

Temporal persistence and stability of soil water storage after rainfall on terrace land

Guoce Xu¹ · Zongping Ren¹ · Peng Li¹ · Zhanbin Li^{1,2} · Shuilong Yuan¹ · Hui Zhang¹ · Dan Wang¹ · Zeyu Zhang¹

Received: 20 November 2015 / Accepted: 25 May 2016 / Published online: 4 June 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract The “Grain for Green” Project on the Loess Plateau of China has converted a large area of cultivated slope farmland to terraces to reduce soil erosion and improve the ecological environment. The area of terraced land on the Loess Plateau was 32,600 km² in 2010. Knowledge of the behavior of soil water storage (SWS) and its spatiotemporal distribution provides essential information concerning hydrological and ecological processes. This study aimed to analyze the temporal stability of SWS after rainfall for different time periods on terraces planted with jujube trees (*Ziziphus jujuba* Mill.). The SWS of 21 locations was obtained from July 19 to September 3 in 2014 and from August 01 to August 31 in 2015. Relative difference analysis and the nonparametric Spearman rank correlation test were used to check the temporal stability of SWS. The SWS on terraces was normally distributed and demonstrated moderate spatial variability. The SWS at three soil depths all showed strong temporal stability with stability in the order of 0–0.6 < 0–1.0 < 0–1.6 m. Rainfall

significantly affected the temporal stability of SWS in the depth of 0–0.6 m. The number of representative locations of SWS was not constant. The best representative locations were not identical for different soil depths; however, a common representative location did exist for the different depths and periods. Moreover, the mean SWS generally increased from the upper to lower slope. The temporal stability of SWS was not significantly affected by rainfall but was significantly negatively correlated with sand content. The total root length and soil organic carbon content did not show any obvious correlations with mean SWS. It was feasible to use the representative locations of SWS to represent the mean SWS over a period of time. However, the cumulative absolute error increased with cumulative days. In conclusion, SWS in the deeper soil depths indicated greater temporal stability than that in shallow soil depth during wet period. The best representative locations for SWS were depth and time dependent.

Keywords Soil water storage · Terrace · Temporal stability · Rainfall · Soil depth

This article is part of a Topical Collection in Environmental Earth Sciences on “Environment and Health in China II,” guest edited by Tian-Xiang Yue, Cui Chen, Bing Xu and Olaf Kolditz.

✉ Peng Li
lipeng74@163.com
Guoce Xu
xuguoce_x@163.com

- ¹ State Key Laboratory Base of Eco-Hydraulic Engineering in Arid Area, Xi’an University of Technology, Xi’an 710048, Shaanxi, China
- ² State Key Laboratory of Soil Erosion and Dry-land Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, China

Introduction

Water content in soil profiles changes with time as a result of rainfall distribution, soil capillarity and drainage, runoff, evapotranspiration and irrigation (Silva 2012; Chaney et al. 2015). It is one of the main factors that affects plant growth and vigor (Magagi and Kerr 2001; Wang et al. 2007; Santos et al. 2014). Information on the dynamics of soil water within soil profiles is vital for the sustainable development of vegetation restoration (Josa et al. 2012; Liu and Shao 2015). However, the high spatial and temporal variability of soil water due to the heterogeneity of soil

texture, topography, vegetation and climate in the natural environment makes soil water in regional scale difficult to estimate (Gómez-Plaza et al. 2001; Hu et al. 2011; Kong et al. 2011; Chaney et al. 2015; Wang et al. 2015).

Despite the strong spatiotemporal variability of soil water, previous studies have indicated that the spatial patterns of soil water show time stability (Vachaud et al. 1985; Kachanoski and de Jong 1988; Schneider et al. 2008; Brocca et al. 2009, 2010; Hu et al. 2010; Liu and Shao 2014). Vachaud et al. (1985) first introduced the concept of temporal stability of soil water, defined as “the time-invariant association between spatial location and classical statistical parameters of a given soil property” and suggested the ranking stability method. The concept was later expanded by Kachanoski and de Jong (1988), who described time stability of soil moisture as “the temporal persistence of a spatial pattern,” potentially evaluated using a simple correlation between successive time intervals (Penna et al. 2013). Since then, the time stability concept has been applied throughout a wide range of spatial and temporal scales (Vanderlinden et al. 2012). Temporal stability provides a useful insight when analyzing spatiotemporal patterns of soil moisture (Brocca et al. 2010; Martínez et al. 2013). The method has been successfully used to find locations that represent the mean soil water content of an area, to down- or upscale soil water measurement, to estimate missing data, and for data assimilation in hydrological research (Vanderlinden et al. 2012; Penna et al. 2013). However, across study areas of various sizes, many environmental factors are linked to the temporal stability of soil moisture, such as soil properties (soil texture, porosity, organic carbon content, bulk density and soil thickness), topography, vegetation, climate and seasonality (Vachaud et al. 1985; Crave and Gascuel-Oudou 1997; Jacobs et al. 2004; Martínez-Fernández and Ceballos 2005; Famiglietti et al. 2008; Zhu and Lin 2011; Vanderlinden et al. 2012; Wang et al. 2015). For example, Martínez-Fernández and Ceballos (2003) found that temporal stability of soil moisture is always higher when the soils are dry than when the water content is high in the central sector of the Duero basin (Spain). In contrast, Zhao et al. (2010) found that soil moisture under wet conditions was more stable than that under dry conditions in a semiarid steppe. Gómez-Plaza et al. (2000) concluded that topography and vegetation were the primary factors responsible for temporally stable locations of soil water content. Conflicting results were reported that contents of clay and organic matter rather than topographic variables appeared to be the primary factors (da Silva et al. 2001; Jacobs et al. 2004). Rivera et al. (2014) reported that most of the variability of soil water content changes is associated with both the amount and intensity of rainfall. The changes in the most

stable point depend on the amount of water entering the soil and the previous state of the soil water content.

