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Temporal stability of soil water content for a shallow and deep soil profile at a small catchment scale

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Abstract

Areal estimation of soil water content (SWC) from point measurements is important to characterize hydrological processes. One of the challenges is to develop sampling strategies for determining mean SWC of large areas with the minimum cost in time and money. In this paper, we use the concept of temporal stability, applied to a catchment with plaque mosaic landscape pattern, to test the existence of certain sample locations which consistently show mean behavior irrespective of soil wetness in the shallow and deep soil layers. Data from 70 sites in an experimental catchment of 0.66 km^2 (Donggou catchment), on the Loess Plateau, China, were used to examine temporal stability of SWC for the 0-20 cm and 0-120 cm soil layers during a rainy season. Temporal stability analysis were conducted using four methods including cumulative frequency distributions, Spearman rank correlation coefficient (r_s), mean relative differences (δ) and Pearson's correlation analysis. The spatial pattern of SWC across the entire catchment was generally temporally unstable, but a few sites were temporal stable. The temporal stability of spatial pattern indicated by r_s decreased with increasing mean SWC. The lowest r_s values were 0.508 and 0.812 respectively for 0-20 cm and 0-120 cm soil layers. The lowest r_s values occurred during the transition periods between dry and wet conditions, when the profile was recharged markedly. The standard deviation of δ ($\sigma(\delta)$) ranged from 4.6% to 34.8% for 0-120 cm soil layer, lower than that of the shallow soil profile. Meanwhile, only 8 out of 70 sites for 0-20 cm soil layer but 32 sites for 0-120 cm soil depth had $\sigma(\delta)$ lower than 10%, which indicated greater temporal stability of SWC of the deeper soil layer. The selected catchment average SWC monitoring locations were situated in land use of grassland or forage. Based on the highly significant correlation between the land use and both the spatial distributions of δ (%) and $\sigma(\delta)$, land use may be a convenient criterion for locating SWC measurement locations for field mean or extremes estimation.

Keywords: Temporal stability; Soil water content; Land use; Loess Plateau.
Abbreviations: SWC-soil water content; CASWCM-catchment average soil water content monitoring; r_s-spearman rank correlation coefficient; δ-relative difference; σ-standard deviation.

Introduction

Soil water content (SWC) is a major factor in soil surface hydrological processes. It is both temporally and spatially heterogeneous due to dynamic interactions between environmental factors such as climate, parent material, land use, and topography (Jenny, 1941). This variability has important consequences for plant community structures and ecological processes (Gallardo and Paramá, 2007). There is, therefore, a need to understand the spatial patterns of SWC and their temporal evolution at the catchment scale, and to find a means by which to predict them according to catchment characteristics. Increasing interest has been paid to the temporal stability of SWC since the study of Vachaud et al. (1985) (Martínez-Fernández and Ceballos, 2003; Starks et al., 2006; Brocca et al., 2009). Temporal stability is described as the temporal persistence of a spatial pattern (Kachanoski and de Jong, 1988), or as the time invariant association between spatial location and classical statistical parametric values. Because spatial variability is often scale dependent, Kachanoski and de Jong, (1988) found that temporal stability of spatial patterns was a function of scale. Based on temporal stability analysis, Grayson and Western (1998) pointed out that there are certain parts of the landscape that may exhibit mean behavior and others that may exhibit definable extreme behavior for a catchment with significant differences in relief. The areal mean SWC could also be accurately predicted from these former selected points. However, the usual way to consider temporal stability is to limit analysis to the uppermost soil layer (Goovaerts and Chiang, 1993; Famiglietti et al., 1998; Gómez-Plaza et al., 2000) and there are few studies that consider the whole soil profile. In practice, the locations that are best for estimating the average water contents for a large area can be different for different soil depths (Kachanoski and de Jong, 1988; Comegna and Basile, 1994; Hupet and Vanclooster, 2002). Besides soil depth, soil texture, land use and topographic position, as well as SWC conditions, may influence the location of these representative sites (Vachaud et al., 1985; Grayson and Western, 1998; Hupet and Vanclooster, 2002). As noted by Cosh et al. (2008), soil type, as characterized by bulk density, clay and sand content, was responsible for nearly 50% of temporal stability. The concept of temporal stability therefore needs to be tested in a variety of places and over a large range of time-space scales. Fu et al. (2000) characterized the Loess Plateau of China as a unique landscape overlying very deep loess deposits, and having a variety of landforms created by severe soil erosion including deep gullies, steep slopes and plateaus. The purpose of this present study was, therefore, to investigate the temporal stability of the SWC for both the 0-20 cm soil layer and the 0-120 cm soil layer in a small catchment of the Loess Plateau. Specific objectives were (1) to analyze the SWC data collected in the small catchment, in order to determine temporal changes in the magnitude and spatial pattern of the SWC variability; (2) to estimate the mean SWC based on temporal stability analysis; (3) to detect the possible relationships between SWC temporal stability and environmental factors.

