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Surface and profile soil moisture spatio-temporal analysis during an excessive rainfall period in the Southern Great Plains, USA

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ABSTRACT

In this work we analyze the temporal stability of soil moisture at the field and watershed scales in the Little Washita River Experimental Watershed (LWREW), as part of the remote sensing Cloud and Land Surface Interaction Campaign (CLASIC07) during June 2007 in south-central Oklahoma. Temporal stability of surface and profile soil moisture data were investigated for 20 LWREW soil moisture measurement stations. In addition, daily surface and profile soil moisture measurements were obtained in four 800 m by 800 m fields (remote sensing footprint), including two rangeland sites and two winter wheat fields. The work aimed to analyze the temporal stability of soil moisture at the watershed and field scale and to identify stations within the watershed, as well as locations within each field, that were representative of the mean areal soil moisture content. We also determined the relationship between sites found to be temporally stable for surface soil moisture versus those determined stable for average profile soil moisture content. For the unusually wet experimental period, results at the watershed scale show that LWREW stations 133 and 134 provided stable underestimates, while stations 132 and 154 provided stable overestimates of the watershed mean at all depths. In addition, station 136 had very high non-zero temporal stability at the 25 cm and 45 cm depths indicating that it could be used as representative watershed site provided a constant offset value is used to acquire a watershed mean soil water content value. In general, the deeper depths exhibited higher soil moisture spatial variability, as indicated by the higher standard deviations. At the field scale, measured average profile soil moisture was higher in the winter wheat fields than the rangeland fields with the majority of the winter wheat depth intervals having high non-zero temporal stability. Field scale temporal stability analysis revealed that 4 of the 16 sampling sites in the rangeland fields and 3 of the 16 sampling sites in the winter wheat fields either under or overestimated the field means in the 0–5 and 0–60 cm depth intervals. Field sites considered temporally stable for the surface soil moisture were not stable for the profile soil moisture, except for the LW45 field where two sites were stable at both the surface and profile soil moisture. This finding is significant in terms of soil moisture ground-truth sampling for calibrating and validating airborne remotely sensed soil moisture products under extremely wet conditions. In addition, identification of temporally stable sites at the watershed and field scales in the LWREW provide insight in determining future measurement station locations and field scale ground sampling protocol, as well as providing data sets for hydrologic modeling.

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1. Introduction

Knowledge of soil moisture is critical to understanding many of the hydrological processes relating to research in soil hydrology, meteorology, and agriculture. From the hydrologic viewpoint, soil moisture controls runoff, infiltration, storage and drainage. In meteorology, soil moisture determines the partitioning of the incoming radiation between latent and sensible heat fluxes. Soil moisture also plays an essential role in irrigation scheduling and yield forecasting. Consequently, the land surface and atmosphere, as well as ground water storage, are inextricably linked to the soil water content. Detailed information of the soil moisture and its spatial distribution are necessary for sustained agricultural production, soil resource conservation, as well as efficient management of water resources in streams and reservoirs (Starks et al., 2003). While surface soil moisture plays a fundamental role in the land surface and atmosphere feedback, the status of profile soil water content is important to understanding water resources management, sediment and chemical transport, and hydrologic modeling of subsurface soil water content.

At present, point scale ground-based measurements of soil moisture are typically obtained using periodic gravimetric sampling,

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calibrated neutron attenuation, or Time domain reflectometry probes (TDR). Nevertheless, the large spatial and temporal variability of soil moisture is not well represented with these methods. Over large areas however, remote sensing techniques are used to estimate the spatial and temporal characteristics of soil moisture fields (Njoku et al., 2002). While remote sensing techniques of the land surface are undergoing significant advances, there is a lack of current measurements of soil water content at depths greater than 5 cm over field and watershed spatial scales. The need for better estimates of the spatial and temporal variability of surface and profile soil moisture has heightened interest in techniques that evaluate the most persistent spatial pattern of soil moisture over time. This in turn, could provide a method for reducing the number of observations needed to characterize the behavior of a field soil under the hypothesis that a particular location would maintain its rank in the cumulative probability function for different sampling times (Vachaud et al., 1985). Therefore, attention must be focused on evaluating the temporal stability of surface and profile soil moisture to adequately select the most representative sites within an area for estimating the areal average soil water content.

Several studies have examined the temporal stability of soil water content for the surface layer (0–5 cm) with the purpose of estimating large scale average soil moisture (Cosh et al., 2004; Jacobs et al., 2004; Cosh et al., 2006). Among them, the Southern Great Plains 1997 (SGP97) remote sensing experiment was conducted to quantify the spatial variability of soil moisture within selected agricultural fields with spatial dimensions matching the Electronically Scanned Thinned Array Radiometer (ESTAR) L-band passive microwave footprint (Jackson et al., 1999). Cosh et al. (2004) investigated watershed scale temporal stability of soil moisture using data from the Soil Moisture Experiment 2002 (SMEX02) in the Walnut Creek Watershed, Iowa. Twelve in situ soil moisture probes were installed across the 100 km^2 watershed to record soil water content at a depth of 5 cm from June 29 to August 19, 2002. Their results demonstrated that the soil moisture pattern exhibited temporal stability for uniform precipitation events, and concluded that representative measurement sites could be used to estimate the watershed scale soil moisture average for long time periods. Jacobs et al. (2004) also investigated the temporal stability of four adjacent fields with high resolution ground sampling from the airborne Polarimetric Scanning Radiometer (PSR) and various combinations of soils, vegetation and topography as part of SMEX02 in the Walnut Creek watershed, Iowa. They found that an appropriately selected single sampling point could provide similar accuracy compared to multiple points across a range of soil moisture conditions. In a study by Cosh et al. (2006) for the Soil Moisture Experiment 2003 (SMEX03) in the Little Washita River Experimental Watershed (LWREW), they were able to validate near-surface soil water content values derived from the Advanced Microwave Scanning Radiometer (AMSR-E). Their analysis also showed that most of the network soil moisture sensors were temporally stable at multiple scales and that four sites were identified as being representative of the watershed mean.

Despite the significance of the profile soil moisture in hydrological and meteorological predictions, few studies have focused on the temporal stability of the whole profile for field and watershed spatial scales. Vachaud et al. (1985) developed the concept of temporal stability of soil moisture using a 2000 m^2 grass field located on the campus of the University of Grenoble St. Martin d'Heres, France. Soil water content was measured using 17 neutron access tubes installed at regular intervals of 10 m to a depth of 100 cm in an alluvial soil characterized by sand lenses in silty clay materials. In their study they found a positive correlation between soil water content and the amount of silt and clay present in the profile. The concept was also tested in Spain and Tunisia with different climate and land cover. Grayson and Western (1998) also applied the concept of temporal stability of soil moisture to three different catchments with significant relief in Australia and in the USA. They measured soil water content at 30, 50, 60, and 120 cm depths in the soil profile. Their results showed lack of temporal stability of the complete soil moisture pattern. However, they identified particular sites within the three catchments where the value of the mean relative moisture content was near zero, indicating that these sites could be used for estimating areal averages. Martinez and Ceballos (2003) analyzed the temporal stability of soil moisture using data from 23 TDR probes installed over an area of 1285 km^2 during a 3-yr measurement period in Spain. Their results showed that the sites that represented dry conditions were much more stable at all depths analyzed (5, 25, 50, and 100 cm) compared to wetter sites. Martinez and Ceballos (2005) also demonstrated that it is possible to reliably select a site that is representative of the mean water content of the soil in a given area, regardless of scale, from a preestablished network of soil moisture measurements over two different regions.

There are few studies that address the relationship between field and watershed scale soil moisture temporal stability. Starks et al. (2006) conducted a temporal stability study of the SGP97 and SMEX03 surface and profile soil moisture data measured in 15 cm increments to a 60 cm depth using eight TDR probes within the 610 km^2 LWREW. The authors sought to determine the best subset of measurements for the watershed average soil water content at various levels in the soil profile, as well as in the total profile. Starks et al. (2006) showed that only two sites of the four identified by Cosh et al. (2006) for surface soil moisture (0–5 cm) exhibited profile temporal stability behavior. These aforementioned results are only applicable to relatively dry periods over the watershed. To date, the spatio-temporal relationships between surface and profile soil moisture at the field (800 m × 800 m) and watershed (610 km^2) scales have not been investigated under extremely wet conditions in the LWREW.

