

Temporal stability analysis of surface soil water content on two karst hillslopes in southwest China

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Abstract Knowledge of the temporal variability of soil water content (SWC) at the hillslope scale is essential for guiding rehabilitation strategies and for optimizing water resource management in the karst region of southwest China. This study aimed to use temporal stability analysis to upscale point-scale measurements to represent mean areal SWC on two typical karst hillslopes. Based on a grid sampling scheme (10 m × 10 m) applied to two 90 m × 120 m plots located on two hillslopes, the SWC at a depth of 0–16 cm was measured 11–12 times across 259 sampling points, using time domain reflectometry (TDR) from April 2011 to October 2012. Soil texture, bulk density (BD), saturated hydraulic conductivity (K_s), organic carbon (SOC), rock fragment content (RFC), and site elevation (SE) were also measured at these locations. Results showed the hillslope with more shrub cover was wetter than the hillslope with mixed grass-shrub cover. This difference was related to the differences in soil texture, soil hydraulic permeability, and topography. Through a comparison of values obtained with the Spearman correlation coefficient (r_s), standard deviation

of mean relative difference (SDRD), and mean absolute bias error (MABE), we inferred that there is a higher degree of temporal stability for SWC in wet conditions than in drier conditions on the two hillslopes. Based on the values of the index of temporal stability (ITS), which combine the mean relative difference (MRD) and SDRD, the two locations were determined to be representative of mean SWC on both hillslopes. Moreover, these locations captured changes in mean SWC (NSCE = 0.69, and 0.65, and RMSE = 1.96, and 1.96 %, respectively). This demonstrates the feasibility of using the temporal stability of SWC to acquire mean SWC on karst hillslopes of southwestern China. The indirect method, which estimates mean SWC by considering the offset between the mean and the measurement value at a time-stable location, predicted mean SWC (NSCE = 0.86, and 0.76, and RMSE = 1.29, and 1.63 %, respectively) more precisely than the direct method (mean SWC directly measured at a time-stable location), because it eliminates deviation by introducing a constant offset (MRD). We recommended the use of the indirect method to acquire mean SWC values, when an allowable bias of 5 % for both MRD and SDRD can not be achieved. In addition, we found that soil texture, RFC, and elevation affect the pattern of SWC on the shrub hillslope. These results are expected to be useful for monitoring soil water dynamics on karst hillslopes, especially for restoration purposes.

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Introduction

Karst regions cover approximately 22.2 million km² globally, accounting for 15 % of the total land area, and are

home to about 17 % of the world population (Zhang et al. 2011). The karst region of southwest China is one of the largest, and most continuous karst landforms in the world. It covers an area measuring 5.4×10^5 km² (Zhang et al. 2011; Yang et al. 2016) and is overpopulated (more than one hundred million people), underdeveloped (about 50 % of China's poor live here), and has complex topography (large mountains areas with steep slope gradients, and a shallow and discontinuous soil layer) (Chen et al. 2009). Deforestation and land reclamation is widespread on karst hillslopes, which represent the least cultivated land per capita. There is a high proportion of sloped fields in this area, which is a leading cause of low and unstable grain yields, severe soil erosion, and karst rocky desertification (Wang et al. 2004). The rocky desertification area in southwest China currently measures 1.2×10^5 km² and increasing by about 2000 km² per year.

To combat rocky desertification, conservation practices such as reconstructing vegetation and erosion control have been implemented in the region (Jiang et al. 2014). Although this region has a subtropical mountainous monsoon climate with a large amount of annual precipitation (more than 1,200 mm), the karst habitat is deficient in soil water for vegetation growth, because of the thin soil layer and relatively high hydraulic conductivity (Fu et al. 2015). In addition, there are a large number of fissures, gaps, channels, and sinkholes, which further decrease water storage capacity (Chen et al. 2009; Chen et al. 2010). Furthermore, the disappearance of vegetation and soil increases infiltration to subsurface systems and drought occurs more frequently (Jiang et al. 2014). Liu et al. (2014) found that southwestern China has generally become drier in relation to global climate change, and that regional mean annual precipitation has decreased by 11.4 mm per decade. Thus, soil water is an important limiting factor for vegetation restoration in the karst areas of southwest China (Chen et al. 2009; Chen et al. 2010; Jiang et al. 2014).

Because hillslopes are fundamental landscape units, it is essential to understand the temporal variability of soil water content (SWC) on a hillslope scale in order to guide rehabilitation strategies and to optimize water resources management, particularly in relation to vegetation restoration (Jia et al. 2013). One approach to quantifying variability in SWC has been to apply temporal stability analysis to point data, which is a statistical approach to describe temporal persistence of spatial patterns of soil water. (Vachaud et al. 1985; Jacobs et al. 2004). Based on the concept of temporal stability, the most time-stable locations (MTSLs) have the ability to represent the mean SWC of a given area over time (Liu and Shao 2014). Plenty of research has been conducted in different countries in identifying the MTSLs, such as Brocca et al. (2009) in Italy, de Souza et al. (2011)

in Brazil, Heathman et al. (2012) in the USA, Sur et al. (2013) in Korea, and Hu et al. (2010a), Jia et al. (2013), She et al. (2015), and Wang et al. (2015) in China. Research has focused on differing land usage, including grassland (Jia et al. 2013), orchard (Gao et al. 2011), farmland (Heathman et al. 2012; Jacobs et al. 2004), steppe (Schneider et al. 2008), and mixed land uses (Hu et al. 2010a); using different scales of measurement including the transect scale (Gao and Shao 2012), area scale (Jacobs et al. 2004; Schneider et al. 2008; She et al. 2015), on a hillslope scale (Penna et al. 2013; Hu and Si 2014), watershed scale (Hu et al. 2010a; Heathman et al. 2012), and regional scale (Cho and Choi 2014). Most research has been conducted on temporal stability of SWC in non-karst, and we are unaware of any study relating to karst areas where there is large spatial variability of soil water due to physical heterogeneity (bedrock outcrop, complex topography, thin and discontinuous soil layer). Temporal stability of SWC should be examined for different climate zones, crops, soil types, topographic conditions, and land uses (de Souza et al. 2011). Therefore, from the viewpoint of guiding appropriate vegetation restoration and overcoming constraints of water scarcity, an investigation of the applicability of the temporal stability analysis of SWC on karst hillslopes in southwestern China will add a new perspective to this methodology.