Results and Discussion

Statistical description of SWC

During the experimental periods in 2007, there were 48 observed rainfall events (Fig. 1). The total precipitation was 386.1 mm. Storms were typically of low intensity with small amounts (< 5 mm) of rain. Most rain fell between August and October, when typically about 30% of the precipitation events occurred as a few large storms corresponding to the regional monsoon period. A typical arid period occurred around July 10 when there was less rainfall but also the highest evapotranspiration (Kimura et al., 2006). Increases in SWC at depth typically follow precipitation events, which have occurred hours, days or weeks earlier (Schneider et al., 2003). Figure 1 shows the relationship between the SWC changes and the 10-days of antecedent precipitation for 10 different dates during the study period. When rainfall was low in the initial part of the study period, little immediate effect of precipitation can be clearly seen in relation to the SWC of either the upper 0-20 cm soil layer or the soil profile of 0-120 cm. The lag time would appear to be greater than 10 days in many instances. Larger or more intense rainfall events (typically occurring near the end of the study period) period, the cumulative effect of rainfall can be seen to recharge soil water for the entire 0-120 cm layer, although there is a greater effect on the upper 0-20 cm layer. With increasing mean SWC, the relative variance decreased, implying that the effects on SWC due to factors other than rainfall became less significant.

Cumulative frequency distribution

Four statistical analyses were used to test the temporal stability of the spatial pattern of SWC, which the experimental data suggested depended on the progress of the rainy season. We considered the cumulative frequency function for the dates on which the minimum (July 10) and the maximum (October 11) field-mean SWC were observed (Fig. 2). These plots allowed us to determine if a given location maintained its rank during the experimental period (Vachaud et al., 1985; Martínez-Fernández and Ceballos, 2003; Starks et al., 2006; Brocca et al., 2009). Figure 2 shows that, for the 0-20 cm soil depth, only 3 sampling sites, (32, 45 and 57) had the same rank for both of the selected extreme conditions. There were notable changes in rank for most of the locations during the transition from drier to wetter conditions. This indicates that the wettest and driest sites did not follow the same trends occurring in the near-surface SWC. There were 9 sites (3, 25, 26, 29, 41, 43, 47, 54 and 59) that maintained their rank in the 0-120 cm soil depth. The results differ from the case of a uniformly covered grass field, reported by Vachaud et al. (1985), where no seasonal changes in SWC rank was found. In our catchment, land use pattern with differing types and degrees of vegetative cover affected temporal changes in SWC due to the seasonal change in soil water demands. Thus, it is not possible to directly estimate SWC means and standard deviations for selected locations through the frequency distribution analysis.

Spearman rank correlation coefficient

Table 1 shows the temporal changes in the value of the Spearman rank correlation coefficient (r_s) for the mean SWC of the whole area. In general, the closer the value of r_s to 1, the more stable is the process (Vachaud et al., 1985). Therefore, the 0-120 cm layer-averaged SWC was more stable than that of the 0-20 cm depth over time, and SWC values for the shallower soil layer followed a clear trend whereby they became less stable over time, which corresponded to increased rainfall amounts. The lowest r_s value was 0.508 for the 0-20 cm soil depth and it occurred in the period when there was the greatest change of SWC due to higher rainfall amounts. This followed the recharge period of Aug.17−Sep.3 when the mean SWC increased by 8.5 %. In contrast, for the 0-120 cm soil layer, the lowest r_s was 0.812 and occurred after the recharge period of Sep.22−Oct.11 when there was a 4.3% increase in mean SWC.

