Agricultural Water Management 102 (2011) 66–73

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Estimating spatial mean soil water contents of sloping jujube orchards using temporal stability

Xiaodong Gao[a,b,c], Pute Wu[a,b,c,*], Xining Zhao[a,b,c], Yinguang Shi[b,c], Jiawen Wang[b,c]

[a] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, China
[b] Institute of Water Saving Agriculture in Arid Regions of China, Northwest Agriculture and Forestry University, Yangling 712100, Shaanxi, China
[c] National Engineering Research Center for Water Saving Irrigation at Yangling, Yangling 712100, Shaanxi, China

ARTICLE INFO

Article history:
Received 13 May 2011
Accepted 11 October 2011
Available online 1 November 2011

Keywords:
Soil moisture
Variability
Temporal persistence
Upscaling
Water management

ABSTRACT

Estimating spatial mean soil water contents from point-scale measurements is important to improve soil water management in sloping land of semiarid areas. Temporal stability analysis, as a statistical technique to estimate soil water content, is an effective tool in terms of facilitating the upscaling estimation of mean values. The objective of this study was to examine temporal stability of soil water profiles (0–20, 20–40, 40–60 and 0–60 cm) in sloping jujube (*Zizyphus jujuba*) orchards and to estimate field mean root-zone soil water based on temporal stability analysis in the Yuanzegou catchment of the Chinese Loess Plateau, using soil water observations under both dry and wet soil conditions. The results showed that different time-stable locations were identified for different depths and the temporal stability of soil water content in 20–40 cm was significantly ($P < 0.05$) weaker than that in other depths. Moreover, these time-stable locations had relatively high clay contents, relatively mild slopes and relatively planar surfaces compared to the corresponding field means. Statistical analysis revealed that the temporal stability of root zone soil water (0–60 cm) was higher in either dry or wet season than that including both, and soil water exhibited very low temporal stability during the transition period from dry to wet. Based on the temporal stability analysis, field mean soil water contents were estimated reasonably (R^2 from 0.9560 to 0.9873) from the point measurements of these time-stable locations. Since the terrains in this study are typical in the hilly regions of the Loess Plateau, the results presented here should improve soil water management in sloping orchards in the Loess Plateau.

1. Introduction

Root zone soil water plays an important role in agricultural practices in semiarid and arid areas. Accurate estimation of mean root-zone soil water from point-scale measurements can improve soil water management effectively. However, it is difficult to acquire the field mean because of the spatial variability of soil water content (Timm et al., 2011). Although a variety of scaling methods, including geostatistical analysis (Western et al., 2004), fractal analysis (Rodriguez-Iturbe et al., 1995) and probability density function analysis (Avissar and Pielke, 1989), have been used to estimate the mean areal soil water content from point observations, each of them requires *in situ* soil water measurements with very fine resolutions both in space and time (Kachanoski and de Jong, 1988; Yoo, 2002) which were time-consuming and laborious. Alternatively, temporal stability analysis, which was introduced by Vachaud et al. (1985) to characterize the time-invariant association between spatial location and traditional statistical parametric values, has been demonstrated as an effective tool to estimate spatial mean soil water content from point-scale observations (Grayson and Western, 1998; Martínez-Fernández and Ceballos, 2005; Pachepsky et al., 2005; Teuling et al., 2006; Guber et al., 2008).

The efforts of identifying soil water time-stable locations have been made widely in different land uses, including rangeland (e.g. Mohanty and Skaggs, 2001), grass (e.g. Vachaud et al., 1985; Jacobs et al., 2010), pasture (e.g. Starks et al., 2006; Heathman et al., 2009), agricultural land (e.g. Martínez-Fernández and Ceballos, 2003; Starr, 2005), shrub (Grant et al., 2004; Williams et al., 2009) and forest (Lin, 2006); in diverse climate zones, including semi-arid (e.g. Gómez-Plaza et al., 2000; Williams et al., 2009; Zhao et al.,

Abbreviations: IPH, Intelligent Profile probe for Hydrological applications; MABE, mean absolute bias error (%); MRD, mean relative difference (%); NDVI, normalized difference vegetation index; PICO, means that probes can measure with TDR accuracies in Picosecond ranges; RMSM, representatives of mean value of soil moisture; SDRD, standard deviation of relative difference (%); SGP97, Southern Great Plains 1997 hydrology experiment, USA; TDR, Time Domain Reflectometry.

* Corresponding author at: Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Northwest A&F University, Yangling 712100, Shaanxi, China. Tel.: +86 29 87010700; fax: +86 29 87011354.
E-mail address: gjzwpt@vip.sina.com (P. Wu).

0378-3774/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2011.10.007

2010), semi-humid (e.g. Heathman et al., 2009) and humid (e.g. Jacobs et al., 2004; Brocca et al., 2010, 2008) zones; in places with various topographical attributes, including rolling (e.g. Starks et al., 2006; Zhao et al., 2010), gentle sloping (e.g. Cosh et al., 2008), and complex terrains (Hu et al., 2009, 2010b). However, little work has been done on orchards and steep hillslopes in semiarid areas. Furthermore, in addition to the recent studies of Hu et al. (2009, 2010b), the temporal stability analysis of spatial soil moisture dynamics has not yet been used in the research on the Chinese Loess Plateau where a large amount of spatial variability of soil water exists due to complex topography (Hu et al., 2009) and land use (Fu et al., 2003). Since topography and land use are two of main factors controlling soil water variability in the Loess Plateau (Hu et al., 2010b), there is a need to examine temporal stability of soil water in orchards with complex topography in this area.