Although temporal stability of SWC has gained a lot of attention, there are some contentious questions need to be clarify. The impact of soil water state (dry or wet) on the degree of temporal stability of SWC is still debated. Martínez-Fernández and Ceballos (2003), working in a semi-arid area in Spain, revealed that soil water spatial patterns over time were more stable during dry conditions. Penna et al. (2013) found that time stability was slightly higher for dry states on two alpine hillslopes. In contrast, Zhou et al. (2007) at the Shale Hills Catchment pointed out that spatial distribution of soil water was more stable during wet seasons, and less stable during the transition period, same results were indicated by Zhao et al. (2010) for a semi-arid steppe, and Jia et al. (2013) on hillslopes of the Loess Plateau in a semi-arid zone. Except for Penna et al. (2013), who researched in alpine climatic conditions (mean annual rainfall is about 1220 mm), most of the investigations assessed the temporal stability of soil water spatial patterns during wet and dry status were conducted in arid or semi-arid regions. These analyses are currently not available for humid karst regions, but urgently needed to improve restoration successes.

No consistent conclusions have been drawn on how to identify the MTSLs. Commonly, locations with MRD close to zero and SDRD at a minimum are identified as the MTSL (Jia and Shao 2013; Gao and Shao 2012); however, there may be no sampling locations fulfilling both requirements

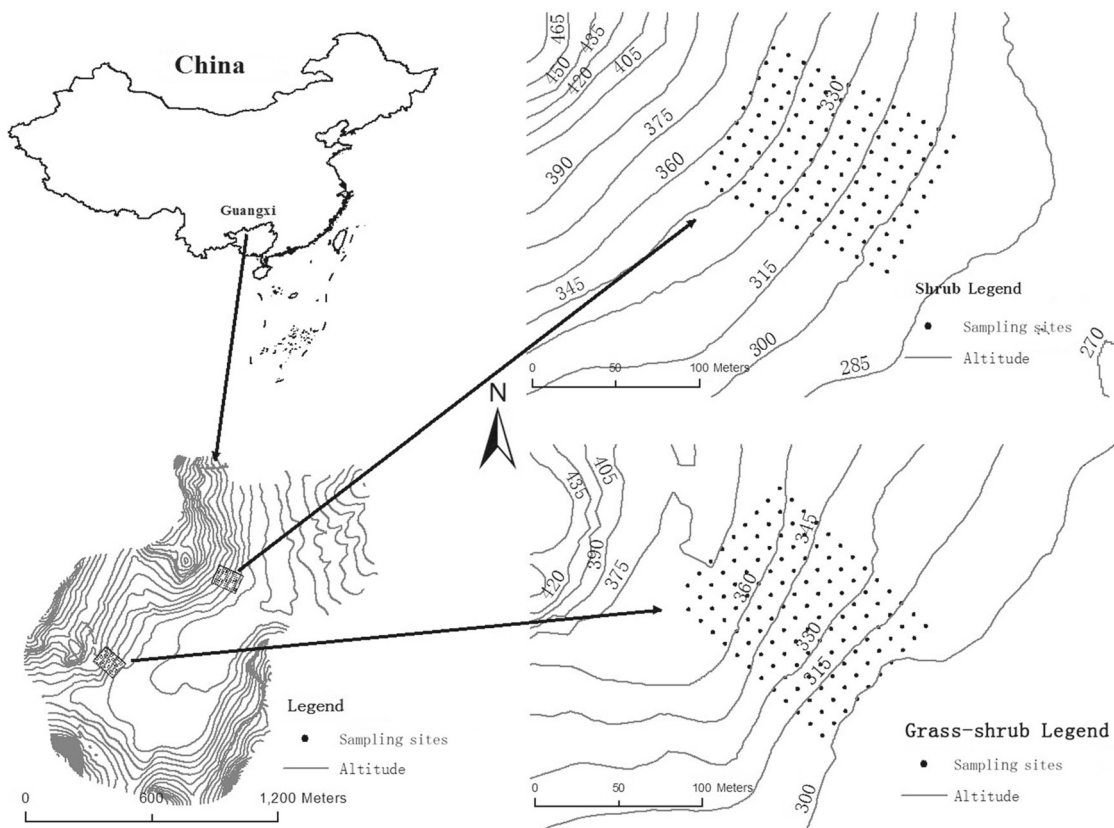


Fig. 1 Experiment area and sampling points

(Jia and Shao 2013). A less strict requirement was suggested by Gao and Shao (2012), that the locations with an allowable bias of 5 % for both MRD and SDRD can be identified as the MTSLs. And yet, Li et al. (2016) found that it was not possible to identify representative locations meeting even this requirement. Jacobs et al. (2004) proposed to use a single criterion, the index of temporal stability (ITS) which combined MRD and SDRD, to identify MTSLs. Jia et al. (2013) identified representative locations using an ITS less than 10 %. Criteria that can identify representative locations, which directly represent the mean SWC of a given area, are defined as direct methods. Grayson and Western (1998) and Hu et al. (2012) proposed the use of an indirect method to estimate mean SWC by introducing a constant offset on the locations with smallest SDRD or mean absolute bias error (MABE). Jia and Shao (2013) assessed four different ways to identify representative locations: from locations with MRD closest to zero, from locations with smallest SDRD, from smallest ITS, and from the indirect method, and found that no one method consistently performed better than another. Soil water may be even more randomly distributed than in the aforementioned studies because of the

high degree of heterogeneity in karst regions (Chen et al. 2009), and the criteria of direct methods may not be fulfilled; thus, it is necessary to evaluate direct and indirect methods to acquire mean SWC for karst regions.

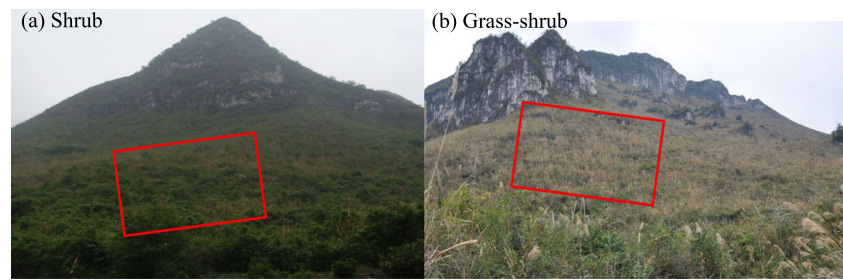
The main objectives of this study are (1) to investigate the applicability of the temporal stability of SWC to acquire mean SWC on karst hillslopes, (2) to evaluate the use of both direct and indirect methods for estimating mean SWC, and (3) to investigate which factors control the temporal variable of SWC on the hillslope scale in a karst region.

