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Spatio-temporal variability and temporal stability of water contents distributed within soil profiles at a hillslope scale

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ABSTRACT

Information about soil water content (SWC) within soil profiles in terms of its spatio-temporal variability and temporal stability is crucial when selecting appropriate soil water management practices. However, detailed profile distribution features for related indices are not clear on the Chinese Loess Plateau. This study aimed to investigate the depth dependency of spatio-temporal variability and temporal stability of SWC at the hillslope scale using an intensive sampling strategy for both horizontal and vertical directions as well as over time. The SWCs at 20 depths within 0–300 cm soil profiles were measured on 20 occasions between July 2008 and October 2010 at 91 locations on a hillslope on the Loess Plateau, China. Results showed that although the profile distributions of investigated statistical parameters differed greatly, they were all depth dependent. Based on both the spatio-temporal variability and the temporal stability characteristics using eight indices, the studied soil profile (0–300 cm) could be divided into three soil layers, i.e., 0–60, 60–160 and 160–300 cm, with a characteristic feature of "irregularly changing", "regularly changing", and "relatively constant", respectively. The deepest rainwater replenishment depth was approximately 160 cm. Therefore, choosing 200 cm as the sampling depth would be sufficient in similar areas. Such findings are useful for designing an optimal strategy for sampling and management of profile soil moisture.

1. Introduction

Soil water content (SWC) is a key variable in understanding a series of hydrological processes, including infiltration, runoff, erosion, and solute transport, at different temporal and spatial scales (Heathman et al., 2009). In semi-arid areas, it is one of the most important limiting factors for vegetation restoration (Hu et al., 2009), and crop productivity (de Souza et al., 2011).

Spatio-temporal variability is one of the most important features of SWC. Soil moisture is highly and nonlinearly variable in both time and space due to heterogeneity of climate and soil across different scales (Heathman et al., 2012). Studies have identified important spatio-temporal variability characteristics of SWC from different aspects, such as the spatio-temporal patterns of SWC (Cantón et al., 2004; Brocca et al., 2007), the relationship between the heterogeneity and its mean values (Hupet and Vanclooster, 2002; Choi and Jacobs, 2007), the spatial scaling of SWC (Western and Blöschl, 1999; Gao and Shao, 2012a), and the controlling factors of spatio-temporal patterns (Gómez-Plaza et al., 2001; Zhao et al., 2010).

However, few studies have explored the depth dependency of spatio-temporal variability characteristics. One of those studies was performed by Choi and Jacobs (2007) but only for a limited soil depth, i.e., the 0–31 cm soil layer, and reported that the standard deviation of SWC tended to decrease as soil depth increased. Another study, carried out by Hupet and Vanclooster (2002) over a limited area (0.63 ha), concluded that the dependency was different in upper soil layers (0–75 cm) from lower ones (100 and 125 cm). Even fewer studies explored the depth dependence of spatio-temporal variability for SWC on the Loess Plateau of China. Gao et al. (2011a) found that the response of the variation of SWC to the rainfall varied with soil depth in the 0–160 cm soil layer in a well-developed gully. However, the spatio-temporal patterns of SWC differed greatly between the hillslope and the gully due to large differences in elevation and vegetation (Gao et al., 2011a). Wang et al. (2013) explored the vertical distribution of SWC within 21-m soil profiles across the Loess Plateau, and found that the variation of SWC and its affecting factors differed down the soil profile. However, their study was carried out at the regional scale with a comparatively small sampling number ($n = 11$), the findings of which were not adaptable to the hillslope scale. Data for the depth dependence of spatio-temporal variability for SWC at the hillslope scale using a high sampling density and deep sampling depth remains scarce.

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Another important feature of SWC is "temporal stability", which indicates the degree by which SWC spatial patterns change over time; a strong temporal stability indicates that the pattern varies little over time even though the actual SWC values may vary greatly within a given area. This phenomenon was first described by Vachaud et al. (1985). The temporal stability concept has been successfully used to identify locations that represent the mean SWC of an area (Penna et al., 2013), to upscale (Grayson and Western, 1998) and to downscale (Blöschl et al., 2009) SWC information, and to complete datasets that have missing data (Dumedah and Coulibaly, 2011).

On the Loess Plateau of China, many studies on the temporal stability of soil moisture have been carried out with diverse focuses. With regard to scale, the temporal stability of soil moisture has been identified at the watershed (Hu et al., 2009), hillslope (Gao and Shao, 2012c) and plot scales (Jia et al., 2013a). Hu et al. (2010) have developed a new index termed the mean absolute bias error to identify the temporal stability locations (TSL). Gao and Shao (2012b) have explored the feasibility of identifying TSL by using soil properties and elevation. Hu et al. (2013) have estimated the mean SWC successfully using the TSL of adjacent or of distant areas. Subsequently, temporal stability patterns have been compared under four types of vegetation (Jia and Shao, 2013), and on two adjacent hillslopes (Jia et al., 2013b).

Several studies also explored the depth dependency of temporal stability in this part of the Loess Plateau that mainly produced qualitative results (Gao and Shao, 2012c; Jia et al., 2013a; Jia et al., 2013b; Gao et al., 2011b). For example, Gao and Shao (2012c) and Jia et al. (2013b) conducted studies at the hillslope scale in the 0–300 cm soil profile with 100 cm depth intervals and concluded that temporal stability increased with increasing soil depth. For a 0–60 cm soil profile and taking 20 cm as the depth interval, Gao et al. (2011b) found that the temporal stability of the 20–40 cm soil layer was significantly ($p < 0.05$) weaker than that of the other soil layers in jujube orchards on hillslopes. Later, Gao and Shao (2012b) found that temporal stability exhibited no significant differences among the soil depths within the 0–60 cm soil profile when taking 10 cm as the depth interval. Jia et al. (2013a) pointed out that vegetation increased the complexity of the spatial patterns of soil moisture within 0–100 cm soil profile.

