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Temporal stability of soil moisture profile

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Abstract

The temporal stability of soil moisture profile across the 610 km^2 Little Washita River Experimental Watershed (LWREW), located in southwestern Oklahoma, is investigated. Experimental data were acquired by time-domain reflectometry (TDR) probes. TDR data were routinely collected at eight locations during the months of June and July in 1997 and in July 2003, coincident with large-scale hydrological remote sensing experiments. Analyses were performed to determine if a subset of the TDR sites could be used to represent watershed averages (i.e. sensor network averages) of soil water content at various levels in the soil profile, as well as in the total profile. The results show that two of the eight TDR sites were temporally stable. One site consistently underestimated and the other consistently overestimated watershed average soil water content at all levels in the soil profile. Because the offset between these under- and over-estimates and the watershed mean are known, these sites can be used to determine the watershed mean values of soil water content at all levels in the profile, as well as to provide ranges of soil water content within the watershed. Identification of these temporally stable sites within the LWERW will assist in the validation of coarse spatial resolution surface soil moisture products derived from remote sensing experiments, as well as providing data sets for watershed hydrologic modeling of subsurface soil water contents.
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Keywords: Soil moisture profile; Remote sensing experiments; Time domain reflectometry; Watershed

1. Introduction

In recent years, much attention has been focused on the spatial variability of surface soil moisture at various scales. Famiglietti et al. (1999) argued that it is necessary to study this variability in order to better understand the nature of soil moisture within a satellite pixel (footprint). To this end, the Southern Great Plains 1997 (SGP97) hydrology experiment (Jackson et al., 1999) was conducted to quantify this variability within selected agricultural fields with spatial dimensions matching the footprint of the aircraft-mounted passive L-band microwave radiometer ESTAR (electronically scanned thinned array radiometer) (Levine et al., 1994) flown during the study. A minimum of 49 daily (June 18–July 17, 1997) soil moisture measurements were manually made within six fields distributed across the 10,000 km^2 study area, from which a number of

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data plots and descriptive statistics were generated characterizing the temporal behavior of these fields during wetting and drying cycles. For short time periods or small remotely sensed footprints, such field studies can be conducted using manual techniques. For long time periods or for large remotely sensed footprints such manual approaches are either too costly or impractical to conduct in a timely fashion.

One objective of the recent soil moisture experiment 2003 (SMEX03) was the validation of near-surface soil water content (θ) derived from the Advanced Microwave Scanning Radiometer (AMSR) on board NASA's aqua and the Japanese aerospace exploration Agency's ADEOS-II satellites (SMEX03, 2003). The AMSR provided estimates of θ at footprint dimensions ranging from 25 to 50 km in diameter (Njoku et al., 2003). Grayson and Western (1998) pointed out that it is unavoidable that point-based measurements will be required to validate remotely sensed estimates of θ.

A number of studies have been conducted to produce spatial estimates of θ using point-based measurements. Warrick et al. (1977); Russo and Bresler (1980) demonstrated that by using soil moisture scaling theory, field averages of (θ could be accurately estimated using point measurements. Other approaches include geostatistical analysis (Western and Bloschl, 1999) probability density function analysis (Avissar and Pielke, 1989) and fractal analysis (Rodriguez-Iturbe et al., 1995). Each of these approaches requires some knowledge of the in situ soil moisture pattern at very fine resolutions which requires either extensive sampling over long periods of time or requires a dense sampling network to capture the spatial character of the soil moisture field (Chen et al., 1997; Kachanoski and De Jong, 1988; Yoo, 2002).

Vachaud et al. (1985) introduced the concept of temporal stability, which is described as the time invariant association between spatial location and classical statistical parametric values. Temporal stability can be viewed as the persistence of the spatial pattern of soil moisture in an area over time (Kachanoski and De Jong, 1988). The purpose of Vachaud et al.'s study was to propose a method of reducing the number of field sampling sites while at the same time accurately characterizing the behavior of θ of the study area over time.

Martinez-Fernandez and Ceballos (2003) provided an excellent review of many of the temporal stability studies conducted since the introduction of the concept by Vachaud et al. (1985). They pointed out that there are few studies that: (1) address areas larger than 1 km^2; (2) few studies refer to the whole soil profile; (3) even fewer studies examine the temporal stability of θ as a function of depth; and (4) that time periods of investigation tend to be short.

As part of SMEX03, Cosh et al. (inpress) performed a temporal stability analysis on surface (0–5 cm) soil moisture measurements made from an automated soil moisture measurement network deployed on the USDA-ARS Little Washita River Experimental Watershed (LWREW). The purpose of their study was to determine if the automated network could be used to validate remotely sensed θ derived from the AMSR satellite instruments. The integrity of the network was analyzed to identify sites that may not be representative of the AMSR footprint scales. The network data were also examined for seasonal and time of day impacts on temporal stability. Additionally, the automated network data were compared to manually collected measurements at selected times during the experiment. Study results indicated that only one of the 13 sites exhibited instability, and that four of the sites provided temporally stable estimates of the network (LWREW) average. It was also shown that the automated measurements compared well to data collected manually. Thus, Cosh et al. (inpress) concluded that the LWREW network could be used to provide groundtruthing for remotely sensed near-surface θ estimates.