Topographic attributes, soil properties and vegetation features have been suggested to discern time-stable locations. Grayson and Western (1998) identified the moderate topographic positions were best to represent mean moisture content at the catchment scale based on soil moisture datasets in three catchments (Tarrawarra, R5-Chickasha and Lockyersleigh). Jacobs et al. (2004) found that the best soil water time-stable locations lay in mild slopes having moderate to moderately high clay content compared to the field means using soil water observations of the Walnut Creek watershed, Iowa. Furthermore, Joshi et al. (2011) observed that both soil properties (silt content and sand content) and topography (elevation and slope) controlled the time-stable behavior of soil moisture at both point and footprint scales in the Walnut Creek watershed in Iowa and Little Washita watershed in Oklahoma. Whereas, Jacobs et al. (2010) found that the most time-stable locations were associated with sandy loam soils and moderately high normalized difference vegetation index (NDVI) values while either topographic attributes or land cover were poor indicators to identify time-stable locations during the SGP97 (Southern Great Plains 1997 hydrology experiment) period. In addition to these local factors, soil wetness conditions and soil depth are also contributing factors to affect soil water temporal stability. Vachaud et al. (1985) detected that locations underwent few variations between the driest and wettest soil conditions, which was also found by Martínez-Fernández and Ceballos (2003) who further showed that the dry locations were more temporally stable than the wet ones. Starks et al. (2006) indicated that similar location rankings existed for the SGP97 period. However, Lin (2006) found that temporal stability of soil water varied between seasons in complex terrains. Temporal stability is also dependent on soil depth (Martínez-Fernández and Ceballos, 2003; Pachepsky et al., 2005; Starks et al., 2006; Guber et al., 2008; Hu et al., 2010b). Guber et al. (2008) found that soil water contents in deeper horizons tended to be more stable.

Because of rapid expansion of jujube planting and the severe water shortage in the key seasons of water requirement for jujube, a micro-irrigation system has been built in some of these orchards to meet the water requirement of jujube in the dry seasons (Wu et al., 2008; Zhao et al., 2009). In order to make efficient use of the finite water resources in this area, information of spatial mean soil water contents in the root zone is necessary to guide irrigation application. The main purpose of this study was to identify time-stable locations of root zone soil water profiles in sloping jujube orchards in the Chinese Loess Plateau and to estimate mean moisture content of jujube orchards using the temporal stability analysis based on the soil water observations under both dry and wet seasons (from April to September). In addition, the relationship between soil water temporal stability and environmental factors (soil texture fractions and topography) and the effects of soil depth and soil wetness conditions on temporal stability of soil moisture content were also examined.

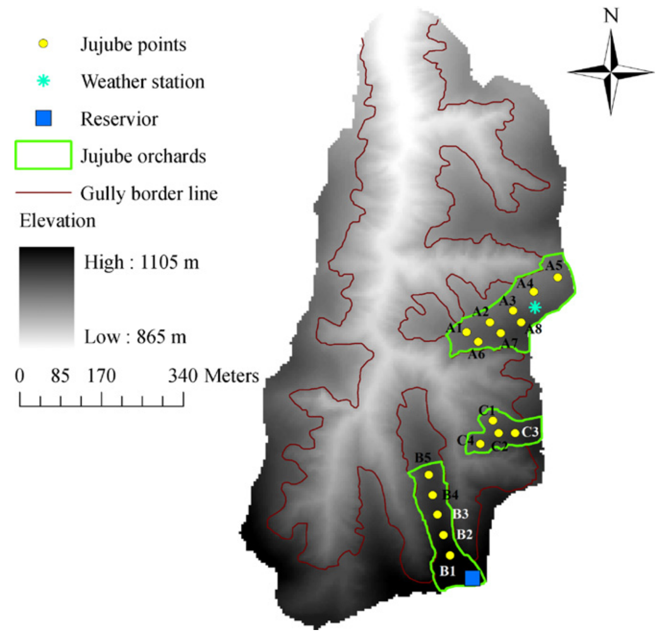

Fig. 1. Study site and sampling locations in the Yuanzegou catchment.

2. Materials and methods

2.1. Study site

The experiment was conducted in jujube (*Zizyphus jujuba*) orchards (37°15′N, 118°18′E) located in the central part of the Loess Plateau (Fig. 1) where steep slopes prevail. This area has a semi-arid continental climate with (based on data for 1956–2006): mean annual precipitation of 505 mm, 70% of which falls during late summer and early autumn (August, September and October); a mean annual temperature of 8.6 °C, with mean monthly temperatures ranging from −6.5 °C in January to 22.8 °C in July; 157 frost-free days and 2720 h of sunshine on average each year (Weather Bureau of Qingjian county, Shaanxi province).

The orchards cover an area of 5.2 ha with elevation ranging from 970 to 1105 m and slope from 27% to 64%. The whole area is covered by loess (Inceptisols, USDA) with silt loam texture, which developed from wind-deposited loess parent material (Zhu et al., 1983). The field capacity and permanent wilting point of the loess in this study site is 24.3% and 8.8% (volumetric water content, hereafter), respectively. The detailed soil and topographic information of sampling points is shown in Table 1.

Jujube trees were planted in spring of 2007. Unlike traditional jujube orchards, the density of the jujube trees was 1650 trees/ha, which was twice that in traditional jujube orchards. In order to meet the water requirement of jujube in dry seasons (June and July), a micro-irrigation system was built in jujube orchards in 2009. Accumulated surface runoff, which was collected in a reservoir near the outlet of the catchment, was pumped to another reservoir located on the top of the highest hill of the catchment (Fig. 1).

2.2. Soil water measurements

A portable Time Domain Reflectometry (TDR) system, TRIME-PICO IPH/T3 (IMKO, Ettlingen, Germany), was used to monitor soil water in this jujube orchard. This TDR system consists of a TRIME-IPH probe, a TRIME-DataPilot datalogger and fiberglass access tubes (ϕ = 40mm). A total of 17 2 m-long tubes were installed (Fig. 1) with a spacing of ca. 20–35 mm between sampling locations. A hand auger (ϕ = 45mm) was used to install fiberglass access tubes instead of the original accessories for installing tubes, which are

Table 1
Topographic features and clay content (<0.002 mm) for all sampling locations in the study site.