None of the aforementioned studies obtained whole profile distribution characteristics of temporal stability indices. For instance, none found a relative steady layer. This was because they either investigated a relatively shallow soil layer, e.g., ≤100 cm (Gao et al., 2011b; Gao and Shao, 2012b; Jia et al., 2013a), or a deep soil layer (e.g., 0–300 cm) but used a large sampling interval such as 100 cm (Gao and Shao, 2012c; Jia et al., 2013b). Using a large sampling interval would inevitably obscure information about the variation and stability of SWC that occurred within that interval. Detailed profile characteristics of soil moisture could provide a better integral understanding of soil moisture dynamics (Hupet and Vanclooster, 2002) and could hence be more valuable in hydrologic applications (Blöschl and Sivapalan, 1995). To date, there appears to have been no studies conducted in order to assess the variability and stability of SWC at the hillslope scale in soil layers deeper than 200 cm using very small sampling intervals (e.g., ≤20 cm).

In order to confront these issues, this study involved the collection of detailed SWC data at 91 locations at multiple depths within 0–300 cm soil profiles over a period of more than two years on a typical hillslope on the Loess Plateau, China. This detailed investigation used eight statistical parameters as indices. The main objectives were: (i) to systematically acquire information about the spatio-temporal variability and temporal stability characteristics of SWC at the hillslope scale; (ii) to determine whether the indices of variability and stability were depth dependent; and (iii) if they were, to further ascertain changes in the distribution of SWC as functions of soil depth and corresponding controlling factors. This was considered useful in order to better understand spatio-temporal variability and temporal stability, which would be helpful for designing optimal sampling strategies for SWC at different soil depths.

2. Materials and methods

2.1. Field site description

The study site was a hillslope (mean gradient of 14°) located in the Liudaogou watershed (110°21′-110°23′ E, 38°46′-38°51′ N) in Shenmu County, Shaanxi Province, China (Fig. 1). The hillslope was approximately 1.4 ha in area (350 m long and 40 m wide) with an elevation ranging from 1160 to 1215 m above sea level. The slope was covered by three main land use types: farmland for millet production (9%), grassland (50%) that mainly consisted of bunge needlegrass (*Stipa bungeana* Trin.) with some alfalfa (*Medicago sativa* L.) and *Artemisia scoparia* Waldst. et Kit., and woodland (41%) that consisted of apricot trees (*Prunus armeniaca*) with a low planting density and undergrowth. The loessial soil at the study site had a silt loam texture in the upper 60 cm layer (clay: 19%; silt 49%; sand 32%, USDA) with a mean soil bulk density of 1.3 g/cm^3.

The study area has a semi-arid, continental climate classed as moderate-temperate: a mean annual precipitation of 437.4 mm, nearly 50% of which falls between July and September (a total of 1093 mm fell during the study period between July 2008 and October 2010); a mean annual potential evapotranspiration of 785 mm; a mean annual temperature of 8.4 °C; and a mean aridity index of 1.8.

2.2. Sampling and measurement

2.2.1. Soil moisture measurement

Ninety-one aluminum neutron probe access tubes (0–300 cm) were installed along three transects extending down the length of the hillslope (Fig. 1). The distances between adjacent transects as well as between adjacent installation locations along each transect were approximately 10 m. The installation locations were situated under the different vegetation types such that they well represented the conditions of the slope. Between July 2008 and October 2010, volumetric SWC was measured at all of the 91 locations using a calibrated neutron probe on 20 occasions at intervals of approximately one month. Measurements were made at 10 cm increments between soil depths of 0 and 100 cm, and at 20 cm increments between soil depths of 100 and 300 cm. Detailed calibration for the neutron probe had been previously carried out in this area by Hu et al. (2009).

The mean SWCs over time and space at each soil depth were calculated from individual measurements of SWC_{ij} at location i and time j as follows:

Mean SWC over time ($\overline{\mathrm{SWC}_i}$):

$$\overline{\mathrm{SWC}_i} = \frac{1}{M}\sum_{j=1}^{M}\mathrm{SWC}_{ij} \tag{1}$$

Mean SWC over space ($\overline{\mathrm{SWC}_j}$):

$$\overline{\mathrm{SWC}_j} = \frac{1}{N}\sum_{i=1}^{N}\mathrm{SWC}_{ij} \tag{2}$$

where M is the number of sampling days and N is the number of measurement locations. In the present study, $M = 20$ and $N = 91$.

2.2.2. Measurement of other main characteristics

Elevation and soil particle size distributions were the main factors affecting the spatial and temporal distributions of soil moisture on this hillslope (Gao and Shao, 2012b). Therefore, the elevation of all the locations and the soil particle size distributions along transect 3 (see Fig. 1) were measured in the present study. The elevation above the sea level was measured by an RTK-GPS receiver (Trimble 5700, USA). The particle size distributions for each of the 31 locations along transect 3 were