Materials and methods

Study site

This study was conducted in a small watershed (area = 1.46 km²) at the Huanjiang Observation and Research Station for Karst Ecosystems under the Chinese Academy of Sciences (24°43′58.9″–24°44′48.8″N, 108°18′56.9″–108°19′58.4″E) in Huanjiang County of northwest Guangxi province, in southwest China (Fig. 1). The watershed is a

Fig. 2 Shrub and grass–shrub hillslopes



typical example of peak-cluster depression karst, characterized by a flat depression surrounded by mountains on three sides, and an outlet in the northeast. The elevation ranges from 272 to 647 m above sea level, and approximately 60 % of hillslope land has a slope greater than 25° . The region has a subtropical mountainous monsoon climate where the average annual temperature and rainfall is 19.9°C and 1389.1 mm, respectively, and 74 % of the precipitation falls during April and August (which is defined as the wet season). The brown calcareous soil of the area is developed from carbonate source rock and has clay to clay loam texture (25–50 % silt and 30–60 % clay), the soil depth varies between 10 and 30 cm on hillslopes, and 50–80 cm in the depressions. Soils are well-drained with a stable infiltration rate varying from 0.7 to 2.1 mmmin^{-1} . The soil organic matter content is comparatively high and ranges from 2.2 to 10.1 %, and the soil has a weak alkaline pH varying between 7.1 and 8.0 (Chen et al. 2011). Bedrock is exposed over 15 % of the depressions and over 30 % on hillslopes, and some rock outcrops are covered with deep-rooted trees.

Until 1985, the watershed in this study area was seriously disturbed by deforestation, cultivation, fire, and grazing. The sloping farmlands were then abandoned after the introduction of the Grain for Green Project in 1985. Thus, this small watershed has been under natural restoration for almost 30 years. The vegetation currently consists of shrubs and grasses, which dominate about 70 % of the hillslopes. In addition, grass-shrub mixtures commonly exist on the southwest facing hillslopes, and shrubland is generally found to the southwest of the depression and on the west facing hillslopes.

Two hillslopes were chosen for establishing plots measuring $90\text{m} \times 120\text{m}$. The first plot was located in shrubland on the western side of the watershed where the vegetation mainly consisted of *Alchornea trewioides*, *Cipadessa cinerascens*, and *Rhus chinensis* (Fig. 2). At the bottom of the slope the soil was fertile and the shrub density was moderate. In the middle of the slope shrubs, perennial herbs and lianas coexisted and the RFC was relatively high. At the top of the slope was dominated by scrubland. The second plot was located on mixed grass-shrubland in the southwest of the watershed where the main species were grasses, and shrubs were only distributed at the bottom of the slope

(Fig. 2). Vegetation cover gradually decreased from bottom to top along the two hillslopes.

Experimental design and data collection

Based on a grid sampling scheme measuring ($10\text{m} \times 10\text{m}$), a total number of 130 observation points were established on the shrub slope (Fig. 2a) and 129 on the grass–shrub slope (Fig. 2b). At this site, one point could not be measured as it was located on a cliff on the hillslope. The positions of the observation points were determined using a South NTS-302R Electronic Total Station (Sursup Precision Instrument Co, Ltd, Shanghai, China), and the geographic information of observation point positions was recorded using a handheld Global Positioning System (GPS) (Etrex 2000, Garmin International Inc, New Taipei City, Taiwan). Distribution of the sampling sites is shown in Figs. 1 and 2.

The soil is shallow on karst hillslopes, and therefore, it is not always possible to measure SWC in a deeper soil layer ($> 20\text{ cm}$), therefore, surface SWC at a depth between 0 and 16 cm was observed approximately once a month in situ using Time-Domain-Reflectometry (TDR, Trime-ezc, IMKO, Germany), the TDR probes was calibrated through gravimetric method. Measurements were conducted in the shrub land a total of 12 times between April 10, 2011 and April 21, 2012, and in the grass-shrub land a total of 11 times between Nov 1, 2011 to Oct 18, 2012. Hu et al. (2012) determined that, in general, five to seven sampling occasions are required to identify MTSLs, and thus, the number of sampling times (12 and 11) was considered sufficient for researching the temporal stability of SWC.

Chen et al. (2009) stated that soil water distribution is controlled by vertical and lateral water divergence and convergence, infiltration recharge, and evapotranspiration in hillslopes or on hilly terrains, and thus, the hydrological properties of the surface soil layer have a considerable effect on SWC. To study the effects of soil properties on SWC, soil samples at a depth of 0–20 cm were collected at each observation point (at a distance of 0.2 m from each sampling point) on the shrub hillslope. Since the grass-shrub hillslope contained steep terrain, soil samples were not collected at every point. Soil particle size distribution was measured using a Mastersizer 2000 (Malvern Instruments, Malvern,

Table 1 Summary statistics of physical properties and soil organic carbon of surface soil and site elevation on both hillslopes

	Shrub			Grass-shrub		
	Mean	SD	CV (%)	Mean	SD	CV (%)
Clay, %	9.2	4.3	46.9	15.5	12.5	81.0
Silt, %	52.6	11.3	21.4	19.7	7.5	37.9
Sand, %	38.2	14.7	38.5	64.9	19.3	29.7
BD, $g.cm^{-3}$	1.0	0.2	18.2	1.1	0.2	16.0
$K_s, mm.min^{-1}$	9.2	8.7	95.1	10.5	6.8	64.5
SOC, $g.kg^{-1}$	47.6	11.7	24.7	54.2	12.8	23.6
RFC, %	25.8	19.1	73.9	23.5	26.6	113.1
SE, m	322.5	19.4	6.0	338.5	22.3	6.9

England), and soil bulk density of undisturbed soil samples (BD, $g.cm^{-3}$) was measured using steel columns (with a diameter of 5 cm, and volume of $100 cm^3$) via the excavation method. The rock fragment content (RFC, %) was determined as being the ratio between the rock weight and the dry soil weight, and soil saturated hydraulic conductivity ($K_s, mm.min^{-1}$) was measured using the constant-head method (Jia et al. 2013). In addition, soil organic carbon (SOC, $g.kg^{-1}$) was determined using the dichromate oxidation method (Jia et al. 2013). Furthermore, site elevation (SE, m) was recorded using the Etrex 2000 and a tipping bucket rain gauge (RG3-M, Onset Computer Corporation, USA) located at middle of the watershed was used to record rainfall, with 0.2 mm resolution. The soil properties of the shrub and grass-shrub hillslopes are presented in Table 1.

