Environmental Earth Sciences (2020) 79:173
https://doi.org/10.1007/s12665-020-08921-8

THEMATIC ISSUE

Temporal stability of soil water content on slope during the rainy season in gully regulation watershed

Jianye Ma[1,2,3,4] · Jichang Han[1,2,3,4] · Yang Zhang[1,2,3,4] · Qiguang Dong[1,2,3,4] · Na Lei[1,2,3,4] · Zhe Liu[1,2,3,4] · Yichun Du[1,2,3,4]

Received: 26 April 2019 / Accepted: 26 March 2020 / Published online: 6 April 2020

Abstract

To increase reserve farmland resources, ensure food security, and to improve the ecological environment, large-scale gully regulation projects in Yan'an area of the Loess Plateau have been undertaken in China since 2013. Understanding the spatial and temporal distribution characteristics of slope soil moisture during the rainy season is, therefore, important for vegetation selection used in restoration measures in this area. The temporal stability of soil water content in the upper 100 cm soil depth in a gully regulation watershed was examined using six measurements taken during the rainy season (May–November 2016). Temporal stability analysis of the soil water content was undertaken using Spearman's rank correlation coefficient and the relative difference method. Results showed that soil water content in the 0–50 cm and 0–100 cm soil depths demonstrated moderate temporal and spatial variability, and soil water content variability gradually decreased with increasing soil depth. Soil water content in both depths had strong temporal stability, having a positive correlation with soil depth. Furthermore, temporal stability may decrease with increasing soil water content ($p < 0.05$). The number and position of representative locations were not constant, which varies with the soil depth and the estimation method. Five methods (mean relative difference, minimum relative difference standard equilibrium, temporal stability index, mean absolute deviation and root mean square error) can be used to determine the representative location of temporal stability. However, the prediction accuracy of the soil water content at representative locations obtained using the different methods for mean slope water content differed. Comparatively, the mean absolute deviation method had a higher accuracy, followed by the minimum relative difference standard equilibrium method. Results indicate that the prediction accuracy of five methods increased with soil depth.

Keywords Soil water content · Gully regulation · Temporal stability · Soil depth

This article is a part of Topical Collection in Environmental Earth Sciences on Water Sustainability: A Spectrum of Innovative Technology and Remediation Methods, edited by Dr. Derek Kim, Dr. Kwang-Ho Choo, and Dr. Jeonghwan Kim.

✉ Jichang Han
hanjichang126@126.com

Jianye Ma
majianye126@126.com

1 Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an 710075, China

2 Key Laboratory of Degraded and Unused Land Consolidation Engineering, The Ministry of Natural Resources, Xi'an 710075, China

3 Shaanxi Provincial Land Consolidation Engineering Technology Research Center, Xi'an 710075, China

4 Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xi'an 710075, China

Introduction

As an important variable of regional eco-hydrology, soil moisture plays an important role in surface runoff, soil erosion and solute transport processes, especially in processes such as rainfall infiltration, evaporation, runoff and sediment production, and hydrothermal migration (Zhang et al. 2013; Vereecken et al. 2015). The Loess Plateau in China experiences an arid and semi-arid climate, and the lack of precipitation results in soil moisture becoming a restrictive factor for regional vegetation restoration. Due to the influence of climate, soil texture, topography, vegetation, and other factors, soil moisture exhibits large spatial variability, making it difficult to accurately estimate (Chaney et al. 2015; Wang et al. 2015). To obtain sufficient soil moisture information, continuous monitoring of a large number of points is required, which is both costly and time consuming (Lei and Shao 2012). Although soil moisture exhibits certain temporal and spatial variability characteristics, Vachaud et al. (1985) identified that its spatial distribution pattern is relatively stable and proposed the concept of temporal stability (Cheng et al. 2017; Xu et al. 2016). Temporal stability is an important characteristic of soil moisture, defined as the temporal persistence of the spatial model of soil water content. Strong stability over time indicates that the spatial distribution pattern of soil moisture is more similar (Zhu et al. 2017). Recently, identifying suitable locations to estimate the status of soil moisture for an area has become one of the most important applications of the concept of temporal stability (Lei and Shao 2012). By reducing the number of measuring locations, studies on soil moisture characteristics over a large area can be undertaken using a lower workload and less financial input, while also ensuring recorded data have high precision. Currently, the temporal stability of soil moisture has been widely examined and successfully applied in different ecosystems, on different research scales and for different soil depths (Bai and Shao 2011; Brocca et al. 2010; Lei and Shao 2012). For example, Jia and Shao (2013) studied the temporal stability variation of soil moisture under four vegetation cover modes in the Loess Plateau; and Martinez et al. (2014) explored the effects of different climate and soil texture on the temporal stability of soil moisture. A lot of work has been done on the temporal stability of soil moisture in the Loess Plateau. However, the Chinese government initiated a large-scale gully regulation project in the Yan'an area of the Loess Plateau in 2013, a total of 14,000 hectares of gully regulation area had been completed in this area by the end of 2015 (Liu and Li 2014; Liu et al. 2015). Engineering practices used in excavation and filling during the gully regulation project changed the topography and vegetation cover of some areas, having a significant impact on the hydrological cycle of the project implementation area and the spatial and temporal distribution of water resources (Sun et al. 2017; Yin et al. 2016). Furthermore, the spatial and temporal distribution characteristics of soil moisture in slopes were affected. Therefore, studies on the temporal stability of soil moisture during the rainy season in a slope under gully regulation conditions are important when examining the restoration of slope vegetation in a gully regulation watershed. Currently, however, few studies have focused on the temporal stability of soil moisture during the rainy season under such engineering conditions.

To further examine the spatial characteristics and temporal stability of soil moisture on a slope during the rainy season, it is important to understand the eco-hydrological effect of gully regulation processes. Currently, little work has been undertaken examining the temporal stability of soil water content. In this study, Spearman's rank correlation coefficient and the relative difference method were used to analyze the temporal stability of soil water content at 15 locations on typical slopes in a gully regulation watershed. Five methods were used to estimate the representative locations with temporal stability, and the prediction accuracy of these methods was evaluated using standard statistical methods. The main objectives of this study were to (1) analyze the temporal stability of soil water content in different soil depths on typical slopes of a gully regulation watershed during the rainy season, (2) identify the representative location of the temporal stability of soil water content, and (3) evaluate the accuracy of different prediction methods and identify the best method for selecting representative temporal stability locations suitable for this area.

Materials and methods

Description of the study area

The study area, located in the Jiulongquangou watershed (36° 11′ 50″–36° 19′ 08″ N, 109° 34′ 26″–109° 39′ 36″ E), 66.80 km southeast of Yan'an City, Shaanxi Province, China (Fig. 1), was in a hilly and gully area characterized by severe erosion. The watershed has a continental monsoon season climate with an area of 69.35 km^2. Mean annual precipitation is approximately 576.9 mm, of which more than 60% falls between July and September. Mean annual temperature is 9.15 °C. Soil in this area is classified as loessial soil, mainly consisting of silt. The mean soil grain size distribution from 15 samples were described as follows: clay (< 0.002 mm; 6.5%), silt (0.002–0.05 mm; 78.6%) and sand (> 0.05 mm; 14.9%) (Table 1). A large-scale gully regulation project was undertaken in this watershed (between 2013 and 2015) which changed the characteristics of water storage in some areas. A typical slope, located downstream in the watershed, was selected for this study, having a slope length of 248 m, an altitude range of 1117–1165 m, and a slope angle of 11°. The main vegetation types on this slope were *Festuca elata* and *Ficus microcarpa*. The mean spacing of *F. microcarpa* was 3 m, and the forest age was 10 years. A rectangular test plot with an area of 20,750 m^2 was set on the slope. Along the length of the hillslope, 15 polycarbonate tubes (length 1.2 m and diameter 44 mm) with a steel cutting shoe were vertically installed along three transects, as shown in Fig. 1c. All tubes were installed so that 1 m was underground and 0.2 m was exposed above the ground (Fig. 1e). From May 13th to November 17th, 2016, observation of soil water content in the 0–50 cm and 0–100 cm soil depths was carried out using a time domain reflectometry (TDR) soil moisture measurement system (TRIME-PICO IPH, Germany) with an interval of 30 days. Volumetric soil water content was calculated using the different transmission time of the electromagnetic wave emitted by the bottom of a cylindrical probe in different dielectric constant substances. The velocity of an electromagnetic wave propagation in the

