sensor at 10 cm (solid line), CS615 sensor at 5 cm (dashed line), buriable-type TDR sensor at 5 cm (solid square) and 10 cm (open square), and connector-type TDR for 0-5 cm (solid circle) and 0–10 cm (open circle).

the sensors; or (ii) physical differences in soil moisture content with depth as a result of natural variation in soil properties. The latter is more likely.

The inset of Fig. 4 shows that both the Virrib and CS615 reflectometer have diurnal variations in the soil moisture measurements. While the CS615 reflectometer measurements do not exhibit the high frequency noise present in the Virrib measurements, which requires filtering before the data can be used, soil moisture measurements as high as 70% v/v were recorded. Such high soil moisture measurements were physically unrealistic for this soil, with a porosity of approximately 60% v/v. The CS615 reflectometer measurements indicated higher soil moisture content

than Virrib measurements during wet periods and lower soil moisture content during dry periods. This is to be expected, with the CS615 reflectometer installed at a shallower depth. Moreover, the same overall trend was apparent and there was a reasonable agreement between CS615 reflectometer and buriable-type TDR measurements, particularly during the southern hemisphere summer of 1997/98.

It is difficult to draw any general conclusions regarding the comparison of connector-type TDR measurements with the other instrument types presented in Fig. 4, or the overall accuracy of any particular system from Figs. 3 or 4. However, Fig. 5(a) shows a generally good agreement between the Virrib and connector-type TDR measurements of soil moisture content in the top 40 cm of the soil profile and a poorer agreement with buriable-type TDR measurements. Qualitatively similar results were obtained for comparisons of aggregated soil moisture over shallower depths. This would suggest that Virrib and connector-type TDR measurement techniques were the most accurate of the four techniques tested, based on the qualitatively similar buriable-type TDR and CS615 reflectometer soil moisture measurements at 5 cm depth, and the good agreement of connector-type TDR and thermogravimetric measurements.

4. Quantitative comparison of techniques: soil considerations

An investigation into the variability of soil moisture content over short length scales was undertaken to see if the differences between Virrib, buriable- and connector-type TDR soil moisture measurements were due to actual differences in soil