This study was conducted in conjunction with the 2007 Cloud and Land Surface Interaction Campaign (CLASIC07) from June 8 to July 7, 2007 in south-central Oklahoma. CLASIC07 was a project led by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program (http://acrf-campaign.arm.gov/clasic/). The goal of the CLASIC07 was to improve understanding of the fundamental physics related to the interactions between clouds and radiative feedback processes in the atmosphere, particularly those associated with the land surface processes. As part of the land surface observations, soil moisture was measured at selected locations to describe the water and energy fluxes and states. The month of June 2007 was one of the wettest on record resulting in extensive and frequent flooding throughout the region. These conditions were not what had been hoped for in the experiment design. However, such extreme conditions provided a unique opportunity to study the spatio-temporal characteristics of soil moisture for near saturated conditions. The specific objectives of this study were to: 1) determine temporally stable sites for surface (0–5 cm) and profile soil moisture (0–60 cm) in four fields within the LWREW under different land management practices and for various soil types, 2) determine the extent of correlation between surface soil moisture and profile soil moisture temporal stability analysis, and 3) analyze the temporal stability of soil moisture at the field and watershed scales to identify stations within the watershed, as well as locations within each field, that were representative of the mean areal soil moisture content. In addition, we compared our findings with those from past studies in the watershed under much drier conditions.

2. Area description, methods and materials studied

2.1. Study area

Four fields were selected within the LWREW to carry out the surface and profile soil moisture experiment (Fig. 1). The LWREW was one of the critical study areas of the CLASIC07 domain. It is located in the US, SGP region in Caddo, Grady, and Comanche Counties in Oklahoma, 34°45′ to

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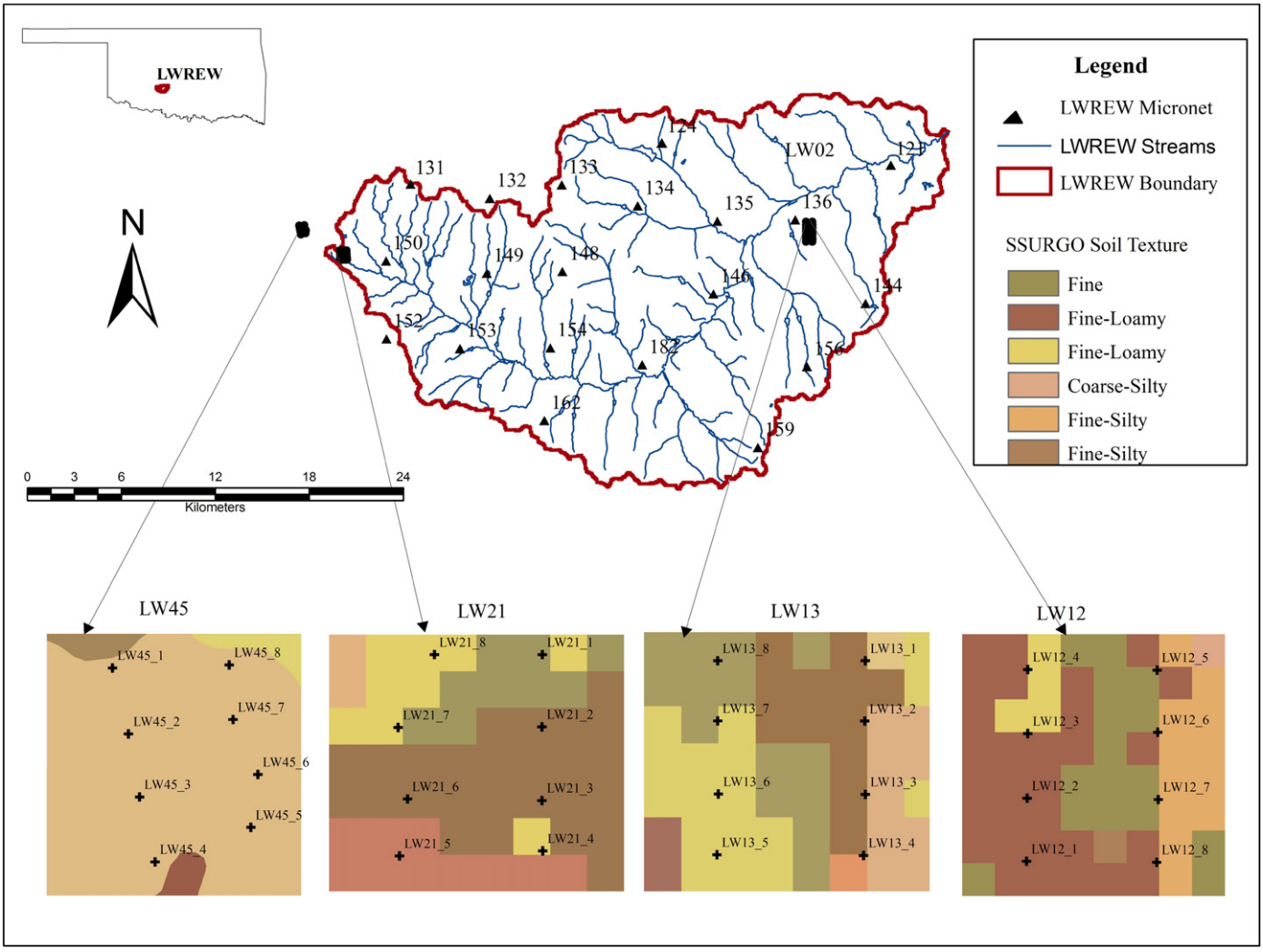

Fig. 1. USDA-ARS micronet and CLASIC07 field profile soil moisture sampling sites across the LWREW, OK.

35°01′N and 97°53′ to 98°18′W, and covers an area of 61,000 ha (Fig. 1). Topography of the watershed varies from moderately rolling to gently sloping in the upland area with approximately 183 m relief (Starks et al., 2006). Soil texture ranges from fine sand to silt loam (Fig. 1). Land use is predominantly pasture (63%) with significant areas of winter wheat and other crops concentrated in the floodplain and the western portion of the watershed. The watershed is located in a sub-humid climate with an annual precipitation of 750 mm. The monthly precipitation ranges from 27 mm in January to 56 mm in July with most events occurring in the spring and fall. The average daily temperature in January is −4 °C and 34 °C in July.

2.2. Field scale surface and profile soil moisture measurements

Ground based surface and profile soil moisture measurements were conducted to coincide with aircraft and satellite overpasses. During the experiment, intensive rainfall caused a significant increase in soil moisture in the entire SGP region which affected the data collection to some degree in regard to field access. Therefore, this study only analyzes data where both surface and profile soil water content were collected from June 9 to June 25. TDR probes (Environmental Sensors, Inc.,[1] British Colombia, Canada) were installed and co-located with CLASIC07 Theta probe (TP) surface soil moisture sites at eight sampling points in 800 m × 800 m fields, including two rangeland field sites (LW12 and LW13) located in the eastern part of the watershed and two winter wheat fields (LW21 and LW45) located in the western part of the watershed, totaling 32 TDR profile sampling sites (Fig. 1). The TDR technique is based on the relationship between the soil water content and the soil apparent dielectric constant as described in Heathman et al. (2003). Table 1 shows the geographical, topographical and soil physical properties of the field sites. LW12 and LW13 are adjacent to each other with rolling topography and experienced similar rainfall. LW21 is relatively flat in topography and under no-till winter wheat production. The wheat was harvested one week after the soil moisture experiment had started in LW21, whereas the wheat under conventional tillage in LW45 was harvested one day before data collection began. The eight sampling points within each field were identified using a Global Positioning System (GPS) and flagged. The average slope for each field was derived from the National Elevation Dataset (NED) from the US Geological Survey (USGS) at ~25 m resolution.