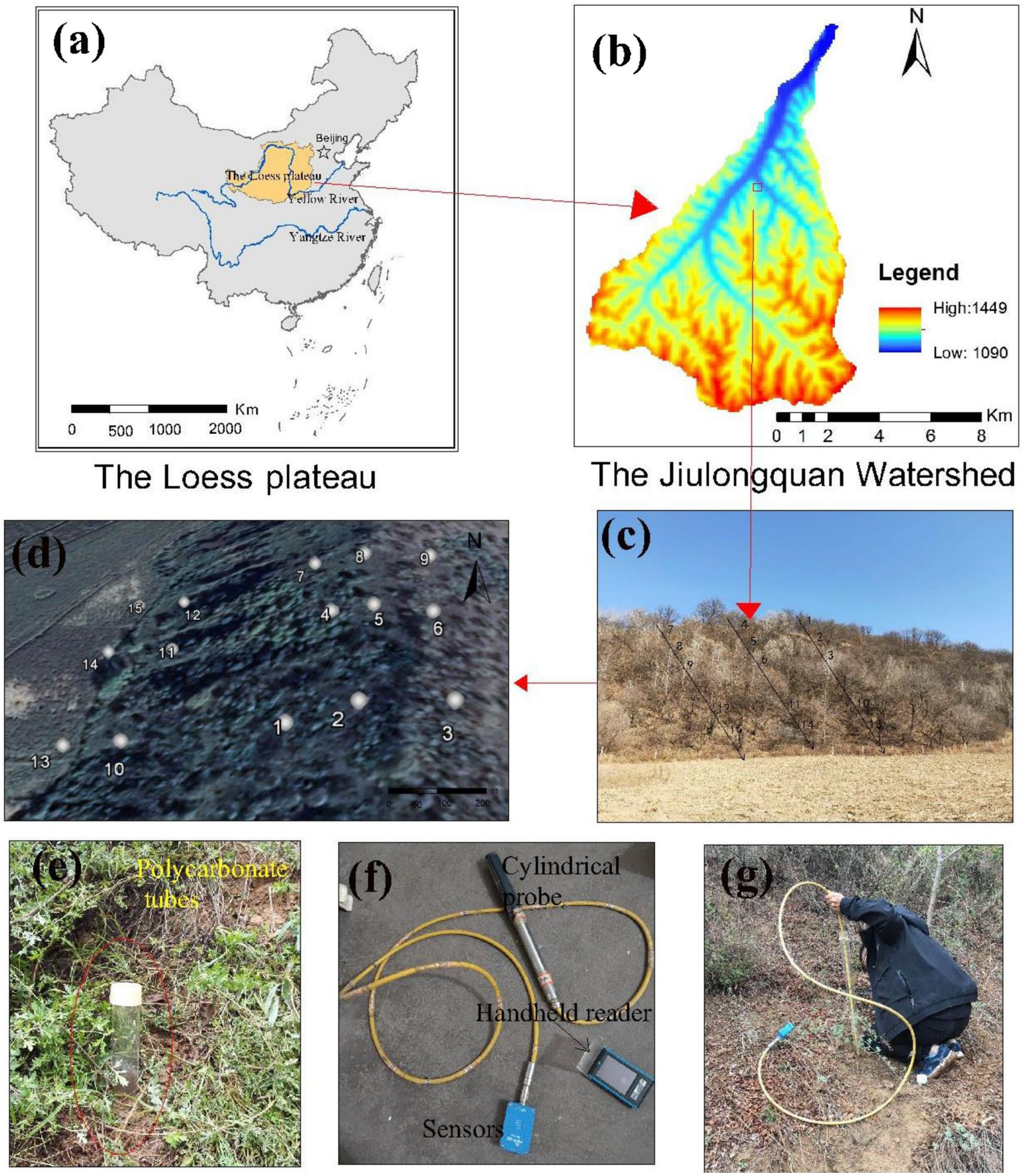

Fig. 1 Location of the study area (**a**, **b**) and the 15 polycarbonate tubes located across the study site (**c**, **d**)

Table 1 Grain size distribution of soil particles

Soil type	Sample number	Grain size distribution (%)		
		Clay (< 0.002 mm)	Silt (0.002 ~ 0.05 mm)	Sand (> 0.05 mm)
Loessial soil	15	6.5	78.6	14.9

medium is inversely proportional to the square root of the dielectric constant of the medium, which can be expressed as

$$C = \frac{C_0}{\sqrt{\varepsilon_{\mathrm{r}} \times \mu_{\mathrm{r}}}}, \tag{1}$$

where C is the velocity of the electromagnetic wave propagation in the medium, C_0 is the velocity of the electromagnetic wave propagation in a vacuum (3 s v^{8}m/s), ε_{r} is the dielectric constant in a medium, and μ_{r} is permeability in a medium. In a nonmagnetic medium, $C = 1$ in the absence of a magnetic medium. The relationship between a dielectric constant and a volumetric water content is (Topp et al. 1980)

$$\varepsilon_{\mathrm{r}} = 3.03 + 9.3\theta_v + 146\theta_v^{\,2} - 76.7\theta_v^{\,3}. \tag{2}$$

During sample measurement, a handheld reader was connected using a Bluetooth connection to sensors before they were inserted into the cylindrical probes (length 20 cm) and located vertically at the bottom of the polycarbonate tube. Volumetric soil water content was calculated from readings taken at intervals of 0.1 m in the polycarbonate tube by raising the cylindrical probe from the base to the top (Fig. 1g). Soil water content in the upper 0–50 cm soil depth was calculated as mean water content of data recorded at 0–10-, 10–20-, 20–30-, 30–40-, 40–50-cm intervals; soil water content of the 0–100-cm soil depth was calculated as the mean water content of 0–50-, 50–60-, 60–70-, 70–80-, 80–90-, 90–100-cm intervals. The distribution of rainfall during the rainy season, accounting for 93% of total annual precipitation is shown in Fig. 2. As variability of precipitation and soil water content in the rainy season is greater, it is important to study the temporal stability of soil moisture during this period.

Data analysis

To describe the distribution of soil water content and its temporal and spatial variability, maximum, minimum, mean, standard deviation and coefficient of variation of soil water content were recorded and calculated six times at 15 locations. The coefficient of variation is the ratio of the standard deviation to the mean. According to the division criteria of Nielsen and Bouma (1985), the coefficient of variation has a weak variability when it is 10% or less, it has a moderate variability when it is between 10 and 100%, and a strong variability when it is more than or equal to 100%.