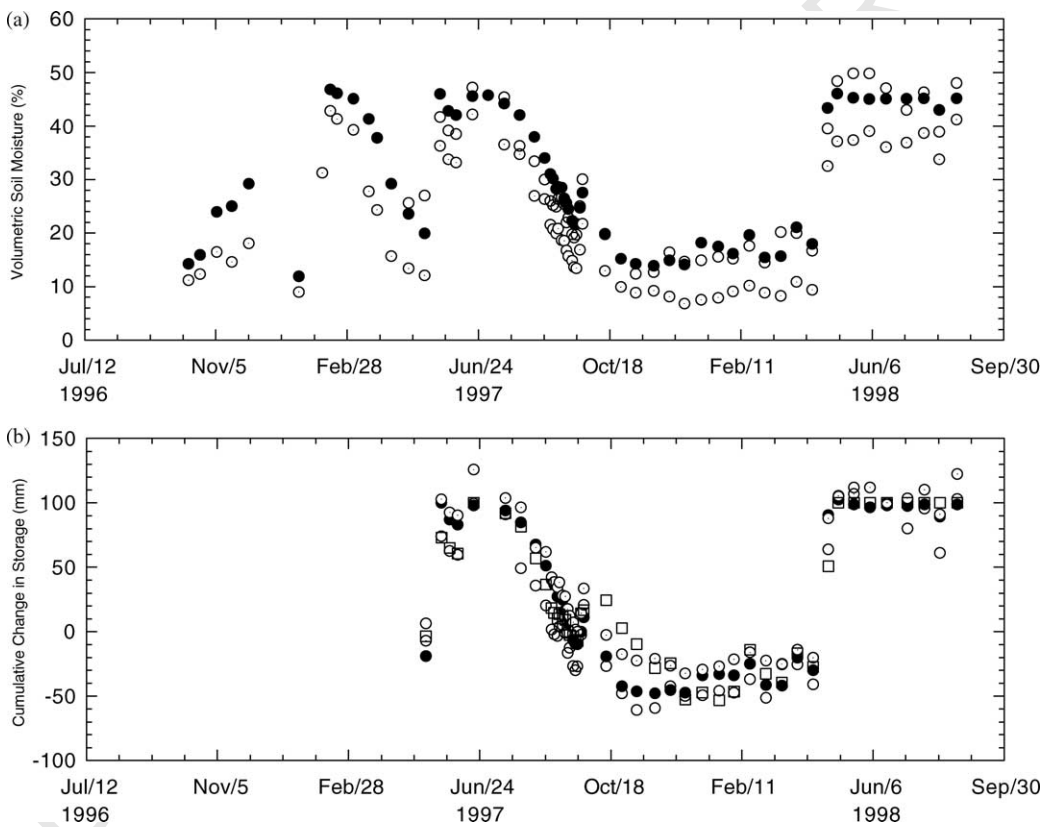

Fig. 5. (a) Comparison of soil moisture measurements for Virrib (solid circle), buriable- (open circle with dot) and connector-type TDR (open circle), to a soil depth of 40 cm; (b) Comparison of cumulative change in soil moisture profile storage for Virrib, buriable- and connector-type TDR, and a bucket water balance model (open square).

moisture as a result of natural variation in soil properties. For this investigation, transects of soil moisture were measured with the 15 cm connector-type TDR waveguides every 0.5 m for a distance of 25 m and every 0.1 m for a distance of 2.5 m, under saturated and unsaturated conditions. Measurements were made in a level area near the intensive soil moisture instrumentation site, with variograms and autocorrelation relationships determined for each of the data sets.

Under saturated soil conditions the measurements reflect the natural variation in soil porosity, whilst the other measurements reflect the variation in soil moisture content due to natural variations in soil properties (such as soil texture), and noise in the measurement technique. The results from this analysis indicated a very short correlation length (less than 0.5 m), with the variogram suggesting a nugget effect due to error in the TDR measurement technique of between 1 and 3% v/v, which is consistent with the manufacturer's specification.

As the large difference between Virrib and buriable-type TDR soil moisture measurements could not be explained by a short scale natural variation in the soil properties, an alternative explanation was sought. The soil disturbance caused by installation of the Virrib sensors was considered to be a contributing factor. Therefore, measurements were made using 15 and 30 cm connector-type TDR waveguide lengths in the disturbed soil where the Virrib sensors were installed, and in the undisturbed soil near the buriable-type TDR sensors. The soil moisture measurements in the disturbed soil (31 July 1997) were 38.2 and 37.4% v/v for the 15 and 30 cm waveguides, respectively, whilst the soil moisture measurements in the undisturbed soil were 35.9 and 35.6% v/v for the 15 and 30 cm waveguides, respectively. Soil moisture measurements were approximately 2% v/v drier in the undisturbed soil in both instances.

This analysis suggests that some of the difference between Virrib and buriable-type TDR soil moisture measurements is attributable to soil disturbance during installation of the Virrib sensors, even nine months after installation. However, this does not account for the entire difference observed, which is possibly due to gaps between the soil and the buriable-type TDR waveguides. Any air or fluid filled gaps around the waveguide due to insertion affect the ability of the TDR technique to measure the soil moisture content accurately. The effect of gaps is reported to be greater for three-rod sensors (i.e. buriable-type TDR) than two-rod sensors (i.e. connector-type TDR and CS615 reflectometer), and if the gaps are filled with water rather than air (Knight et al., 1997).

5. Quantitative comparison of techniques: simple analysis

Immediately following periods of infiltration (14 February 1997, 22 May 1997 and 28 April 1998), the soil moisture measurements by the Virrib sensors indicated systematic increases in soil water storage greater than those indicated by both the buriable- and connector-type TDR soil moisture measurements (Fig. 5a). To identify if the Virrib sensors were over-estimating or if the TDR sensors were under-estimating the changes in soil moisture content, a comparison of cumulative change in soil moisture storage based on the soil moisture measurements was made with a simple bucket type water balance model (Fig. 5b).