	ID of locations																
	A1	A2	A3	A4	A5	A6	A7	A8	B1	B2	B3	B4	B5	C1	C2	C3	C4
Slope (%)	33.2	50.3	38.5	59.2	58.9	27.3	31.9	66.7	41.1	38.8	27.7	27	31.3	48.9	52.1	50.4	35.8
Aspect (°)	310.9	318.7	331.1	336.3	336.1	262.9	327	310.7	358.9	10.2	352.4	328.4	352.2	314.1	307.1	311.7	308.1
Elevation (m)	998	998.8	996.3	1000.1	996.6	1009.4	1010.8	1013.8	1083	1070	1055	1045	1036.5	1011.9	1028.3	1038.8	1023.7
Curvature	2.2	0.1	−4.7	8.3	5.7	2.2	3.9	13.6	9.2	−5.2	−1.2	−0.8	4.1	−7.6	−0.7	−0.8	4
Clay (%)																	
0–20 cm	26.6	22.5	20.1	22.3	29.1	26.4	19.1	16.7	16	14.4	13.8	20.4	13.7	20.7	17.2	16.6	16.2
20–40 cm	23.8	21.6	20	21.5	27.5	21.5	20.6	19.6	15.3	14.6	13.7	20.8	16.5	14.7	11.4	13.6	24.2
40–60 cm	21.1	20	20	20	24.3	17.1	14	21.1	14.9	16.1	15	19.7	12.3	15.2	14.2	13.9	26.1

difficult to operate on hillslopes. Soil slurry was poured around the access tube to ensure good soil contact. Installation of tubes was done in July 2009. The TRIME–TDR system has been shown to provide accurate soil water measurements in the Loess Plateau region after local calibration (Li et al., 2005). Therefore, the system was gravimetrically calibrated for the specific local soils (Inceptisols, USDA) examined in this study, as follows. Soil water contents were measured using the TDR tool at 0–20, 20–40, 40–60, 60–80 and 80–100 cm depths. Meanwhile, a 1 m-deep pit was excavated 0.5 m away from the access tubes to collect undisturbed soil cores from the corresponding depths in order to obtain measurements of the dry soil bulk density and gravimetrical soil water content (θ). Values of θ were then transformed to volumetric moisture contents (Hu et al., 2009), and a calibration curve was obtained by plotting the measured TDR-derived moisture values (x, $cm^3\,cm^{-3}$) against the volumetric moisture contents (y, $cm^3\,cm^{-3}$), and fitting a regression equation:

$$y = 0.9471x - 4.3796, \quad R^2 = 0.904, \quad \mathrm{RMSE} = 2.68\% \tag{1}$$

Soil water contents were measured using TDR at these locations at depths of 0–160 cm at 20 cm intervals from 5 April to 27 September 2010. A total of 28 measurement events were recorded during the entire sampling periods. It has been shown that measuring frequency has little influence on soil water temporal stability and the estimation of mean soil water content (Guber et al., 2008). Moreover, Brocca et al. (2010) found that the soil water time-stable locations derived from 12 sampling events (total 35 sampling events for two years) could correctly represent the field means for more than 90% of cases in their study. Therefore, 16 of 28 sampling events (the other 12 sampling events contained missing values) were selected to analyze the temporal stability of soil water profile in this study. On each sampling event, soil water contents were measured within 4 min at each sampling location. In order to minimize the temporal variation of soil water as much as possible, all the soil water measurements were taken within 2 h during each sampling event.

A field survey indicated that 92% of the root mass of jujube was distributed within the 0–60 cm depth. Hence we define 0–60 cm as the root zone soil layer and only soil water measurements over 0–60 cm were used for temporal stability analysis in this paper.

2.3. Assessing temporal stability of soil water profiles

Two methods were employed to assess the temporal stability of soil water content. The main tool for temporal stability analysis is the mean relative difference plot (Cosh et al., 2008). Following Vachaud et al. (1985), relative difference at sampling location i at depth k for sampling event j is defined as:

$$\delta_{ikj} = \frac{\theta_{ikj} - \bar{\theta}_{kj}}{\bar{\theta}_{kj}} \tag{2}$$

A temporal mean relative difference (MRD) and its standard deviation (SDRD) over time are calculated as:

$$\bar{\delta}_{ik} = \frac{1}{T}\sum_{j=1}^{T}\delta_{ikj} \tag{3}$$

and

$$\sigma(\bar{\delta}_{ik}) = \sqrt{\sum_{j=1}^{T}\frac{(\delta_{ikj} - \bar{\delta}_{ik})^2}{T-1}} \tag{4}$$

where θ_{ikj} is the soil water content at location i and depth k for jth sampling event. $\bar{\theta}_{kj}$ is the computed mean moisture content at depth k among all sampling locations for a given time j. T is the total number of sampling events. In this sense, the time-stable locations tend to be those having low values of SDRD.

In the second method, the mean absolute bias error (MABE), developed by Hu et al. (2010a,b), was used to determine time-invariant sites as well as estimate error. Rearranging Eq. (2) leads to:

$$\bar{\theta}_{kj} = \frac{\theta_{ikj}}{1+\delta_{ikj}} \quad (5)$$

Assuming a constant offset $\bar{\delta}_{ik}$ for a time-stable site (Grayson and Western, 1998), the estimated $\bar{\theta}_{kj}$, $\tilde{\theta}_{kj}$, can be expressed as:

$$\tilde{\theta}_{kj} = \frac{\theta_{ikj}}{1+\bar{\delta}_{ik}} \quad (6)$$

Hence, the estimate error of mean moisture content can be calculated as:

$$\varepsilon_{ikj} = \frac{\tilde{\theta}_{kj} - \bar{\theta}_{kj}}{\bar{\theta}_{kj}} \quad (7)$$

substituting $\bar{\theta}_{kj}$ from Eq. (5) and $\tilde{\theta}_{kj}$ from Eq. (6) into Eq. (7), one has:

$$\varepsilon_{ikj} = \frac{\delta_{ikj} - \bar{\delta}_{ik}}{1+\bar{\delta}_{ik}} \quad (8)$$

and its absolute value as:

$$\left|\varepsilon_{ikj}\right| = \left|\frac{\delta_{ikj} - \bar{\delta}_{ik}}{1+\bar{\delta}_{ik}}\right| \quad (9)$$

Then the mean absolute value of bias error (MABE), is defined as:

$$\overline{\left|\varepsilon_{ik}\right|} = \frac{1}{T}\sum_{j=1}^{T}\left|\frac{\delta_{ikj} - \bar{\delta}_{ik}}{1+\bar{\delta}_{ik}}\right| \quad (10)$$

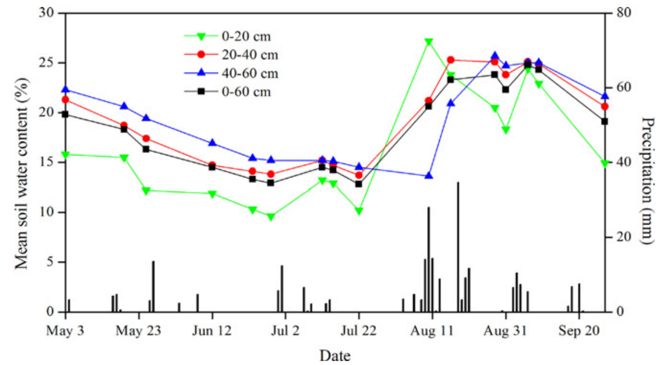

Fig. 2. Temporal evolutions of soil water for various depth intervals and the root zone profile.