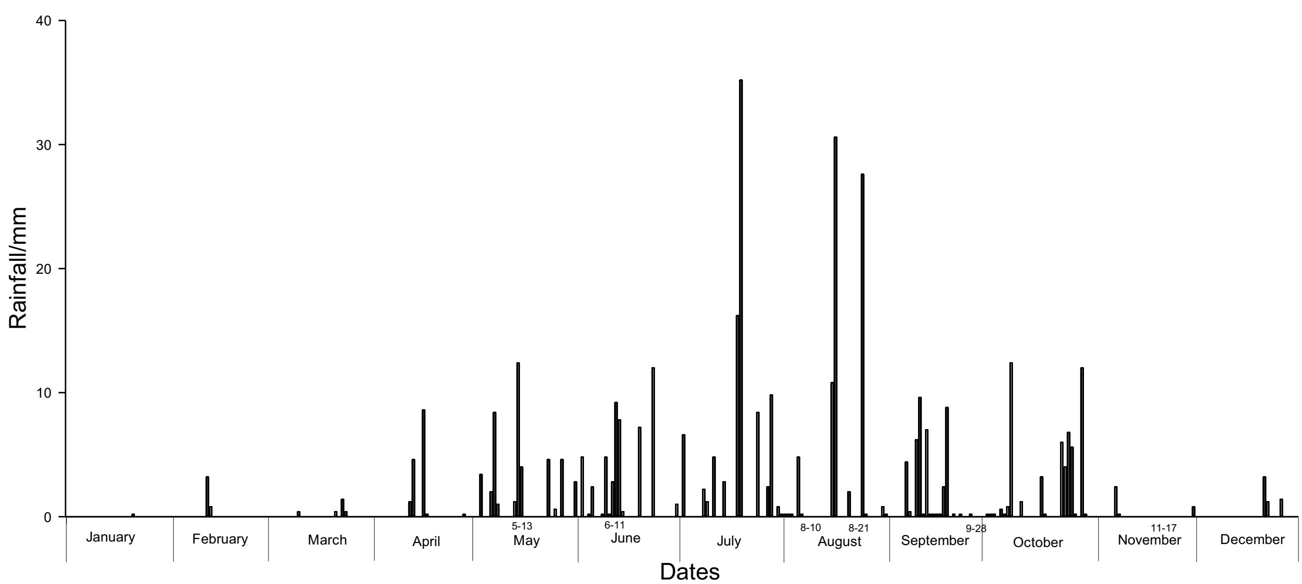

Fig. 2 Rainfall distribution from May–November 2016

Temporal stability

In this study, Spearman's rank correlation coefficient and the relative difference method were adopted to examine the temporal stability of soil water content. Spearman's rank correlation coefficient method reflects the spatial similarity of observed locations at different observation times (Vachaud et al. 1985). A rank correlation coefficient r_s value close to 1 indicates that the spatial distribution pattern of the soil water content is more similar over time. That is, the temporal stability of soil water content is stronger. The calculation formula of r_s is

$$r_s = 1 - \frac{6\sum_{i=1}^{N}(R_{ij} - R_{ij'})}{N(N^2 - 1)}, \tag{3}$$

where R_{ij} is the rank of the observed value of the soil water content at location i on day j; $R_{ij'}$ is the rank of the same value at the same location, but on day j′; and N is the number of observation locations ($n=15$).

The relative difference method is based on the theory of relative difference. According to Vachaud et al. (1985), equations for calculating the relative difference value of soil water content at observation locations i at observation time j are

$$\delta_{ij} = \frac{\theta_{ij} - \bar{\theta}_j}{\bar{\theta}_j}, \tag{4}$$

$$\bar{\theta}_j = \frac{1}{N}\sum_{i=1}^{N}\theta_{ij}, \tag{5}$$

where θ_{ij} is the observed value of soil water content at location i on day j, and θ_j is the mean value of soil water content at all locations on day j. Therefore, the mean relative difference (θ_j) and the relative difference standard deviation $\sigma(\delta_i)$ at the measuring location i can be calculated as

$$\bar{\delta}_i = \frac{1}{M}\sum_{I=1}^{M}\delta_{ij}, \tag{6}$$

$$\sigma(\delta_i) = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(\delta_{ij} - \bar{\delta}_i)^2}, \tag{7}$$

where M is the number of observations ($n=6$).

The mean relative difference is generally used to determine the proximity of soil water content at the measured location to the mean soil water content at the sample site. A relative difference value of the measuring location close to 0 indicates more soil water content can represent the mean soil water content of the sample site. When the relative difference value is greater than or less than 0, the mean soil water content of the sample site is overestimated or underestimated, respectively. The temporal stability of soil water content can also be determined using the relative difference standard deviation. A smaller temporal stability value indicates a stronger temporal stability of the soil water content at the measuring location. When there is a certain measuring location on the slope, the mean relative difference is close to 0, and the standard deviation of the relative difference is very small, then the water content at this location can be used to represent the mean soil water content in the sample site.

A method for determining the representative measuring location of temporal stability

The representative measuring location of the temporal stability of soil water content was determined using the methods of mean relative difference, minimum relative difference standard equilibrium, temporal stability index, mean absolute deviation, and root mean square error. Previous studies by Jacobs et al. (2004) and Zhao et al. (2010) determined the measuring location of temporal stability using the temporal stability index, a composite index of mean relative difference and standard deviation of the relative difference. The equation for this calculation is

$$I_{ts} = \sqrt{\delta_i^2 - \sigma(\delta_i)^2}. \tag{8}$$

The most temporally stable location notably has the lowest I_{ts}. The I_{ts} can also be used to identify representative location for directly estimating the mean soil water content. Generally, the location with the time stability index less than 10% can be considered as the representative location of temporal stability. The location corresponding to the minimum value can be considered as the best representative location of temporal stability.

The minimum relative difference standard equilibrium method considers that the location corresponding to the minimum value can be considered as the best representative location of temporal stability. The equation is used to correct the measured soil water content at the representative measuring location. The equation for this calculation is

$$\bar{\theta}'_{oj} = \frac{\theta_{oij}}{1 + \bar{\theta}_{oi}}, \tag{9}$$

where θ_{oij} is soil water content at the representative measuring location at location i on day j, θ_{oj} is the soil water content after calibration of the representative measuring location, and θ_{oi} is the mean relative difference value of the representative measuring location i for temporal stability.

Hu et al. (2010a) and Lei et al. (2012) proposed the method to determine representative measuring locations of temporal stability using mean absolute deviation (MABE) and root mean square error (RMSE), respectively. For this, MABE and RMSE were calculated for each measuring location, with the minimum value representing the measuring location of temporal stability. Equations for MBE and RMSE are.

$$M_{\mathrm{ABE}i} = \frac{1}{M}\sum_{j=1}^{M}\left|\frac{\delta_{ij} - \bar{\delta}_i}{1 + \bar{\delta}_i}\right| \tag{10}$$

$$R_{\mathrm{MSE}i} = \sqrt{\frac{1}{M}\sum_{j=1}^{M}\left(\frac{\theta_{ij}}{1 + \bar{\delta}_i} - \frac{\theta_{ij}}{1 + \delta_{ij}}\right)}, \tag{11}$$

Smaller values for MABE and RMSE indicate stronger temporal stability of the soil water content. The location corresponding to the minimum value can be considered as the best representative location of temporal stability.