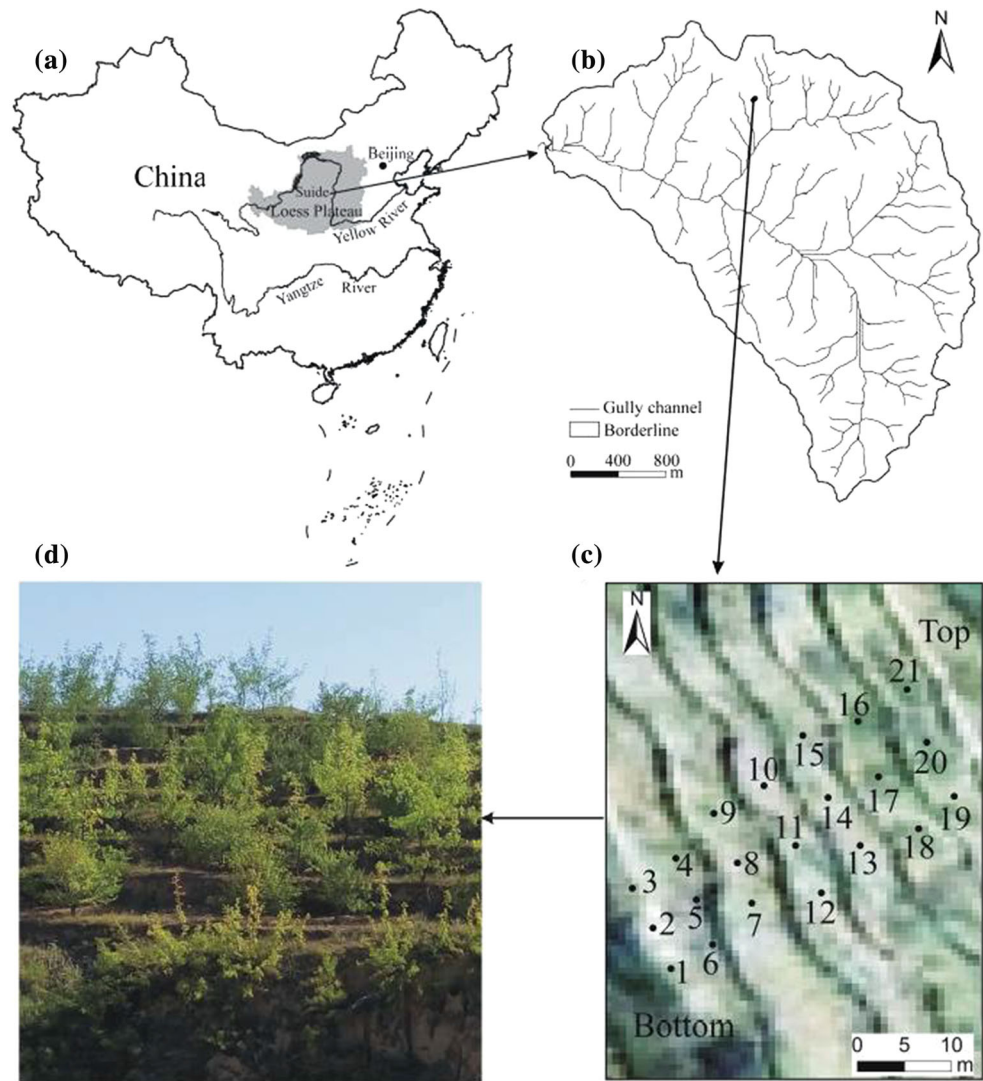
On the Loess Plateau, the Chinese government has implemented many management programs of vegetative restoration since the late 1990s that have converted cropland to terraces, forests or grassland to improve the ecological status and to reduce soil erosion and restore vegetation (Chen et al. 2008; Liu and Shao 2015). The area of terraced land on the Loess Plateau was 32,600 km² in 2010. Therefore, understanding the spatial patterns and stability of soil water storage (SWS) in terraces is essential for a thorough comprehension of the hydrological and vegetation restoration processes on the Loess Plateau. However, few studies have explored the depth dependency of spatiotemporal variability characteristics (Gao et al. 2015). Little work has examined the effect of research period on the temporal stability and representative location of SWS. Furthermore, no study appears to have analyzed the temporal stability of SWS in terraces after rainfall. In this study, the spatial patterns and stability of SWS at different soil depths based on 21 locations along terraces planted with jujube trees (*Ziziphus jujuba* Mill.) were analyzed. We then evaluated the predictive accuracies of the representative locations in different research periods and the relationships between temporal stability of SWS and some parameters. The specific objectives of this study were to: (1) analyze the spatial patterns and stability of SWS for different soil layers in the terraces, (2) evaluate the predictive accuracies of the representative locations of SWS during different research periods and (3) examine the primary factors responsible for temporal stability after rainfall.

Materials and methods

Description of study area

The study was conducted on terraced land located in the Wangmaogou Watershed (110°20′26″–110°22′46″E, 37°34′13″–37°36′03″N), 5 km north of Suide County, Shaanxi Province, China (Fig. 1). The watershed has a continental monsoon climate with an area of 5.97 km². The altitude is in the range of 940–1200 m.a.s.l., and the mean annual temperature is 10.2 °C. The mean annual precipitation is approximately 513 mm, of which more than 60 % falls between July and September. The watershed is in the center of the water erosion region of the Loess Plateau. The soil in the study area is loessial soil mainly consisting of particles of size <0.25 mm, with fine sand and silt accounting for 60 %. Rock fragment contents are very low. The bulk density of topsoil is generally 1.1–1.3 g/cm³. The primary land-use types in the watershed are grassland

Fig. 1 Distribution of 21 tube locations across the terraces (c, d) located in the Wangmaogou watershed (b) on the Loess Plateau of China (a)



(36.51 %), sloping farmland (22.32 %), terraces (25.78 %), forestland (9.15 %), and dam farmlands (6.24 %).

Soil sampling and analysis

Polycarbonate tubes (2 m long and diameter 44 mm) with a steel cutting shoe were installed at 21 locations along the terraces planted with jujube trees. The mean spacing of the trees was 3.88 m and their age was 14 years. The mean distance between adjacent tube locations in the terraces was approximately 5.5 m. The elevation range was 1048–1056 m. From each location, soil samples with roots at intervals of 0.2 m down to a depth of 1.6 m were collected. The root length and diameter were measured using a WinRHIZO 2013 image analyzer system (Regent Instruments Inc., Canada). The root diameter was defined as follows: <0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0 and >2.0 mm. Soil

particle size distribution was described in terms of the percentages of silt (<0.002 mm), clay (0.002–0.05 mm) and sand (0.05–2.0 mm). Soil particle composition was measured by laser diffraction using a Mastersizer 2000 particle size analyzer (Malvern Instruments, Malvern, England). Soil organic carbon (SOC) content was determined in duplicate for each sample using a multi N/C 3100 analyzer (Analytik Jena AG, Germany). From July 19 to September 3 in 2014 and from August 01 to August 31 in 2015, volumetric soil water contents (SWCs) were obtained approximately every day at intervals of 0.2 m down to a depth of 1.6 m at 21 locations. The rainfall distribution from July to September in 2014 and 2015 are shown in Fig. 2. Time domain reflectometry (TDR) soil moisture measurement system (TRIME-PICO IPH, Germany) was used to measure the volumetric water content (% v/v) of soil moisture at each location.