In the simple bucket model, it was assumed there was no drainage from the bottom of the soil profile, all rainfall infiltrated up to the maximum soil moisture storage (porosity × soil depth), and actual evapotranspiration was estimated from the Penman-Monteith potential evapotranspiration, reduced by a soil moisture stress index. The soil moisture stress index used in this study was the average column soil moisture content divided by the average column porosity. There was no calibration of the model. Soil moisture storage calculations were commenced from installation of the connector-type TDR probes (24 April 1997), and were normalised so that soil moisture storage estimates were the same for each sensor type at commencement of calculations. This removed the systematic bias between Virrib and buriable-type TDR soil moisture measurements. The results from this analysis indicate that the Virrib sensors were over-estimating the changes in soil moisture content, with connector-type TDR soil moisture measurements and the crude water balance calculations having a good agreement for the two major infiltration events when there was data from all three sensor types.

Analysis of the buriable-type TDR measurements indicated close agreement with the changes in soil water storage from the Virrib sensors.

The other obvious discrepancy between Virrib and connector-type TDR soil moisture measurements (Fig. 5a) was the dry down period from July 1997 to October 1997. During this period, data from the Virrib sensor showed a consistently wetter estimate of the soil moisture content. The comparison with water balance calculations (Fig. 5b) was again best for the connector-type TDR measurements. The discrepancy of water balance calculations with measurements from October 1997 to January 1998 was a result of the model assumption that all rainfall infiltrated. At lower soil moisture contents and for heavy rainfall this is not the case, with infiltration capacities being less than the rainfall rate. Due to the poor agreement between connector- and buriable-type TDR data, and the concern over the installation of buriable-type TDR sensors resulting in gaps, the buriable-type TDR measurements are not used further in this paper.

6. Quantitative comparison of techniques: detailed analysis

This section uses a one-dimensional Richards equation based soil moisture model (see Walker et al., 2001b for details) to further explore the accuracy of Virrib and connector-type TDR soil moisture data. To allow instrument settling time and avoid the period of erroneous Virrib soil moisture data identified above (moisture data suggested that more rainfall occurred than was recorded by the raingauges during wetting up periods), the soil moisture model was calibrated for the 100 day dry down period from 16 June 1997 (Julian day 167) to 24 September 1997 (Julian day 267); approximately eight months after installation of the Virrib sensors.

6.1. Observed model parameters

Several of the parameters required by the soil moisture model could be defined directly from field observations and measurements. Soil layer thicknesses were set to the observed soil horizon thicknesses with the exception of the surface layer, which was set to a thickness of 1 cm. The depression storage parameter was set at 5 mm, based on measurements of root mean square surface roughness. Likewise, the saturated hydraulic conductivity (K_S) was estimated from Guelph permeameter and double ring infiltrometer measurements. The porosity (ϕ) and residual soil moisture content (θ_r) for each of the model layers were estimated from an analysis of the soil moisture measurements over the entire record of data. These parameter values are given in Tables 1 and 2.

6.2. Calibrated model parameters

The model parameters requiring calibration were the van Genuchten parameter n (van Genuchten, 1980), for relating hydraulic conductivity to saturated hydraulic conductivity, and MGRAD, a maximum matric head gradient parameter (Walker et al., 2001b) that is dependent on soil type and used to estimate the matric head gradient for vertical redistribution of soil moisture. Calibration of these parameters was performed with the Bayesian non-linear regression program NLFIT. The NLFIT program suite (Kuczera, 1994) is an interactive optimisation package, employing the Shuffled Complex Evolution Method

Table 1
Soil parameters for the one-dimensional soil moisture model from calibration to Virrib soil moisture data