Results and discussion

Temporal and spatial dynamic analyses of soil water content

Results for the temporal variation of rainfall from May to November 2016 are shown in Fig. 2. Results for the temporal variation of soil water content and its corresponding standard deviation and coefficient of variation for the depths of 0–50 cm and 0–100 cm (Fig. 3) indicate that the mean soil water content at two soil depths was 12.70% and 13.00%, respectively. The range of variation was from 2.64 to 25.95%. Although our results indicate that soil water content increased with increasing soil depth, the bilateral t test indicated that there was no significant difference in soil water content between the two soil depths ($p > 0.05$). This result is consistent with the findings of Hu et al. (2010b), who recorded no significant difference in soil water content at depths of 40, 60, and 80 cm in the same watershed. At the same time, the standard deviation of soil water content in both soil depths was below 5%, indicating that the spatial variation of soil water content was small at different measuring times. The mean coefficients of variation were 0.31 and 0.29, respectively, indicating that the soil water content had moderate spatial variability at different measuring times. This result was similar to the spatial variation characteristics of soil water content obtained by Zhang and Shao (2013) in northwestern China. By comparing these results to rainfall, it can be seen that soil water content and rainfall had good synchronization, i.e., high levels of rainfall in July and August coincided with the maximum records for soil water content. In September, both rainfall and water content decreased.

Soil water content mean value, standard deviation, and variation coefficient recorded during six measurement periods in the two soil depths are shown in Table 2. Mean standard deviation for the two depths of 0–50 cm and 0–100 cm was 4.01% and 3.77%, respectively, and the distribution range was 3.05–4.88% and 2.91–4.57%, respectively. The mean values of the coefficient of variation were 0.32 and 0.29, and the distribution range was 0.27–0.38 and 0.25–0.34, respectively. The standard deviation of soil water content was small, and the variation coefficient was greater than 10%. Our results indicate that the soil water content of the two soil depths recorded moderate variability over time. In addition, spatially standard deviations of the standard deviation and variation coefficient over time for soil water

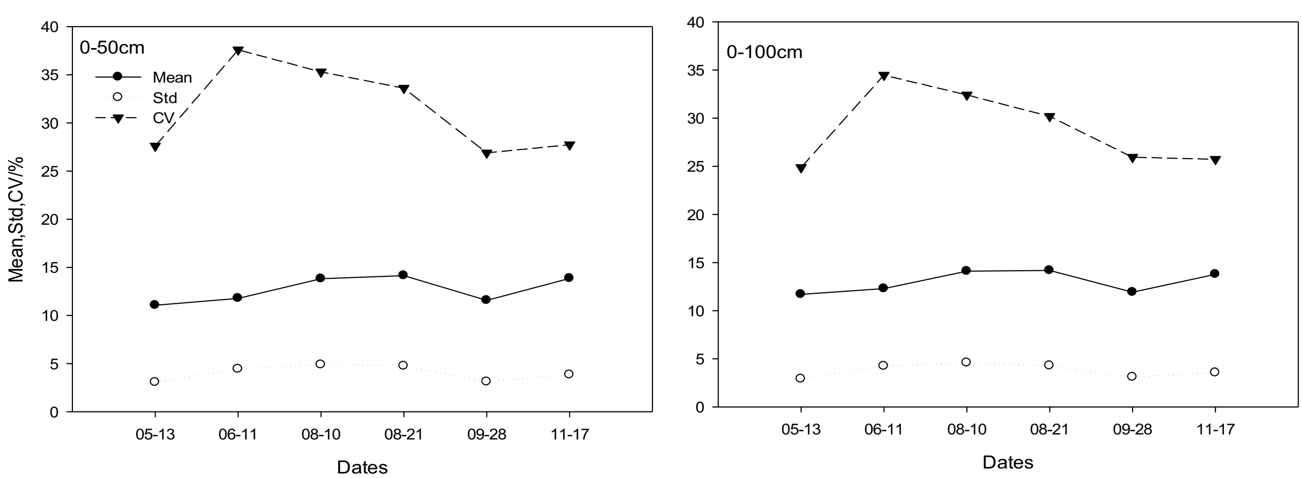

Fig. 3 Mean value, standard deviation and variation coefficient of spatial average soil water content

Table 2 Spatial statistical characteristics of mean value, standard deviation, and variation coefficient of soil moisture content over time

Soil depth (cm)	Variable	Min	Max	Mean	STD	CV
0–50	Mean (%)	11.06	14.14	12.70	1.38	0.11
	STD (%)	3.05	4.88	4.01	0.80	0.20
	CV	0.27	0.38	0.32	0.05	0.14
0–100	Mean (%)	11.69	14.19	13.00	1.15	0.09
	STD (%)	2.91	4.57	3.77	0.69	0.18
	CV	0.25	0.34	0.29	0.04	0.13

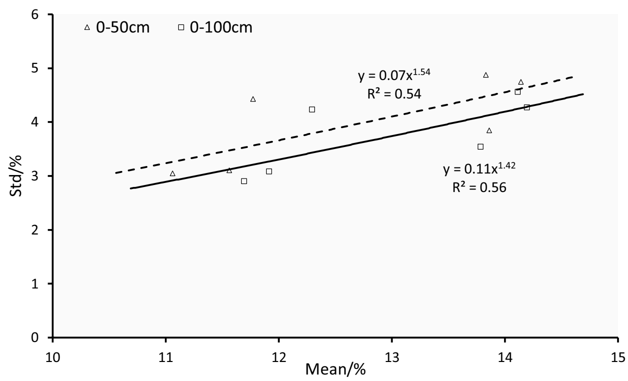

Fig. 4 The relationship between mean soil water content and corresponding standard deviation

content in the 0–50 cm soil depth were 0.80% and 0.05, and the coefficients of variation were 0.50 and 0.14, respectively. The spatially standard deviations of standard deviation and variation coefficient over time for soil water content in the 0–100 cm soil depth were 0.69% and 0.04, and the coefficients of variation were 0.18 and 0.13, respectively. These results indicate that temporal variability of soil water content had no significant spatial change at the 15 locations, and that spatial variability of soil water content over time in the soil depth of 0–100 cm was weaker than that in the depth of 0–50 cm. This result was consistent with the findings of Zhu et al. (2017).

Mean soil water content had a good correlation with standard deviation at $p < 0.05$ (Fig. 4), indicating that the variability of soil water content was higher when soil water content was larger. Penna et al. (2009) recorded that when the soil water content was 23–29%, the variability of soil water content reached a maximum. However, when soil water content was lower than 20%, soil was in an unsaturated state, and soil water was difficult to move under the action of matrix potential. Therefore, the variability of soil water content increases with its availability. The R^2 of the mean value and standard deviation of soil water content in the soil depths of 0–50 cm and 0–100 cm was 0.54 and 0.56, respectively. Compared with the conclusions of Zhu et al. (2015), our results are relatively low. One reason for our results may be because the soil water content variability of the two soil depths not only has a good correlation with the soil water content but is also affected by external factors such as climate, vegetation, evaporation, and vegetation. Differences in soil water status, study scales, and sampling strategies between the studies may also present differences in results (Brocca et al. 2007). At the same time, soil water content in the upper soil layers is more susceptible to external factors, reflected by the R^2 value in the 0–50 cm soil depth being lower than that recorded in the 0–100 cm soil depth. Results by Lei and Shao (2012) also recorded R^2 of the fitting relationship between soil water content and standard deviation in the 0–100 cm soil depth to be low (0.33).