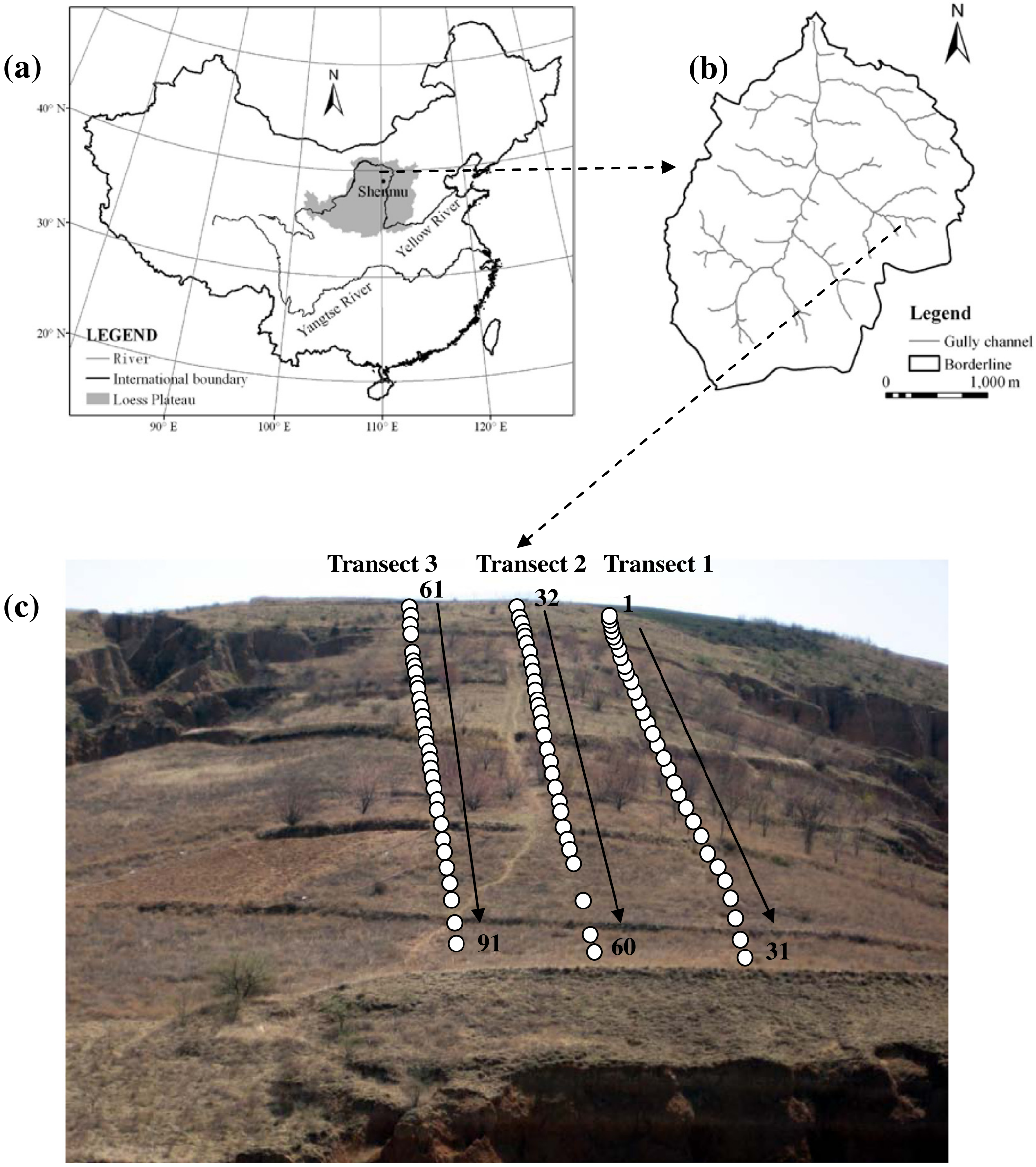

Fig. 1. The distribution of 91 neutron access tubes across the hillslope (c) located in the Liudaogou watershed (b) on the Loess Plateau of China (a). Distances between adjacent transects and between adjacent sampling sites along each transect are both approximately 10 m.

measured for disturbed soil samples collected from 10 soil layers: 0–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–150, 150–200, 200–250 and 250–300 cm using a Longbench MasterSizer 2000 (Malvern Instruments, England).

2.3. Method of data analysis

2.3.1. Statistical analysis

The SD and CV of SWC over time (SD_T and CV_T) and space (SD_S and CV_S) were used to represent the temporal and spatial variability of SWC, respectively. One-way analysis of variance (ANOVA) was carried out to determine the differences of the statistical parameters among different soil layers. Pearson correlation was used to determine the correlation between any two statistical parameters, e.g., between SD and mean SWC, at each depth. These analyses were carried out using the Statistical Program for Social Sciences (SPSS) 11.0.

2.3.2. Temporal stability analysis

Two techniques were employed to evaluate the temporal stability of SWC based on Vachaud et al. (1985). First, a relative difference analysis, which was based on the difference (Δ_{ij}) between an individual measurement of SWC_{ij} and the daily spatial mean of water content $\overline{SWC_j}$ at the same sampling time for all locations, was carried out using:

$$\Delta_{ij} = SWC_{ij} - \overline{SWC_j} \tag{3}$$

The relative difference (δ_{ij}) was then calculated from:

$$\delta_{ij} = \frac{\Delta_{ij}}{\overline{SWC_j}} \tag{4}$$

Two indices of temporal stability were then determined: the mean relative difference (MRD), $\overline{\delta}_i$, and the standard deviation of relative difference (SDRD), $\sigma(\delta_i)$, defined as:

$$\overline{\delta_i} = \frac{1}{M}\sum_{j=1}^{M}\delta_{ij} \tag{5}$$

and

$$\sigma(\delta_i) = \left[\frac{\left(\delta_{ij}-\overline{\delta_i}\right)^2}{M-1}\right]^{1/2}. \tag{6}$$

Relative difference analysis identified locations that consistently either represented the mean SWC of the study area or that under- or over-estimated it while at the same time yielding a measure of variability (Mohanty and Skaggs, 2001). The time-stable location should have the MRD value that was closest to zero and the minimum SDRD value over time. Locations with MRD values close to zero indicated their mean SWC would be close to the mean SWC of the study area, whereas locations with MRD values that were greater or less than zero would over- or under-estimate the mean SWC of the study area, respectively. Locations where the SDRD values were small were considered to be temporally stable (Grayson and Western, 1998); hence, the lower the SDRD value was, the more time-stable the location was. The ranges of MRD and SDRD reflected the differences in spatio-temporal variability among the locations sampled and provided information about the representative locations.