Layer	Thickness (mm)	Horizon	Observed			Calibrated	
			K_S (mm/h)	ϕ (% v/v)	θ_r (% v/v)	n	MGRAD (mm)
1	10	A1	15	60	6	1.15	432
2	45	A1	15	60	6	1.15	432
3	68	A2	15	46	8	2.42	384
4	112	B1	3	42	12	1.64	389
5	225	B2	0.4	48	18	2.25	32

Table 2
Soil parameters for the one-dimensional soil moisture model from calibration to connector-type TDR soil moisture data (from Walker et al., 2001b)

Layer	Thickness (mm)	Horizon	Observed			Calibrated	
			K_S (mm/h)	ϕ (% v/v)	θ_r (% v/v)	N	MGRAD (mm)
1	10	A1	15	60	6	2.18	23
2	45	A1	15	60	6	2.18	23
3	68	A2	15	46	8	1.34	22
4	112	B1	3	42	12	2.19	50
5	225	B2	0.4	48	18	1.46	275

developed by Duan et al. (1994). The data used for calibration were the Virrib soil moisture measurements of model layers 3 and 4 (model layers 1 and 2 were too shallow for comparison with soil moisture measurements and soil moisture measurements of model layer 5 were not used as a good fit to the data could not be obtained when using those measurements) and the connector-type TDR measurements of depth integrated soil moisture over model layers 1–5 (see Table 3 for depth comparisons). The n and MGRAD parameter values from calibration to the different data types are given in Tables 1 and 2.

Initial soil moisture values were set to the soil porosity values, given that calibration commenced when the soil was saturated. With the soil column being underlain by a low permeability sandstone, a zero-moisture flux boundary condition was applied to the base of the soil column. The surface soil moisture flux boundary condition was set at a fixed value for half hour simulation periods. This surface soil moisture flux was taken as the average of 10 min measurements of Penman–Monteith potential evapotranspiration rate, reduced by the soil stress index, except for periods during which rainfall was recorded. During these periods, it was assumed that no evapotranspiration occurred and that the rainfall recorded had a uniform rainfall rate over the half hour period. Ponding greater than the depression storage depth was instantly disposed of as runoff.

6.3. Calibration to virrib measurements

Parameter values from calibrating to the Virrib observations (Table 1) gave a very good agreement between the model predictions and Virrib soil moisture data (Fig. 6) in model layers 3 and 4 (comparison with layer 4 not shown). However, the comparison with Virrib soil moisture data in model layer 5 was very poor from Julian day 200–260. It was believed that this poor agreement in model layer 5 was a result of poor quality soil moisture data in this layer, rather than a weakness of the model. Installation of the Virrib soil moisture sensors required excavation and recompaction of the soil around the sensors. Hence, even after eight months the soil may not have returned to its original state, particularly at greater depths. In addition, just prior to the calibration period the Virrib soil moisture sensors over-responded to the increase in soil moisture content relative to the amount of rainfall recorded. It was also found that

Table 3
Model and measurement depths used in comparisons

Model		Virrib		Model		Connector	
Layers	Depth (mm)	Sensors	Depth (mm)	Layers	Depth (mm)	Waveguide length(s) (mm)	Depth (mm)
3	55–123	1	40–160	1–3	0–123	100/150	0–125
4	123–235	2/3	90–260	1–4	0–235	200/300	0–250
5	243–460	4/5	260–460	1–5	0–460	400	0–400