Temporal stability analysis

Two techniques were used to evaluate temporal stability in the present study: a non-parametric Spearman’s rank correlation test (r_s) and relative difference analysis (Vachaud et al. 1985). The first technique determined whether the location ranks persisted over time, and r_s was estimated by:

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

where N is the number of observation locations, $R_{i,j}$ is the rank of the variable $SWC_{i,j}$ observed at location i and at time j , $R_{i,j'}$ is the rank of the same variable at the same location, but at sampling time j' . Values of r_s closer to 1 indicated greater SWC temporal stability.

In the second technique, the relative difference ($\delta_{i,j}$) can be expressed as:

$$\delta_{i,j} = \frac{\theta_{i,j} - \bar{\theta}_j}{\bar{\theta}_j} \tag{2}$$

where $\theta_{i,j}$ is the SWC at location i and at time j , $\bar{\theta}_j$ is the area mean SWC at the same time j .

The mean of the relative difference (MRD, $\bar{\theta}_i$) and its standard deviation (SDRD, $\zeta(\bar{\theta}_i)$) for each location were used to determine the MTSLs, and are determined as:

$$\bar{\delta}_i = \frac{1}{m} \sum_{j=1}^m \delta_{i,j} \tag{3}$$

$$\zeta(\bar{\theta}_i) = \sqrt{\frac{\sum_{j=1}^m (\delta_{i,j} - \bar{\delta}_i)^2}{m - 1}} \tag{4}$$

where m is the number of measurements at a single location. When MRD values are plotted from smallest to largest value, it is possible to determine whether the field averaged SWC is under- or over-estimated at an observation location with a non-zero MRD. The smaller SDRD of an observation location indicates a greater tendency of that location being temporally stable.

Direct and indirect methods for estimating mean SWC

Direct and indirect methods were used to identify representative locations for obtaining mean SWC for a given area. The direct method was introduced by Jacobs et al. (2004), in which an index of temporal stability (ITS) can be computed using a combination of MRD and the associated SDRD as:

$$ITSi = \sqrt{\bar{\delta}_i^2 + \zeta^2(\bar{\theta}_i)} \tag{5}$$

The ITS provides a single metric for identifying sampling locations that are most representative of mean hillslope SWC (i.e. low MRD) and are also simultaneously stable (i.e., low SDRD).

The indirect method used to estimate the mean SWC was proposed by Hu et al. (2012). The most temporally stable location, i , that has the smallest mean absolute bias error (MABE) with non-zero MRD can be used to calculate mean SWC as:

$$\bar{\theta}_j = \frac{\theta_j(i)}{1 + \bar{\delta}_i} \tag{6}$$

where the MABE is calculated as:

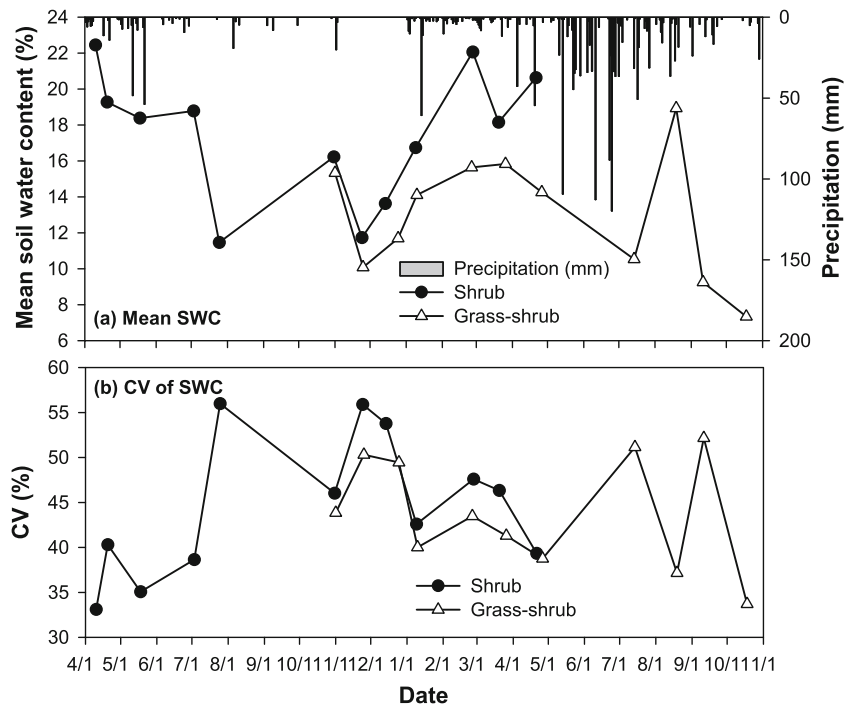
$$MABE_i = \frac{1}{m} \sum_{j=1}^m \left(\frac{|\delta_{i,j} - \bar{\delta}_i|}{1 + \bar{\delta}_i} \right) \tag{7}$$

Locations with lower values of MABE tend to be more temporally stable and to produce less estimate error.

Statistical indicators

Based on the research of Hu and Si (2014), two statistical indicators, the Nash-Sutcliffe coefficient of efficiency (NSCE), and the root mean square error (RMSE), were employed to evaluate the predicted and measured values.

Fig. 3 Experimental field rainfall, mean SWC, and CV of SWC at 0–16 cm depths at measurement points during study period



The two indicators are defined as:

$$NSCE = 1 - \frac{\sum_{i=1}^n (y_i - y'_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \tag{8}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - y'_i)^2} \tag{9}$$

where n is the number of observations, and y_i and y'_i are the observed and estimated values of the SWC, respectively, and \bar{y}_i is the mean of y_i . In general, a prediction with a RMSE less than 2 % is reliable (Cosh et al. 2008).