During SGP97 and SMEX03 TDR waveguides (herein called probes) were co-located at many of the stations used in the study of Cosh et al. (inpress). The main purpose of this study is to address the first three aforementioned observations by Martinez-Fernandez and Ceballos (2003). An additional objective is to determine if temporally stable sites identified in the TDR network coincide with temporally stable sites identified by Cosh et al. (inpress), which focused only on the 0–5 cm layer and used a different soil moisture measurement technique.

2. Materials and methods

2.1. Little Washita River Experimental Watershed

The LWREW is approximately 610 km^2 in size and is located in southwestern Oklahoma (Fig. 1). Land use on the LWREW is approximately 60% rangeland, 20% cropland, and 20% miscellaneous (forests, riparian areas, water bodies, urban areas, and oil waste land). The topography is gently to moderately rolling with maximum relief of about 183 m. Average annual rainfall is 74.7 cm, with most precipitation occurring in spring and autumn. Summers are typically long, hot and relatively dry. The average daily high temperature for July is 34 °C, and the average cumulative rainfall for July is 5.6 cm. Winters are typically short, temperate, and dry but are usually very cold for a few weeks. The average daily low temperature for January is −4 °C, and the average cumulative precipitation for the month is 2.7 cm.

A network of 45 ARS meteorological sites (Micronet, Fig. 1) was established on the watershed in 1994. The Micronet provides measurements of rainfall, incoming solar radiation, air temperature, relative humidity and soil temperature at three depths. The data are measured every 5 min and reported to a central facility every 15 min where they are quality controlled and archived. The TDR probes

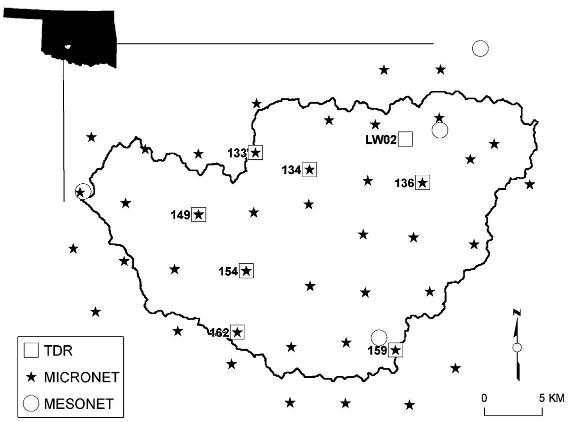

Fig. 1. Map of Little Washita river experimental watershed, distribution of the agricultural research service micronet and Oklahoma climate survey mesonet sites (meteorological stations) and location of the eight TDR stations.

(described below) were co-located at selected Micronet sites, and were co-located with the surface soil moisture sensors utilized in the study of Cosh et al. (inpress). Most of the Micronet raingages were in the process of being replaced during the January through July 1997 time frame. Four Oklahoma Climate Survey (OCS) Mesonet raingages are also located on or near the study basin.

Soils in the watershed have been categorized into one of several hydrologic groups on the basis of the soil properties that are known to influence infiltration and runoff. In general, soils with moderate infiltration rates cover approximately 70% of the watershed. Certain areas of shallow soils in the western portion, as well as a few soils in the eastern region of the watershed have high runoff potential. The central portion of the watershed contains areas with very low runoff potential and higher infiltration due to predominately sandy soils (Allen and Naney, 1991). Soil cores were collected at each study site and sand, silt and clay fractions determined using the hydrometer method (Day, 1965).

2.2. Ground-based soil moisture measurements

TDR is now widely used to measure volumetric water content in soils (Dirksen and Dasberg, 1993; Jacobsen and Schjønning, 1993; Hilhorst, 1998; Chan and Knight, 1999; Heathman et al., 2003). The technique is based on the relationship between θ and the measured apparent dielectric constant. Segmented TDR probes (E.S.I. Environmental Sensors, Inc.[1], Victoria, BC, Canada) were co-located at eight Micronet stations (Fig. 1). The sites were selected based on preexisting instrumentation, soil physical and hydraulic properties, and location within the watershed.

The TDR probes used in this study were constructed of rectangular stainless steel bars (1.3 cm in width) separated by 1.5 cm of epoxy. The probes are segmented devices having known distances between segment endpoints. Probe design is based on TDR remote diode shorting technology (Hook et al., 1992) that enables profile measurements

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors or the USDA.

of θ. The probes were permanently installed at each site using a probe insertion/extraction tool kit. The probes used in this experiment consisted of four-segments with each segment measuring 15 cm in length enabling measurement of θ in the following depth intervals: 0–15, 15–30, 30–45, and 45–60 cm. Calibration of the TDR probes is described in Heathman et al. (2003).