Temporal variation of the spatial pattern of soil water content

The spatial pattern of soil water content was analyzed using the Spearman's rank correlation coefficient method (Table 3). Results indicate that soil water content in the 0–50 cm and 0–100 cm soil depths all had good correlation during the six measuring periods ($p < 0.01$). This result indicates that soil water content had strong temporal stability in both soil depths. Mean Spearman's rank correlation coefficients of soil water content in the two soil depths were 0.714 and 0.688, respectively, and variation ranged from 0.579–0.895 and 0.525–0.852, respectively. The temporal stability of soil water content in the 0–50 cm soil depth was stronger than that in the 0–100 cm soil depth. These results differed from the majority of previous studies, whereby the temporal stability of soil water content increased with soil depth (Hu et al. 2010b; Huang et al. 2018; Xu et al. 2016). Analysis of correlations between soil water content on set days (e.g., June 11 and other monitoring periods) was weak ($p > 0.05$). Regardless of the water content on June 11, the mean Spearman's rank correlation coefficients were 0.750 and 0.753 for the 0–50 cm and 50–100 cm depths, respectively. This result indicated a stronger temporal stability for the underlying soil water content. Lei and Shao (2012) showed that differences in soil water content stability in different soil depths were mainly due to differences in water absorption, the utilization of plant roots, and the water retention capacity of the soil structure. Loess in the Loess Plateau is homogeneous, and the soil structure is less different, resulting in a low difference in the stability of its water content.

Stability analysis of soil water content

Relative difference analysis

Relative difference standard deviation and Spearman's rank correlation coefficient are two different concepts related to temporal stability. The relative difference standard deviation is used to characterize the temporal variability of certain measuring locations, and Spearman's rank correlation

Table 3 Spearman's rank correlation coefficients corresponding to soil water content data measured on different periods

Soil depth (cm)	Sampling date	05–13	06–11	08–10	08–21	09–28	11–17
0–50	05–13	1	0.598**	0.730**	0.675**	0.671**	0.719**
	06–11		1	0.599**	0.579**	0.616**	0.660**
	08–10			1	0.847**	0.734**	0.895**
	08–21				1	0.719**	0.869**
	09–28					1	0.799**
	11–17						1
0–100	05–13	1	0.637**	0.708**	0.686**	0.613**	0.658**
	06–11		1	0.547**	0.565**	0.595**	0.525**
	08–10			1	0.833**	0.741**	0.852**
	08–21				1	0.747**	0.836**
	09–28					1	0.780**
	11–17						1

*Correlation is significant at the 0.05 level

**Correlation is significant at the 0.01 level

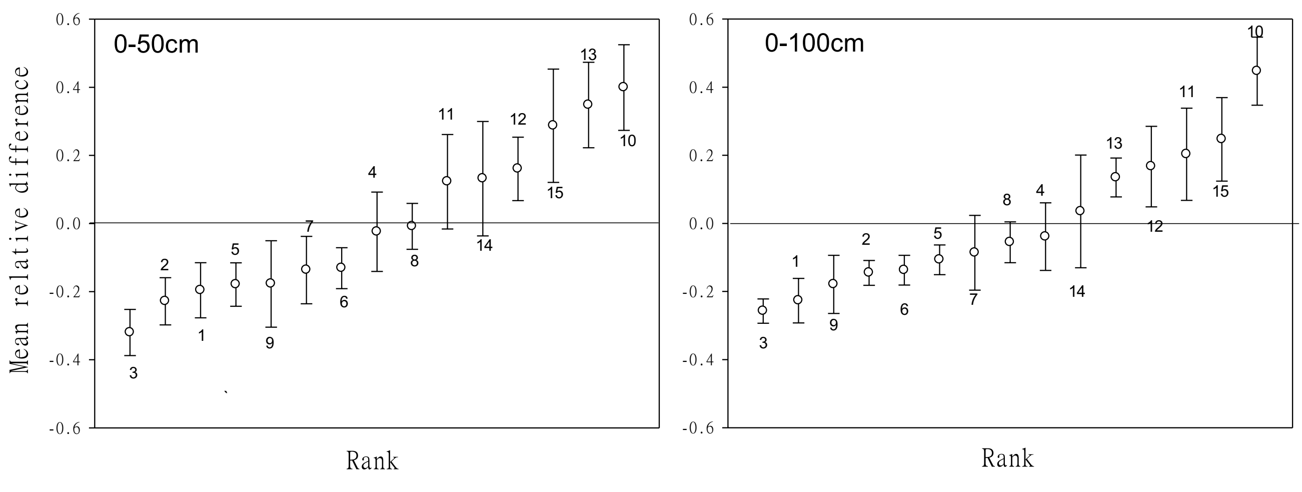

Fig. 5 Mean relative difference of soil water content at different soil depths. Vertical bars represent ± standard deviation

Table 4 Mean relative difference value and its corresponding standard deviation

Soil depth (cm)	Parameter	Min	Max	Range	Mean	STD
0–50	Mean relative difference	− 0.32	0.40	0.72	0.00	0.23
	Standard deviation of relative difference	0.06	0.47	0.41	0.12	0.10
0–100	Mean relative difference	− 0.26	0.45	0.71	0.00	0.20
	Standard deviation of relative difference	0.04	0.47	0.43	0.11	0.11

coefficient method is used to describe the similarity of spatial distribution features in different periods. The temporal stability of soil water content at each measuring location was analyzed using the relative difference method. The mean relative difference value of soil water content (from small to large) and its corresponding relative difference standard deviation are shown in Fig. 5; results in Table 4 indicate the statistical characteristic values of the two soil depths. Soil water content mean relative difference values between the two soil depths of 0–50 cm and 0–100 cm were −0.32 ~ 0.40 and −0.26 ~ 0.45, having a range of 0.72 and 0.70, respectively. The absolute value of the minimum value of the relative difference was recorded to be lower than the maximum value. This result was similar to the conclusions of Hu et al. (2010a) and Cosh et al. (2008). At the same time, because the loess of the Loess Plateau has a vertical homogeneous structure, the relative difference values of the different soil depths were similar (Lei and Shao, 2012). The relative difference standard deviations of soil water content were 0.06–0.47 and 0.04–0.47, with mean values of 0.12 and 0.11, respectively. As soil depth increased, the relative difference standard deviation gradually decreased, indicating that water content of the 0–100 cm soil depth had strong temporal stability. However, the difference was not obvious ($p > 0.05$). These findings are similar to those recorded using the Spearman's rank correlation coefficient method. As soil in the 0–50 cm depth was more susceptible to climate, vegetation, and other factors, it, therefore, has weak stability. However, as the 0–100 cm soil depth is also affected by these factors to some extent, a small difference in the standard deviation between the two soil depths was recorded.

At the same time, we found that the variation law of soil water content stability with soil depth was similar to that of soil water content: soil water content and its temporal stability increased with increasing soil depth, but variability of both decreased. A significant positive linear correlation may also exist between temporal stability and the mean soil water content ($p < 0.05$, Pearson test), indicating that the temporal stability of soil water content at the measuring location was higher during a drought period. However, as the R^2 values of the fitting relationship between water content and relative difference in the soil depths of 0–50 cm and 0–100 cm were 0.70 and 0.65, respectively (Fig. 6), low water content may not necessarily indicate higher temporal stability. Accuracy for these results obtained by this method was lower than the conclusions obtained using the method of relative difference score deviation (Lei and Shao, 2012). This result was similar to previous findings indicating that soil water content had more temporal stability in locations with a low soil water content (Cosh et al. 2008; Jabobs et al. 2004).

Identification of representative locations of temporal stability

One of the most important applications of temporal stability of soil water content is to estimate mean soil water content using soil water content values from representative measuring locations. In this study, the representative measuring locations of temporal stability were determined using the methods of mean relative difference, minimum relative difference standard equilibrium, temporal stability index, mean absolute deviation and root mean square error.