The use of MABE in this way not only allows the identification of time-stable locations, but also produces the temporal mean estimate error of using location *i*. Locations with lower values of MABE tend to be more temporal stable and to produce less estimate error.

2.4. Estimating spatial mean soil water content

For a given depth, those locations having both the nearest-zero MRD and low value of SDRD could be used directly to estimate mean moisture content (Martínez-Fernández and Ceballos, 2005). Martínez-Fernández and Ceballos (2005) defined these locations as representatives of the mean value of soil water content for that specific depth (RMSM).

However, locations having the nearest-zero MRD may be not time-stable. These locations may produce poor estimates of mean moisture content on some occasions. Alternatively, the most time-stable locations with non-zero MRD could be used to calculate

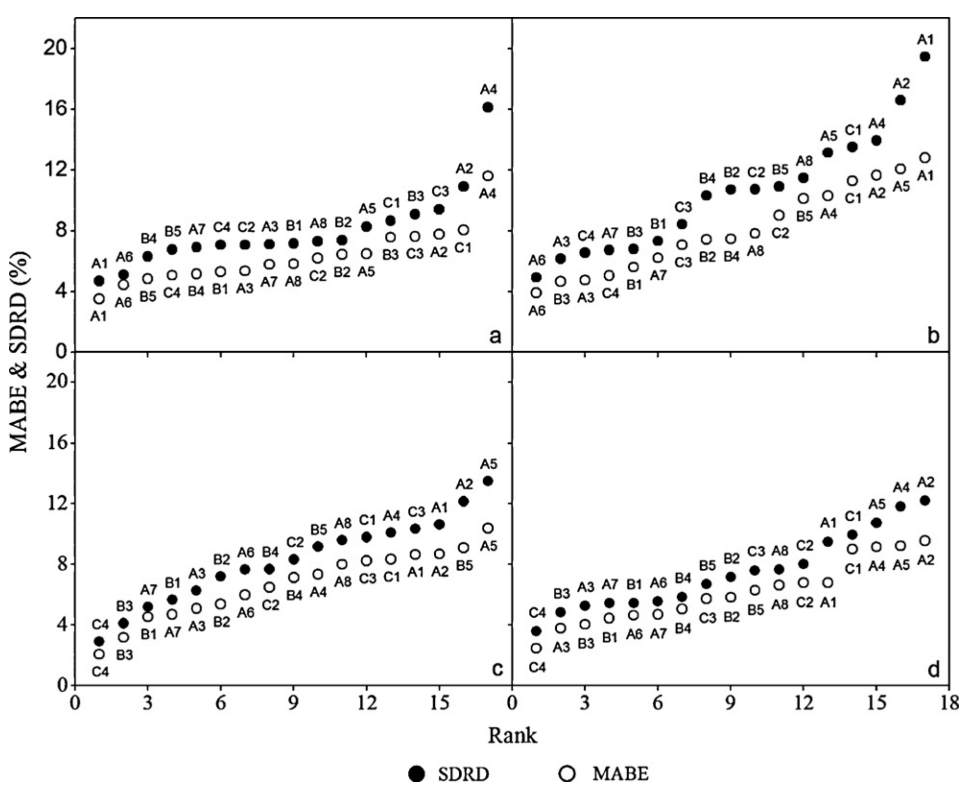

Fig. 3. Ranked SDRD and MABE over the study period for 0–20 cm (a), 20–40 cm (b), 40–60 cm (c) and 0–60 cm (d) depths.

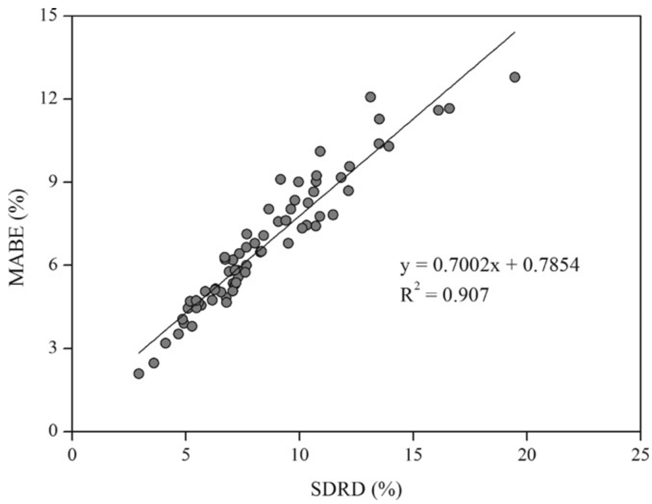

Fig. 4. Relationship between MABE and SDRD for the whole data set.

the mean moisture content (Grayson and Western, 1998). This is because the most time-stable locations have the lowest SDRD values. Hence the relative difference at any sampling event (δ_{ikj}) approximates the mean relative difference ($\bar{\delta}_{ik}$). In this sense, spatial mean moisture content at depth k for jth sampling event could be estimated using Eq. (6).

3. Results and discussion

3.1. Statistical analysis

Temporal evolutions of soil water for various depth intervals and total profile are shown in Fig. 2. The uppermost depth interval exhibited the largest temporal variation in volumetric moisture content (9.6–27.4%) from 3 May to 27 September 2010. It was driest during the drying-down period and became wettest following a distinctive rainfall event (e.g., 28.1 mm precipitation in 11 August 2010). In the 20–40 cm interval, a change of 11.6% in volumetric moisture content occurred during the same period, while a similar change of 12.1% existed in the 40–60 cm interval. Note that soil water in 40–60 cm indicated a noticeable lag in response to precipitation.