2.3. Study periods

The Southern Great Plains 1997 (SGP97) hydrology experiment was a collaborative effort by an interdisciplinary science team composed of researchers from the National Aeronautic and Space Administration (NASA), the US Department of Agriculture-Agricultural Research Service (USDA-ARS), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and other agencies and universities (Jackson et al., 1999). The experiment was conducted over a 1-month period from June 18 to July 17, 1997. The TDR data were manually collected daily during the campaign, weather permitting. The SMEX03 field campaign was likewise a multidisciplinary and interagency hydrology experiment. The Oklahoma phase of SMEX03 took place from July 2 to July 18, 2003. Since conditions were dry during the experimental period, the TDR data were collected every 2–3 days.

2.4. Statistical analysis

Vachaud et al. (1985) defined temporal stability as the time invariant association between spatial location and classical statistical parameters. In regards to θ, temporal stability suggests that the pattern of spatial variability does not change with time when the individual θ are ranked according to their magnitudes or when scaled against the mean value for the area under consideration (Van Pelt and Wierenga, 2001).

Following Vachaud et al. (1985), two techniques are used to evaluate temporal stability of the TDR data. The first technique is based upon the difference (Δ_{ij}) between an individual measurement of θ_{ij} at location i and time j and the daily spatial mean of water content ($\bar{\theta}_j$) at the same time from all locations:

$$\Delta_{ij} = \theta_{ij} - \bar{\theta}_j, \tag{1}$$

where

$$\bar{\theta}_j = \frac{1}{N}\sum_{i=1}^{N}\theta_{ij}, \tag{2}$$

and N is the number of sampling locations. From Eqs. (1) and (2), relative differences (δ_{ij}) are then calculated from

$$\delta_{ij} = \frac{\Delta_{ij}}{\bar{\theta}_j}. \tag{3}$$

A temporal mean relative difference ($\bar{\delta}_i$) and its standard deviation ($\varsigma(\bar{\delta}_i)$) are determined for each location from

$$\bar{\delta}_i = \frac{1}{m}\sum_{j=1}^{m}\delta_{ij} \tag{4}$$

and

$$\varsigma(\bar{\delta}_i) = \left[\sum_{j=1}^{m}\frac{(\delta_{ij}-\bar{\delta}_i)^2}{m-1}\right]^{1/2}, \tag{5}$$

where m is the number of sampling days. The use of relative differences in this way allows the identification of sites that systematically either represent the watershed mean or under- or over-estimate it while at the same time yielding a measure of variability (Vachaud et al., 1985; Mohanty and Skaggs, 2001). Results from Eqs. (4) and (5) are used to rank and plot the locations (from lowest mean relative difference to highest) and to assess temporal stability at each location. Locations with $\bar{\delta}_i$ near zero indicate sites having a mean θ close to the watershed average, whereas other locations with $\bar{\delta}_i$ higher or lower than zero are over- or under-estimating, respectively, the watershed mean. Locations with small $\varsigma(\bar{\delta}_i)$are considered to be temporally stable.

In the second technique, the non-parametric Spearman's rank correlation test is used to determine if the location ranks persist over the study period. In this approach, R_{ij} is the rank of the variable θ_{ij} at location i on day j, and $R_{ij'}$ is the rank of the same variable at the same location, but on day j'. Spearman's rank correlation coefficients are calculated as

$$r_s = 1 - \frac{6\sum_{i=1}^{n}(R_{ij}-R_{ij'})^2}{n(n^2-1)}, \tag{6}$$

where n is the number of observation sites. An r_s of 1 indicates perfect time stability between dates.

3. Results

3.1. Weather and soil conditions

Schneider et al. (2003) showed that increases in soil moisture at depth often lag precipitation that was received days to weeks earlier. Because the Micronet raingages were not operating prior to SGP97 the four OCS Mesonet raingages were used to provide January through July monthly rainfall totals for 1997 and 2003 (Table 1). Rainfall for the 1997 time period was about 90% of normal, and that for 2003 was 61% of normal, providing a contrast in soil moisture conditions, particularly at the deeper levels, prior to the experimental periods.

Micronet raingages at all the study sites, except LW02, were fully operational during both SGP97 and SMEX03. No precipitation occurred during SMEX03. SGP97 site rainfall totals are shown in Fig. 2. The rainfall value given for LW02 is an average of the total rainfall observed at the immediately surrounding sites. A total of eight rainfall events occurred during the study period that produced measurable precipitation for at least one site. Four precipitation events were recorded at all seven sites, two events produced rainfall at six sites, and one event produced measurable rainfall at only two sites. Site-specific rainfall totals ranged from 40.12 mm at site LW02 to 163.8 mm at site 162. Average rainfall for the study period from these sites was 97.7 mm (±38.37 mm). A thunderstorm on July 10 produced maximum rainfall values at all seven sites with storm totals ranging from 34.1 mm at site 134 to 116.8 mm at site 162.

Textural analysis of the soil cores revealed variable soil conditions across sites (Table 2). Some sites exhibited similar textures throughout the 0–60 cm profile, while others exhibited layering. Bulk density was determined for each depth interval at each study site, and was found to vary from about 1.30 to 1.54 g cm^{-3}.