Results and discussion

Precipitation and mean surface SWC

Responses of the mean and coefficient of variation (CV) of surface SWC varied in accordance with precipitation on both hillslopes (Fig. 3). Precipitation was approximately 622.8 mm during the SWC observation period on the shrub hillslope (April 1, 2011—April 30, 2012), and about 1637.1 mm during the observation period on the grass-shrub hillslope (Nov 1, 2011—Oct 30, 2012). A summary of the statistics obtained for surface SWC over the entire measurement period reveals that mean SWC ranged from 11.5 %

to 22.5 %, with a mean value of 17.5 % on the shrub slope; and from 7.4 % to 19.0 %, with a mean value of 13.0 % on the grass-shrub hillslope, respectively. CV values of SWCs ranged from 33.3 % to 56.1 %, and from 33.9 % to 51.3 % on the two hillslopes, respectively, which indicates that there was moderate variation in the surface SWC on both hillslopes. A moderate variation in the surface SWCs at a hillslope scale have also been determined by other researchers (Gómez-Plaza et al. 2001; Chen et al. 2010). Results of linear regression analysis imply that there was a significant negative linear relationship between mean SWCs and CV of SWCs on shrub hillslope ($R^2= 0.646$, $p < 0.01$) and grass-shrub hillslope ($R^2= 0.804$, $p < 0.01$), a similar result was previously reported by Chen et al. (2010).

During the same observation period (Oct 31, 2011—April 26, 2012), the mean surface SWC on the shrub hillslope was significantly higher than those on the grass-shrub hillslope (Fig. 3) ($P < 0.05$, paired-sample t -test). These differences in SWC can be attributed to the difference in soil texture on the two hillslopes, which determines the water-holding capacity and permeability of the soil. Vachaud et al. (1985) indicated that water-holding capacity is highly related to the silt+clay content, and in this study the silt+clay content was higher on the shrub hillslope than on the grass-shrub hillslope (Table 1). In addition, the K_s of the shrub hillslope was smaller than that of the grass-shrub hillslope (Table 1), and thus the soil water was retained for a longer period of time on the shrub hillslope. Moreover, the mean slope gradient

Table 2 Spearman’s rank correlation between series of SWC measurements on shrub hillslope

Shrub	4/10	4/20	5/18	7/3	7/25	10/31	11/24	12/14	1/9	2/27	3/20	4/21
SWC (%)	22.5	19.3	18.4	18.8	11.5	16.3	11.8	13.7	16.8	22.1	18.2	20.7
Min (%)	7.6	6.2	6.6	7.7	3.9	5.1	3.7	5.6	5.8	5.5	5.5	6.2
Max (%)	47.1	40.2	32.6	34.8	26.5	32.0	30.0	34.5	37.8	60.4	35.6	38.5
CV (%)	33.3	40.4	35.2	38.8	56.1	46.2	56.0	53.9	42.7	47.7	46.5	39.5
4/10	1											
4/20	0.86**	1										
5/18	0.83**	0.86**	1									
7/3	0.78**	0.85**	0.82**	1								
7/25	0.82**	0.80**	0.78**	0.81**	1							
10/31	0.74**	0.73**	0.73**	0.68**	0.70**	1						
11/24	0.75**	0.75**	0.71**	0.68**	0.71**	0.84**	1					
12/14	0.68**	0.72**	0.67**	0.61**	0.68**	0.79**	0.86**	1				
1/9	0.75**	0.77**	0.80**	0.79**	0.76**	0.70**	0.74**	0.62**	1			
2/27	0.78**	0.82**	0.80**	0.72**	0.75**	0.73**	0.72**	0.67**	0.75**	1		
3/20	0.82**	0.83**	0.86**	0.77**	0.77**	0.74**	0.76**	0.68**	0.85**	0.88**	1	
4/21	0.81**	0.75**	0.78**	0.74**	0.77**	0.74**	0.75**	0.69**	0.77**	0.78**	0.85**	1

** $P < 0.01$

of the grass-shrub slope (33°) was greater than that of the shrub slope (35°), which undoubtedly reduced water retention because of the downslope drainage. Chen et al. (2009) identified that about 0.82 % decrease of SWC for per degree increase of slope angle on the karst hillslopes of southwest China. In summary, the shrub hillslope was wetter than the grass-shrub hillslope.

Temporal stability analysis of SWC

Temporal stability: Spearman’s rank correlation test

The temporal stability of SWC spatial patterns between different sampling days on the two hillslopes was evaluated using the Spearman’s rank correlation presented in Tables 2

Table 3 Spearman’s rank correlation between series of SWC measurements on grass-shrub hillslope

G-s	11/1	11/25	12/25	1/10	2/26	3/26	4/26	7/14	8/19	9/11	10/18
SWC (%)	15.4	10.1	11.7	14.1	15.7	15.9	14.3	10.6	19.0	9.3	7.4
Min (%)	5.7	3.8	4.2	6.6	5.1	4.7	6.5	4.8	6.6	2.1	2.4
Max (%)	33.2	27.7	29.1	28.7	31.8	31.2	27.8	26.8	37.0	29.4	18.0
CV (%)	43.9	50.4	49.6	40.1	43.6	41.4	38.9	51.3	37.3	52.3	33.8
11/1	1										
11/25	0.73**	1									
12/25	0.68**	0.84**	1								
1/10	0.63**	0.65**	0.63**	1							
2/26	0.75**	0.76**	0.72**	0.77**	1						
3/26	0.74**	0.71**	0.65**	0.69**	0.76**	1					
4/26	0.68**	0.71**	0.64**	0.66**	0.71**	0.76**	1				
7/14	0.71**	0.75**	0.71**	0.64**	0.69**	0.67**	0.72**	1			
8/19	0.74**	0.69**	0.66**	0.68**	0.73**	0.70**	0.68**	0.74**	1		
9/11	0.45**	0.56**	0.48**	0.48**	0.52**	0.48**	0.50**	0.54**	0.58**	1	
10/18	0.38**	0.34**	0.39**	0.31**	0.32**	0.34**	0.36**	0.48**	0.48**	0.31**	1

** $P < 0.01$

and 3. Values of r_s all reached a statistical significance level at 0.01, indicating that SWC was temporally stable despite heterogeneity (Chen et al. 2011; Chen et al. 2010). On the shrub hillslope (Table 2), values of r_s ranged from 0.61 (r_s between 07/03/2011 and 12/14/2011) to 0.88 (r_s between 02/27/2012 and 03/20/2012), with a mean value of 0.76. Furthermore, on the grass-shrub hillslope (Table 3), r_s ranged from 0.31 (r_s between 09/11/2012 and 10/18/2012) to 0.84 (r_s between 11/25/2011 and 12/25/2011), with a mean value of 0.61. The mean r_s values of the two karst hillslopes obtained in this study are thus higher than the mean values revealed by Tallon and Si (2004) (0.54, in a semi-arid crop/fallow rotation field, Canada), and Jia and Shao (2013) (0.66, 0.51 for, 0.43, and 0.34 for purple alfalfa, Korshinsk peashrub, natural fallow, and millet land on northern Loess Plateau of China, respectively), and were approximately equal to the mean values reported by Gao and Shao (2012) (0.63–0.83, on a hillslope of the Loess Plateau, China), and Wang et al. (2013) (0.64, 0.85, and 0.86 at depths of 0–6, 0–15 and 0–30 cm in an artificial revegetation desert area, China).