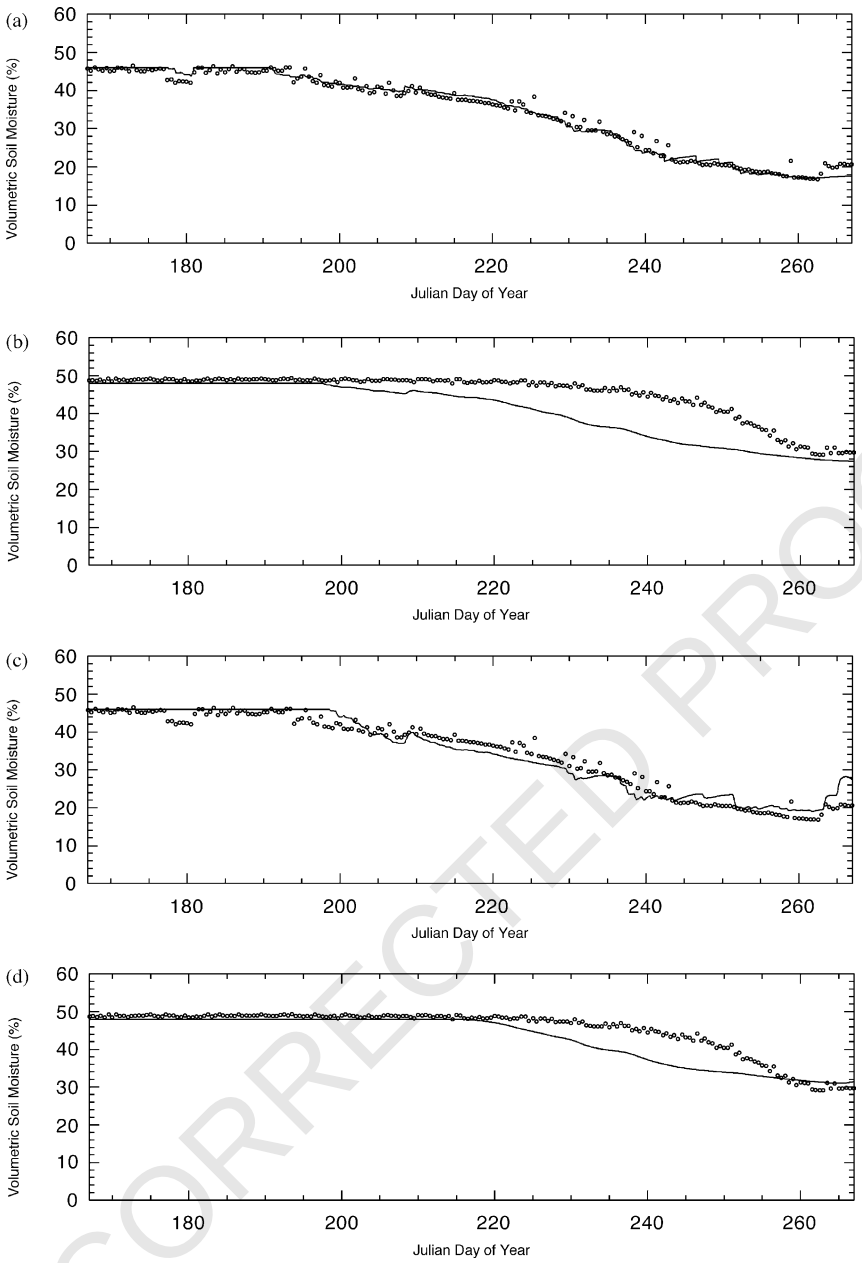

Fig. 6. Comparison of Virrib soil moisture measurements (open circles) with the Richards equation based soil moisture model prediction (solid line): (a) model layer 3 and (b) model layer 5 with calibration to Virrib soil moisture measurements; (c) model layer 3 and (d) model layer 5 with calibration to connector-type TDR soil moisture measurements.

connector TDR soil moisture measurements did not agree well with the Virrib soil moisture measurements during this period, and that connector TDR soil moisture measurements agreed better with soil moisture calculations using a simple bucket water balance model (Fig. 5b).