3.2. Statistical description

Daily watershed averages of θ were calculated for each depth interval and for the total profile for each study period. A broad range in θ occurred at all depths during SGP97. The uppermost depth interval dried at a faster rate than the deeper intervals (Fig. 3), decreasing by 0.11 m^3 m^{-3} from day of year (DOY) 169 to DOY 191. In the 15–30 cm interval, a change of 0.07 m^3 m^{-3} occurred over the same time period, while in the 30–45 and 45–60 cm depth intervals θ decreased by only 0.04 m^3 m^{-3}. Precipitation from storm events during the SGP97 study period tended not to reach the lower two depth intervals, and only the larger rainfall event on DOY 192 managed to increase θ in the 15–30 cm interval (Fig. 3).

Soil water content at the start of the SMEX03 study period was about 0.04 m^3 m^{-3} lower, at all depth intervals, than that observed at the beginning of the SGP97 experiment. As in the SGP97 data set, the SMEX03 data show relatively large ranges in soil moisture across the LWREW. As no rainfall occurred during SMEX03, all depth intervals reflect an uninterrupted drying cycle (Fig. 4), with the surface drying to near 0.08 m^3 m^{-3} by the end of the study.

3.3. Temporal stability—depth intervals

Time-averaged values of θ at each experimental site are shown as cumulative frequency functions, by

Table 1
January through July monthly rainfall (mm) received on the study basin during 1997 and 2003 and the 30-year January through July monthly normals

Time period	Precipitation amount							
	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Total (mm)
SGP97	5.82	88.2	7.55	159.76	145.29	57.94	47.05	511.61
SMEX03	0.57	28.06	33.84	46.54	64.4	164.53	9.08	347.02
1971–2000 (normal)	35.56	46.23	78.99	87.63	139.70	114.30	65.79	568.20

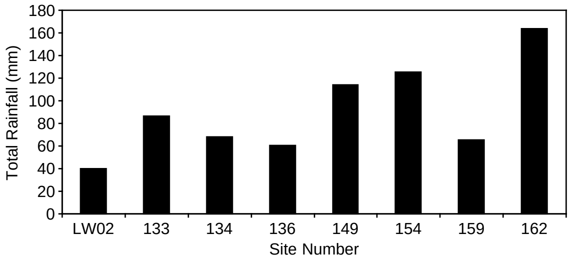

Fig. 2. Site-specific rainfall totals during the SGP97 study period.

depth interval, in Fig. 5(a)–(d). The cumulative frequency plots allow one to determine if a given location maintains its rank across the experimental periods, while also allowing identification of sites that represent the watershed average (cumulative frequency = 0.5) or some other value such as one standard deviation from the mean. General observation of the plots indicates that the soil profile was drier during SMEX03 than during SGP97. Qualitative assessments of TDR site rankings from these plots indicate that in the 0–15 cm interval, only sites 136, 149, and 154 maintained their rankings between study periods. Sites 133, 134, and 136 maintained their rankings in all the lower depth intervals in both study periods. Sites 159 and LW02 maintained ranks in the 15–30 cm intervals as did site 162 in the 45–60 cm interval. In the 45–60 cm depth interval, site 159 moved up four positions from its ranking in SGP97.

Table 2
Soil physical properties at the eight TDR study sites in the study basin

Site number	Depth (cm)	Sand (%)	Site (%)	Clay (%)	Texture name	Bulk density (g cm^{-1})
133	0–15	70.8	19.6	9.6	SL	1.41
	15–30	72.8	7.6	9.6	SL	1.43
	30–45	70.8	17.6	11.6	SL	1.45
	45–60	68.8	19.6	11.6	SL	1.38
134	0–15	77.2	17.6	5.2	LS	1.45
	15–30	79.2	15.6	5.2	LS	1.43
	30–45	81.2	11.6	7.2	LS	1.41
	45–60	79.2	13.6	7.2	LS	1.42
136	0–15	50.8	35.6	13.6	L	1.37
	15–30	54.8	25.6	19.6	SL	1.42
	30–45	52.8	26.0	21.2	SCL	1.41
	45–60	48.8	25.6	25.6	SCL	1.44
149	0–15	29.2	53.6	17.2	SiL	1.47
	15–30	25.2	53.6	21.2	SiL	1.41
	30–45	25.2	49.6	25.2	L	1.48
	45–60	25.2	47.6	27.2	CL	1.46
154	0–15	36.8	37.6	25.6	L	1.43
	15–30	46.8	25.6	27.6	SCL	1.42
	30–45	48.8	21.6	29.2	SCL	1.44
	45–60	50.8	21.6	27.6	SCL	1.39
159	0–15	78.8	8.7	12.5	SL	1.31
	15–30	77.8	9.7	12.5	SL	1.33
	30–45	76.8	9.7	13.5	SL	1.30
	45–60	78.8	8.7	12.5	SL	1.32
162	0–15	62.4	15.2	22.4	SCL	1.33
	15–30	62.4	19.2	18.4	SL	1.38
	30–45	58.4	23.2	18.4	SL	1.33
	45–60	60.4	21.2	18.4	SL	1.35
LW02	0–15	28.4	45.2	26.4	L	1.53
	15–30	24.4	47.2	28.4	CL	1.49
	30–45	26.4	47.2	26.4	L	1.54
	45–60	26.4	53.2	20.4	SiL	1.54

Symbols used in the texture name category are as follows: S, sand; L, loam; Si, silt; C, clay.