The second technique used to determine temporal stability was the non-parametric Spearman's rank correlation test (r_s), which determined whether the ranking order of the location persisted over the study period. In this approach, R_{ij} was the rank of the variable SWC_{ij} observed at location i on day j, while $R_{ij'}$ was the rank of the same variable at the same location, but on day j'. Using SPSS software, r_s was calculated from:

$$r_s = 1-\frac{6\sum_{i=1}^{N}\left(R_{ij}-R_{ij'}\right)^2}{N(N^2-1)}. \tag{7}$$

Correlation (r_s) values close to 1 occurred when the ranks of the SWCs were similar during the study period and indicated a strong temporal persistence of spatial patterns.

The indices of SDRD and r_s represent two different aspects of temporal stability. The SDRD characterizes the degree of temporal stability at just one location while r_s indicates the similarity or stability of the spatial distribution for the SWC of many locations at different times.

3. Results

3.1. The spatio-temporal variability of SWC at various soil depths

3.1.1. Spatio-temporal variability

The temporal variability of the mean SWC over space, as expressed by both SD_T and CV_T for 20 soil depths (Fig. 2a), initially decreased with increasing soil depth until attaining approximately constant values at 160 cm. Spatial variability of mean SWC over time as indicated by SD_S and CV_S generally increased with increasing soil depth (Fig. 2b). Within the 0–300 cm soil profile, three soil layers could be identified that exhibited different patterns of changes in SD_S and CV_S: a relatively stable layer I (0–70 cm); a layer with greater changes in spatial variability (70–140 cm); and a second relatively stable layer II (140–300 cm). The corresponding SD_S values in the three layers ranged from 2.9% (10 cm) to 3.1% (70 cm), to 4.5% (140 cm), and to 4.7% (300 cm) with the maximum value of 4.9% occurring at 240 and 260 cm. The differences among the SD_S values in the three layers were significant ($p < 0.05$) based on one-way ANOVA. The CV_S values followed a similar trend to the SD_S values except that the CV_S values were much greater in the upper 20 cm of soil than those occurring at other depths in the stable layer I. The different behavior observed for the two parameters were mainly due to the significantly lower SWC in the upper 20 cm layer.

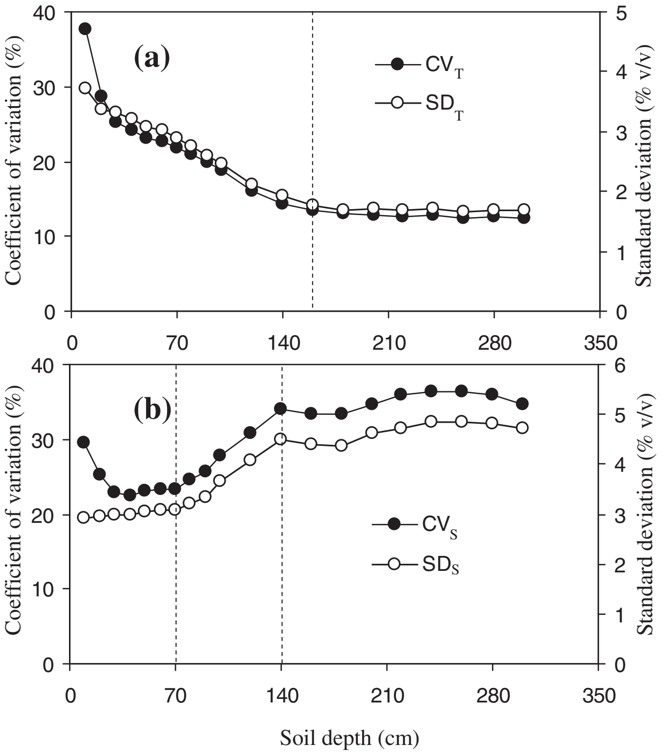

Fig. 2. Changes in the standard deviation (SD) and coefficient of variation (CV) of mean soil volumetric water contents within soil profiles in (a) time (SD_T and CV_T) and (b) space (SD_S and CV_S) measured at 91 sampling locations on 20 occasions.

3.1.2. The relationship between the heterogeneity of soil water and its mean values

The SD of the SWC was positively correlated with the daily mean SWC ($p < 0.01$, Pearson test) at all 20 soil depths, which indicated that SWC was more heterogeneously distributed during wet periods than during dry ones for each soil depth. Furthermore, in this study the positive correlation between the SD of the SWC and its mean was depth dependent (Fig. 3). The lowest correlation between the SD of SWC and its mean was observed at 30 cm depth ($R^2 = 0.32$). Within the 0–300 cm soil profile, three different distributions of the R^2 values with increasing soil depth were exhibited in three soil layers: (i) decreasing from 0.86 to

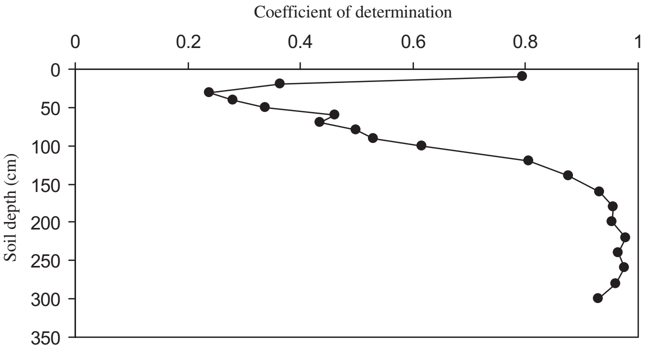

Fig. 3. Distribution within a soil profile of the determination coefficients for the power function relationships between the mean soil volumetric water content and its standard deviation at various soil depths based on data from 91 locations.