The results of the temporal pattern analysis indicate a clear trend whereby the temporal stability of SWC declined with increasing mean SWC, especially notable for the 0-20 cm soil layer. This conforms to the suggestion of Famiglietti et al. (1998) that there was greater stability during dry periods. However, other authors have argued that stability is greater with higher SWC (Gómez-Plaza et al., 2000; Qiu et al., 2001; Hupet and Vanclooster, 2002). In this case, it could attribute the initial stability under drier conditions to the greater influence of topographical characteristics, soil texture, and bulk density. For deeper soil layers, soil water contents were less influenced by this factors (Hu et al., 2010), resulting in a tim-stability in 0-120 cm than that in the 0-20 cm soil layer. Similar results have also been reported (Martínez-Fernández and Ceballos, 2003; Cichota et al., 2006).

Relative differences approach

For a better understanding of the effect of the temporal stability of SWC distributions, the relative difference, δ (%), of SWC between each location related to the average SWC in the 0-20 cm and 0-120 cm soil layers, was presented in an ascending order (Fig.3). The group of sites below a relative difference value of zero would systematically underestimate the mean SWC value while those above zero would overestimate it. The ranges of variation in the δ values (-50.7% to 68.2% in the 0-20 cm soil layer; -61.0% to 72.0% in the 0-120 cm soil layer) were higher than other published results (Vachaud et al., 1985; Grayson and Western, 1998; Schneider et al., 2008). This could be due to the more diverse and complex nature of the study area in relation to soil texture and land use. The effect of soil texture is evident in that the least δ value for both 0-20 cm and 0-120 cm soil layers were observed at site 47, which had a soil

Table 1. Spearman's rank correlation coefficients (r_s) between SWC on consecutive measured dates.

Measurement period	0-20 cm soil layer		0-120 cm soil layer	
	Evolution	r_s	Evolution	r_s
Apr 20 - May 12	Drying (-1.43)^a	0.758**	Drying (-0.68)	0.867**
May 12 - Jun 01	Recharge (+1.94)	0.847**	Recharge (+0.84)	0.899**
Jun 01 - Jun 23	Recharge (+4.15)	0.685**	Recharge (+0.50)	0.878**
Jun 23 - Jul 10	Drying (-6.73)	0.752**	Drying (-1.41)	0.925**
Jul 10 - Jul 31	Recharge (+4.72)	0.723**	Recharge (+1.12)	0.936**
Jul 31 - Aug 17	Drying (-4.43)	0.568**	Drying (-0.99)	0.902**
Aug 17 - Sep 03	Recharge (+8.48)	0.508**	Recharge (+3.06)	0.889**
Sep 03 - Sep 22	Drying (-6.17)	0.585**	Drying (-1.80)	0.864**
Sep 22 - Oct 11	Recharge (+7.23)	0.536*	Recharge (+4.32)	0.812*

** Statistical significance level at α=0.01, * Statistical significance level at α=0.05. ^{a} The values between parenthesis indicate the increment or decrement of mean SWC during each period.

Table 2. Main plant species, percentage distributions, and sampling point numbers for the various land use types in the Donggou catchment, Loess Plateau of China.

Land use types	Main plant species	Percentage distribution (%)	Number of sampling points
Shrubland	Korshinsk Peashrub (*Caragana Korshinskii Kom*)	7	8
Orchard	Apricot (*Prunus armeniaca*)	5	3
Grassland	Bunge Needlegrass (*Stipa bungeana Trin.*)	25	20
Forage land	Alfalfa (*Medicago sativa*)	13	18
Fallow land	Annual grass	9	11
Cropland	Millet in husk [*Setaria italica (L.)Beauv.*], Bean (*Phaseolus vulgaris*)	10	10