Data were collected on a daily time scale concurrent with CLASIC07 surface soil moisture sampling times to obtain profile soil moisture in 15 cm intervals to a depth of 60 cm. Additional soil profile samples were collected for texture and bulk density determinations. Time delay readings from the TDR sensors were converted to soil moisture records using factory calibrations. In addition, gravimetric samples were collected via a Scoop Tool in two sites for the surface and three

[1] Mention of trade names and company names does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable.

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Table 1
Geographical, topographical and soil physical properties of the field sites.

Site ID and characteristics	Depth (cm)	Sand	Silt	Clay	Texture	Bulk density (g cm^{-3})
		(%)				
LW12	0–6[a]					1.28
E 566047	0–15	31	55	14	SiL	1.43
N 3863463	15–30	34	53	14	SiL	1.40
[b]Slope = 6.9%	30–45	25	62	13	SiL	1.38
Pasture	45–60	25	61	14	SiL	1.29
LW13	0–6					1.12
E 563550	0–15	26	57	17	SiL	1.49
N 3865172	15–30	27	54	19	SiL	1.35
[b]Slope = 6.8%	30–45	22	58	20	SiL	1.41
Pasture	45–60	24	57	19	SiL	1.44
LW21	0–6					1.46
E 595638	0–15	27	57	16	SiL	1.46
N 3865530	15–30	25	57	18	SiL	1.58
[b]Slope = 1.9%	30–45	22	57	22	SiL	1.63
Winter wheat	45–60	23	52	24	SiL	1.60
LW45	0–6					1.35
E 595701	0–15	44	43	13	L	1.64
N 3864517	15–30	48	38	15	L	1.52
[b]Slope = 2.0%	30–45	39	39	23	L	1.37
Winter wheat	45–60	34	40	26	L	1.22

S, sand; L, loam; Si, silt; C, clay. Coordinate system is in NAD83, UTM Zone 14N.
[a] Bulk density value at 0–6 cm depth is from the CLASIC07 study.
[b] Mean field slope.

sites for the profile soil water content for the texture and bulk density analyses. The wet and dry gravimetric soil samples were measured in the laboratory of the Oklahoma State University Experimental Station in Chickasha, OK. The texture analysis was performed using the hydrometer method at the USDA-ARS National Soil Erosion Research Laboratory in West Lafayette, Indiana.

2.3. Watershed scale surface and profile soil moisture measurements

The US Department of Agriculture, Agricultural Research Service (USDA-ARS), Grazinglands Research Laboratory at El Reno, OK operates an in situ meteorological and hydrological network in the LWREW. During the CLASIC07 experiment there were 20 micronet stations that measured rainfall, relative humidity, air temperature at 1.5 m, and incoming solar radiation. The micronet stations were also equipped with Stevens-Vitel Hydra probes (Stevens Water Monitoring Systems Inc.) that measured soil moisture and temperature at three soil depths (5, 25 and 45 cm). Based upon a factory calibration equation the dielectric constant of the soil is converted to volumetric soil moisture (Campbell, 1990). The meteorological data are measured every 5 min with soil moisture and temperature data collected every 15 min. Data are transferred via radio telemetry every 15 min to the central archive of the Oklahoma Climatological Survey, located at the University of Oklahoma, Norman, OK, for quality control. The soil physical properties for these sites at four depth intervals were taken from Starks et al. (2006) and are shown in Table 2.

2.4. Statistical analysis

The soil moisture data from the field sites and the LWREW were analyzed using standard deviation, one-way analysis of variance (ANOVA), post-hoc analysis using Tukey's studentized range test at 0.05 probability level, temporal stability analysis, and Pearson's correlation coefficient. A one-way ANOVA and the Fischer's Least Significant Different (LSD) test at 0.1 probability level were performed for the rainfall data set across the watershed for the same period of the soil moisture campaign. The standard deviation (σ) was used to explain the spatial variability of the soil moisture. The ANOVA was analyzed to identify statistically significant differences among field mean values. The temporal stability of the surface and profile soil water content was conducted using the mean and the standard deviation of the relative difference. The mean relative difference quantifies the bias in soil moisture by location and identifies whether a location was wetter or drier than the field on average (Jacobs et al., 2004). It is based on the difference between the measured soil moisture and the mean soil moisture at the same time (Vachaud et al., 1985; Grayson and Western, 1998; Starks et al., 2006). The mean and standard deviation of the relative difference are formulated as

$$\bar{\delta}_i = \frac{1}{m}\sum_{j=1}^{m}\frac{\theta_{ij}-\bar{\theta}_j}{\theta_j} \tag{1}$$

and

$$\sigma(\delta_i) = \sum_{j=1}^{m}\left(\frac{\left(\delta_{ij}-\bar{\delta}_i\right)^2}{m-1}\right)^{1/2} \tag{2}$$

where $\bar{\delta}_i$ is the mean relative difference, δ_{ij} is the relative difference, $\sigma(\delta_i)$ is the standard deviation of the relative difference, m is the number of sampling days, (θ_{ij}) is the soil water content at location i at time j, and $\bar{\theta}_j$ is the mean soil water content. A site that represents the field mean exhibits a zero $\bar{\delta}_i$ and small standard deviation $\sigma(\delta_i)$. Locations with higher or lower $\bar{\delta}_i$ than zero over or under-estimate the field mean and represent the wettest and driest conditions, respectively.

The degree of linear correlation was examined using the Pearson's correlation coefficient (r_p) (Kachanoski and de Jong, 1988). The value of r_p indicates the correlation of the soil moisture pattern between two days. Values of r_p close to 1, 0 and −1 indicates highly correlated,

Table 2
Profile soil physical properties at selected TDR sites in the LWREW (Starks et al., 2006).

Site ID	Depth (cm)	Sand	Silt	Clay	Texture	Bulk density (g cm^{-3})
		(%)				
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	SL	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

S: sand(y), L: loam(y), Si: silt, C: clay.

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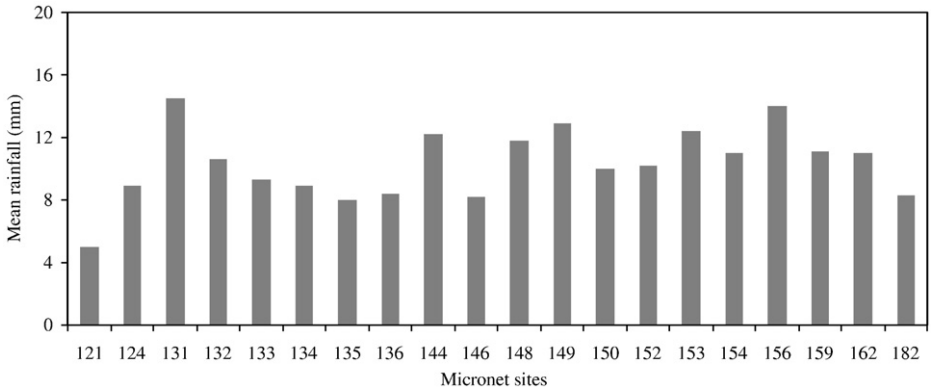

Fig. 2. Mean rainfall from the USDA-ARS micronet rain gauges across the LWREW from June 9 to June 25, 2007.

uncorrelated and inversely correlated patterns, respectively (Giraldo et al., 2008).

3. Results and discussion

In the following sections we provide the results for soil moisture spatio-temporal data analysis during the CLASIC07 field campaign at the field and watershed scales. Field scale analyses provide insight as to the soil moisture dynamics within the 800 m by 800 m pixel size observations of remotely sensed surface soil moisture. Surface and profile soil moisture analyses at the watershed scale help to characterize the response of the entire drainage basin during a period of record rainfall events. The results at both scales are helpful in determining effective strategies for establishing future ground-truth sampling sites and instrument stations. They also provide important information that relates surface moisture conditions to profile soil moisture.