The lowest r_s values in our study (< 0.6) were found between at 09/11/2012 and 10/18/2012 on the grass-shrub slope, when the SWC was very low (9.3 % and 7.4 %, respectively). A comparison of r_s values shows a higher degree of temporal persistence of spatial patterns on the shrub hillslope than on the grass-shrub hillslope. Since the shrub hillslope was wetter than the grass-shrub hillslope, it is possible to conclude that there is a higher degree of temporal stability in the soil water during wet conditions than in dry conditions in our study, consistent with the conclusions of other studies (Zhou et al. 2007; Zhao et al.

2010; Heathman et al. 2012; Jia et al. 2013). However, other researchers (Martínez-Fernández and Ceballos 2003; Penna et al. 2013) found contrasting results and determined that the temporal stability of SWC was higher under dry conditions. Therefore, there is no clear and consistent conclusion relating to the effect that the study areas properties have on the temporal stability of soil water. Clearly, water movement on hillslopes in complex involving many mechanisms that are controlled by many factors, such as soil properties, terrain, vegetation, climate, land uses, and their interactions (Chen et al. 2010; Zhu and Lin 2011).

Identification of representative locations for acquisition of mean SWC

Figures 4 and 5 present the mean relative difference (MRD) ascending order, the associated standard deviation of MRD (SDRD), and the ITS for each observation point on the two hillslopes. On the shrub hillslope (Fig. 4), 79 locations's MRD had values of less than 0, which indicates that the SWC in these locations was generally less than the mean SWC in the study area. However, in the remaining 51 locations, the SWC had larger values than the mean within the area, regardless of sampling time. On the grass-shrub hillslope (Fig. 5), the MRD at 81 locations was less than 0, and positive at 48 locations. The variable amplitudes of MRD were 154.2 % (from -57.0 to 97.2 %) and 153.1 % (from -51.1 to 102.0 %) on the two hillslopes, respectively. Thus, the minimum, maximum, and ranges of MRD were similar on both hillslopes. However, the variable amplitudes of MRD were larger than those found by Gao and Shao (2012) and Wang et al. (2013), whose studies were conducted on

Fig. 4 Ranked MRD of SWC and index of time stability (ITS) for each sampling location on shrub hillslope. Squares represent MRD, error bars indicate SDRD, bold curve indicates ITS, and MTSL is marked in blue

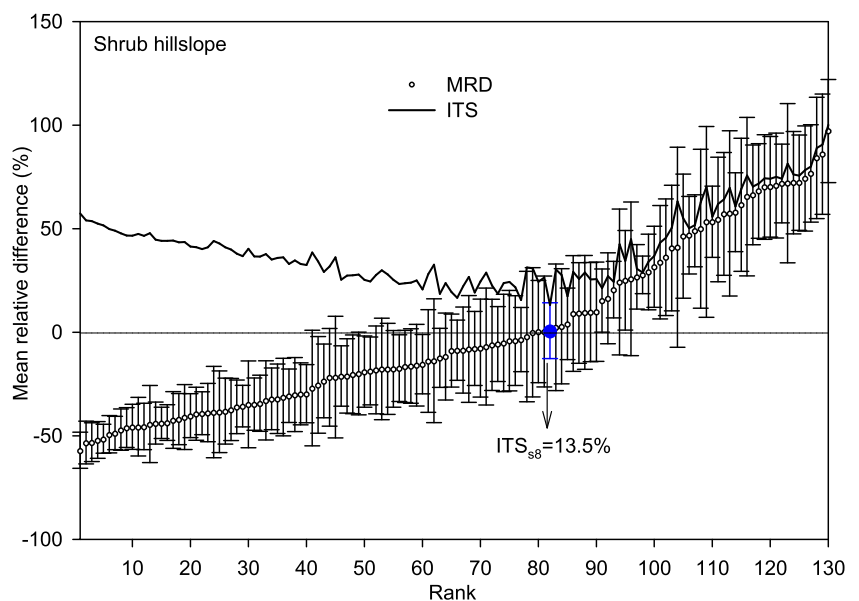
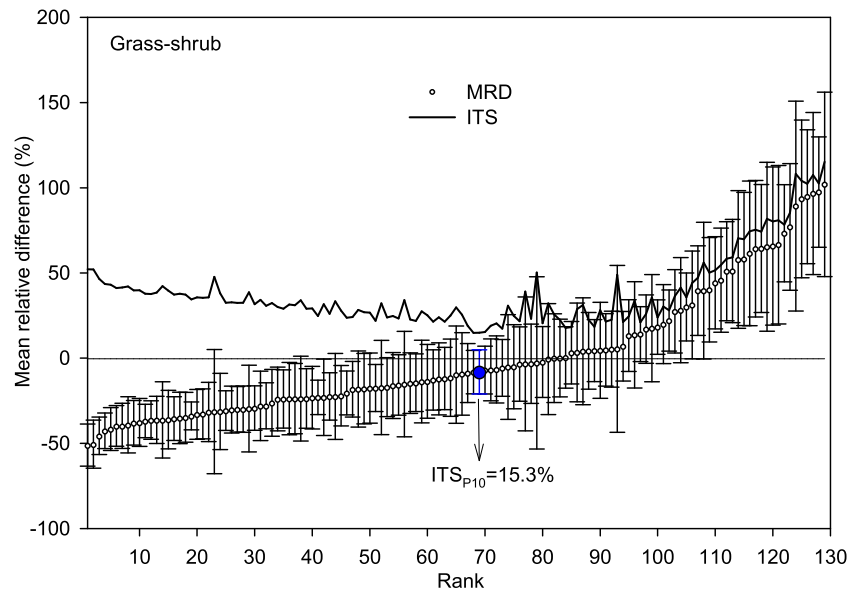


Fig. 5 Ranked MRD of SWC and the index of time stability (ITS) for each sampling location. *Squares* represent MRD, *error bars* indicate SDRD, *bold curve* indicates ITS, and MTSL is marked in *blue*