0.32 (0–30 cm); (ii) increasing from 0.32 to 0.94 (30–160 cm); and (iii) stable with fluctuations between 0.94 and 0.98 (160–300 cm).

3.2. Profile distribution of temporal stability characteristics for SWC

3.2.1. Standard deviation of relative difference (SDRD) and Spearman's rank correlation (r_s)

Profile distributions of the mean SDRD over space and of the mean r_s over time are presented in Fig. 4. The mean SDRD tended to decrease with increasing soil depth, ranging from 20.1% (10 cm) to 5.7% (280 cm) (Fig. 4a). These values within the 0–200 cm layer significantly decreased with soil depth ($p < 0.01$, Pearson test), implying that temporal stability increased with increasing soil depth. Furthermore, the temporal stability of locations was notably less for the 10 cm depth (20.1%) than for the 20 cm depth (14.6%).

The changes in r_s with soil depth (Fig. 4b) showed that the temporal patterns of the spatial distribution of SWC tended to increase down the soil profile. However, in the upper 60 cm layer, r_s initially increased and then decreased; at 20 cm, the spatial pattern was the most temporally stable ($r_s = 0.79$). Between 60 and 140 cm, the temporal stability consistently increased with increasing soil depth, which was similar to the SDRD-based results (Fig. 4a). Below 140 cm, the temporal stability of SWC was relatively high and constant; all the r_s values were greater than 0.95.

3.2.2. The ranges of mean relative difference (MRD) and SDRD

The ranges of MRD and SDRD as a function of soil depth are presented in Fig. 5. Within the 0–300 cm soil profile, different patterns of changes in the ranges of MRD (Fig. 5a) were identified in three soil layers: in layer 1 (0–70 cm), the range of MRD declined from 152.7% (10 cm) to 103.7% (70 cm); in layer 2 (70–140 cm), the range increased abruptly from 103.7% (70 cm) to 154.8% (100 cm), and was 174.7% at 140 cm; and in layer 3 (140–300 cm) the range fluctuated at high values of between 168.0% (300 cm) and 179.7% (220 cm). One-way ANOVA showed that the mean values of the ranges of MRD were significantly different ($p < 0.01$) among the three layers. The boundaries of these three layers and the trends observed within them were generally consistent with those found for SD_S and CV_S (Fig. 2b), and especially so for CV_S. This similarity might be expected since, by definition, MRD relates to the variability of SWC over space. However, the range of MRD reflects the magnitude of the difference between the locations having the most extreme SWCs in the study area, while SD_S or CV_S represents the variability in space for all the locations. Hence, there were small differences in the trends between these parameters.

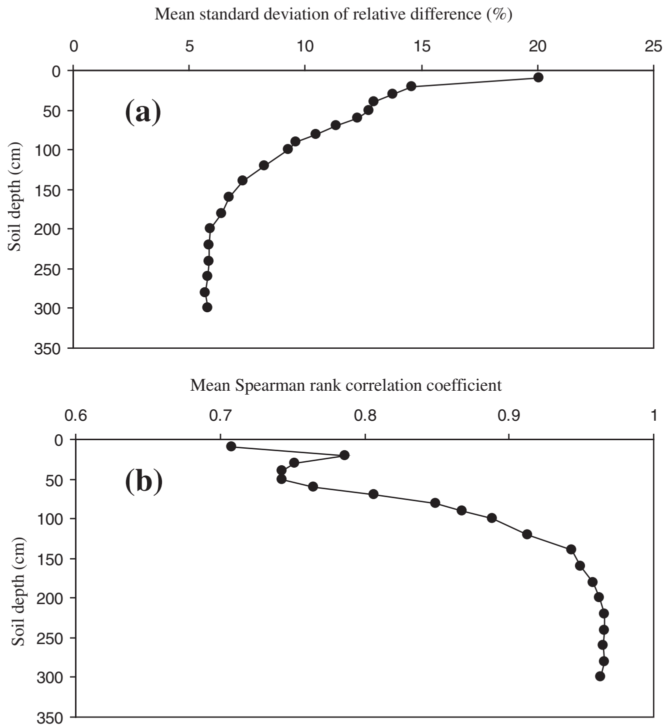

Fig. 4. Distribution within the soil profile of temporal stability indicators for soil water content (a) the mean standard deviation of relative difference, and (b) the mean Spearman rank correlation coefficient at different soil depths based on data from 91 locations.

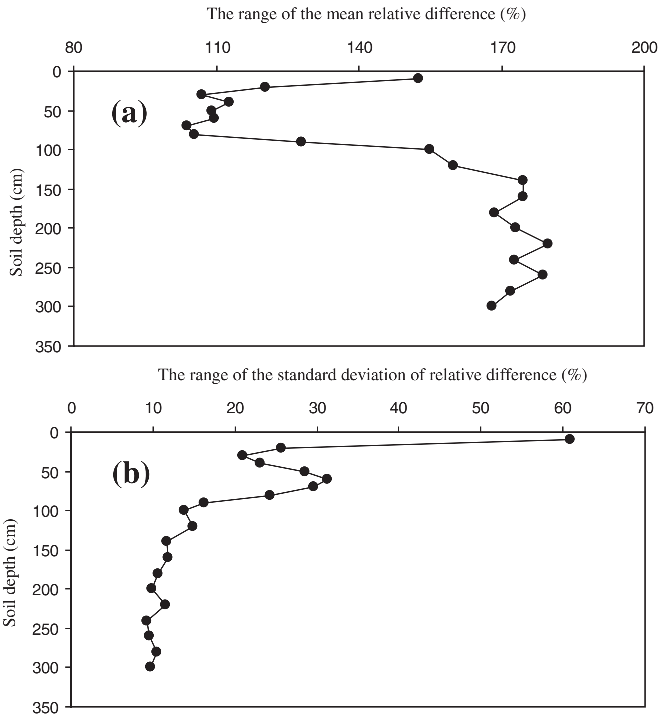

Fig. 5. Depth series of temporal variables for soil water content: (a) the range of mean relative difference, and (b) the range of standard deviation of relative difference based on data from 91 locations.