3.1. Precipitation events

Weather during the month of June 2007 was exceptionally wet over the LWREW, resulting in one of the wettest months on record. Fig. 2 is a graphical representation of the mean daily rainfall recorded during the study period across the LWREW micronet rain gauge network. The rainfall records from June 9 to June 25 show that all the micronet sites received a considerable amount of rain (Fig. 2). Results of a one-way ANOVA and subsequent LSD test indicated that the mean rainfall values for 18 of the 20 micronet sites across the watershed were significantly different ($P>0.1$). The mean rainfall values from June 9 to June 25 from micronet sites 131 and 156 were not significantly different at the same probability level. The lowest rainfall amount was recorded at micronet 121, while the highest rainfall was recorded at micronet 131. The two micronet stations nearest the field profile soil moisture sampling sites recorded 8.38 mm (136 station) and 10.05 mm (150 station) of rain, respectively.

3.2. Field scale surface and profile soil moisture

Data analyses of surface and profile soil moisture were performed only on days when both measurements were taken. The surface soil moisture data correspond to the 0–5 cm TP measurements obtained by the CLASIC07 sampling teams, while the 0–60 cm data refer to the profile soil water content measured with TDR segmented probes. The mean and standard deviation values of the surface and profile soil moisture for each field are presented in Table 3. In LW12 and LW13 fields, the mean and standard deviation values of the surface soil moisture were higher than those of the profile soil moisture at all sites. In the 0–5 and 0–60 cm depth intervals, LW12-2 and LW12-6 sites of

Table 3
Mean and standard deviation of field surface and profile soil moisture for each TDR site.

Site	Mean ($m^3\ m^{-3}$) 0–5 cm	σ	Mean ($m^3\ m^{-3}$) 0–60 cm	σ	Site	Mean ($m^3\ m^{-3}$) 0–5 cm	σ	Mean ($m^3\ m^{-3}$) 0–60 cm	σ
LW12-1	0.329 c	0.022	0.265 d	0.010	LW13-1	0.309 a	0.059	0.274 cd	0.011
LW12-2	0.374 ab	0.014	0.333 a	0.023	LW13-2	0.323 a	0.073	0.323 ab	0.017
LW12-3	0.323 c	0.031	0.302 bc	0.028	LW13-3	0.273 a	0.075	0.266 d	0.030
LW12-4	0.336 c	0.029	0.256 d	0.013	LW13-4	0.327 a	0.050	0.315 ab	0.017
LW12-5	0.312 c	0.026	0.260 d	0.018	LW13-5	0.328 a	0.069	0.337 a	0.018
LW12-6	0.386 a	0.013	0.324 ab	0.015	LW13-6	0.322 a	0.065	0.283 cd	0.020
LW12-7	0.340 bc	0.030	0.278 cd	0.013	LW13-7	0.282 a	0.070	0.297 bc	0.020
LW12-8	0.379 a	0.009	0.293 c	0.007	LW13-8	0.281 a	0.054	0.272 cd	0.015
LW21-1	0.289 a	0.045	0.285 b	0.013	LW45-1	0.252 a	0.028	0.249 d	0.031
LW21-2	0.303 a	0.043	0.299 ab	0.009	LW45-2	0.248 a	0.030	0.277 abcd	0.015
LW21-3	0.318 a	0.053	0.320 a	0.007	LW45-3	0.254 a	0.036	0.295 a	0.020
LW21-4	0.303 a	0.073	0.305 ab	0.006	LW45-4	0.237 a	0.020	0.273 abcd	0.020
LW21-5	0.313 a	0.037	0.288 b	0.015	LW45-5	0.244 a	0.023	0.260 bcd	0.025
LW21-6	0.244 a	0.041	0.230 c	0.028	LW45-6	0.265 a	0.040	0.288 abc	0.017
LW21-7	0.288 a	0.048	0.257 c	0.022	LW45-7	0.252 a	0.030	0.291 ab	0.029
LW21-8	0.263 a	0.034	0.194 d	0.017	LW45-8	0.246 a	0.037	0.254 cd	0.012

Means with different letters are statistically different ($P<0.05$).
σ: standard deviation.

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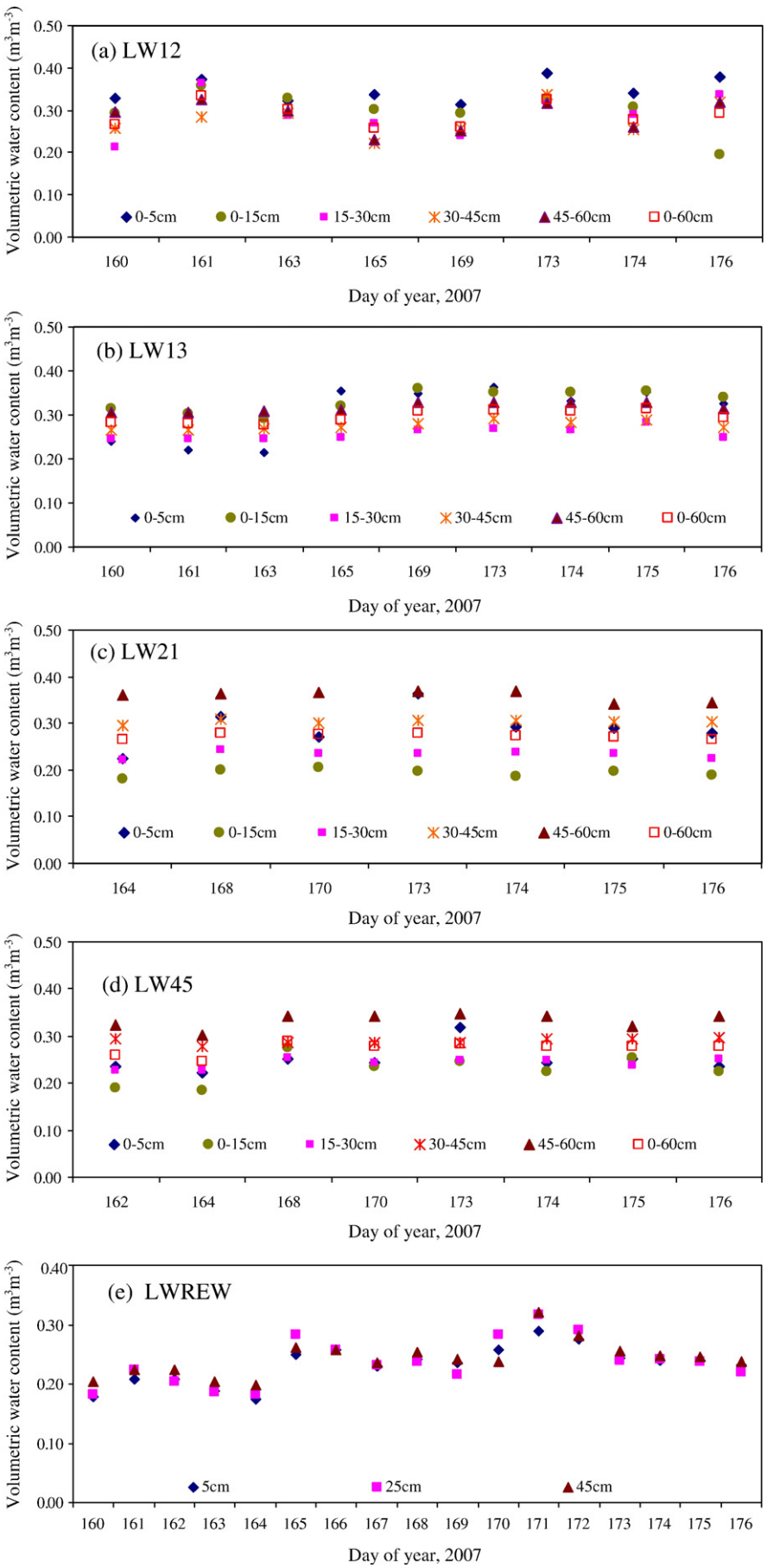

Fig. 3. Time series of volumetric soil water content for LW12 (a), LW13 (b), LW21 (c), LW45 (d), and LWREW (e) at various depth intervals.