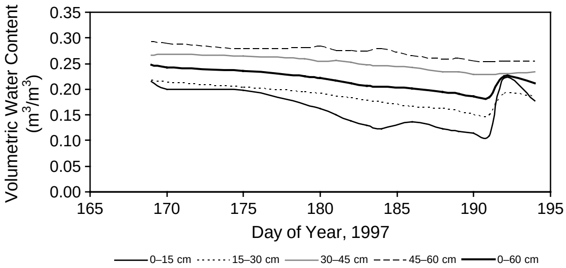

Fig. 3. Time series of volumetric soil water content at various depth intervals during SGP97. The time series reflects the average of all eight TDR locations (i.e. the watershed average).

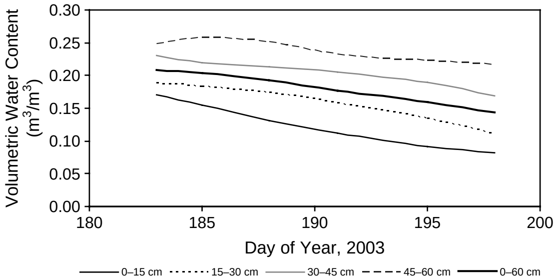

Fig. 4. Time series of volumetric soil water content at various depth intervals during SMEX03. The time series reflects the average of all eight TDR locations (i.e. the watershed average).

Mean relative differences $(\bar{\delta}_i) \pm$ one standard deviation $(\varsigma(\bar{\delta}_i))$ are given for both study periods by depth interval in Fig. 6(a)–(d). In the 0–15 cm interval (Fig. 6(a)), temporally stable estimates of watershed mean θ was acquired at site 159, but only during SMEX03. Site 133 slightly underestimated the watershed mean during SGP97, but was not stable. Site 134 exhibited very stable underestimates of the watershed mean in both study periods, while site 154 yielded nearly identical stable overestimates of the watershed mean in both study periods. During SMEX03, sites 133 and 134 yielded essentially the same information. For the 0–15 cm depth interval, sites 134 and 154 provide temporally stable under- and overestimates of watershed mean θ, respectively. No single site represented the watershed mean for both study periods.

No site represented the average watershed θ in the 15–30 cm interval in either study period (Fig. 6(b)). Sites tending to underestimate during SGP97 also underestimated during SMEX03, while sites overestimating during SGP97 also overestimated during SMEX03. Similar underestimates were observed at site 134 in both study periods, but greater stability was exhibited during SMEX03. Mean relative differences at site 154 were nearly the same in both study periods, but measurements during SMEX03 tended to be less stable than in SGP97.

During SGP97, site 162 yielded very stable estimates of the watershed average θ in the 30–45 cm depth interval (Fig. 6(c)), but no site estimated the watershed mean θ during SMEX03. Similar and stable underestimates of watershed mean θ during both study periods were observed at site 134. Sites 149 and 159 yielded temporally stable and similar overestimates of watershed mean θ during SGP97, as did sites 154 and 159 during SEMX03.

In the 45–60 cm depth interval, similar and stable underestimates were obtained at site 133 during both study periods (Fig. 6(d)), with the SGP97 data set displaying more stability. Site 134 also provided similar underestimates in both study periods, but these estimates were not as stable as those in the other depth intervals at this site. Temporally stable overestimates were obtained at sites 162 and LW02 during SGP97 and at sites 149 and 154 during SMEX03. No single site represented the watershed mean in this depth interval during both study periods, but site 159 did slightly overestimate it during SGP97 with $\bar{\delta}_i = 6 \pm 3.6\%$.

Observation of Figs. 5(a)–(d) and 6(a)–(d) reveals that at times site rankings vary between study periods, thus Spearman's rank correlation analysis was used to quantify the persistence of site rankings within and between study sites. For the SGP97 data set the r_s were all significant at $P < 0.05$ for all depth intervals. Likewise the SMEX03 r_s were all significant at $P <$ 0.06.