The ranges of the SDRD tended to decrease with soil depth in the 0–300 cm profile (Fig. 5b), and varied between 60.9% (10 cm) and 9.3% (240 cm). Both the maximum and minimum values for SDRD also tended to decrease with increasing soil depth (data not shown). However, the rate of decrease of the maximum values was greater than that of the minimum values, which varied between 69.7% (10 cm) and 11.8% (240 cm) and between 11.8% (10 cm) and 2.2% (280 cm), respectively. Furthermore, the distribution of the ranges of the SDRD was more scattered, especially for the 0–60 cm soil layer, than that of the mean values of the SDRD (Fig. 4a).

3.2.3. The relationship between MRD and SDRD

Fig. 6 shows the profile distribution of the linear determination coefficient values for the relationship between MRD and SDRD, which lay between 0.07 (80 cm) and 0.37 (10 and 300 cm). There was a significant positive correlation ($p < 0.01$; Pearson test) for all depths. This positive correlation meant that the drier sampling locations in the study area were always more stable than the wetter locations in terms of representing the mean SWC of the area.

Three soil layers within the 0–300 cm soil profile could be identified that exhibited different patterns of changes in R^2 values (Fig. 6). In the first layer (0–80 cm), R^2 decreased with increasing soil depth. This suggested that the probability that the drier locations were more time-stable than the wetter ones decreased with increasing soil depth in the upper 80 cm layer. In the second layer, R^2 increased from 0.07 (80 cm) to 0.36 (160 cm), which meant that the soil moisture status

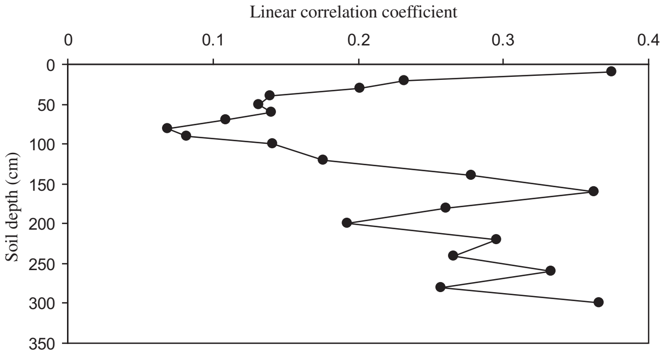

Fig. 6. Linear correlation coefficients for the relationships between the mean relative difference and its standard deviation for soil water contents at different soil depths based on data from 91 locations.

of the locations had greater effects on temporal stability at deeper soil depths. In the third layer (160–300 cm), R^2 fluctuated greatly with soil depth. The observed R^2 distributions were similar to those of the variability of spatial SWC (Fig. 2b). The linear correlation coefficient for the relationship between R^2 and CV_S was 0.52 ($p < 0.001$, Pearson test), which indicated that the correlation between temporal stability and soil moisture status was higher for an area that exhibited greater spatial variability. This suggested that choosing locations with low SWC as the places that were temporally stable would be more meaningful for an area with more extensive spatial variability in SWC.

3.3. Profile distribution of related factors to SWC

In this study, a significant inverse relationship between elevation and SWC was detected. The Pearson correlation coefficients (r) between the elevation and the SWC were related to soil depth by an exponential function ($R^2 = 0.93$) in which the absolute values of the coefficients increased with increasing soil depth (Fig. 7). This means that elevation became more of an influencing factor on SWC as depth increased and, correspondingly, that other factors became less significant. Furthermore, the spatial variability of elevation among the 91 locations would be expected to affect to different degrees the spatial variability of SWC at different soil depths.

The profile distribution of the spatial variability for the clay content based on the 31 locations along Transect 3 (Fig. 8) showed that the vertical distribution of clay content was relatively homogeneous. The weakest and the strongest variation occurred at depths of 40–60 and 250–300 cm, with relatively similar CV values of 19% and 34%, respectively. The differences in the variation among different soil layers were larger in the shallow soil layers (<80 cm) than those in the deeper soil layers (80–300 cm). The large differences in the shallow soil layer may be related to the stronger physical, chemical and biota activity that occurs in the soils of the shallow layers. The vertical variation in clay contents in the deeper soil layers was much less than those in the shallow layers, e.g., between 80 and 250 cm the CV values only changed between 26% and 27%. The small variation in clay content was an important factor that explained the low variation of SWC in the deeper soil layer (160–300 cm).

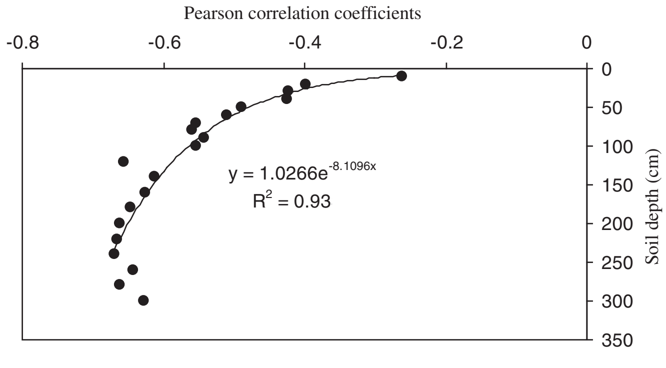

Fig. 7. Distribution within the soil profile of Pearson correlation coefficients derived for relationships between elevation and the soil water content at various soil depths based on data from 91 locations.