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LW12 field had higher soil moisture values. Although these two sites have slightly different percent slope, they are similar in texture (Fig. 1). In LW13 field, LW13-2 and LW13-5 had higher surface and profile soil water content. The mean values of the surface and profile soil moisture of three sites in LW21, LW21-1, LW21-3, and LW21-4, were not significantly different at 0.05 probability level, although the mean of the surface soil moisture was higher than that of the profile soil moisture. Moreover, the standard deviation values of the surface soil moisture were higher than those of the profile soil moisture. The LW21-3 site exhibited higher surface and profile soil moisture. In LW45 field, while the mean values of the profile soil moisture were higher than those of the surface soil moisture, the standard deviation values of the surface soil moisture were lower than those of the profile soil moisture. In this study the dominant factors influencing soil moisture spatial distributions appear to be texture and topography.

Time series of the field mean surface and profile soil moisture values for each depth interval are represented in Fig. 3(a–d). These plots reflect the mean of all eight TDR locations, i.e. the field mean. At the beginning of the experiment, soil water content was relatively low for nearly all depth intervals since no appreciable rainfall occurred over the area during the first few days prior to the experiment; however, thereafter all depth intervals reflect an uninterrupted wetting cycle with the soil surface and profile wetting to near 0.40 $m^3\ m^{-3}$ throughout the rest of the study period. LW12 and LW13 fields exhibited higher soil water content than LW21 and LW45 for the 0–5 cm depth interval, although LW13 had lower water content than LW12 during the first three days of the experiment. The profile soil moisture values in the rangeland fields differ from the winter wheat fields, in that the wheat fields exhibited higher water content values for the deepest depth interval (45–60 cm). LW12 and LW13 fields are under permanent bermuda grass vegetation, with gently rolling topography (Mohanty and Skaggs, 2001) with an average slope of 6% with predominantly silt loam soils. In contrast to the rangeland fields, the lower water content values observed in the upper depth intervals of the winter wheat fields indicate that after harvest, the soil was exposed to a greater evaporative demand.

Results of a one-way ANOVA and subsequent post-hoc analysis using Tukey's studentized range test indicated that the mean surface soil moisture values of the eight sites in LW13, LW21 and LW45 fields were not significantly different at 0.05 probability level (Table 3). The

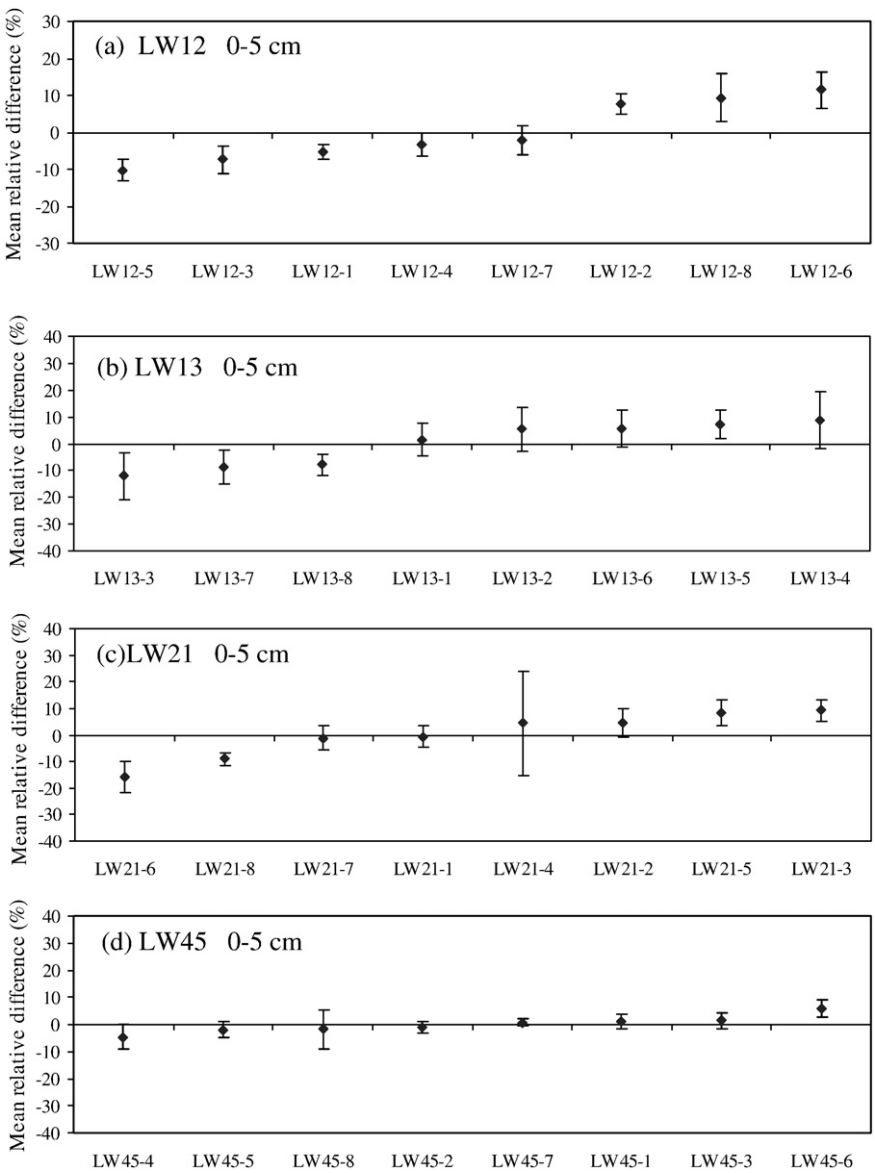

Fig. 4. Mean relative differences for LW12 (a), LW13 (b), LW21 (c), and LW45 (d) at the 0–5 cm depth interval.

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surface and the profile soil moisture means at site LW13-3 were the lowest in the LW13 field. In the LW12 field, the surface soil moisture mean at site LW12-5 was the lowest, while LW12-4 site had the lowest profile soil moisture mean. The profile soil moisture means at site LW21-8 and LW45-1 were significantly lower than those of the other sites. The Pearson correlation coefficient (r_p) values calculated for each field were highly significant at $P<0.001$ for both the surface and profile soil moisture indicating that the soil moisture values in each of the fields exhibited similar variation during the study period.

3.3. Field scale surface and profile soil moisture temporal stability

The mean and the standard deviation of the relative difference values ranked from the smallest to the largest for the surface and profile soil moisture for each field are shown in Figs. 4 and 5, respectively. Table 4 shows the mean and the standard deviation of the relative difference values for the 15 cm increment in the 0–60 cm depth interval. Previous studies in the watershed reported mean relative difference values between −50% and 50%, and standard deviation of the relative difference less than 30% of the surface (Cosh et al., 2006) and profile (Starks et al., 2006) soil moisture. Our results showed that in the 0–5 cm and 0–60 cm depth intervals the mean relative difference values were between −16% and 18% and the standard deviation of the relative difference values were between 0.6% and 20%, except LW21-8 site in the 0–60 cm depth of field LW21 that exhibited a mean relative difference value of −29%. Moreover, the other depth intervals of most of the fields exhibited mean relative difference values between −40% and 40%, and standard deviations of the relative difference between 2% and 46%.

For the rangeland fields, four sites, LW12-3, LW13-1, LW13-6, and LW13-7 were not consistent at the two depth intervals, in that, although these sites exhibited small mean and standard deviation of the relative difference values, they either overestimated or underestimated the fields' means. In contrast to the grassland fields, the winter wheat fields had only three sites that did not maintain their ranks. While sites LW21-1, LW45-1 and LW45-2 had the lowest mean relative difference values for the soil surface, they did not show the same behavior for the 0–60 cm depth interval.