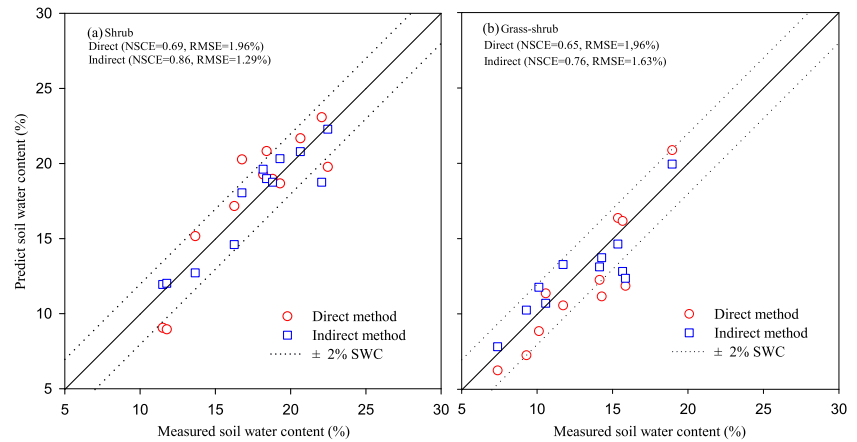
transects, but were lower than those of Hu et al. (2010a), who investigated soil water in a small watershed. In addition, Schneider et al. (2008) reported that the range of MRD increased with the observation scale because of an expected increase in the variation of soils properties, terrain, and vegetation. Furthermore, Brocca et al. (2009) determined that a decrease in the clay content with an increase in the slope of the terrain causes an increase in the variability of MRD. Moreover, four locations on the shrub hillslope and on the grass-shrub hillslope had MRD values lower than $\pm 2\%$: V8 (-0.01%), R7 (0.37%), U5 (0.39%), and S8 (0.77%); and W12 (-0.51%), T5 (0.03%), W10 (0.10%), and W8 (0.39%), respectively, indicated that the SWC in these locations was always within $\pm 2\%$ of the mean hillslope value.

MTSLs not only need to have a MRD value close to 0 but also a small standard deviation of the MRD value as well. The SDRD values on the shrub slope were found to range from 7.0% (location: O12) to 48.3% (location: N2), with a mean value of 20.6%. On the grass-shrub slope, the SDRD values ranged from 8.2% (location: R9) to 61.6% (location: X1), with a mean value of 23.5%. In other studies, the mean SDRD at a soil depth of 0–15 cm soil depth was found to be 19.6% (Wang et al. 2013), and at depths of 0–10 cm and 10–20 cm was 19.2 and 14.2%, respectively (Gao and Shao 2012). Therefore, the SDRD in our study was generally in agreement with that of other studies. The SDRD shown in Figs. 4 and 5 illustrates that the drier points tend to have lower variability and ITS values than the wetter points. This finding is consistent with that of Jacobs et al. (2004), who observed low SDRD for $MRD < 0$ and high SDRD for $MRD > 0$. In this study, there was a stronger temporal stability on the shrub than on the grass-shrub hillslope, consistent with the r_s values.

Finally, based on the previous analysis, locations with MRD values lower than $\pm 2\%$ were not the same as those with small SDRD values, and we thus selected the most time-stable locations (MTSLs) relying on the lowest ITS values, to represent the mean SWC for the two hillslopes. Values of ITS on the shrub hillslope ranged from 13.5% (S8) to 100.3%, and thus, location S8 was selected to represent mean SWC on the slope as it has adequate predictive accuracies ($NSCE=0.69$, $RMSE=1.96\%$). On the grass-shrub hillslope, values of ITS ranged time-stable location ($NSCE=0.65$, $RMSE=1.96\%$). The predictive accuracy in this study was analogous with that of others (Brocca et al. 2009; Gao et al. 2011; Gao and Shao 2012; Heathman et al. 2012; Penna et al. 2013). In addition, the calculation accuracy was considered reliable in accordance with that determined by Cosh et al. (2008), who stated that an estimation was accurate when the RMSE was less than 2%. Figure 6 compares SWCs acquired from MTSLs and the mean SWCs on the two hillslopes, which demonstrates that SWC at S8 and P10 can be used to represent changes in mean SWC.

We then estimated mean SWC using the indirect method. On the shrub hillslope, MABE ranged from 5.4% to 31.1%, with a mean value of 16.9%, and location M5 had the lowest MABE (5.4%), indicating that SWC was time-stable (Hu et al. 2010a). Based on Eq. 6, SWC at location M5 was then used to estimate mean SWC on the investigated slope. Results of a linear-fitting analysis between the estimated and measured means SWC on the shrub slope demonstrated that the indirect method can be successfully used to estimate mean SWC ($NSCE = 0.86$, $RMSE = 1.29\%$). Similarly, MABE ranged from 9.9% to 37.1% on the grass-shrub hillslope with a mean value of 18.1%, location R9 had

Fig. 6 Comparisons the mean SWC acquired from ITS-based and MABE-based method



the lowest MABE (9.9 %) and was thus used to calculate mean SWC with reliable results ($NSCE = 0.76$, $RMSE = 1.63\%$). In addition, with respect to mean MABE, there was a higher degree of temporal stability on the shrub hillslope than on the grass-shrub hillslope, which is in accordance with the previous analyses. Figure 6 presents the mean SWC acquired using both the direct and indirect methods, which shows that the indirect method is able to predict mean SWC better than direct method ($NSCE$ is increased by 0.17 and 0.11, respectively, while $RMSE$ is reduced 0.67 and 0.33 %). Other researchers have also shown that estimating mean SWC by the indirect method gives more accurate results than using the direct method (Hu et al. 2012; Li et al. 2016). This is because the MRD of MTSLS deviates slightly from zero in the direct method (the MRDs of MTSLS was 0.77 and -8.09% on the two hillslopes, respectively), which causes the SWC of the MTSLS to deviate to some extent from the mean SWC of an area (Starks et al. 2006; Hu et al. 2010b), whereas the indirect method eliminates the deviation by introducing a constant offset (MRD). Because of the high heterogeneity of the karst land form (thin and discontinuous soil, caves and sinkholes formed by the dissolution of highly soluble carbonate rock, and rock outcrop (Chen et al. 2010)) soil water is more randomly distributed than in non-karst regions. For example, soil water after rainfall is redistributed in relation to the random occurrence of exposed bedrock, and thus locations with MRD values close to 0 may be not time-stable (a smaller SDRD and MABE). There would be no MTSLS based on some principles in the karst area, such as an allowable bias of 5 %

for both MRD and SDRD (Li et al. 2016). In this case, time-stable locations with non-zero MRD could then be applied to estimate the mean SWC by using Eq. 6. Because the locations have the smallest values of SDRD/MABE, the relative difference at any time is approximately equal to the MRD, and mean SWC can then be estimated by introducing a constant offset (MRD). When an allowable bias of 5 % for both the MRD and SDRD cannot be obtained, we therefore recommend use of the indirect method to acquire mean SWC.