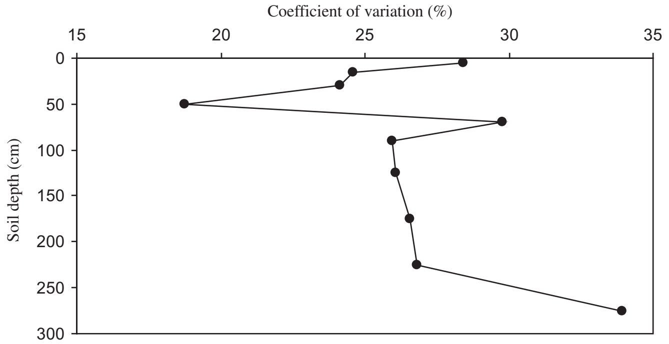

Fig. 8. Distribution of the coefficients of variation for the clay content at various depths within a 0–300 cm soil profile based on data from the 31 locations along Transect 3.

4. Discussion

4.1. The depth-dependence of spatio-temporal variability and temporal stability indices

In the present study, eight indices were chosen to assess the spatio-temporal variability (SD_T, SD_S, and COR1, i.e., the correlation between the SD_S and the mean SWC values), and the temporal stability (the mean of SDRD, the mean of r_s, the range of MRD, the range of SDRD, and COR2, i.e., the correlation between MRD and SDRD). As reported in Section 3, the eight indices followed different distribution patterns within the soil profile that may have appeared to be irregular on the first inspection. However, when the investigated profile (0–300 cm) was divided into three layers, i.e., 0–60 cm, 60–160 cm, and 160–300 cm, common depth-dependent characteristics for both variability and temporal stability indices were identifiable.

In the first layer (0–60 cm), four of the index values decreased (SD_T, mean SDRD, the range of MRD, and COR2) and three index values changed irregularly (COR1, mean r_s and the range of SDRD), while the index of SD_S remained relatively constant. Hence, we called this layer the "irregularly changing layer". In the second layer (60–160 cm), the SD_S, COR1, the range of MRD, mean r_s, and COR2 all increased with increasing soil depth, while the other three indices decreased with increasing depth. Hence, we called this layer the "regularly changing layer". In the third soil layer (160–300 cm), all the eight indices remained approximately constant with increasing soil depth. Hence, we named this layer the "relatively constant layer".

These divisions were different from those of Wang et al. (2013), who explored the vertical distribution of SWC sampled at similar depth intervals to those in our study within 21-m soil profiles at 11 locations on the Loess Plateau of China. Wang et al. (2013) divided the soil profile into three soil layers (0–2.5, 2.5–5 and 5–21 m) in which the SWC was characterized as "decreasing", "increasing", and "increasing with fluctuations", respectively. There were two main reasons that could account for this difference in the division of the soil profiles. Firstly, the two studies were conducted at different scales, i.e., the hillslope scale in this study and the regional scale in theirs. A larger sampling extent would inevitably introduce more variability into the SWCs (Western and Blöschl, 1999). For example, much greater heterogeneity in climate, elevation, land use, and soil properties exists across the Loess Plateau region than on the hillslope, which would greatly affect the recharge depth of rainwater and other soil moisture movement processes leading to more complex spatial patterns in SWC. Secondly, the target indices in the two studies were different, i.e., SWC itself for the study of Wang et al. (2013) while we used statistical variables pertaining to the variability and stability of SWC. In addition, the sampling intensity in our study was much greater than that of theirs, i.e., 91 locations over the studied hillslope (1.5 ha) as compared to only 11 locations across the entire Loess Plateau (620,000 km^2). Higher sampling densities increase the reliability of results (Western and Blöschl, 1999).

4.2. Controlling factors of variability and temporal stability indices

The depth-dependencies of the spatio-temporal variability and temporal stability indices of SWC were mainly due to different factors that affected SWC in different soil layers. The temporal variation of SWC was negatively correlated with its temporal stability. This was indicated by the high linear correlation coefficient between CV_T and mean SDRD ($R^2 = 0.99$) and between CV_T and r_s ($R^2 = 0.86$). Therefore, the controlling factors of temporal variation and temporal stability indices were similar.

Due to the semi-arid climate of the study area, local factors, including vegetation type and distribution, and soil properties, would greatly influence the redistribution of SWC (Grayson et al., 1997). Based on this, three possible explanations may be proposed for the decreasing temporal variability and the increasing temporal stability observed within the 0–160 cm soil layer. Firstly, vegetation and climate factors have greater effects on upper soil layers than on deeper ones (Kamgar et al., 1993). Although part of vegetation roots (e.g. *Medicago sativa* L.) could reach a depth of 300 cm, the maximum root indices (e.g. length density, root weight density) appeared in the 0–30 cm soil layers in the present study area based on the works of Wang et al. (2010). The active root zone of the study area in our study was generally 0–60 cm (data not shown), which means that soil water mainly was absorbed from upper 100 cm soil layer. Secondly, Korsunskaya et al. (1995) argued that the soil structure and its ability to retain water are more stable at lower depths. Thirdly, most disturbances caused by the activities of humans and fauna tend to affect the upper rather than the deeper soil layers, and represent an additional source of variability. The combination of the variability due to these three sources, i.e., humans, fauna and vegetation, might be the reason for the observed “irregular changes” in the mean r_s values observed in the upper 60 cm soil layer.