Of the four study fields, LW45 had more sites with mean and standard deviation of the relative difference values approaching zero at

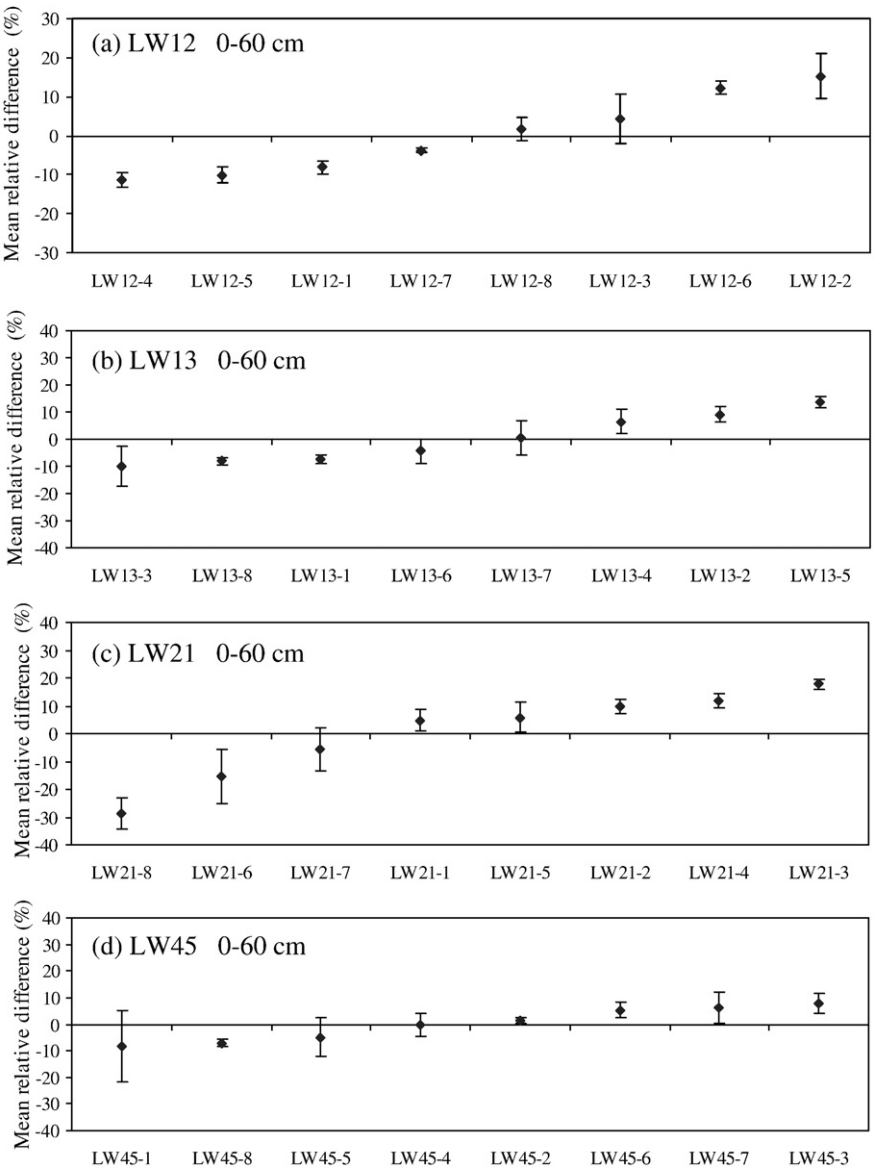

Fig. 5. Mean relative differences for LW12 (a), LW13 (b), LW21 (c), and LW45 (d) at the 0–60 cm depth interval.

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Table 4
Mean and standard deviation of the relative difference of TDR soil moisture.

	0–15 cm			15–30 cm			30–45 cm			45–60 cm	
	$\bar{\delta}_i$	$\sigma(\delta_i)$		$\bar{\delta}_i$	$\sigma(\delta_i)(\%)$		$\bar{\delta}_i$	$\sigma(\delta_i)$		$\bar{\delta}_i$	$\sigma(\delta_i)$
LW12-8	−34.60	16.61	LW12-1	−25.85	2.60	LW12-4	−20.06	2.28	LW12-4	−19.27	1.58
LW12-5	−3.08	7.79	LW12-5	−17.18	3.20	LW12-7	−8.02	3.26	LW12-5	−12.48	9.49
LW12-1	−2.54	3.52	LW12-4	−6.77	5.07	LW12-5	−7.77	3.76	LW12-7	−9.95	2.00
LW12-4	0.13	5.45	LW12-3	−1.60	23.13	LW12-1	−7.05	3.09	LW12-1	2.74	1.85
LW12-7	2.23	5.39	LW12-7	0.13	5.79	LW12-2	1.42	19.82	LW12-3	4.05	2.99
LW12-3	9.06	5.63	LW12-6	8.86	4.27	LW12-3	5.03	5.56	LW12-6	9.96	1.89
LW12-6	9.07	3.85	LW12-8	16.76	5.49	LW12-8	14.71	4.88	LW12-8	11.72	4.87
LW12-2	19.72	5.02	LW12-2	25.65	3.57	LW12-6	21.74	4.34	LW12-2	13.24	2.93
LW13-8	−13.73	5.89	LW13-8	−18.86	2.39	LW13-6	−13.10	7.83	LW13-3	−16.90	11.26
LW13-3	−8.21	5.35	LW13-1	−14.67	3.13	LW13-8	−8.04	1.84	LW13-6	−15.70	13.39
LW13-6	−2.95	5.45	LW13-6	−11.45	13.26	LW13-1	−5.34	2.93	LW13-1	−5.55	5.31
LW13-1	−1.68	4.56	LW13-5	−1.70	10.21	LW13-3	−4.70	10.13	LW13-7	0.97	9.13
LW13-7	1.14	11.80	LW13-2	4.29	3.25	LW13-7	−2.05	3.14	LW13-8	2.90	5.29
LW13-2	2.43	4.30	LW13-7	10.00	10.58	LW13-4	7.65	2.92	LW13-5	8.96	3.43
LW13-4	5.84	8.54	LW13-4	13.44	7.49	LW13-2	11.88	5.91	LW13-2	10.57	3.92
LW13-5	17.16	7.09	LW13-3	18.95	7.35	LW13-5	13.70	1.93	LW13-4	14.76	4.41
LW21-8	−25.08	7.91	LW21-8	−36.39	3.76	LW21-8	−23.61	3.85	LW21-8	−30.39	10.50
LW21-4	−23.84	11.65	LW21-7	−30.48	2.51	LW21-6	−23.57	14.48	LW21-6	−12.69	20.96
LW21-2	−17.04	12.22	LW21-6	−17.55	14.61	LW21-1	−4.38	2.35	LW21-1	−8.09	6.46
LW21-5	−7.80	22.63	LW21-1	6.69	14.86	LW21-7	−1.81	5.22	LW21-7	4.95	17.34
LW21-6	−5.56	8.71	LW21-2	13.29	2.00	LW21-5	4.54	5.03	LW21-5	5.66	11.66
LW21-7	−1.45	8.00	LW21-5	19.19	10.99	LW21-3	5.45	1.88	LW21-4	12.23	4.19
LW21-1	40.17	6.59	LW21-3	20.36	4.97	LW21-2	18.86	2.60	LW21-2	14.13	8.18
LW21-3	40.60	7.26	LW21-4	24.89	3.35	LW21-4	24.51	3.32	LW21-3	14.19	3.84
LW45-4	−4.12	37.64	LW45-2	−16.13	2.88	LW45-1	−14.62	20.97	LW45-1	−23.58	22.20
LW45-8	−3.67	34.34	LW45-5	−9.80	7.65	LW45-2	−8.82	3.84	LW45-8	−18.24	4.89
LW45-5	8.25	44.08	LW45-4	−4.60	2.47	LW45-8	−7.61	2.96	LW45-5	−6.08	10.65
LW45-6	15.15	46.30	LW45-6	−3.70	3.28	LW45-5	−0.25	4.13	LW45-7	1.29	10.48
LW45-1	15.23	32.27	LW45-7	1.52	8.00	LW45-3	3.72	4.40	LW45-4	6.23	5.32
LW45-3	18.10	22.08	LW45-3	7.06	4.36	LW45-7	4.99	8.86	LW45-6	8.84	9.68
LW45-2	20.59	31.36	LW45-1	8.26	2.04	LW45-6	10.08	3.71	LW45-3	13.50	6.59
LW45-7	30.49	42.19	LW45-8	17.38	2.32	LW45-4	12.51	6.83	LW45-2	18.04	4.16