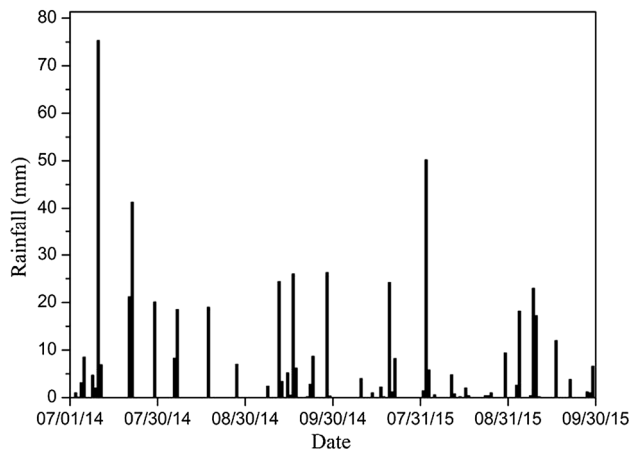


Fig. 2 Rainfall distribution in the study area during the rainy season (July–September 2014 and July–September 2015)

Data analysis

To capture possible changes in the spatial pattern, samples of soil moisture should be collected on at least 13 occasions (Martínez-Fernández and Ceballos 2005; Schneider et al. 2008). Therefore, the SWS for 07/19/14–08/02/14 were selected to determine the temporal stability and representative locations of SWS at different soil depths. The SWS for 07/19/14–09/03/14 and 08/01/15–08/31/15 was used to verify the prediction accuracy of representative locations of SWS. SWC (i, j, k) was assumed to be the SWC at location i , time j and soil depth k , and was defined as:

$$\text{SWS}(i, j, k) = \text{SWC}(i, j, k) \cdot h \quad (1)$$

and the SWS at location i , time j and 0– k soil depth was:

$$\text{SWS}_{ij} = \sum \text{SWS}(i, j, k) \quad (2)$$

where SWS is in mm, SWC is in %, cm^3/cm^3 and h is the height of SWS (in mm).

Two approaches were used to evaluate the temporal stability of SWS in this study: nonparametric Spearman's rank correlation test and relative difference analysis. Spearman's rank order correlation is a nonparametric (free distribution) test that can indicate the strength and direction of the same variable observed at different dates (Douaik 2006). The representative locations should be those with mean relative difference (MRD) closest to zero and the minimum associated standard deviations. The locations with MRD values within ± 0.05 were considered to be close to zero. Another condition that must be fulfilled is for the representative locations to have low standard deviation of relative difference (SDRD) values (Jacobs et al. 2004; Gao and Shao 2012a; Xu et al. 2015).

The root mean square error (RMSE) is a frequently used measure of the difference between values predicted and the

values actually observed (Gao and Shao 2012a; Liu and Shao 2014). The mean absolute error (MAE) is another useful measure widely used to evaluate predictive accuracy (Hu et al. 2010). MAE and RMSE were calculated based on the following equations:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |P_i - p_i| \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - p_i)^2} \quad (4)$$

where P_i and p_i are the predicted and measured values, respectively.

Results

Descriptive statistics for SWS

Summary statistics of SWS in part of and the entire monitoring period at different soil depths are given in Table 1. Due to rainfall on 07/20/14, 07/21/14 and 07/29/14, the mean and minimum SWS in 07/19/14–08/02/14 were larger than those of 07/19/14–09/03/14 and 08/01/15–08/31/15. The standard errors of SWS were larger during the period 07/19/14–08/02/14 than during 07/19/14–09/03/14 and 08/01/15–08/31/15. The standard errors of SWS at different soil depths were small and increased with increasing soil depth. The coefficient of variation (CV) can be used to qualitatively ascertain the magnitude of the spatial variability. Specifically, this value is considered weak when $\text{CV} < 10\%$, moderate at $10\% < \text{CV} < 100\%$ and strong when $\text{CV} > 100\%$ (Nielsen and Bouma 1985). Hence, the SWS demonstrated moderate spatial variability, with CV values in the range of 12–23%. The CV values decreased with increasing depth. Moreover, the SWS at the 21 locations for the entire monitoring period showed significant differences ($p < 0.01$). The SWS at the 21 locations was normally distributed for the same time point ($p > 0.05$), and the SWS in each location during the entire monitoring period was also normally distributed ($p > 0.05$).

Temporal stability of SWS using Spearman's correlation test

The r_s values of the three soil depths for the periods 07/19/14–08/02/14, 07/19/14–08/31/15 are shown in Table 2 and Fig. 3, respectively. The r_s values for periods 07/19/14–08/02/14 and 07/19/14–08/31/15 were within the range of 0.76–0.99 and 0.64–0.90, respectively. The lowest mean r_s values in depths of 0–0.6, 0–1.0 and 0–1.6 m for the periods 07/19/14–08/02/14 and 07/19/14–08/31/15 were

Table 1 Summary statistics of soil water storage at different soil depths

Dates	Depths (m)	Mean (mm)	Min (mm)	Max (mm)	SE (mm)	CV (%)
07/19/14–08/02/14	0–0.6	89.08	46.26	114.60	0.83	16
	0–1.0	139.38	79.46	182.78	1.19	15
	0–1.6	204.49	108.34	274.78	1.74	14
07/19/14–09/03/14	0–0.6	75.86	30.94	114.60	0.57	23
	0–1.0	124.05	60.26	182.78	0.79	19
	0–1.6	188.69	92.6	274.78	1.08	17
08/01/15–08/31/15	0–0.6	56.24	15.56	102.50	0.47	19
	0–1.0	95.42	40.84	146.18	0.61	14
	0–1.6	152.11	75.34	206.34	0.85	12

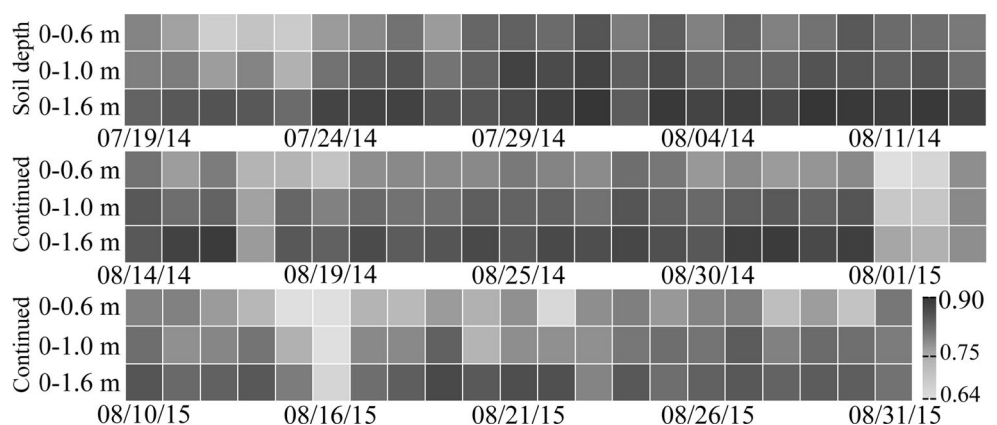
Min minimum value, *Max* maximum value, *SE* standard error, *CV* coefficient of variation

Table 2 Spearman’s rank correlation coefficients for each sampling date with the 13 other sampling dates at each soil depth