3.4. Temporal stability-total profile

Mean relative differences $(\bar{\delta}_i) \pm$ one standard deviation $(\varsigma(\bar{\delta}_i))$ are given in Fig. 7 for the 0–60 cm profile for both the SGP97 and SMEX03 study periods. It is observed that site 159 yields stable estimates near the watershed mean $(\bar{\delta}_i = -2 \pm 2\%)$ during SGP97, but no site adequately represented the watershed average during SMEX03. Site 134 underestimated the watershed mean by 37% in both study periods. Further, these underestimates were relatively

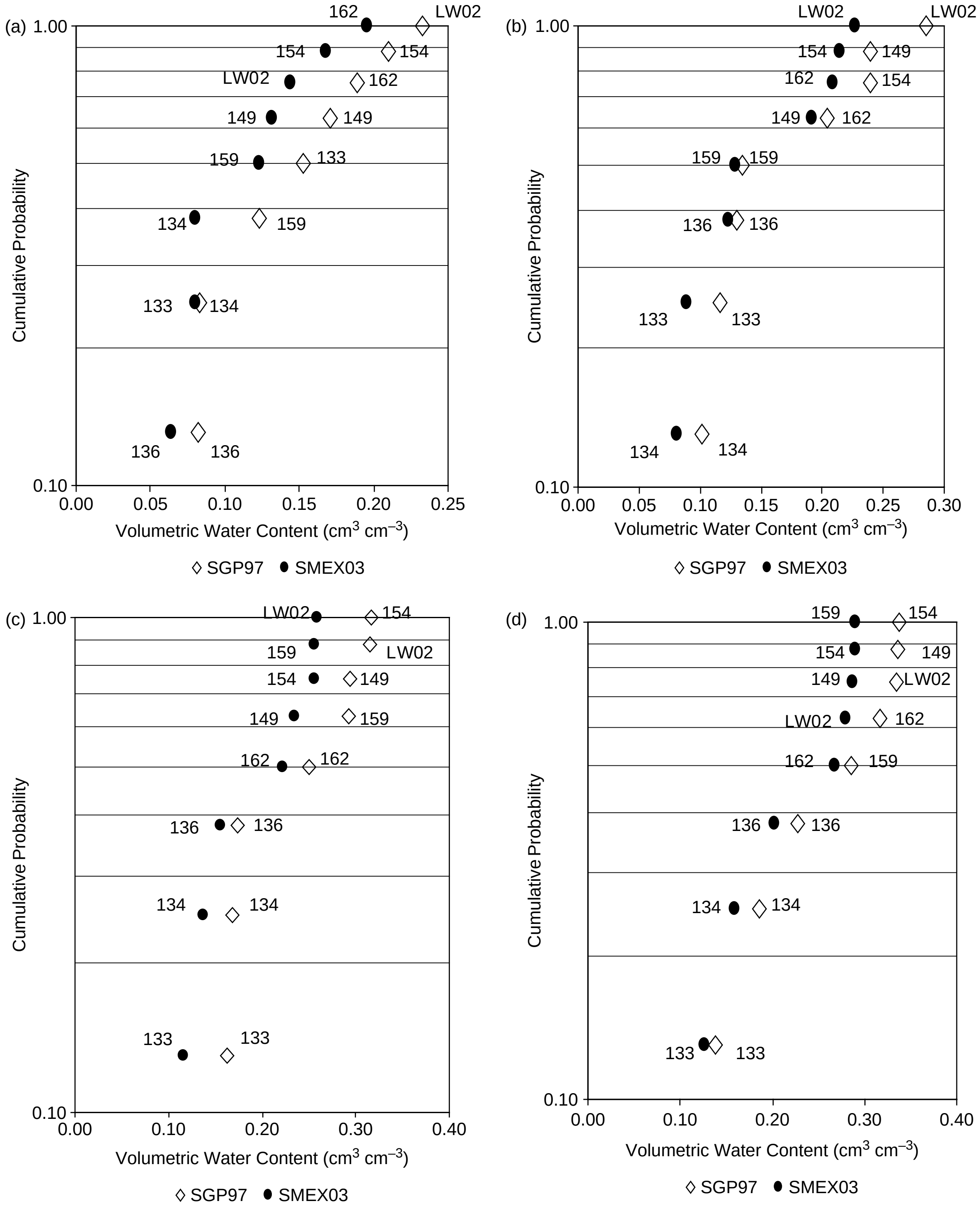

Fig. 5. Comparison of SGP97 and SMEX03 cumulative frequency functions for the 0–15 cm (a), 15–30 cm (b), 30–45 cm (c) and 45–60 cm (d) depth intervals. At each site the time-averaged water content is considered.