$\bar{\delta}_i$: Mean relative difference; $\sigma(\delta_i)$: standard deviation of the relative difference.

both the 0–5 and 0–60 cm depth intervals than the other fields. The largest mean and standard deviation of the relative difference values were observed in LW21. These results showed that most of the sites in LW45 could be used to estimate the field's average moisture content for all depth intervals, except for the 0–15 cm. Soil moisture in that depth interval exhibited high variability as shown by the large standard deviation of the mean relative difference values. Although LW21 and LW45 were both winter wheat fields and have similar topography, measured moisture conditions were found to be different. This difference in soil moisture behavior could be due to the difference in management practices between the two winter wheat fields. While LW45 is under conventional tillage, LW21 is under no-till management.

Table 5
Mean and standard deviation of LWREW soil moisture micronet network.

Micronet	Mean ($m^3\ m^{-3}$) 5 cm	σ	Mean ($m^3\ m^{-3}$) 25 cm	σ	Mean ($m^3\ m^{-3}$) 45 cm	σ
121	0.319 a	0.088	0.369 ab	0.030	0.375 a	0.044
124	0.188 c	0.024	0.307 abc	0.016	0.185 fgh	0.018
131	0.266 ab*	0.027	0.165 efghi	0.110		
132	0.118 ef	0.035	0.100 i	0.047	0.064 j	0.021
133	0.153 cde	0.033	0.159 fghi	0.020	0.108 ij	0.014
134	0.152 cdef	0.035	0.162 fghi	0.020	0.128 hi	0.017
135	0.261 b	0.026	0.234 cdef	0.020	0.265 cde	0.020
136	0.267 ab	0.024	0.238 cdef	0.022	0.227 efg	0.017
144	0.140 cdef	0.045	0.150 ghi	0.058	0.213 efg	0.028
146	0.251 b	0.043	0.185 defgh	0.053	0.232 defg	0.034
148	0.304 ab	0.030	0.245 cde	0.093	0.174 gh	0.076
149	0.286 ab	0.023	0.251 cd	0.077	0.242 cdef	0.077
150	0.249 b	0.041	0.282 c	0.023	0.286 cd	0.012
152	0.298 ab	0.033	0.288 bc	0.094	0.294 bc	0.067
153	0.272 ab	0.022	0.302 abc	0.054	0.263 cde	0.015
154	0.267 ab	0.061	0.375 a	0.032	0.384 a	0.028
156	0.122 def	0.030	0.125 hi	0.025	0.216 efg	0.030
159	0.179 cd	0.025	0.228 cdefg	0.040	0.345 ab	0.086
162	0.295 ab	0.071	0.277 c	0.127	0.378 a	0.035
182	0.100 f	0.019	0.112 hi	0.026	0.102 ij	0.011

* Means with different letters are statistically different ($P<0.05$).
σ: standard deviation.

3.4. Watershed scale surface and profile soil moisture

Time series of the mean surface and profile soil moisture for the watershed micronet sites in the LWREW from June 9 to June 25, 2007 are shown in Fig. 3(e). The watershed mean soil moisture ranged from 0.10 to 0.32 $m^3\ m^{-3}$, 0.10 to 0.38 $m^3\ m^{-3}$, and 0.06 to 0.38 $m^3\ m^{-3}$ at

Table 6
Matrices of Pearson's correlation coefficients of surface and profile soil moisture for LW45.

	6/11/07	6/13/07	6/17/07	6/19/07	6/22/07	6/23/07	6/24/07	6/25/07
0–5 cm								
6/11/07	1							
6/13/07	0.82	1						
6/17/07	0.73	0.95	1					
6/19/07	0.95	0.89	0.84	1				
6/22/07	0.88	0.94	0.95	0.93	1			
6/23/07	0.96	0.94	0.88	0.95	0.97	1		
6/24/07	0.85	0.96	0.91	0.88	0.91	0.94	1	
6/25/07	0.83	0.98	0.97	0.90	0.97	0.94	0.92	1
0–60 cm								
6/11/07	1							
6/13/07	0.83	1						
6/17/07	0.87	0.98	1					
6/19/07	0.76	0.95	0.96	1				
6/22/07	0.80	0.97	0.98	0.97	1			
6/23/07	0.79	0.98	0.98	0.96	1.00	1		
6/24/07	0.86	0.96	0.98	0.97	0.97	0.97	1	
6/25/07	0.82	0.99	0.98	0.94	0.99	0.99	0.96	1

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Table 7
Matrices of Pearson's correlation coefficients of surface and profile soil moisture for selected dates in the LWREW.

	6/11/07	6/13/07	6/17/07	6/19/07	6/22/07	6/23/07	6/24/07	6/25/07
5 cm								
6/11/07	1							
6/12/07	0.98							
6/13/07	0.97	1						
6/17/07	0.88	0.93	1					
6/22/07	0.90	0.94	0.94	0.95	1			
6/23/07	0.85	0.92	0.89	0.90	0.98	1		
6/24/07	0.89	0.88	0.83	0.84	0.95	0.99	1	
6/25/07	0.89	0.91	0.92	0.89	0.97	0.97	0.95	1
45 cm								
6/11/07	1							
6/13/07	0.99	1						
6/17/07	0.80	0.85	1					
6/19/07	0.96	1.00	0.83	1				
6/22/07	0.90	0.88	0.77	0.94	1			
6/23/07	0.93	0.99	0.79	0.96	0.99	1		
6/24/07	0.92	1.00	0.79	0.96	0.99	1.00	1	
6/25/07	0.91	0.99	0.80	0.95	1.00	0.99	0.99	1

the 5, 25, and 45 cm depths, respectively. The deepest depth interval also exhibited higher mean soil water content. Table 5 shows the results of one-way ANOVA and subsequent post-hoc analysis using Tukey's studentized range test of soil moisture at 0.05 probability level for 20 micronet sites at 5 cm, 25 cm and 45 cm depths. This analysis indicated that the mean soil moisture values for some of the micronet sites were significantly higher than others. Table 5 also shows the standard deviation of the soil moisture at 5 cm, 25 cm, and 45 cm depths. The standard deviation values slightly increased between the 5 cm and the 45 cm depths. However, the standard deviation values at the 25 cm depth are significantly higher than the other two depths (Table 5). Tables 6 and 7 give the Pearson's correlation coefficients at different depths for each field and at the watershed scale, respectively, with the results being similar at both scales. An example of the rp matrices for LW45 field in the 0–5 cm and 0–60 cm depth intervals is presented in Table 6. Table 7 shows the Pearson's correlation coefficient values (r^p) at 5 cm and 45 cm depths in the LWREW. The r^p values were all significant at $P<0.001$ indicating that the micronet sites experienced similar soil moisture variations from one day to another, as was also the case at the field scale.