3.2. Selection of time-stable locations

Fig. 3 shows the ranked SDRD and MABE over the study period for various depth intervals (a–c) and the root zone profile (d). Overall, SDRD exhibited higher values for all depths than MABE, which was in accordance with the findings of Hu et al. (2010b). Those locations with low SDRD values also tended to have low values of MABE. Correlation analysis indicated a strong positive relationship (R^2 = 0.907) existed between them (Fig. 4). However, Hu et al. (2010b) found a much weaker relationship between them with R^2 ranging from 0.044 to 0.515. This can be ascribed to the single ground cover in our study while there were eight land uses in their study site complicating space–time soil moisture patterns. Because of the strong correlations between SDRD and MABE in this study, only SDRD was used to analyze soil water temporal stability hereinafter.

As found in other studies (Hu et al., 2010b; Guber et al., 2008; Starks et al., 2006; Martínez-Fernández and Ceballos, 2003), we also detected different time-stable locations at different depths; but increasing temporal stability with depth was not found in this study. In the 0–20 cm depth interval, location A1 was the most temporally stable with the lowest SDRD (4.67%) values, while A4 was the most unstable location with the highest values of SDRD (11.60%). Note that eight locations (B5, A7, C4, C2, A3, B1, A8 and B2) had very similar SDRD values (from 6.77% to 7.36%); this suggested similar, time-stable features existed among them. The values of SDRD at the 20–40 cm depth were significantly larger (P < 0.05; statistical results are not shown here) than other ones and they also showed a broad range. For the 20–40 cm depth, the most stable location was A6 (SDRD = 4.92%) while A1 exhibited very unstable rank over the study period. For the 40–60 cm depth interval and the root zone profile (0–60 cm), C4 yielded the most stable estimate of mean moisture content (SDRD = 2.93% and 3.98%, respectively) over the study period. The location A5 was the least time-stable at the 40–60 depth while the location A2 was the most unstable location for the soil water within the entire root zone.

Table 2
Means ± standard deviation of SDRD over various depths for the total dataset and different wetness conditions.

Soil depth (cm)	ST (%)	SD (%)	SW (%)
0–20	7.95 ± 2.59	6.94 ± 3.05	5.32 ± 2.25
20–40	10.45 ± 3.99	7.58 ± 6.28	8.27 ± 4.64
40–60	8.26 ± 2.84	4.72 ± 2.91	6.29 ± 3.62
0–60	7.49 ± 2.56	5.43 ± 3.35	4.73 ± 2.14

Abbreviations: ST: SDRD for total data set; SD: SDRD for data of dry seasons; SW: SDRD for data of wet seasons.

The relationships of SDRD to clay content and to topographic indices for each depth (0–20, 20–40 and 40–60 cm, respectively) are shown in Fig. 5, with labeling the three locations of the lowest SDRD values. Overall, these time-stable locations had relatively high clay contents (except for 40–60 cm) (Fig. 5a and b), relatively mild slopes (Fig. 5d–f) and relatively planar surfaces (Fig. 5j–l) as compared to the field means. This was in line with the previous findings (Grayson and Western, 1998; Jacobs et al., 2004). Note that the clay content of the most time-stable location A1 (0–20 cm), C4 (20–40 cm) and C4 (40–60 cm) was 26.6%, 24.2% and 26.1%, respectively. Similarly, Jacobs et al. (2004) found that 27% clay soils had the best soil water time-stable feature in the watershed, Iowa, and Joshi et al. (2011) also found that locations having 24–26% clay content exhibited the best soil water time-stable behavior in the Walnut Creek watershed. However, the elevation of the three time-stable locations fell in a broad range (Fig. 5c, g and k); a few of them located in the relatively higher elevation (B4 in the 0–20 cm and B3 in the 40–60 cm) while others located in the relatively lower elevation; suggesting the effect of elevation on SDRD was weak. However, Joshi et al. (2011) found that elevation was one of the main topographic indices affecting soil water temporal stability and the time-stable locations were located in the higher elevation. In fact, it is difficult to determine the relationships between SDRD and clay content and topographic indices because of the very scattered points. This implies that both soil properties (clay content) and topographic indices (slope and curvature) should be considered when identifying the time-stable locations in this area.

Cumulative probability functions of soil water content for the total profile in dry and wet soil situations are given in Fig. 6. The rank of the time-stable location C4 acquired from the whole data set underwent few variations in either dry or wet soil conditions. However, its rank changed a lot when soil wetness transferred from dry to wet, and this phenomenon was also observed for most of other locations. This implies that soil water temporal stability becomes very low during this transition period. Similar findings were reported by Martínez-Fernández and Ceballos (2003). The calculated means of SDRD and MABE based on soil water contents in either dry (June and July) or wet seasons (August and September) were noticeably lower than those based on the whole datasets for various depths (Table 2). This means that soil water profiles tend to be more time-stable in a dry or a wet season than those