texture with a relatively high percentage of sand in the upper 40 cm layer (66.5% of sand compared with a mean of 39.8% for the whole catchment). The greater δ values for both soil layers were obtained for cropland or fallow land sites (e.g., sites 26, 10, 24, and 45). Low standard deviation values, $\sigma(\delta)$, are an indicator of temporal stability. Figure 3 shows that sites having δ values greater than zero had much weaker temporal stability than those with δ values lower than zero. For the 0-20 cm soil layer, the values of $\sigma(\delta)$ ranged from 6.2% to 44.0%, and only 8 of the 70 sites had $\sigma(\delta)$ values lower than 10%. For the 0-120 cm soil layer, the values of $\sigma(\delta)$ ranged from 4.6% to 34.8%, but there were 32 sites with $\sigma(\delta)$ lower than 10%, which indicated greater temporal stability of the SWC of the deeper soil layer. An increase in temporal stability with depth was expected due to the reduced dependence on the climatic, biological, and hydrological factors that determined the SWC dynamics (Martínez-Fernández and Ceballos, 2003; Hu et al., 2009), which was also observed by Cassel et al. (2000) for cropland and by Lin (2006) for forest watersheds. Considering that the $\sigma(\delta)$ values for majority of the sites were larger than 10% for both soil layers, it concluded that the overall spatial pattern of SWC in the study area was not temporally stable, but that some specific locations within the catchment were temporally stable. It could be useful to identify whether any of these temporally stable sites were representative of the mean catchment SWC, and that temporally stable sites were defined as a Catchment Average SWC Monitoring (CASWCM) site (Grayson and Western, 1998). The CASWCM site would have a δ value that is the closest to zero and, additionally, a low $\sigma(\delta)$ value (Grayson and Western, 1998). Therefore, for the 0-20 cm soil layer, the best CASWCM site was number 57, while sites 8 and 56 could also be considered as alternative CASWCM sites; for the 0-120 cm soil depth data, site 3 was the best, with sites 5 and 57 also being acceptable. These selected sites were situated in land use types of grassland or under forage that, when combined, occupied 38% of the surface area of the catchment (Table 2). Thus, the phenology of the vegetation might play a significant role in the temporal stability of the spatial patterns of SWC, as Hupet and Vanclooster (2002) concluded. To confirm the suitability of the selected sites as CASWCM for the catchment, we considered the SWC measurements of the CASWCM made throughout the study period as estimated values, using site 57 for the 0-20 cm soil depth and site 3 for the 0-120 cm soil depth, and those of the remaining 69 sites as mean values for the catchment for each measurement time. It found a good linear relationship between the CASWCM SWC values (y) and the mean catchment SWC values (x) (Fig. 4). The high R^2 values combined with linear gradients having a value close to 1.0, indicates that the selected CASWCM sites would provide good estimates of mean catchment SWC. Pearson´s correlation coefficients were used to detect possible relationships over time between the spatial distributions of δ (%) or $\sigma(\delta)$ and land use, soil and topographic characteristics (Table 3). The correlation coefficients in grassland and forageland were significantly negative, indicating that most soils under these land uses were generally drier and had greater temporal stability compared with those under other land use types. The opposite was found to be the case for fallowland and cropland where the low temporal stability of higher SWC values are probably mainly due to the lower water demands of cultivated vegetation and annual grasses. Comegna and Basile (1994) and Gómez-Plaza et al. (2000) also found evidence for this effect of cultivation. Although there were significant relationships between δ and both soil texture and bulk density, soil physical parameters generally had no significant relationships with $\sigma(\delta)$. This would not be necessarily be the case in other areas since, for example, Cosh et al. (2008), reported that soil parameters not only accounted for approximately 50% of the variability of δ but also accounted for 60% of the $\sigma(\delta)$ variability. Of the topographic properties, only slope had a significant effect on temporal stability for the 0-20 cm soil layer (Table 3), suggesting that surface SWC at sites with lower gradients had stronger temporal stability.