Dates	0–0.6 m			0–1.0 m			0–1.6 m		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
07/19	0.89	0.94	0.83	0.90	0.94	0.85	0.89	0.95	0.82
07/20	0.88	0.94	0.81	0.89	0.96	0.81	0.91	0.96	0.84
07/21	0.85	0.96	0.77	0.86	0.92	0.77	0.92	0.96	0.84
07/22	0.88	0.96	0.79	0.89	0.96	0.78	0.93	0.98	0.84
07/23	0.87	0.96	0.82	0.87	0.96	0.76	0.89	0.94	0.84
07/24	0.90	0.95	0.87	0.90	0.94	0.85	0.94	0.98	0.88
07/25	0.89	0.92	0.82	0.90	0.96	0.85	0.92	0.97	0.88
07/26	0.91	0.98	0.82	0.92	0.99	0.85	0.94	0.99	0.88
07/27	0.90	0.95	0.84	0.90	0.95	0.85	0.91	0.97	0.88
07/28	0.91	0.98	0.83	0.91	0.99	0.84	0.92	0.99	0.86
07/29	0.86	0.94	0.78	0.92	0.96	0.87	0.92	0.96	0.88
07/30	0.90	0.96	0.82	0.90	0.98	0.79	0.92	0.97	0.88
07/31	0.90	0.96	0.80	0.90	0.98	0.81	0.92	0.97	0.88
08/02	0.86	0.92	0.77	0.86	0.95	0.76	0.89	0.95	0.84

Correlations are all significant at $p < 0.01$ (two-tailed)

Fig. 3 Spearman’s rank correlation coefficients for each sampling date with the 66 other sampling dates at each soil depth



0.85, 0.86 and 0.90 and 0.64, 0.66 and 0.70, respectively. The r_s values were close to 1 and the correlations were all highly significant ($p < 0.01$), indicating that the SWS of

the three soil depths in the two periods both showed strong temporal stability. The mean r_s values indicated an order of $0-0.6 < 0-1.0 < 0-1.6$ m. There were significant

differences among the three soil depths ($p < 0.01$), indicating that temporal stability of SWS was strongest for 0–1.6 m. Moreover, the correlation coefficients between the two periods in corresponding soil depths were significantly different ($p < 0.01$).

Temporal stability of SWS based on relative difference analysis

Relative difference analysis was used to quantitatively identify the locations that were consistently greater, less than or equal to the mean SWS of the terrace land. The rank ordered MRD and corresponding SDRD for SWS at the three soil depths in the three periods are presented in Fig. 4. The ranges of MRD in 0–0.6, 0–1.0 and 0–1.6 m for the period 07/19/14–08/02/14 were –0.38 to 0.20, –0.36 to 0.27 and –0.32 to 0.31, respectively; and correspondingly for 07/19/14–09/03/14 were –0.37 to 0.28, –0.36 to 0.35 and –0.33 to 0.37; for 08/01/15–08/31/15 were –0.46 to 0.19, –0.39 to 0.15 and –0.36 to 0.16. The mean SDRD in 0–0.6, 0–1.0 and 0–1.6 m for the periods 07/19/14–08/02/14, 07/19/14–09/03/14 and 08/01/15–08/31/15 were 0.05, 0.04 and 0.03, 0.06, 0.05 and 0.03 and 0.05, 0.04 and 0.03, respectively. This indicated a downward trend with increased soil depth, which was closely related to the CV values. The best representative locations in 0–0.6, 0–1.0 and 0–1.6 m for the periods 07/19/14–08/02/14, 07/19/14–09/03/14 and 08/01/15–08/31/15 were locations 7, 19

and 21, locations 14, 21 and 9 and locations 20, 20 and 19, respectively. The best representative locations for SWS were depth dependent and showed some differences. There was more than one representative location for each soil depth. Other studies also found that the numbers of representative locations were not constant in other land-use types (Hu et al. 2010; Coppola et al. 2011; de Souza et al. 2011; Gao and Shao 2012a). Therefore, the best representative locations for SWS were depth and time dependent. However, a common representative location (i.e., location 9) occurred for the different depths and periods.

Prediction analysis using the representative locations of SWS

The prediction analysis of the best representative locations for the mean SWS at the three soil depths are shown in Fig. 5. The relationships between mean SWS and the SWS at best representative locations could be fitted by linear functions, which were all significant at $p < 0.01$. The regression coefficient (R^2) values of mean SWS and the SWS at best representative locations were all >0.77 . The low RMSE and MAE values indicated high predictive accuracy of the best representative locations during the period 07/19/14–08/02/14 (Fig. 4a). However, the predictive accuracies of the best representative locations for the two monitoring periods of 07/19/14–08/02/14 were significantly lower than those of the best representative

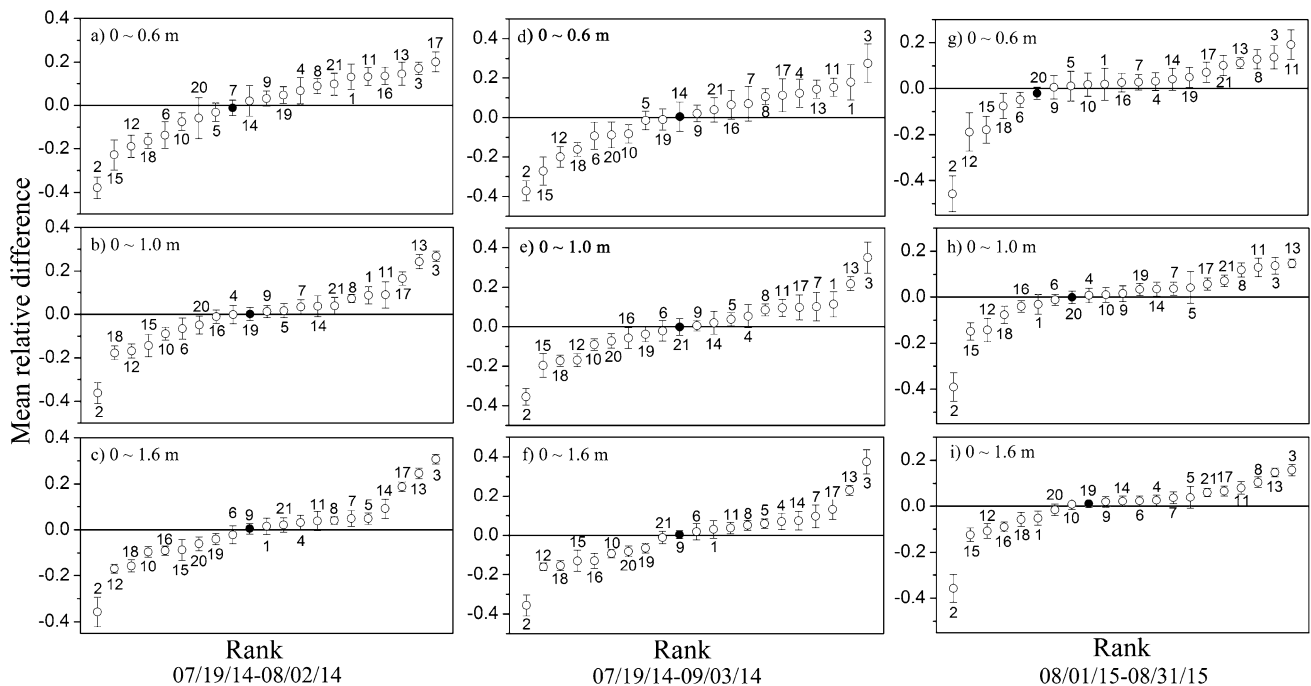


Fig. 4 Mean relative difference of soil water storage at different soil depths. Vertical bars represent \pm standard deviation. The best representative locations of each depth are marked in black