Relationship between SWC and soil properties

The spatial variation of SWC is related to characteristics of the soil, topography, and vegetation (Jacobs et al. 2004; Zhu et al. ; Chen et al. 2009; Chen et al. 2010; Hu et al. 2011; Jia et al. 2013). To analyze the relationship between SWC or MRD and soil properties and topography on the karst hillslope, a Pearson correlation analysis was conducted. This analysis was only performed on the shrub hillslope. Table 4 shows the correlation between MRD and rock fragment content (RFC), bulk density (BD), saturated soil hydraulic conductivity (Ks), clay content (Clay), silt content (Silt), sand content (Sand), soil organic matter (SOC), and site elevation (SE). Thus, soil texture (clay, sand and silt content), SE, and RFC had a significantly higher correlation with MRD than BD, Ks, or SOC (Table 4).

There was a highly significant correlation between MRD and soil texture ($P < 0.01$) (Table 4). The MRD was positively correlated with the clay and silt content and

Table 4 Pearson correlation coefficients between MRD and investigated variables

	RFC	BD	Ks	Clay	Silt	Sand	SOC	SE
MRD	-0.745**	-0.482**	-0.367**	0.799**	0.863**	-0.893**	0.344**	-0.754**

**Significant at 0.01 probability level

negatively correlated with sand content, suggesting that SWC is strongly related with the silt+clay content. This result is also consistent with that of previous studies (Vachaud et al. 1985; Zhao et al. 2010; Gao and Shao 2012; Jia et al. 2013). In addition, a highly significant ($P < 0.01$) negative correlation was observed between BD and MRD in our study, similar results were also reported by Gao and Shao (2012), and Jia et al. (2013).

SE was negatively correlated with MRD ($p < 0.01$) at a value of -0.754 . The negative correlation between SWC and elevation was consistent with other studies (Zhao et al. 2010; Biswas and Si 2011; Gao and Shao 2012; Jia et al. 2013). The significant correlation between elevation and soil moisture in this study was attributed to the relatively high difference in elevation (64.72 m) between measurement points. Thus, it is considered that topography should be taken into account when researching SWC spatial patterns in areas characterized by diverse or complex terrain (Lin 2006; Jia et al. 2013), such as karst hillslopes.

Karst mountainous regions are often characterized by the presence of rock fragments in the surface soil, which have a large effect on various hydrologic processes (Chen et al. 2011). RFC was extremely significantly negatively correlated with MRD (-0.745), and this may be due to the fact that rock fragments increased the occurrence of macro pores at the interface of soil and rock (Fu et al. 2015), thus reducing the capacity for holding the rainfall.

A significantly negative correlation was observed between K_s and MRD in this study ($P < 0.01$) (Table 4). However, this result is inconsistent with the results of previous studies by Gao and Shao (2012) and Wang et al. (2013), and the discrepancy could be related to the much higher mean K_s value (Fu et al. 2015) in our study area (54.9 cm/h) compared to non-karst areas (2.55 cm/h of loess soil, and 0.03 cm/h of glacial till soil). Higher K_s indicates either that there is an easy and rapid method of rain water infiltration into the deeper soil layers or bedrock via percolation and drainage, or that water can be lost by evapotranspiration, which induces a lower MRD.

SOC also was extremely significantly correlated with MRD, this result is consistent with other studies (Gómez-Plaza et al. 2001; Zhao et al. 2010; Biswas and Si 2011; Wang et al. 2013). A high SOC content is always accompanied by high soil porosity, high root content, and activity by soil organisms (Fu et al. 2015), which improve soil structure, and may have a great effect on the spatial and temporal variation of soil water. However, SOC can only partly explain variations in SWC, as revealed by Schneider et al. (2008), and as determined by our study, the correlation coefficient was only 0.344.

The order of absolute values of Pearson correlation coefficients between MRD and influencing factors was sand content (0.893) > silt content (0.863) > clay content

(0.799) > SE (0.754) > RFC (0.745) > BD (0.482) > K_s (0.367) > SOC (0.344). We thus conclude that SWC on the shrub hillslope is controlled by soil texture, SE, and RFC.

Conclusions

This study investigated characteristics of temporal stability of SWC on two typical karst hillslopes (shrub and grass-shrub) in southwest China, with the aim to acquire mean SWC values using a small number of sampling locations. Based on the datasets for SWC (in the 0–16-cm layer) measured from 130 and 129 locations at 12 and 11 sampling times on the two hillslopes, respectively, the following conclusions were drawn:

- (1) The shrub hillslope was wetter than the grass-shrub hillslope, mainly due to differences in soil texture, hydraulic permeability, and topography. There was a significantly negative relationship between the mean and coefficient of variation of SWC on both hillslopes.
- (2) By comparing the values of r_s , SDRD, and MABE, it can be inferred that there was a higher degree of temporal stability of SWC during wet conditions than during dry conditions.
- (3) Based on values of ITS, which were a combination of MRD and SDRD, two locations were determined to be representative of mean SWC on the two hillslopes. These locations were capable of capturing changes in mean SWC (NSCE = 0.69, 0.65, and RMSE = 1.96, 1.96 %, respectively), which demonstrates the applicability of temporal stability of SWC in acquiring mean SWC on karst hillslopes.
- (4) The indirect method was successfully used to estimate mean SWC (NSCE = 0.86, 0.76, and RMSE = 1.29, 1.63 %, respectively). It predicted mean SWC more closely than the direct method, as it eliminates deviation by introducing a constant offset (MRD). We therefore recommend the use of the indirect method for acquiring mean SWC, when an allowable bias of 5 % for MRD and SDRD cannot be achieved.
- (5) Soil texture, RFC, and elevation were primarily responsible for the pattern of SWC on the karst hillslope.

These findings will contribute to understanding SWC patterns on karst hillslopes, with implications for ground sampling design, and the management of soil water resource.

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