The mean relative difference method is generally used to determine the closeness of the soil water content of measuring locations to the mean water content of the sample site. If the value is close to 0 and the relative difference standard deviation is small, then the soil water content of

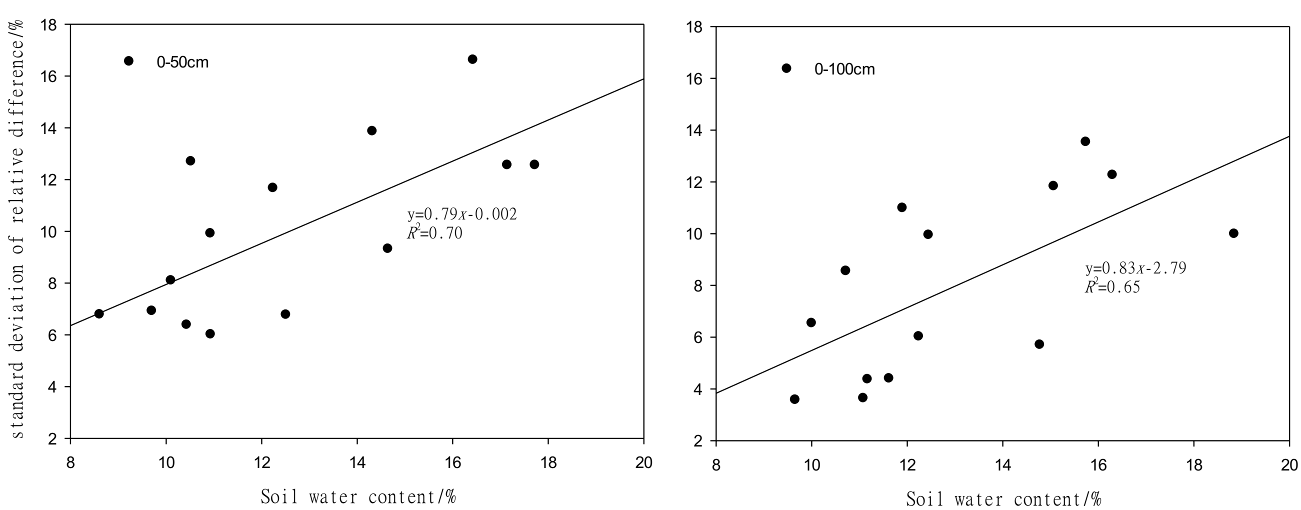

Fig. 6 The linear relationship between the standard deviation of relative difference and the soil water content for the two soil depths

these locations can represent the mean soil water content in the sample site (Vachaud et al. 1985). As shown in Fig. 5, the representative measuring locations of the 0–50 cm soil depth were measuring location nos. 4 and 8, which had a mean relative difference value close to 0 and an error range of −5% to 5%. The relative difference standard deviation of the two representative measuring locations was 0.12 and 0.07, respectively. As measuring location no. 8 had a relatively smaller difference standard deviation, this site was deemed the best representative measuring location. Mean relative difference and relative difference standard deviation of measuring location no. 4 in the 0–100 cm layer were 0.039% and 0.10, respectively, indicating that this location was the best representative measuring location for this soil depth. The temporal stability index is a synthesis indicator of mean relative difference and relative difference standard deviation. A smaller temporal stability index indicates a stronger soil water content temporal stability. Results for the order diagram of temporal stability index (ranging from small to large; Fig. 7) indicate that only measuring location no. 8 had a temporal stability index of less than 10% for each soil depth (0.07 and 0.08, respectively). The order of the mean absolute deviation, from small to large, indicated that the minimum value of mean absolute deviation for the 0–50 cm soil depth was at measuring location no. 12 (0.05; Fig. 8). The minimum value of the mean absolute deviation for the 0–100 cm soil depth was at measuring location no. 3 (0.03); in this soil depth, seven measuring locations recorded values less than 5%. The order of the root mean square error, from small to large, recorded a minimum value in the 0–50 cm soil depth at measuring location no. 6 (0.79; Fig. 9); the minimum value recorded in the 0–100 cm soil depth was at measuring location no. 2 (0.50). Measuring location no. 6 recorded the minimum value for the minimum relative difference standard equilibrium method (0.06) in the