A comparison of connector-type TDR soil moisture measurements with model predictions from this

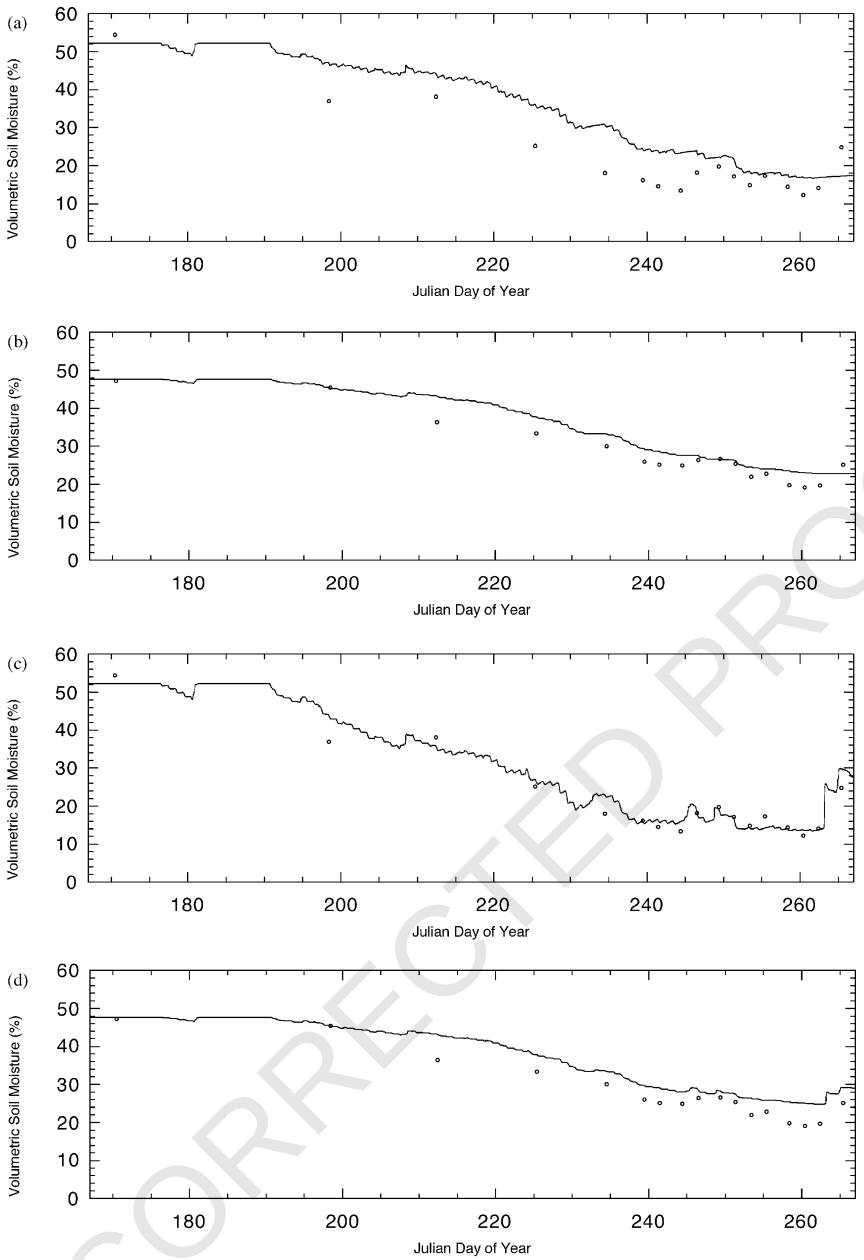

Fig. 7. Comparison of connector-type TDR soil moisture measurements (open circles) with the Richards equation based soil moisture model prediction (solid line): (a) model layers 1 to 3 and (b) model layers 1–5 with calibration to Virrib soil moisture measurements; (c) model layers 1–3 and (b) model layers 1–5 with calibration to connector-type TDR soil moisture measurements.

calibration (Fig. 7) found a good agreement for the average soil moisture content of model layers 1–4 (comparison not shown) and model layers 1–5, but a rather poor agreement for the average soil moisture content of model layers 1–3. Furthermore, the model simulation did not respond to the wetting up towards the end of the calibration period, as indicated by the observed data.