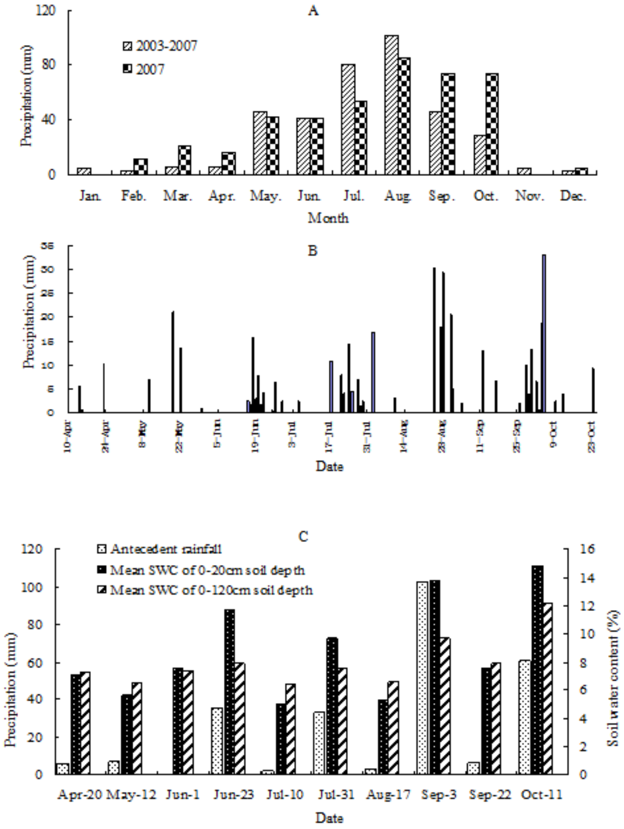

Fig 1. Monthly precipitation distributions of a 5-year (2003-2007) mean and the experimented year, 2007 (A); Individual rainfall distribution during the experimental periods in 2007 (B); The antecedent rainfall (10 days) and the mean SWC for the two soil layers (C).

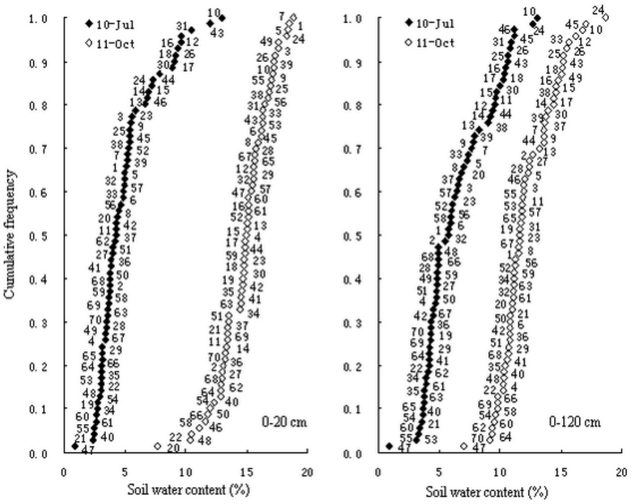

Fig 2. Cumulative probability function (unit less) of the mean SWC of the 0-20 cm and 0-120 cm soil depths for the two extreme soil water conditions during the studied period. Numbers refer to measurement locations.

Material and methods

Study site description

The study site was the Donggou catchment (0.66 km^2) located on the Loess Plateau in Shenmu County, Shaanxi Province, China (38°46′～38°51′N, 110°21′～110°23′E). This is a typical wind-water erosion crisscross zone where soil erosion by wind and water occurs (Fig. 5). The predominant soil is a loessal mein soil (Los-Orthic Entisol, Chinese Taxonomic System (Gong, 1999). The loessal soil profile, showing non-stratified and unconsolidated characteristics, has developed immaturely. There are just two horizons, e.g. A horizon (0-20 cm) and C horizon (below 20 cm) along the soil profile, with no distinct division between them. The C horizon is homogeneous and highly porous. The climate is semi arid with a mean annual rainfall of 364 mm (measured locally between 2003-2007) and a mean annual pan evaporation of 785.4 mm. About 73% of the annual rainfall is received between June and September (Fig. 1).