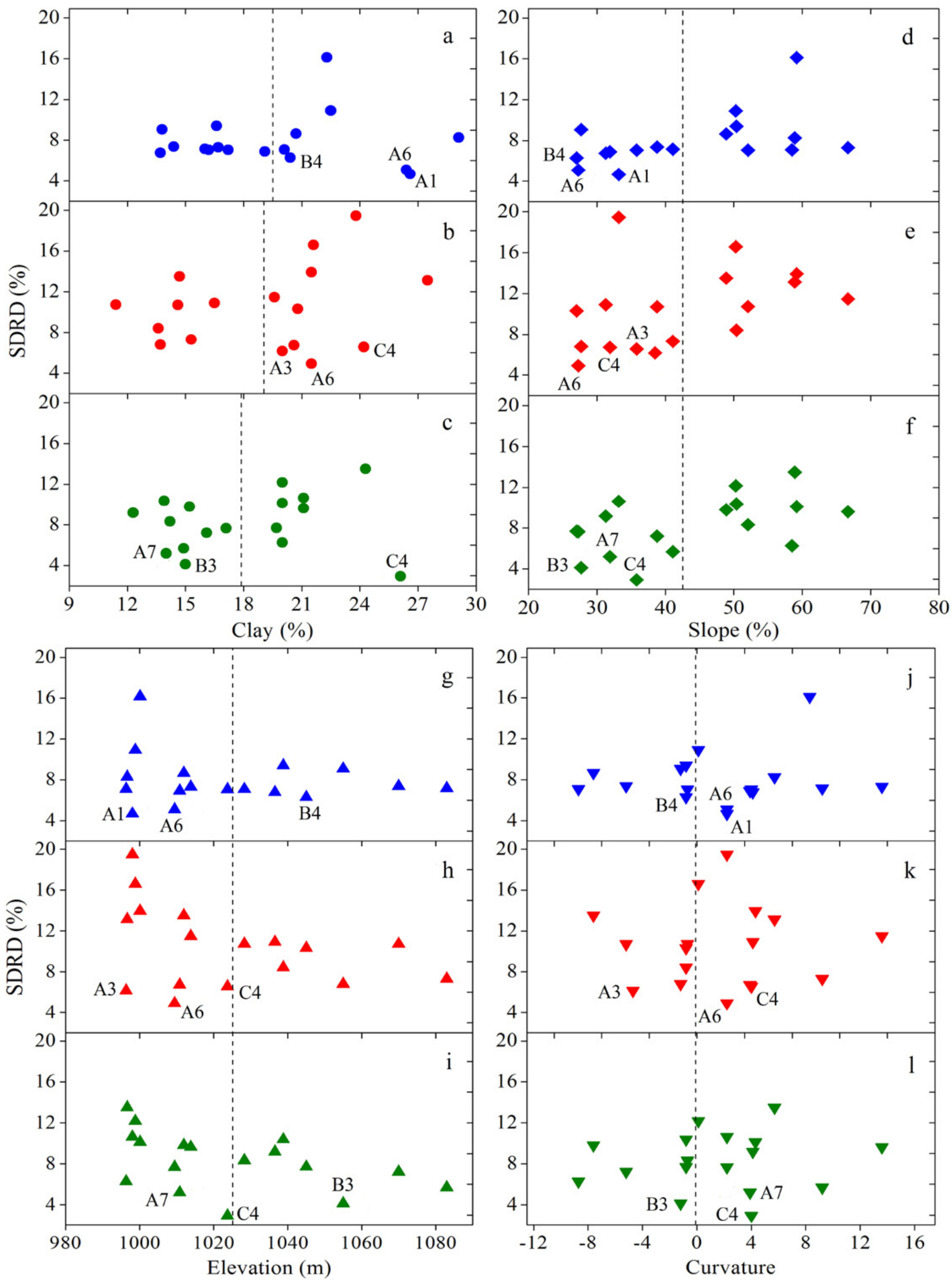

Fig. 5. Relationships between SDRD and clay content (a–c) and topographic indices including slope (d–f), elevation (g–i) and curvature (j–l) in different depth intervals (0–20, 20–40, and 40–60 cm from top to bottom for each column). The dash lines in the first three columns denote the mean values of affecting factors, and that in the last column denotes the zero value of curvature.

including both. Moreover, the degree of soil water temporal stability in the two wetness conditions varied with depth. In the 0–20 cm, soil water temporal stability in the wet seasons was higher than in the dry seasons according to the SDRD values while in the other two depth intervals contrary phenomena were observed. However, Martínez-Fernández and Ceballos (2003) found that the soil water temporal stability in dry soil conditions was always higher than in the wet soil conditions. Moreover, Starks et al. (2006) reported time-stable locations tended to maintain their ranks independent of soil wetness conditions. This disagreement could be attributed to the relatively gentle landform at their sites. Temporal stability in soil water spatial patterns is expected to vary between seasons in complex terrains (Lin, 2006), as exhibited in this study.

3.3. Mean soil water content estimation using temporal stability

Fig. 7 shows the mean relative differences and its standard deviation for the study period by depth. Locations with

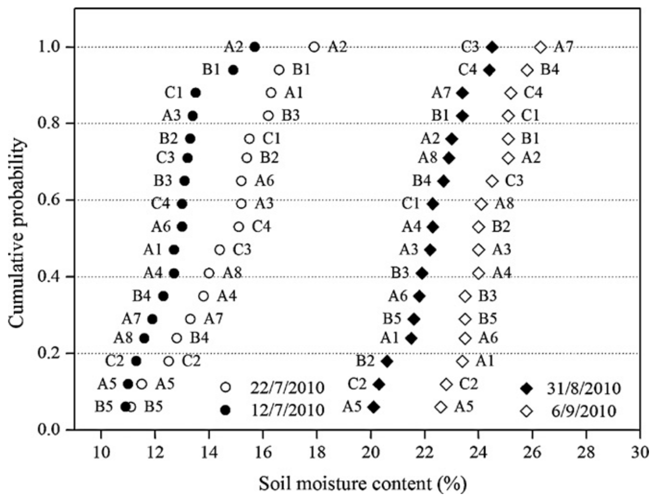

Fig. 6. Comparison of cumulative probability functions in selected dates for different wetness conditions.

Table 3
Linear fitting results between mean moisture content in jujube orchards (y) and soil water content of RMSM (x) for various depths.

Depth (cm)	RMSM	Fitting equation	R^2	RMSE
0–20	A1	$y = 1.0248x - 0.0936$	0.9844	0.0076
20–40	A6	$y = 1.0916x - 1.4912$	0.9560	0.0103
40–60	C4	$y = 1.0479x - 0.7498$	0.9835	0.0060
0–60	A7	$y = 0.8304x + 3.0412$	0.9873	0.0100

Table 4
Linear fitting results between mean moisture content in jujube orchards (y) and soil water content of time-stable location (x) for various depths using Eq. (6).

Depth (cm)	Time-stable location	Fitting equation	R^2	RMSE
0–20	A1	$y = 0.9781x + 0.3486$	0.9844	0.0068
20–40	A6	$y = 0.8830x + 2.1640$	0.9560	0.0100
40–60	C4	$y = 0.9450x + 1.0283$	0.9835	0.0056
0–60	C4	$y = 1.1347x - 3.1944$	0.9873	0.0107

above-zero MRDs would systematically overestimate the mean moisture content and those with below-zero ones would underestimate it. In the light of this criterion suggested by Martínez-Fernández and Ceballos (2005) in Section 2.3, location A1 for 0–20 cm, A6 for 20–40 cm, C4 for 40–60 cm and A7 for 0–60 cm depth were selected as RMSM for the corresponding depth. Linear fitting analysis indicated that the selected RMSMs can directly estimate well the mean moisture content for jujube orchards (Table 3). However, it is difficult to set a threshold for "the low value of SDRD" (Martínez-Fernández and Ceballos, 2005) because SDRD varies across scales. For instance, the SDRD in this study, representing a small area (5.2 ha), was much lower than that in the reports of Starks et al. (2006) and Cosh et al. (2008), which were representing larger areas. Furthermore, a mismatch existed for 0–60 cm depth (Fig. 6d); location A7 had a MRD closest to zero while C4 was the most time-stable location. The most time-stable location with non-zero MRD obtained in Section 3.2 for various depths was used indirectly to estimate mean moisture content in jujube orchards via Eq. (6). Linear fitting analysis between the estimates from Eq. (6) and the measured mean moisture content indicated that these time-stable locations also produced good estimates of the mean moisture content in jujube orchards (Table 4). Results in Tables 3 and 4 suggested that the two methods had similar and good performances in the estimation of field-mean moisture content in this study.