3.5. Watershed surface and profile soil moisture temporal stability

Fig. 6 shows the mean and standard deviation of the relative difference soil moisture values ranked from the smallest to the largest for the LWREW micronet sites at 5, 25, and 45 cm depths. These results showed that the highest $\bar{\delta}_i$ values were observed at the 45 cm depth, ranging between −72% (micronet 132) and 61% (micronet 154), followed by the 25 cm depth with values ranging between −57% (micronet 132) and 63% (micronet 154), while the 5 cm depth showed the lowest $\bar{\delta}_i$ values with a range between −58% (micronet 182) and 34% (micronet 148). The $\bar{\delta}_i$ of micronet 121 was 0.64% above the watershed mean in the 45 cm depth, i.e. the $\bar{\delta}_i$ approached zero; however, the $\sigma(\delta_i)$ was the highest being 78%. It can be observed that micronet 121 had the highest $\sigma(\delta_i)$ at all depths. Moreover, the 5 cm depth had smaller $\sigma(\delta_i)$ as compared to the other depths. It can be

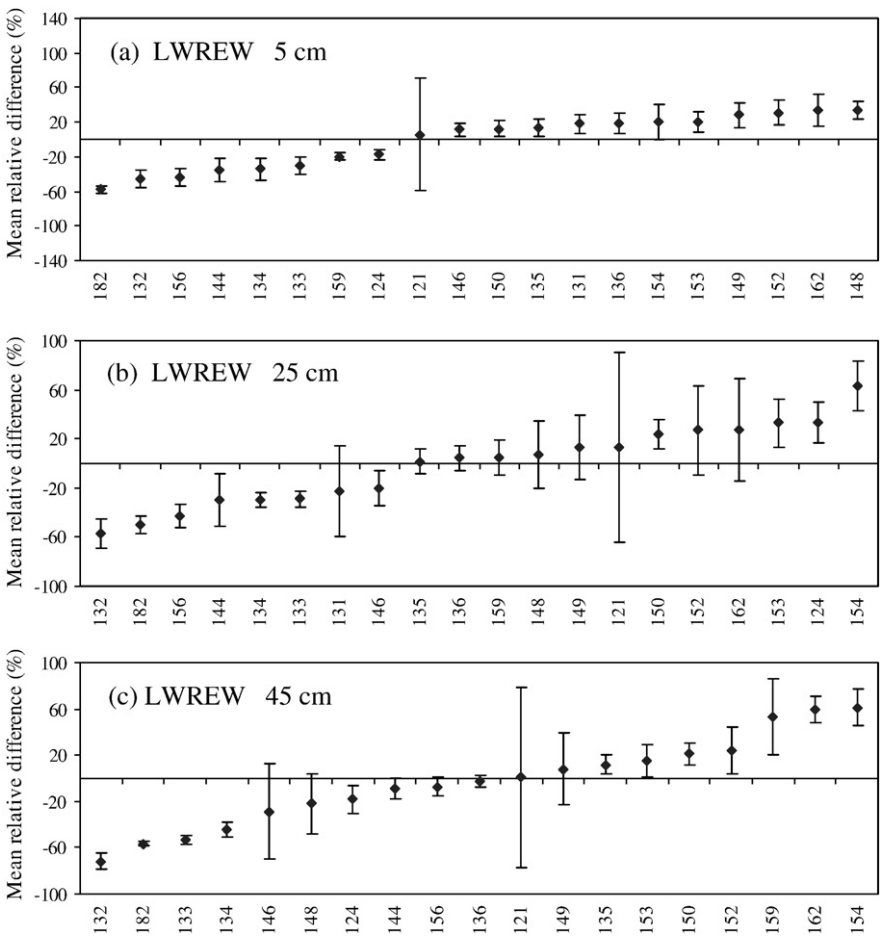

Fig. 6. Mean relative differences for LWREW micronet sites at 5 (a), 25 (b), and 45 (c) depth intervals during CLASIC07.

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observed that sites 135, 136, and 159 at the 25 cm depth, and sites 136 and 156 at the 45 cm depth showed consistent behavior, i.e. their temporal fluctuations could be considered similar to those of the watershed mean. Although micronets 132, 133, 134, 144, 156, and 182 underestimated the watershed mean, and micronets 121, 135, 149, 150, 152, 153, 154, and 162 overestimated the watershed mean at all depths, it is noticeable that in the 25 cm and the 45 cm depths micronets 132 and 154 represented the driest and the wettest sites, respectively.

When comparing the results of this study with that of Starks et al. (2006) using only micronets 133, 134, 136, 149, 154, 159, and 162, the mean relative difference values showed similar behavior. While they reported mean relative difference values of ±50%, those from this study fluctuated between −34% and 26% at the 5 cm depth, −35% and 54% at the 25 cm depth, and −59% and 47% at the 45 cm layer. They also observed that sites 133 and 134 were consistently 'dry' temporally stable sites, while 154 was a 'wet' temporally stable site compared to the other micronet sites. Although Cosh et al. (2006) reported small standard deviation of the relative difference ($\sigma(\delta_i)<30$) for 13 micronet sites in the LWREW, only four of them were considered as representative of the watershed average based solely on surface soil moisture analysis. The mean relative difference values reported by Cosh et al. (2006) fluctuated between −59 and 46%.

4. Conclusions

Surface (0–5 cm) and profile (0–60 cm) soil water content were measured in four fields during the June 2007 CLASIC07 experiment in the LWREW, in south-central Oklahoma. Time domain reflectometry probes used to measure soil water content from 0–60 cm in 15 cm increments were co-located with the CLASIC07 Theta probe surface soil moisture (0–5 cm) sites at eight sampling points in four 800 m × 800 m fields, including two rangeland (LW12 and LW13) and two harvested winter wheat fields (LW21 and LW45). Surface and profile soil moisture data from the entire LWREW USDA-ARS micronet network were also analyzed in this study. The concept of temporal stability was used to analyze whether sites that were temporally stable for the surface soil moisture were also temporally stable for the soil profile soil moisture. This study also compared whether the sites identified as stable during drier periods associated with previous temporal stability studies in the watershed were the same as those found in this study.

Surface mean soil moisture values were higher in the rangeland field sites than in the winter wheat fields during the study period, while the winter wheat fields exhibited higher profile soil moisture than the rangeland fields. The temporal stability results indicated that only one site in LW12, three sites in LW13, one site in LW21, and two sites in LW45 did not maintain their rank in the 0–5 and 0–60 cm depth intervals. Field scale temporal stability analysis revealed that 4 of the 16 sampling sites in the rangeland fields and 3 of the 16 sampling sites in the winter wheat fields either under or overestimated the fields' means in the 0–5 and 0–60 cm depth intervals. Sites LW12-7 and LW12-8, and LW13-1 and LW13-7 were temporally stable for surface and profile soil moisture, respectively. There were no sites that were found to be stable in the 0–60 cm depth interval for LW21 field; although, LW21-1 and LW21-7 exhibited small mean and standard deviation values of the relative difference values for soil surface. Of the eight sites in LW45, two sites (LW45-4 and LW45-6) were not stable in the 0–5 cm depth intervals, while only two sites (LW45-2 and LW45-4) were stable in the 0–60 cm depth interval. This study revealed that not all the same sites considered temporally stable for the surface soil moisture were stable for the profile soil moisture.

For the LWREW only micronet site 136 was found stable at the 25 cm and 45 cm depths. For the extremely wet conditions in this study, micronets 133 and 134 provided stable underestimates while micronet sites 132 and 154 provided stable overestimates of the watershed mean at all depth intervals. Our results agree in part with those presented in Starks et al. (2006) in that sites 134 and 154 were found to produce good estimates of the watershed mean soil moisture. Thus, soil moisture measurements from these sites could be adjusted, given an offset values, to estimate the watershed mean soil moisture (Starks et al., 2006). However, it should also be noted that a degree of caution should be exercised in determining whether a particular site may be "representative", considering that many seasons of measured data under wet and dry conditions are be needed to gain absolute confidence in the choice of sites.

Although record amounts of rainfall occurred over the study area during the experimental period that hindered continuous measurements of the soil moisture, the data have proved to be very useful in terms of temporal stability analysis for wet conditions. This finding is significant in terms of soil moisture ground-truth sampling for calibrating and validating airborne remotely sensed soil moisture products under extremely wet conditions. In addition, identification of temporally stable sites at the watershed and field scales in the LWREW provide insight in determining future measurement station locations and field scale ground sampling protocol, as well as providing data sets for hydrologic modeling. Future work will be aimed at integrating the ground sampling data base with the remotely sensed surface soil moisture data.

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