6.4. Calibration to connector TDR measurements

To improve the comparison of model predictions with the observed connector-type TDR soil moisture measurements, a calibration was made to the connector-type TDR soil moisture data. The parameter values from this calibration (Table 2) gave a very good agreement between model predictions and the connector-type TDR soil moisture data (Fig. 7) for model layers 1–3 and 1–4 (comparison not shown), and an equally good agreement for model layers 1–5 as for the calibration to Virrib soil moisture data. The model simulation also responded to the wetting up at the end of the calibration period. In addition, the MGRAD values from calibration to the connector-type TDR data increased with depth, rather than decrease as with the calibration to Virrib soil moisture data. Increasing MGRAD values with depth agree better with intuition, as the clay content in the soil profile increased with depth, and hence the maximum matric suction gradient should be greater at deeper depths. The consistent slight over-estimation of soil moisture storage for the entire soil profile as compared to the connector-type TDR measurements may be a result of: (i) the no drainage boundary condition at the bottom of the soil profile, (ii) an incorrect estimate of rainfall and/or evapotranspiration, or (iii) a systematic error in the 40 cm TDR measurement. A joint calibration to Virrib and connector-type TDR data and/or use of a gravity drainage boundary condition was unable to improve the results.

A comparison of the model prediction is made with the Virrib soil moisture data in Fig. 6. This comparison shows a good agreement with model layer 3 and an even better agreement in model layer 5 than for the calibration to Virrib soil moisture data itself. However, the comparison with model layer 4 (comparison not shown) was slightly degraded. This analysis provides further support to the accuracy of connector-type TDR soil moisture measurements over the Virrib (and other) techniques tested in this paper.

7. Conclusions

This paper found a good agreement between the Soil Moisture Equipment Corporation TRASE® connector-type time domain reflectometry (TDR) and thermogravimetric soil moisture measurements. However, there were significant differences between the other electronic soil moisture techniques studied, which included Virrib® soil moisture sensors, a Campbell Scientific CS615 water content reflectometer, and Soil Moisture Equipment Corporation TRASE buriable-type TDR soil moisture sensors. The conclusion drawn from an analysis of these measurements was that the differences in the soil moisture measurements from the various sensors were the result of a combination of factors.

Firstly, the installation procedure for the Virrib sensors involved major disturbance to the soil in which soil moisture was being measured, thus altering the physical properties of the soil, and still influencing the physical moisture content of the soil in comparison to the undisturbed soil even nine months after installation. Secondly, the different sensors use different measurement techniques and measure the soil moisture of different size volumes of soil. Thirdly, any air or fluid filled gaps around the TDR waveguides due to insertion affect the ability of the TDR technique to measure the moisture content of the soil accurately, with the effects being greater for buriable-type sensors (having three-prong waveguides) than the connector-type and CS615 reflectometer sensors (having two-prong waveguides). Thus the dry soil conditions at time of installation for the buriable-type TDR sensors may have resulted in poor installation of the buriable-type TDR sensors, resulting in gaps which introduce further errors in the measurements, especially under wet soil conditions.

Both the Virrib and CS615 reflectometer soil moisture sensors displayed diurnal variations in soil moisture content and the Virrib sensors displayed high frequency noise that required filtering. Moreover, comparison with a simple water balance 'bucket' model showed that measured changes in soil moisture storage using the Virrib and buriable-type TDR sensors exceeded the recorded rainfall amounts during infiltration events. Furthermore, the CS615 reflectometer soil moisture sensor predicted soil moisture contents that exceeded the soil porosity during periods of saturation. While buriable-type TDR sensors yielded systematically lower measurements of soil moisture content in comparison to Virrib measurements, these two sensor types yielded similar estimates of change in water storage. Comparison between Virrib and

connector-type TDR measurements of total profile water storage was generally good, with the exception of the major infiltration events and towards the end of the major dry down event. In addition to the good agreement with thermogravimetric measurements, the connector-type TDR soil moisture measurements yielded better agreement with Richards equation based model predictions of soil moisture than did the Virrib measurements, providing further evidence that these sensors yielded the most accurate measurements of soil moisture content. It was not possible to attain a good agreement between Richards equation based model predictions and Virrib measurements of deep soil moisture content, even with calibration to that data.

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