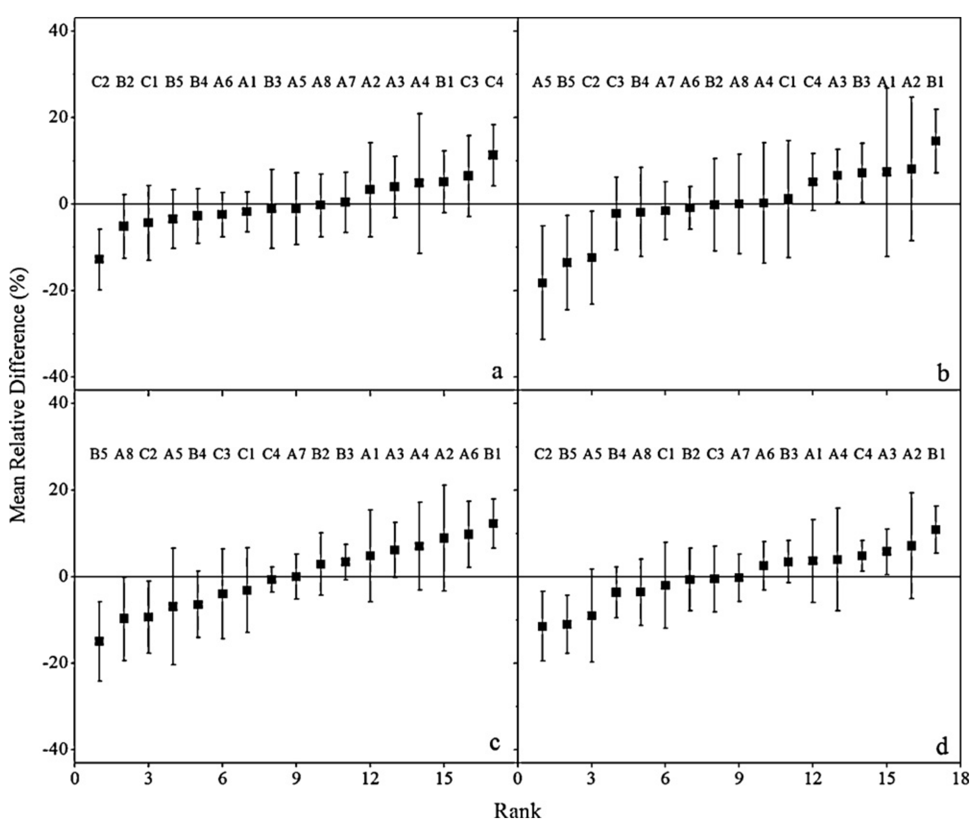

Fig. 7. Ranked mean relative differences over the study period for the 0–20 cm (a), 20–40 cm (b), 40–60 cm (c) and 0–60 cm depth (d). Error bars denote standard deviation of the relative differences.

4. Conclusions

Spatial mean soil water estimation of sloping jujube orchards using temporal stability was investigated in the Yuanzegou catchment of the Loess Plateau, based on soil water observations under both dry and wet soil conditions. Time-stable locations can be identified for different depths in the jujube orchards using two time-stability approaches. Different time-stable locations were detected for different depths wherein temporal stability of soil water content in 20–40 cm was significantly ($P < 0.05$) weaker than that in other depths. Furthermore, these time-stable locations have relatively high clay contents, relatively mild slopes and relatively planar surfaces compared to the corresponding field means, and these analyses suggested both soil properties and topographic indices are necessary to identify time-stable locations. Soil wetness conditions were found to be linked with soil water temporal stability. Statistical analysis revealed that soil water profiles tend to be more temporally stable in either a dry or a wet season than those including both. In addition, soil water temporal stability became very low during the transition period from dry to wet. Based on the time-stability analysis, these time-stable locations can be used to estimate well the mean soil water content both directly and indirectly.

The results presented here provide evidence for the existence of time-stable locations in jujube orchards with steep slopes and a reliable method to estimate field mean moisture content from point-based observations in this area. The method should provide useful information for soil water management in semiarid, sloping jujube orchards in this area.

Acknowledgements

We would like to thank Heping Liu for his assistance with daily routines and experiments during the study period. We also would like to thank Dr. Liusan Cheng for help with soil water measurements. Special thanks are given to Dr. Xiaobo Zhou and all members of the Rainfall Research Team for their valuable comments on this manuscript. This work was jointly supported by the Special Foundation of National Science & Technology Supporting Plan (grant no. 2011BAD29B09), the National Natural Science Foundation of China (31172039), the Supporting Project of Young Technology Nova of Shaanxi Province (grant no. 2010KJXX-04) and the Supporting Plan of Young Elites of Northwest A & F University.

References

Avissar, R., Pielke, R.A., 1989. A parameterization of hetero-geneous land surfaces for atmospheric numerical models and its impact on regional meteorology. Monthly Weather Review 117, 2113–2136.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2008. Soil water temporal stability over experimental areas in Central Italy. Geoderma 148, 364–374.

Brocca, L., Melone, F., Moramarco, T., Morbidelli, R., 2010. Spatial–temporal variability of soil water and its estimation across scales. Water Resources Research 46, W02516, doi:10.1029/2009WR008016.

Cosh, M.H., Jackson, T.J., Moran, S., Bindlish, R., 2008. Temporal persistence and stability of surface soil water in a semi-arid watershed. Remote Sensing of Environment 112, 304–313.

Fu, B., Wang, J., Chen, L., Qiu, Y., 2003. The effects of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena 54, 197–213.

Gómez-Plaza, A., Alvarez-Rogel, J., Albaladejo, J., Castillo, V., 2000. Spatial patterns and temporal stability of soil water across a range of scales in a semiarid environment. Hydrological Processes 14, 1261–1277.