In the third soil layer (160–300 cm), vegetation, rainfall, solar radiation, etc., all have little if any effect on SWC. Thus, in this layer, the temporal variability and stability indices fluctuate around a high value and these fluctuations correspond to those due to the heterogeneity in soil properties. The fluctuation of these indices suggested an absence of depth-dependent variables that could affect SWC variability or stability.

The interactive effects of the related factors help to explain the different spatial variability observed in the three soil layers. In the 0–60 cm layer, the impacts of elevation and clay content on the spatial variation of SWC differed, increased (Fig. 7) and decreased (Fig. 8) with increasing soil depth, respectively. These different roles in controlling the spatial variation resulted in relative uniformity of SWC within this soil layer. In addition, the 0–60 cm soil layer corresponds to the active root zone in which the vegetation tends to uptake water held in the soil at the highest potentials at faster rates than that held at lower potentials. This phenomenon leads to the distribution of SWC within the rooting depths becoming more uniform among locations (Biswas and Si, 2011). Thus, the vegetation can reduce the spatial variability of SWC that would otherwise be greater if it resulted from the heterogeneity of the topography (Hawley et al., 1983) and texture (Tallon and Si, 2004) alone. Thus, the relatively constant spatial variability of SWC in the first layer resulted from the interaction among the factors of elevation, clay content, and vegetation.

Vegetation had diverse effects on SWC in the second layer (60–160 cm). Each vegetation type has each root distribution. For example, the roots of bunge needlegrass (*Stipa bungeana* Trin.) were predominantly distributed in the 0–100 cm soil layer while alfalfa (*Medicago sativa* L.) could reach 300 cm soil layer in the present study area (Wang et al., 2010). In addition, the root distributions varied over space though for the same vegetation type. In other words, plant roots could only reach and directly affect a given depth (Zhu and Lin, 2011) within this layer at a fraction of the sampling locations, and the number of such locations decreased with the increase in soil depth. This change enabled the role of other factors in controlling the variability in SWC to become more apparent in this layer. The variation in elevation among the sampling locations became more important in influencing the variability of SWC in the deeper soil layers (Fig. 7) resulting in stronger variability in SWC in the second layer. Furthermore, the almost constant variability in clay content had little effect on SWC variability in the second layer (Fig. 8). Hence, due mainly to the effect of elevation, the spatial variability of SWC increased with increasing soil depth within this layer.

In the third layer (160–300 cm), elevation and clay content become more important on the spatial variability of SWC, due to the increasing effects from vegetation and rainfall. Furthermore, while the rate of increase of the effect of elevation on SWC was declining (Fig. 7), the variability of the clay content was increasing, especially between 250 and 300 cm (Fig. 8). Hence, the slight fluctuations of the spatial variability of SWC in this layer might be due largely to the effects of interactions between elevation and clay content on the SWC.

4.3. Soil water recharge depth by rainwater

The depth to which soil water recharge can occur is an important factor affecting the distribution pattern of soil water within the soil profile. Wang et al. (2010) found that the rainwater recharge depth was about 100 cm for soils under both *Caragana korshinskii* Kom and alfalfa (*Medicago sativa* L.) in the watershed in which our study area was located. They further indicated that *C. korshinskii* and *M. sativa* consumed more water than crops and natural grassland. Hence, it was reasonable to consider that the recharge depth would be deeper than 100 cm on the studied hillslope, since natural grassland was the dominant land use. In addition, Chen et al. (2008) suggested that infiltrating rainwater would usually recharge the 0–200 cm soil layer in the Loess Plateau region. The rainfall of their study area was 460 mm, which was a little higher than the rainfall amount occurring during our study (430 mm). In addition, the mean soil bulk density of the 0–60 cm layer was lower in their study (1.1 g/cm^3) than in our study (1.3 g/cm^3). These factors would mean that the recharge depth would have been greater in their study than in ours. Therefore, it was likely that the maximum soil water recharge depth by rainwater was more than 100 cm but less than 200 cm on the studied hillslope. Therefore, based on the variability and temporal stability for SWC being relatively steady below 160 cm, it was reasonable to infer that the maximum soil water recharge depth was approximately 160 cm in the study area. This recharge depth was comparable with the finding of Gao et al. (2011a), who concluded that infiltration could reach depths of 140–160 cm at the Yuanzegou catchement, which was close to the hillslope in our study.

When spatio-temporal variability and temporal stability characteristics of SWC are investigated along soil profile, the sampling depth should at least extend to the layer in which the indices are approximately constant. Therefore, the sampling depth must be deeper than 160 cm in the study area. Furthermore, taking into account the need to reduce costs in terms of both money and time, choosing 200 cm as the maximum soil sampling depth would be sufficient in areas where conditions are similar to those of this study.

5. Conclusions

In this study, the spatio-temporal variability and the temporal stability characteristics of the SWC within 0–300 cm soil profiles on a hillslope of the Loess Plateau, China, were investigated in detail using eight statistical parameters as indices. Although the spatial distributions within the soil profile differed greatly among the investigated eight statistical parameters, they were all depth dependent. Overall, the indices for both spatio-temporal and temporal stability could be divided into three layers: an "irregularly changing layer" (0–60 cm); a "regularly changing layer" (60–160 cm), and a "relatively constant layer" (160–300 cm). The patterns of dependency mainly depended on the interactions among topography, soil properties, and vegetation. The equilibrium depth between ET and rainfall was approximately 160 cm in the study area. Below this depth, the investigated parameters were almost constant or fluctuated slightly. Therefore, when spatio-temporal variability and temporal stability characteristics in SWC are investigated, choosing 200 cm as the maximum soil sampling depth would be sufficient in areas with conditions similar to those of the study area.

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