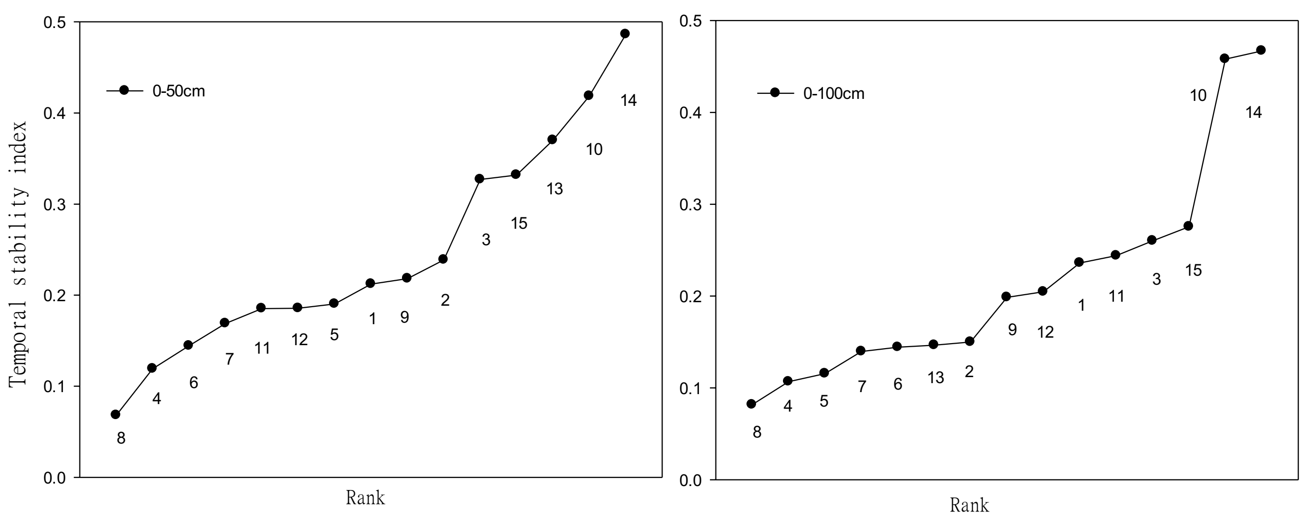

Fig. 7 Ranked temporal stability index of soil water content

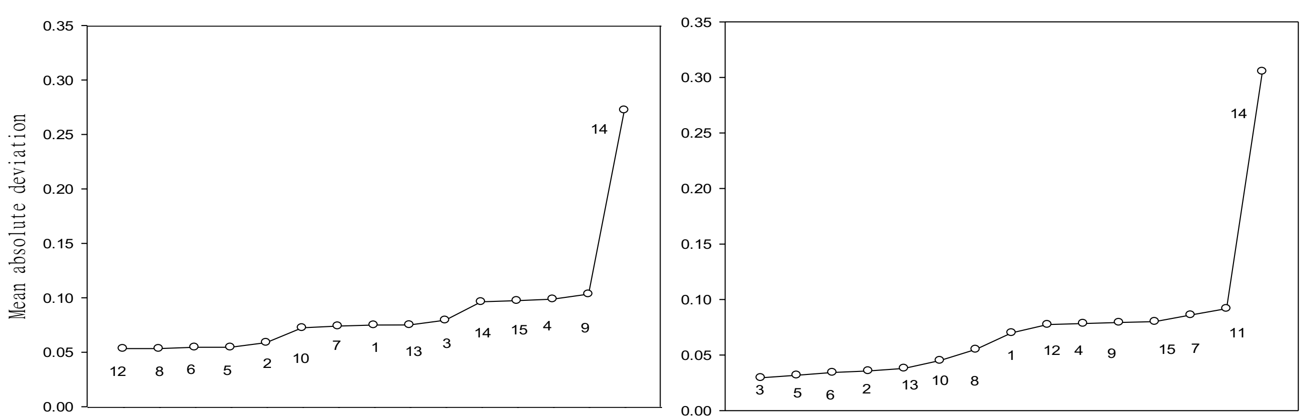

Fig. 8 Ranked mean absolute deviation of soil water content

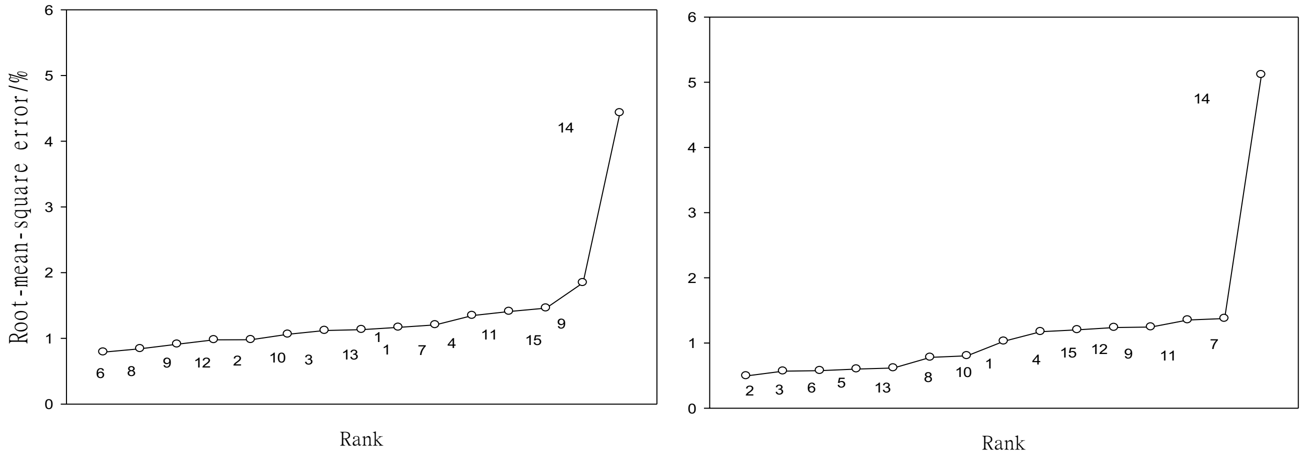

Fig. 9 Ranked root-mean-square error of soil water content

0–50 cm soil depth; measuring location no. 3 recorded the minimum value (0.04) for the 0–100 cm soil depth.

Results from our analysis indicate that representative locations of temporal stability in the different soil depths and at different periods differ. Due to factors such as soil biology, soil erosion and vegetation growth years, multiple representative measuring locations may be evident (Zhao et al. 2010). Therefore, representative measuring locations of the temporal stability of soil water content in the 0–50 cm soil depth were nos. 8, 12, and 6, and the representative measuring locations for the 0–100 cm soil depth were nos. 4, 8, 2, and 3.

The selection of the best representative measuring locations and optimal estimation method for the temporal stability of soil water content

Statistical values of the accuracy parameters of soil water content estimated using the five methods and the mean soil water content of the sample sites (Table 5) were used to determine the best representative measuring locations of temporal stability. The root-mean-square error (RMSE), the Nash coefficient (NSE), the mean absolute error (MAE), and the linear regression coefficient (R^2) were used to estimate the error between the mean soil water content of the sample site and the soil water content of the representative measuring locations corrected using Eq. (8). In the 0–50 cm soil depth, MAE of measuring location nos. 6, 8, and 12 was 0.70, and the variation was small. For these three measurement locations, the NSE value had the order of 6 (0.58) > 8 (0.53) > 12 (0.38), RMSE had the order of 12 (0.99) > 8 (0.86) > 6 (0.81), and R^2 had the order of 6 (0.71) > 8 (0.54) > 12 (0.48). RMSE reflects the extent to which measured data deviates from the true value, and a smaller RMSE value indicates a higher accuracy. NSE is generally used to evaluate the quality of a model, and an NSE value close to 1 indicates good model quality, and that the model has high credibility. MAE is

Table 5 Validation of estimation accuracy of the different methods

Soil depth (cm)	Method	Representative location	Fitting relation	R^2	RMSE	NSE	MAE
0–50	Mean relative difference method	No. 8	$y = 0.90x + 1.40$	0.74	0.86	0.53	0.70
	Minimum relative difference standard equilibrium method	No. 6	$y = 1.67\,x + 8.34$	0.84	0.81	0.58	0.71
	Temporal stability index method	No. 8	$y = 0.90x + 1.40$	0.74	0.86	0.53	0.70
	Mean absolute deviation method	No. 12	$y = 0.69x + 3.69$	0.69	0.99	0.38	0.70
	Root mean square error method	No. 6	$y = 1.67\,x + 8.34$	0.84	0.81	0.58	0.71
0–100	Mean relative difference method	No. 4	$y = 0.34\,x + 8.61$	0.31	1.21	-0.32	0.95
	Minimum relative difference standard equilibrium method	No. 3	$y = 0.71\,x + 3.75$	0.92	0.57	0.71	0.71
	Temporal stability index method	No. 8	$y = 0.78\,x + 2.91$	0.70	0.78	0.45	0.73
	Mean absolute deviation method	No. 3	$y = 0.71\,x + 3.75$	0.92	0.57	0.71	0.71
	Root mean square error method	No. 2	$y = 1.02\,x + 0.26$	0.88	0.50	0.78	0.46

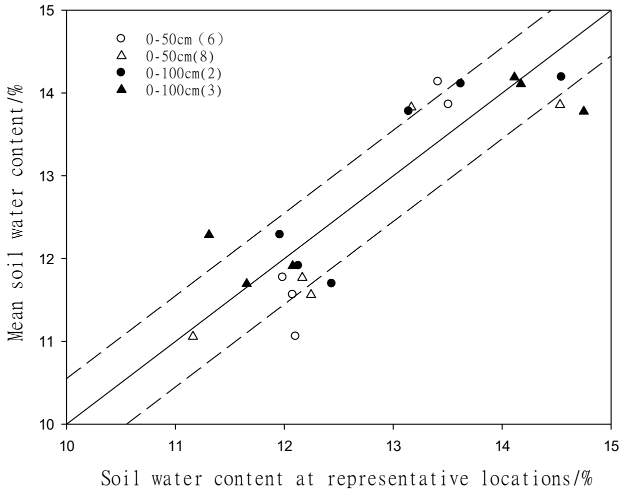

Fig. 10 Comparison of mean soil water content with corrected soil water content at representative locations at different depths

the mean absolute deviation of all individual observations from the mean arithmetic; the smaller the MAE, less error between the measured value and the predicted value is recorded, and simulation accuracy is greater. In summary, accuracy of the predicted value of the mean soil water content and the measured value at the sample site was the highest at measuring location no. 6, followed by measuring locations nos. 8 and then 12 (this having the lowest accuracy).