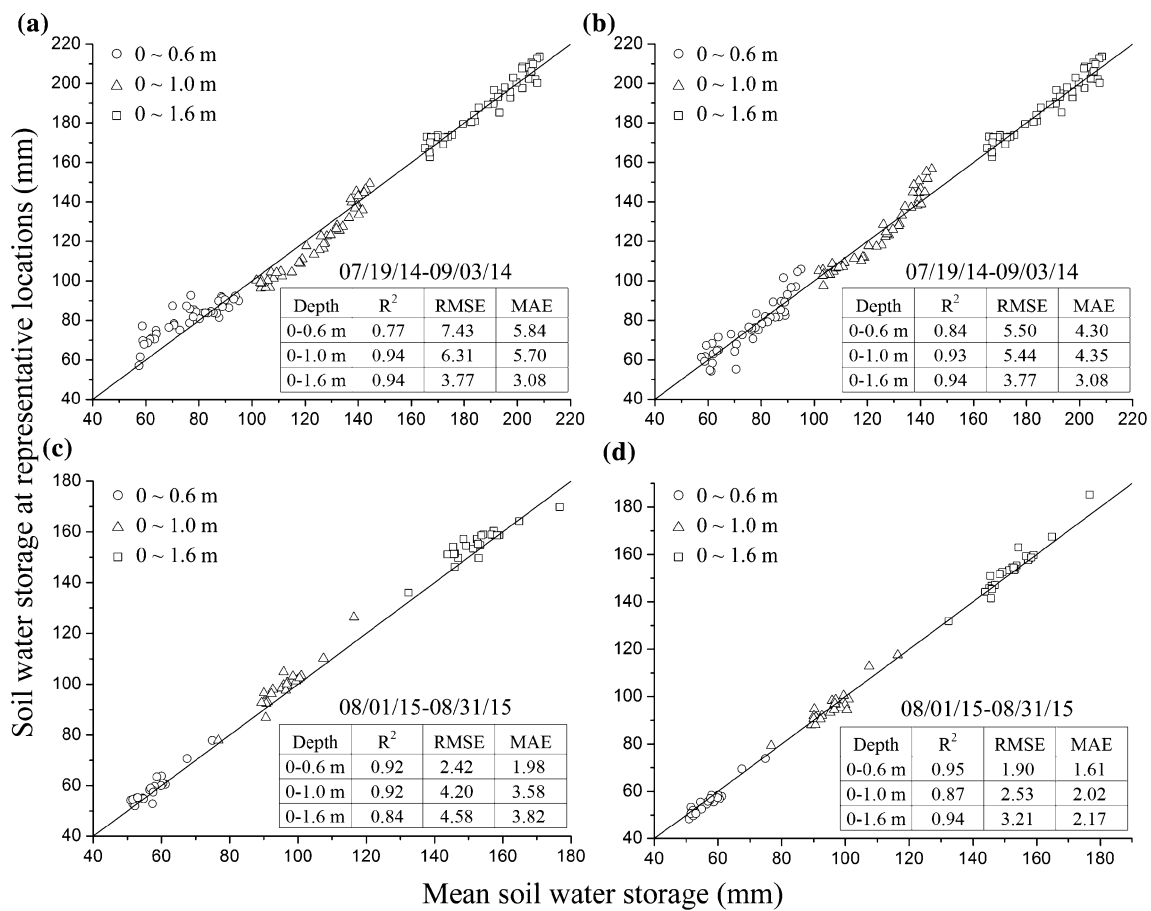


Fig. 5 Comparison of mean soil water storage with the soil water storage at representative locations at different soil depths: representative locations calculated for 07/19/14–08/02/14 (a, c), 07/19/14–09/03/14 (b) and 08/01/15–08/31/15 (d)

locations calculated for 07/19/14–09/03/14 and 08/01/15–08/31/15 ($p < 0.05$, Fig. 4b, c). The largest differences in RMSE and MAE values were 7.43 and 5.84 mm, respectively. The percentages of RMSE values in mean SWS at the depths of 0–0.6, 0–1.0 and 0–1.6 m for the periods 07/19/14–09/03/14 and 08/01/15–08/31/15 were 10, 5 and 2 and 4, 4 and 3 %, respectively. Correspondingly, the percentages of MAE values in mean SWS were 8, 5 and 3 and 4, 4 and 3 %. The percentages of RMSE and MAE values in mean SWS decreased as soil depth increased, indicating that the predictive accuracies of the best representative locations increased with increasing soil depth.

Cumulative absolute error of SWS for the representative locations

The relationships between cumulative absolute error using the best representative locations for the mean SWS and the cumulative days at different soil depths are shown in Fig. 6. The increase rates of cumulative absolute error in the three soil depths for the best representative locations

were significantly larger for 07/19/14–08/02/14 than for 07/19/14–09/03/14 and 08/01/15–08/31/15 ($p < 0.01$). The cumulative error between the mean SWS of the terrace land during the period 07/19/14–09/03/14 and the SWS at the best representative locations calculated for 07/19/14–08/02/14 and 07/19/14–09/03/14 at soil depths of 0–0.6, 0–1.0 and 0–1.6 m were 197, 191 and 30 and 17, 4 and 30 mm, respectively. The cumulative error between the mean SWS of the terrace land during the period 08/01/15–08/31/15 and the SWS at the best representative locations calculated for 07/19/14–08/02/14 and 08/01/15–08/31/15 at soil depths of 0–0.6, 0–1.0 and 0–1.6 m were 37, 78 and 69 and 28, 3 and 41 mm, respectively. This indicated that the best representative locations calculated for the short period resulted in a larger cumulative absolute error when used to evaluate the mean SWS of the long period. The cumulative absolute error indicated an obvious increasing trend with the cumulative days, suggesting that it may not be suitable to use the representative locations for the study of SWS in a long time sequence. Moreover, the differences between the mean SWS and the best representative location were not consistently positive or consistently negative.