Experimental design

Five transects were used to establish a total of 49 sampling locations (Fig.5). Each transect passed through one of five down-slope strips under typical land use patterns on adjacent hillslopes. A further 21 sampling sites were located throughout the catchment, producing a total of 70 locations. Gravimetric SWC was determined at each sampling site. All the sites were located on the main soil type. The elevation for the sites ranged from 1,078 m to 1,117 m. Slope aspects ranged between 200^o and 340^o, but along each transect the aspect remained relatively constant (< 55^o). The slope gradients of most sites were around 15°, which was a clear indicator of intensive erosion. The main plant species, their percentage distributions, and the number of sampling points for the different land uses are shown in Table 2. The area occupied by roads, other man-made structures, and inaccessible areas such as gullies, accounts for 31 % of the total catchment area (She and Shao, 2009). Soil samples were collected from each site at 10 occasions during the growing season from April to October, 2007 with approximately 20 day intervals. At each sampling point, soil samples were taken from 0 to 120 cm with 10 cm intervals using a hand auger (sampling diameter of 4 cm). Soil samples were oven dried at 105°C for 24 h for gravimetric SWC measurement. At the end of the experiment in October, undisturbed soil samples were taken from the 0-40 cm layer for determining soil bulk density. An additional five disturbed soil samples from 0 to 40 cm were collected near to the SWC measurement points with a 5 cm diameter hand auger. These five replicate samples were homogenized using hand mixing and a subsample of about 1 kg was brought to the laboratory. Plant roots and shoots, and stones were removed. The remaining soils were air-dried, passed through 1.0 mm sieves for soil mechanical composition determination using a Malvern MasterSizer2000 laser particle size analyzer.

Methods of statistical analysis

Statistical analyses were carried out using Microsoft Excel (version 2003) and SPSS (version 13.0) software. Four statistical techniques were used for temporal stability analysis (Vachaud et al., 1985; Grayson and Western, 1998; Starks et al., 2006):

1. Cumulative probability functions of SWC data at different sampling occasions. With this method, the ability to conserve their ranks for different sampling sites was evaluated.

Table 3. Pearson's correlation coefficients between indices of SWC temporal stability and environmental indexes.

Soil depth	0-20 cm		0-120 cm	
Indices	δ (%)	σ(δ)	δ (%)	σ(δ)
Shrubland	-0.232	0.190	-0.188	0.098
Orchard	-0.097	-0.235	-0.086	-0.116
Grassland	-0.238*	-0.190	-0.286*	-0.364**
Forage land	-0.392**	-0.551**	-0.428**	-0.330**
Fallow land	0.485**	0.366**	0.423**	0.302*
Cropland	0.561**	0.517**	0.686**	0.547**
Clay	0.382**	-0.080	0.319**	-0.120
Silt	0.643**	0.258*	0.556**	-0.033
Sand	-0.632**	0.228	-0.531**	0.003
Bulk density	-0.245*	0.123	-0.35m*	-0.198
Slope degree	0.172	0.254*	0.169	0.166
Cos(aspect)	-0.012	0.125	-0.003	0.107
Relative elevation	0.156	0.179	0.017	-0.222

δ (%) is the Mean Relative Difference and σ(δ) is the Standard Deviation of the Relative Difference. * Significant at P=0.05. ** Significant at P=0.01.

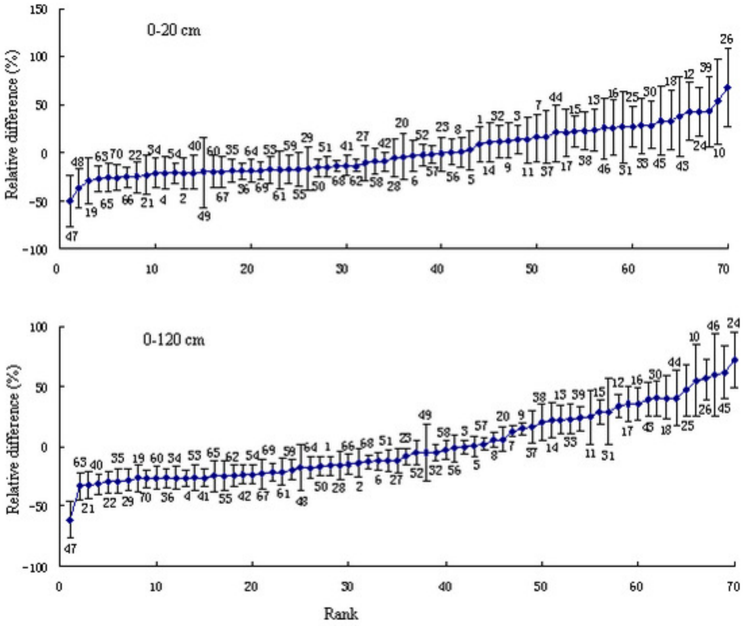

Fig 3. Ranked averages of the relative differences of the SWC data at soil depths of 0-20 cm and 0-120 cm. Bars represent ± one standard deviation, σ (δ), number refers to the measurement location.