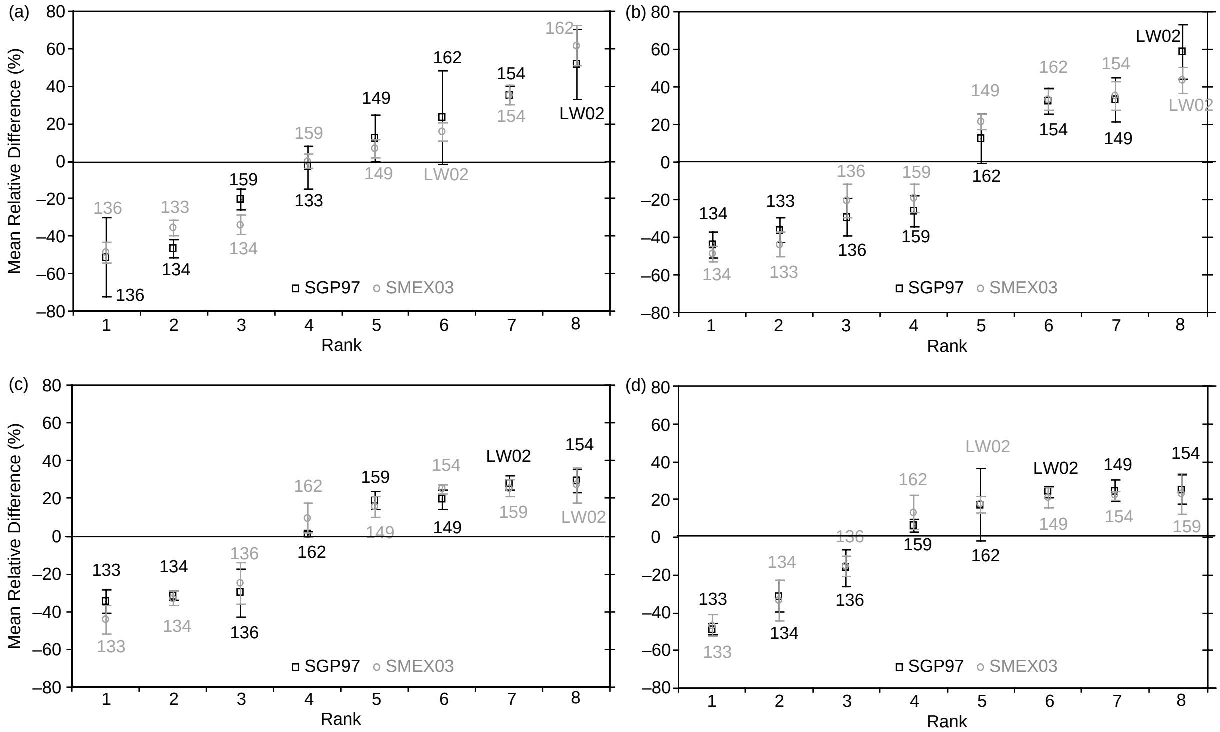

Fig. 6. Ranked mean relative differences for the SGP97 and SMEX03 study periods for the 0–15 cm (a), 15–30 cm (b), 30–45 cm (c) and 45–60 cm (d) depth intervals. The mean relative differences ± one standard deviation and site identifications are shown.

stable with a $\varsigma(\bar{\delta}_i)$ of about 5% in both study periods. Site 154 overestimated the watershed mean by about 29% in both study periods with $\varsigma(\bar{\delta}_i)$ of 4% in SGP97 and 3% in SMEX03.

4. Discussion

Overall, the temporal stability analysis suggests that sites 134 and 154 provided stable under- and

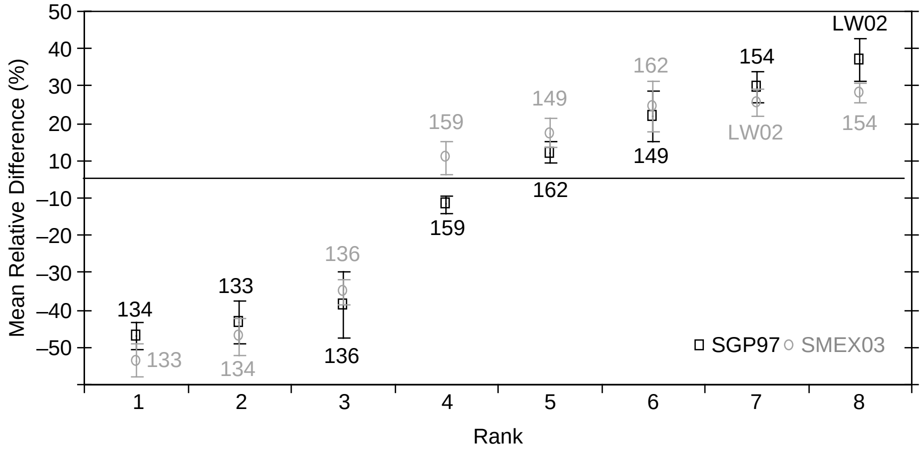

Fig. 7. Total profile (0–60 cm) ranked mean relative differences for the SGP97 and SMEX03 study periods. The mean relative differences ± one standard deviation and site identifications are shown.

Table 3
Regression equations and coefficients (r^2) derived from linear regression of depth-specific measured watershed mean volumetric water content (X) and mean watershed volumetric water content estimated from Eq. (7) (y) for two sites having temporally stable, non-zero mean relative differences

Depth interval (cm)	Site 134	Site 154
0–15	$Y=1.211X+0.006$ (0.98)	$y=1.107X$–0.008 (0.99)
15–30	$Y=1.277X$–0.055 (0.98)	$y=1.253X$–0.031 (0.97)
30–45	$Y=1.66X$–0.13 (0.95)	$y=0.957X+0.002$ (0.94)
45–60	$Y=4.045X$–0.654 (0.91)	$y=1.056X$–0.015 (0.95)
0–60	$Y=1.618X$–0.108 (0.95)	$y=1.059X$–0.012 (0.98)

over-estimates, respectively, of watershed mean θ in each of the four 15 cm depth intervals. These two sites were also identified by Cosh et al. (inpress) as having the same characteristics for the shallow surface layer (0–5 cm). Unlike the findings of Cosh et al., (in press) no site provided a stable estimate of watershed mean θ in both study periods for any depth interval.