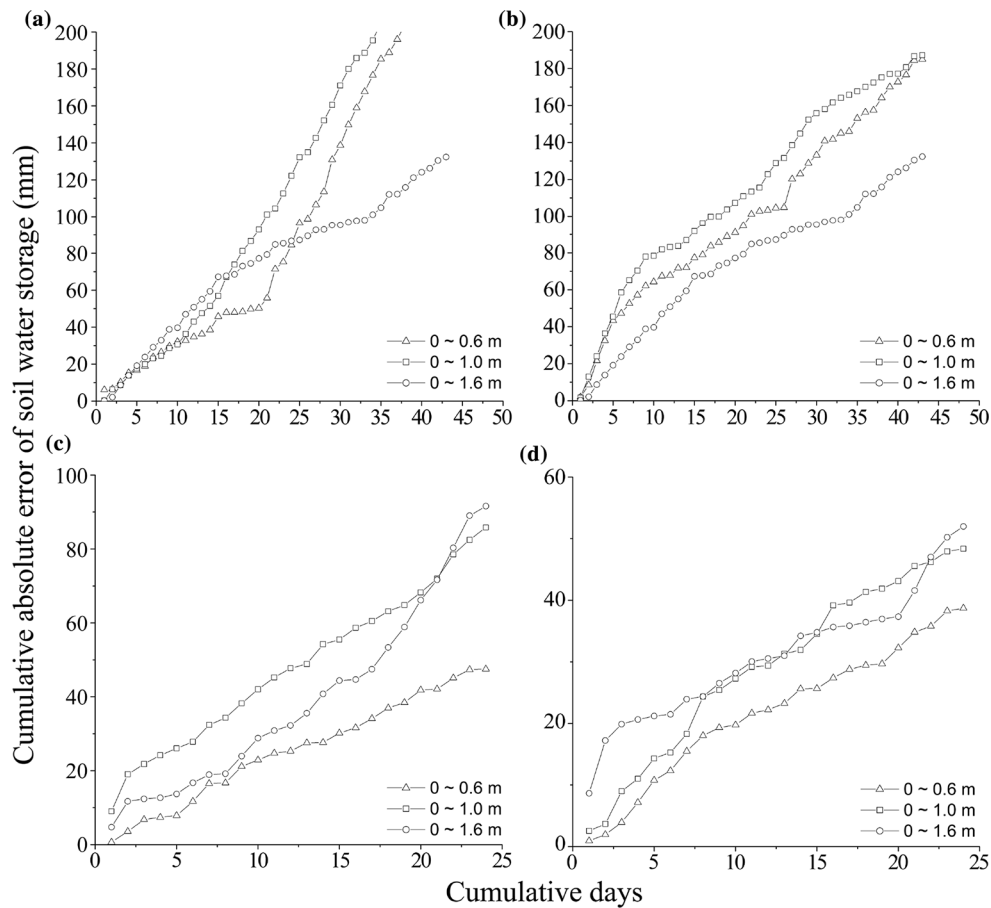


Fig. 6 Cumulative absolute error between the mean soil water storage and the soil water storage at the representative locations for each soil depth: representative locations calculated for 07/19/14–08/02/14 (a, c), 07/19/14–09/03/14 (b) and 08/01/15–08/31/15 (d)

Spatial change in SWS across the slope

Considering that locations 1–3 were in the same terrace as locations 4–6 and there may have been an edge effect, locations 1–3 were not selected to study the SWC change along the terraces. The mean SWC and some corresponding variables at different slope positions over the entire monitoring period are given in Table 3. Locations 16–21, 10–15 and 4–9 represented the upper, middle and lower slopes, respectively. The mean SWS and the total root length were highest for the lower slope; mean SWS and total root length generally increased from the upper to the lower slope, as also did the mean SOC and silt content. The sand content showed an opposite trend to mean silt content. However, the total root length, clay content, silt content and SOC did not show significant correlations with mean SWS ($p > 0.05$). There was a significant negative correlation between mean SWS and sand content ($p < 0.05$). Therefore, sand content had the greatest effect on the temporal stability of SWS in the terrace land.

Discussion

The rainfall on 07/20/14, 07/21/14 and 07/29/14 resulted in a significant difference of SWS among 07/19/14–08/02/14, 08/03/14–09/03/14 and 08/01/15–08/31/15 ($p < 0.01$). The rainfall resulted in the change in temporal stability of the SWS spatial patterns. The CV values and mean SDRD all decreased with increasing soil depth, indicating that SWS had smaller differences in deep compared to shallow soil. The trend was similar to the findings of Hu et al. (2010) and Wang et al. (2015). Distributions with a high kurtosis have sharper peaks and longer, fatter tails, while a low kurtosis indicates a more rounded peak and shorter, thinner tails. The kurtosis values of SWS in the depths 0–0.6, 0–1.0 and 0–1.6 m in the entire monitoring period were -0.45 , -0.17 and 0.37 ($n = 903$), respectively. This indicated that the SWS distribution was more concentrated in deeper soil during the wet period. The SWS in the present study was far less than that in the study area of Martínez-Fernández and Ceballos (2003) during wet period. Smaller differences in SWS in deeper soil showed stronger temporal stability.

Table 3 Mean soil water storage for different slope positions over the entire monitoring period

Depth (m)	Location	Mean value					SOC (g/kg)
		Soil water storage (mm)	Total root length (cm)	Clay (%)	Silt (%)	Sand (%)	
0–0.6	16–21	69.19	281.01	0.25	68.80	30.96	9.56
	10–15	66.83	441.57	0.24	69.42	30.34	11.26
	4–9	70.92	603.31	0.30	70.34	29.36	13.24
0–1.0	16–21	110.98	344.98	0.23	69.81	29.96	9.71
	10–15	112.44	547.40	0.24	70.33	29.43	10.41
	4–9	118.25	723.55	0.29	71.27	28.44	13.27
0–1.6	16–21	169.28	434.56	0.22	70.34	29.44	9.30
	10–15	175.09	632.78	0.22	70.51	29.27	10.18
	4–9	183.77	848.63	0.26	70.79	28.95	12.92

The mean r_s values indicated an order of $0-0.6 < 0-1.0 < 0-1.6$ m. The result was similar to the findings of Hu et al. (2010), who found that the temporal stability of SWS in deeper soil layers (>1 m) was stronger than in the 0–1 m soil layer. Other studies also concluded that temporal stability increased with depth (Nielsen et al. 2000; Guber et al. 2008; Gao and Shao 2012b). It should be noted that the study area of Hu et al. (2010) and Gao and Shao (2012b) was on the Loess Plateau with a continental monsoon climate while the study areas of Nielsen et al. (2000) and Guber et al. (2008) were of approximately twice mean annual precipitation than that of the Loess Plateau.

The representative locations of SWS were similar at different soil depths. Other studies also found that the representative locations of soil water content could be similar for different depths (Cassel et al. 2000; Gao and Shao 2012a). However, the best representative locations for SWS were not the same and changed with time and soil depths. The best representative locations in our study were not identical for different soil depths, which was consistent with previous reports (Guber et al. 2008; Martinez et al. 2013; Li and Shao 2014). Moreover, the best representative locations calculated for the period 07/19/14–08/02/14 were not the same as those for 07/19/14–09/03/14 and 08/01/15–08/31/15. The result was in agreement with that by Rivera et al. (2014), who found that different locations and depths are representative of processes at different time scales. The predictive accuracies of the best representative locations for the different monitoring periods calculated for 07/19/14–08/02/14 were significantly lower than those calculated for 07/19/14–09/03/14 and 08/01/15–08/31/15 ($p < 0.05$). The predictive accuracies increased with increasing soil depth. The predictions were reliable compared with those reported by Cosh et al. (2008) and Brocca et al. (2009). The number of representative locations of SWS was not constant. The number of representative

locations was found to be changed in different study areas (Hu et al. 2010; Coppola et al. 2011; de Souza et al. 2011; Gao and Shao 2012a).