Grant, L., Seyfried, M., McNamara, J., 2004. Spatial variation and temporal stability of soil water in a snow-dominated, mountain catchment. Hydrological Processes 18, 3493–3511.

Grayson, R.B., Western, A.W., 1998. Towards areal estimation of soil water content from point measurements: time and space stability of mean response. Journal of Hydrology 207, 68–82.

Guber, A.K., Gish, T.J., Pachepsky, Y.A., van Genuchten, M.T., Daughtry, C.S.T., Nicholson, T.J., Cady, R.E., 2008. Temporal stability in soil water content patterns across agricultural field. Catena 73, 125–133.

Heathman, G.C., Larose, M., Cosh, M.H., Bindlish, R., 2009. Surface and profile soil water spatio-temporal analysis during an excessive rainfall period in the Southern Great Plains, USA. Catena 78, 159–169.

Hu, W., Shao, M.A., Wang, Q.J., Reichardt, K., 2009. Time stability of soil water storage measured by neutron probe and the effects of calibration procedures in a small watershed. Catena 79 (1), 72–82.

Hu, W., Shao, M.A., Reichardt, K., 2010a. Using a new criterion to identify sites for mean soil water storage evaluation. Soil Science Society of America Journal 74, 762–773.

Hu, W., Shao, M.A., Han, F.P., Reichardt, K., Tan, J., 2010b. Watershed scale temporal stability of soil water content. Geoderma 158, 181–198.

Jacobs, J.M., Mohanty, B.P., Hsu, E.C., Miller, D., 2004. SMEX02: field scale variability, time stability and similarity of soil water. Remote Sensing of Environment 92, 436–446.

Jacobs, J.M., Hsu, E., Choi, M., 2010. Time stability and variability of electronically scanned thinned array radiometer soil water during southern great plains hydrology experiments. Hydrological Processes 24, 2807–2819.

Joshi, C., Mohanty, B.P., Jacobs, J.M., Ines, A.V.M., 2011. Spatiotemporal analyses of soil moisture from point to footprint scale in two different hydroclimatic regions. Water Resources Research 47, W01508, doi:10.1029/2009WR009002.

Kachanoski, R.G., de Jong, E., 1988. Scale dependence and the temporal persistence of spatial patterns of soil water storage. Water Resources Research 24, 85–91.

Li, X.Y., Bi, H.X., Diao, Y.M., Liu, L.F., Li, G.X., Li, J., 2005. The measurement principles of TRIME–TDR system and its application in Caijiachuan watershed of Loess Plateau, China. Science of Soil and Water Conservation 3 (1), 112–115 (in Chinese).

Lin, H., 2006. Temporal stability of soil water spatial pattern and subsurface preferential flow pathways in the shale hills catchment. Vadose Zone Journal 5, 317–340.

Martínez-Fernández, J., Ceballos, A., 2003. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Science Society of America Journal 67, 1647–1656.

Martínez-Fernández, J., Ceballos, A., 2005. Mean soil water estimation using temporal stability analysis. Journal of Hydrology 312, 28–38.

Mohanty, B.P., Skaggs, T.H., 2001. Spatio-temporal evolution and time-stable characteristics of soil water within remote sensing footprints with varying soil, slope and vegetation. Advances in Water Resources 24, 1051–1067.

Pachepsky, Y.A., Guber, A.K., Jacques, D., 2005. Temporal persistence in vertical distributions of soil water content. Soil Science Society of America Journal 69, 347–352.

Rodriguez-Iturbe, I., Vogel, G.K., Rigon, R., Entekhabi, D., Castelli, F., Rinaldo, A., 1995. On the spatial organization of soil moisture fields. Geophysical Research Letters 22, 2757–2760.

Starks, P.J., Heathman, G.C., Jackson, T.J., Cosh, M.H., 2006. Temporal stability of soil water profiles. Journal of Hydrology 324, 400–411.

Starr, G.C., 2005. Assessing temporal stability and spatial variability of soil water patterns with implications for precision water management. Agricultural Water Management 72, 223–243.

Teuling, A.J., Uijlenhoet, R., Hupet, F., van Loon, E.E., Troch, P.A., 2006. Estimating spatial mean root-zone soil water from point-scale observations. Hydrology and Earth System Sciences 10, 755–767.

Timm, L.C., Dourado-Neto, D., Bacchi, O.O.S., Hu, W., Bortolotto, R.P., Silva, A.L., Bruno, I.P., Reichardt, K., 2011. Temporal variability of soil water storage evaluated for a coffee field. Soil Research 49, 77–86.

Vachaud, G., Passerat de Silans, A., Balabanis, P., Vauclin, M., 1985. Temporal stability of spatially measured soil water probability density function. Soil Science Society of America Journal 49, 822–828.

Western, A.W., Zhou, S., Grayson, R.B., McMahon, T.A., Blöschl, G., Wilson, D.J., 2004. Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes. Journal of Hydrology 286, 113–134.

Williams, C.J., McNamara, J.P., Chandler, D.G., 2009. Controls on the temporal and spatial variability of soil water in a mountainous landscape: the signature of snow and complex terrain. Hydrology and Earth System Sciences 13, 1325–1336.

Wu, P.T., Wang, Y.K., Xin, X.G., Zhu, D.L., 2008. Integration and demonstration of the date micro-irrigation technology in the hilly of Shanbei. Agricultural Research in the Arid Areas 26 (4), 1–6 (in Chinese).

Yoo, C., 2002. A ground validation problem of remotely sensed soil moisture data. Stochastic Environmental Research and Risk Assessment 16, 175–187.

Zhao, X.N., Wu, P.T., Feng, H., Wang, Y.K., Shao, H.B., 2009. Towards development of eco-agriculture of rainwater harvesting for supplemental irrigation in the semi-arid Loess Plateau of China. Journal of Agronomy and Crop Science 195, 399–407.

Zhao, Y., Peth, S., Wang, X.Y., Lin, H., Horn, R., 2010. Controls of surface soil water spatial patterns and their temporal stability in a semi-arid steppe. Hydrological Processes 24, 2507–2519.

Zhu, X.M., Li, Y.S., Peng, X.L., Zhang, S.G., 1983. Soils of the loess region in China. Geoderma 29 (3), 237–255.