Grayson and Western (1998) noted that time-stable sites having a non-zero $\bar{\delta}_i$ could be used to represent watershed average θ provided that the offset between the mean value and the non-zero time-stable sites were known. To demonstrate this, it is assumed that the mean of the measurements made at the eight TDR sites, at a given depth interval, represents θ of the watershed in that depth interval. Then, from Grayson and Western (1998), an estimate of the watershed mean θ_{wd} at some depth interval d can be obtained from

$$\theta_{\mathrm{wd}} = \frac{\theta_{\mathrm{md}}}{1 + \bar{\delta}_{\mathrm{id}}}, \qquad (7)$$

where θ_{md} is the measured volumetric water content from a temporally stable site having a non-zero mean relative difference in the same depth interval ($\bar{\delta}_{\mathrm{id}}$). The $\bar{\delta}_{\mathrm{id}}$ determined for sites 134 and 154 from the SGP97 were applied in Eq. (7) to estimate θ_{wd} for the SMEX03 data set. Linear regression of the estimates from Eq. (7) and the measured watershed mean revealed that both sites produced good estimates of the watershed mean at all depth intervals (Table 3), accounting for over 90% of the variability in the measured data.

Grayson and Western (1998) further stated that because sites are temporally stable, the offset is a constant irrespective of the time of year (or average wetness) so any measurement from such a site could be simply adjusted to give the watershed average value. Findings from sites 134 and 154 seem to support this thesis as does the graphical data given from a 3-year temporal stability study conducted by Martinez-Fernandez and Ceballos (2003). However, this assumption can be violated. For example, site 159 exhibited a temporally stable value of $\bar{\delta}_{\mathrm{i}}$ near 0% in the 0–15 cm depth interval, while giving a temporally stable value of $\bar{\delta}_{\mathrm{i}}$ near -20% during SMEX03 (Fig. 5) in that same interval.

There are a number of contributing factors that can affect temporal stability, including soil texture, topography (slope and aspect), vegetation and climate (primarily precipitation) (Grayson and Western, 1998; Mohanty and Skaggs, 2001). The TDRs used in this study were located in relatively level, warm season grass pastures. Similarity of topographic and vegetative conditions at the study sites minimized these a factors affecting temporal stability. The effect of spatially variable precipitation on temporal stability is difficult to determine from this study. There are, however, some indications that spatially variable rainfall did not significantly affect temporal stability. First, viewing the study period rainfall totals for SGP97 (Fig. 2), it is observed that the 'dry' θ sites (133, 134, 136) appear to be associated with areas of the study basin that received below study period average rainfall, while the 'wet' sites (149, 154, 162) were associated with higher than average study period rainfall. Results from the Spearman rank correlation analysis indicated a high level of similarity of site rankings from day to day over the SGP97 study period; i.e. dry sites were persistently dry and wet sites were persistently wet. Additionally, a high degree of similarity in site rankings across the two study periods was observed despite the lack of rainfall during the SMEX03 study period.

Second, by limiting the analysis to sites 134 and 154 it was discovered that of the seven rainfall events that occurred simultaneously at sites 134 and 154, rainfall at site 134 equaled or exceeded that at site 154 on four occasions, yet site 134 was a 'dry' temporally stable site while site 154 was a 'wet' temporally stable site. Reference to Table 2 shows that the soil at site 134 is loamy sand, which should drain more quickly than the sandy clay loam soil at site 154. Moreover, it is also observed that site LW02, the site receiving the least amount of rainfall during the study period (Fig. 2) but was consistently 'wet' relative to study basin average θ (Figs. 6(a)–(d) and 7), has a high clay content soil throughout much of its profile. Taken together these limited data suggest that soil factors contributed more to temporal stability than did spatially variable precipitation, for this study. In light of this finding, it would seem appropriate that prior to deploying soil moisture measurement sites in ungauged basins that the soils should first be characterized before localizing the measurement sites.

5. Conclusions

A temporal stability analysis of profile soil water content measurements was conducted on TDR volumetric soil water content data collected during the SGP97 and SMEX03 field studies. The purpose of this study was to investigate the temporal stability of θ as a function of depth in the soil profile as well as the total soil profile, and to conduct such a study in an area larger than 1 km^2. Additionally, we wanted to determine if temporally stable sites in the soil profile coincided with temporally stable surface layer (0–5 cm) sites previously identified by Cosh et al. (in press) in the study area.

Only two measurement sites exhibited temporal stability; one consistently overestimated and the other consistently underestimated the watershed mean soil water content at all depth intervals. These two sites were also identified by Cosh et al. (in press) as temporally stable in the surface layer. Because the offset between these under and over-estimates and the watershed mean is known, these sites can be used to determine the watershed mean values of soil water content at all levels in the profile as well as providing ranges of soil water content within the watershed.

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