The mean SWS and total root length were both highest for the lower slope, suggesting that roots were distributed more in the areas with higher SWS in the terraces. The result was similar to the findings of Ji et al. (2012), who found that the maximum moisture content was in the lower slope. They also found that the root number and root area ratio were positively correlated with soil moisture content ($p < 0.001$). In contrasting studies, higher fine root biomass was located upslope, and was negatively correlated with soil moisture content (Enoki et al. 1996; Tateno et al. 2004)—a difference likely due to different seasons. SWC is negatively correlated with total root length during dry seasons. In the present study, data were collected during the rainy season, explaining why the roots were distributed more in areas with higher SWS. In addition, the jujube trees did not significantly affect the spatial variability of SWS in the terrace land. The CV values of SWS in the present terrace land was similar to that of cropland in the study of Liu and Shao (2014), who found that the CV values of SWS in cropland were weaker than those in fallow land, shrubland and grassland in different soil layers. The result was similar to the findings of Cassel et al. (2000) and Martinez et al. (2013), who reported that the temporal variability of soil water was higher when evaporation and transpiration were combined than when they were considered separately.

The clay and silt contents did not have a significant effect on the temporal stability of SWS. However, there was a significant negative correlation between the mean SWS and sand content ($p < 0.05$). This result was similar to other findings (Vachaud et al. 1985; da Silva et al. 2001; Biswas and Si 2011; Gao and Shao 2012a; Manns et al. 2015), which emphasized the importance of soil texture on

the temporal stability characteristics of SWC. Soil porosity affects the SWC distribution along the slope and a soil profile texture with higher sand content may result in both high plant evapotranspiration and low soil water retention (She et al. 2015). That SOC did not have a significant effect on the temporal stability of SWS was similar to previous studies that reported that SWC was only slightly affected by SOC (Schneider et al. 2008; Gao and Shao 2012a). Moreover, the effect of roots on the temporal stability of SWS has seldom been studied. In the present study, there was no significant relationship between total root length and SWS. A common representative location (i.e., location 9) occurred for the different depths and periods. This was likely because the soil particle size distribution, SOC and total root length all did not show large difference with the average values of the terrace land. Grayson and Western (1998) and Vivoni et al. (2008) also reported that the representative locations of mean soil water content of a catchment should be the locations which capture the average characteristics of that catchment.

Conclusions

The SWS on the terraces was normally distributed and demonstrated moderate spatial variability. The spatial variability decreased with increasing soil depth. The SWS at the three soil depths all showed strong temporal stability in the order of $0-0.6 < 0-1.0 < 0-1.6$ m. Rainfall significantly affected the temporal stability of SWS in the soil depth of 0–0.6 m. The number of representative locations of SWS was not constant. The best representative locations for SWS were depth and time dependent. However, a common representative location did exist for the different depths and periods. The best representative locations calculated for a short period resulted in a larger cumulative absolute error when used to evaluate the mean SWS for a long period. Moreover, mean SWS generally increased from the upper to lower slope. The temporal stability of SWS was not significantly affected by rainfall but showed a significant negative correlation with sand content. The total root length and SOC did not show an obvious correlation with mean SWS. It was feasible to use the representative locations of SWS to represent the mean SWS over a period of time; however, the cumulative absolute error increased with cumulative days.

Acknowledgments This research was supported by the National Natural Science Foundations of China (Nos. 41330858, 41401316 and 41271290), the New Star Foundation on Shaanxi Province Youth Science and Technology (2016KJXX-68) and the Key Laboratory Scientific Research Program Funded by Shaanxi Provincial Education Department (No. 15JS065). In addition, we thank the reviewers for their useful comments and suggestions.

References

- Biswas A, Si BC (2011) Identifying scale specific controls of soil water storage in a hummocky landscape using wavelet coherency. *Geoderma* 165:50–59
- Brocca L, Melone F, Moramarco T, Morbidelli R (2009) Soil moisture 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 moisture and its estimation across scales. *Water Resour Res* 46:1–8
- Cassel DK, Wendroth O, Nielsen DR (2000) Assessing spatial variability in an agricultural experiment station field: opportunities arising from spatial dependence. *Agron J* 92:706–714
- Chaney NW, Roundy JK, Herrera-Estrada JE, Wood EF (2015) High-resolution modeling of the spatial heterogeneity of soil moisture: applications in network design. *Water Resour Res* 51(1):619–638
- Chen HS, Shao MA, Li YY (2008) Soil desiccation in the Loess Plateau of China. *Geoderma* 143:91–100
- Coppola A, Comegna A, Dragonetti G, Lamaddalena N, Kader AM, Comegna V (2011) Average moisture saturation effects on temporal stability of soil water spatial distribution at field scale. *Soil Tillage Res* 114:155–164
- Cosh MH, Jackson TJ, Moran S, Bindlish R (2008) Temporal persistence and stability of surface soil moisture in a semi-arid watershed. *Remote Sens Environ* 112:304–313
- Crave A, Gascuel-Oudoux C (1997) The influence of topography on time and space distribution of soil surface water content. *Hydrol Process* 11(2):203–210
- da Silva AP, Nadler A, Kay BD (2001) Factors contributing to temporal stability in spatial patterns of water content in the tillage zone. *Soil Tillage Res* 58:207–218
- de Souza ER, Montenegro AADA, Montenegro SMG, de Matos JDA (2011) Temporal stability of soil moisture in irrigated carrot crops in Northeast Brazil. *Agric Water Manag* 99:26–32
- Douaik A (2006) Temporal stability of spatial patterns of soil salinity determined from laboratory and field electrolytic conductivity. *Arid Land Res Manag* 20:1–13
- Enoki T, Kawaguchi H, Iwatsubo G (1996) Topographic variation of soil properties and stand structure in a *Pinus thunbergii* plantation. *Ecol Res* 11:299–309
- Famiglietti JS, Ryu D, Berg AA, Rodell M, Jackson TJ (2008) Field observations of soil moisture variability across scales. *Water Resour Res* 44:W01423. doi:10.1029/2006WR005804
- Gao L, Shao MA (2012a) Temporal stability of shallow soil water content for three adjacent transects on a hillslope. *Agric Water Manag* 110:41–54
- Gao L, Shao MA (2012b) Temporal stability of soil water storage in diverse soil layers. *Catena* 95:24–32
- Gao L, Shao MA, Peng XH, She DL (2015) Spatio-temporal variability and temporal stability of water contents distributed within soil profiles at a hillslope scale. *Catena* 132:29–36
- Gómez-Plaza A, Alvarez-Rogel J, Albaladejo J, Castillo VM (2000) Spatial patterns and temporal stability of soil moisture across a range of scales in a semi-arid environment. *Hydrol Process* 14:1261–1277
- Gómez-Plaza A, Martínez-Mena M, Albaladejo J, Castillo VM (2001) Factors regulating spatial distribution of soil water content in small semi-arid catchments. *J Hydrol* 253:1261–1277
- Grayson RB, Western AW (1998) Towards areal estimation of soil water content from point measurements: time and space stability of mean response. *J Hydrol* 207:68–82
- Guber AK, Gish TJ, Pachepsky YA, van Genuchten MT, Daughtry CST, Nicholson TJ, Cady RE (2008) Temporal stability in soil