In the 0–100 cm soil depth, temporal stability results using mean relative difference, temporal stability, and root mean square error indicated that the best representative measuring locations were nos. 4, 8 and 2. Results using the minimum relative difference standard equilibrium method and mean absolute deviation method indicated that no. 3 had the best representative measuring location. RMSE between water content-corrected value of the representative measuring locations and mean soil water content of the sample site was in the order of 4 (1.21) > 8 (0.78) > 3 (0.57) > 2 (0.50). The value order of NSE was 2 (0.78) > 3 (0.71) > 8 (0.45) > 4 (-0.32), the order of *MAE* was 4 (0.95) > 8 (0.73) > 3 (0.71) > 2 (-0.46), and the order of R^2 was 3 (0.92) > 2 (0.88) > 8 (0.70) > 4 (0.31). These results indicate that the accuracy of predicted mean soil water content values compared with measured values was the highest at measuring location no. 2, and the R^2 was also relatively higher. Measuring location no. 2 had the best representative temporal stability in the 0–100 cm soil depth, followed by measuring location nos. 3, 8, and 4.

Results from our study, therefore, indicate that the best representative measuring locations of temporal stability in the 0–50 cm and 0–100 cm depths were nos. 6 and 8, and nos. 2 and 3, respectively. Among the five methods used in our analysis, RMSE had higher estimation accuracy, followed by the minimum relative difference standard equilibrium method. All results indicated that the estimation accuracy of the methods gradually increased with increasing soil depth. Results for statistical regression of corrected water content of representative measuring locations and measured value of mean water content at sample sites (Fig. 10) indicate that the majority of soil water content values of the representative measuring locations were within ± 5% of the error range of $y = x$. This result verifies the reliability of representative measuring locations selection.

Conclusions

From May to November 2016, soil water content was analyzed during the rainy season at 15 locations on a typical gully regulation watershed slope in the Loess Plateau. Results indicate that mean soil water contents in the soil depths of 0–50 cm and 0–100 cm were 12.70% and 13.00%, respectively. The soil water content of both soil depths had good temporal stability, and temporal stability gradually increased with soil depth. A significant positive correlation was recorded between soil water content and temporal stability ($p < 0.05$). Although soil water content was lower under drought conditions, it may still have strong temporal stability. Due to the influence of soil depth and the estimation method, the number and location of representative measuring locations of soil water content was not constant, and multiple representative measuring locations may be present. In addition, water content of the best representative measuring locations obtained using the root mean square error had better accuracy for predicting water content during the rainy season. Results also indicated that estimation accuracy gradually increased with increasing soil depth.

Acknowledgements This research was supported by the National Key R&D Program of China (No. 2017YFC0504705), the Fundamental Research Funds for the Central University, CHD (No. 300102279502), and the Internal Scientific Research Projects of Shaanxi Land Construction Group (No. DJNY2019-19). In addition, we thank the reviewers for their useful comments and suggestions.

References

Bai YR, Shao MA (2011) Temporal stability of soil water storage on slope in rain-fed region of Loess Plateau. Trans Chin Soc Agric Eng 27:45–50 **(In Chinese with English abstract)**

Brocca L, Morbidelli R, Melone F, Moramarco T (2007) Soil moisture spatial variability in experimental areas of central Italy. J Hydrol 333:356–373

Brocca L, Melone F, Moramarco T, Morbidelli R (2010) Spatial-temporal variability of soil moisture and its estimation across scales. Water Resour Res 46(2):W02516.1–W02516.14

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 51:619–638

Cheng SD, Li ZB, Xu GC, Peng L, Zhang TG, Cheng YT (2017) Temporal stability of soil water storage and its influencing factors on a forestland hillslope during the rainy season in China's Loess Plateau. Environ Earth Sci 76:539

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

Hu W, Shao MA, Han FP, Reichardt K, Tan J (2010a) Watershed scale temporal stability of soil water content. Geoderma 158:181–198

Hu W, Shao MG, Reichardt K (2010b) Using a new criterion to identify sites for mean soil water storage evaluation. Soilence Soc Am J 74:762–773

Huang Z, Liu Y, Cui Z, Fang Y, He HH, Liu BR, Wu GL (2018) Soil water storage deficit of alfalfa (Medicago sativa) grasslands along ages in arid area (China). Field Crops Res 221:1–6

Jacobs JM, Jennifer M, Mohanty BP, Binayak P, Hsu E-C, Douglas M (2004) SMEX02: field scale variability, time stability and similarity of soil moisture. Remote Sens Environ 92:436–446

Jia YH, Shao MA (2013) Temporal stability of soil water storage under four types of revegetation on the northern Loess Plateau of China. Agric Water Manag 117:33–42

Lei G, Shao MA (2012) Temporal stability of soil water storage in diverse soil layers. CATENA 95:24–32

Liu YS, Li YH (2014) China's land creation project stands firm. Nature 511(7510):410–410

Liu YS, Guo YJ, Li YR, Li YH (2015) GIS-based effect assessment of soil erosion before and after gully land consolidation: a case study of Wangjiagou Project Region, Loess Plateau. Chin Geogra Sci 25:137–146

Martinez G, Pachepsky YA, Vereecken H (2014) Temporal stability of soil water content as affected by climate and soil hydraulic properties: a simulation study. Hydrol Process 28:1899–1915

Nielsen DR, Bouma J (1985) Soil spatial variability. Pudoc Wageningen, 2–30

Penna D, Borga M, Norbiato D, Fontana GD (2009) Hillslope scale soil moisture variability in a steep alpine terrain. J Hydrol 364:311–327

Sun PC, Gao JE, Han SQ, Yan Y, Zhou MF, Han JQ (2017) Simulation study on the effects of typical gully land consolidation on runoff-sediment-nitrogen emissions in the loess hilly-gully region. J Agro Environ Sci 36(06):1177–1185 **(In Chinese with English abstract)**

Topp GC, Davis JL, Annan AP (1980) Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour Res 16(3):574–582

Vachaud GA, Silans APD, Balabanis P, Vauclin M (1985) Temporal stability of spatially measured soil water probability density function1. Soil Sci Soc Am J 49:822–828

Vereecken H, Huisman JA, Franssen HJH, Brüggemann N, Bogena HR, Kollet S, Javaux M, Kruk JVD, Vanderborght J (2015) Soil hydrology: recent methodological advances, challenges, and perspectives: Soil hydrology. Water Resour Res 51:2616–2633

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, Ren ZP, Peng L, Li ZB, Yuan SL, Hui Z, Dan W, Zhang ZY (2016) Temporal persistence and stability of soil water storage after rainfall on terrace land. Environ Earth Sci 75:966

Yin XX, Chen LW, He JD, Feng XQ, Zeng W (2016) Characteristics of groundwater flow field after land creation engineering in the hilly and gully area of the Loess Plateau. Arab J Geosci 9:646

Zhang PP, Shao MA (2013) Temporal stability of surface soil moisture in a desert area of northwestern China. J Hydrol 505:91–101

Zhang YY, Wu PT, Zhao XN, Wang ZK (2013) Simulation of soil water dynamics for uncropped ridges and furrows under irrigation conditions. Can J Soil Sci 93(1):85–98

Zhao Y, Peth S, Wang XY, Lin H, Horn R (2010) Controls of surface soil moisture spatial patterns and their temporal stability in a semi-arid steppe. Hydrol Process 24:2507–2519

Zhu XC, Shao MA, Zhu JT, Zhang YJ (2017) Temporal stability of surface soil moisture in Alpine Meadow Ecosystem on Northern Tibetan Plateau. Trans Chin Soc Agric Mach 48(8):212–218 (**In Chinese with English abstract**)

Zhu Q, Shi BQ, Liao KH (2015) Optimal monitoring design of soil moisture based on hierarchical. Chin J Soil Sci 46:74–79 (**In Chinese with English abstract**)