- water content patterns across agricultural fields. *Catena* 73(1):125–133
- Hu W, Shao MA, Reichardt K (2010) Using a new criterion to identify sites for mean soil water storage evaluation. *Soil Sci Soc Am J* 74:762–773
- Hu W, Shao M, Han F, Reichardt K (2011) Spatio-temporal variability behavior of land surface soil water content in shrub- and grass-land. *Geoderma* 162(3–4):260–272
- Jacobs JM, Mohanty BP, Hsu EC, Miller D (2004) SMEX02: field scale variability time stability and similarity of soil moisture. *Remote Sens Environ* 92(4):436–446
- Ji JN, Kokutse N, Genet M, Fourcaud T, Zhang ZQ (2012) Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (*Robinia pseudoacacia*) and Arborvitae (*Platycladus orientalis*) stands on the Loess Plateau, China. *Catena* 92:139–154
- Josa R, Jorba M, Vallejo VR (2012) Opencast mine restoration in a Mediterranean semi-arid environment: failure of some common practices. *Ecol Eng* 42:183–191
- Kachanoski R, De Jong E (1988) Scale dependence and the temporal persistence of spatial patterns of soil water storage. *Water Resour Res* 24(1):85–91
- Kong X, Dorling S, Smith R (2011) Soil moisture modeling and validation at an agricultural site in Norfolk using the Met Office surface exchange scheme (MOSES). *Meteorol Appl* 18:18–27
- Li DF, Shao MA (2014) Temporal stability analysis for estimating spatial mean soil water storage and deep percolation in irrigated maize crops. *Agric Water Manag* 144:140–149
- Liu BX, Shao MA (2014) Estimation of soil water storage using temporal stability in four land uses over 10 years on the Loess Plateau, China. *J Hydrol* 517:974–984
- Liu BX, Shao MA (2015) Modeling soil–water dynamics and soil–water carrying capacity for vegetation on the Loess Plateau, China. *Agric Water Manag* 159:176–184
- Magagi RD, Kerr YH (2001) Estimating surface soil moisture and soil roughness over semiarid areas from the use of the copolarization ratio. *Remote Sens Environ* 75:432–445
- Manns HR, Berg AA, Colliander A (2015) Soil organic carbon as a factor in passive microwave retrievals of soil water content over agricultural croplands. *J Hydrol* 528:643–651
- Martinez G, Pachepsky YA, Vereecken H, Hardelauf H, Herbst M, Vanderlinden K (2013) Modeling local control effects on temporal stability of soil water content. *J Hydrol* 481:106–118
- Martínez-Fernández J, Ceballos A (2003) Temporal stability of soil moisture in a large-field experiment in Spain. *Soil Sci Soc Am J* 67:1647–1656
- Martínez-Fernández J, Ceballos A (2005) Mean soil moisture estimation using temporal stability analysis. *J Hydrol* 312:28–38
- Nielsen D, Bouma J (1985) Soil spatial variability. Pudoc, Wageningen
- Nielsen D, Cassel D, Wendroth O (2000) Assessing spatial variability in an agricultural experiment station field, opportunities arising from spatial dependence. *Agron J* 92(4):706–714
- Penna D, Brocca L, Borga M, Dalla Fontana G (2013) Soil moisture temporal stability at different depths on two alpine hillslopes during wet and dry periods. *J Hydrol* 477:55–71
- Rivera D, Lillo M, Granda S (2014) Representative locations from time series of soil water content using time stability and wavelet analysis. *Environ Monit Assess* 186(12):9075–9087
- Santos WJR, Silva BM, Oliveira GC, Volpato MML, Lima JM, Curi N, Marques JJ (2014) Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale. *Geoderma* 221–222:91–95
- Schneider K, Huisman JA, Breuer L, Zhao Y, Frede HG (2008) Temporal stability of soil moisture in various semi-arid steppe ecosystems and its application in remote sensing. *J Hydrol* 359:16–29
- She D, Zhang W, Hopmans JW, Carlos TL (2015) Area representative soil water content estimations from limited measurements at time-stable locations or depths. *J Hydrol*. doi:10.1016/j.jhydrol.2015.10.016
- Silva BM (2012) Dinâmica espaço-temporal da água no solo cultivado com cafeeiro nas condições climáticas do Alto São Francisco (MG). Master dissertation, Federal University of Lavras, 78 pp
- Tateno R, Hishi T, Takeda H (2004) Above- and belowground biomass and net primary production in a cool-temperate deciduous forest in relation to topographical changes in soil nitrogen. *For Ecol Manage* 193:297–306
- Vachaud G, de Silans AP, Balabanis P, Vauclin M (1985) Temporal stability of spatially measured soil water probability density function. *Soil Sci Soc Am J* 49:822–828
- Vanderlinden K, Vereecken H, Hardelauf H, Herbs M, Martínez G, Cosh MH, Pachepsky YA (2012) Temporal stability of soil water contents: a review of data and analyses. *Vadose Zone J*. doi:10.2136/vzj2011.0178
- Vivoni ER, Gebremichael M, Watts CJ, Bindlish R, Jackson TJ (2008) Comparison of ground-based and remotely-sensed surface soil moisture estimates over complex terrain during SMEX04. *Remote Sens Environ* 112:314–325
- Wang X, Xie H, Guan H, Zhou X (2007) Different responses of MODIS-derived NDVI to root-zone soilmoisture in semi-arid and humid regions. *J Hydrol* 340:12–24
- Wang YQ, Hu W, Zhu YJ, Shao MA, Xiao S, Zhang CC (2015) Vertical distribution and temporal stability of soil water in 21-m profiles under different land uses on the Loess Plateau in China. *J Hydrol* 527:543–554
- Xu GC, Lu KX, Li ZB, Li P, Liu HB, Cheng SD, Ren ZP (2015) Temporal stability and periodicity of groundwater electrical conductivity in Luohuiqu Irrigation District, China. *Clean Soil Air Water* 43(7):995–1001
- Zhao Y, Peth S, Wang XY, Lin H, Hom R (2010) Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. *Hydrol Process* 24(18):2507–2519
- Zhu Q, Lin H (2011) Influences of soil, terrain, and crop growth on soil moisture variation from transect to farm scales. *Geoderma* 163(1–2):45–54