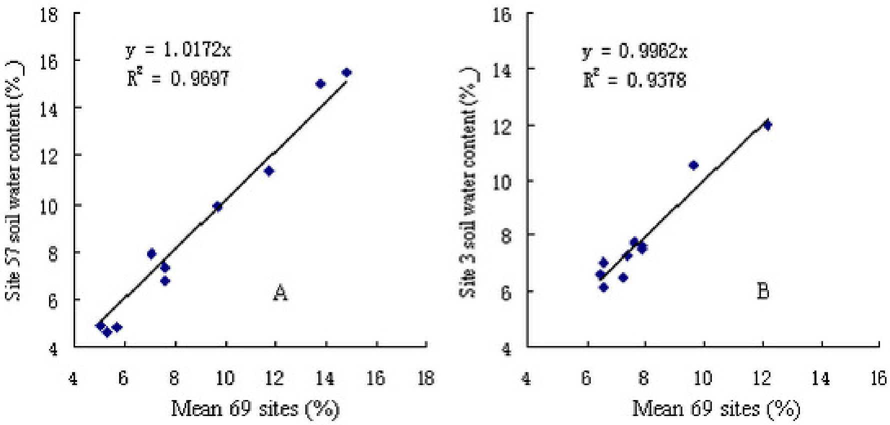

Fig 4. 0-20 cm average soil water content data of the representative mean soil water content at site 57 and the mean soil water content of the remaining 69 sites comparison during the calibration period (A); 0-120 cm average soil water content data of the representative mean soil water content at site 3 and the mean soil water content of the remaining 69 sites comparison during the calibration period (B).

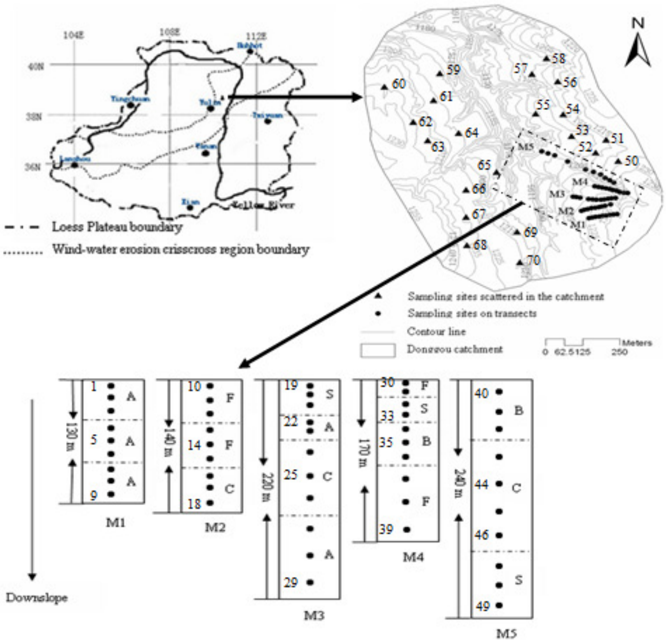

Fig 5. Location of the studied area and distribution of sampling sites: (M1, M2, M3, M4 and M5 refer to sampling transects. A, F, C, S, B refer to grassland, fallow land, cropland, shrubland, and forage land, respectively. Sampling locations are shown by marks that are consecutively numbered. Modified from She and Shao (2009)

2. Parametric test of relative difference. The relative difference, δ_{ij}, is defined as (Vachaud et al., 1985):

$$\delta_{ij} = \frac{\Delta_{ij}}{\overline{S}_j} \qquad [1]$$

where

$$\Delta_{ij} = S_{ij} - \overline{S}_j \qquad [2]$$

and

$$\overline{S}_j = \frac{1}{n}\sum_{i=1}^{n} S_{ij} \qquad [3]$$

S_{ij} being the soil water content at location i at time j, and n the sampling locations. Thus, for each location i, the mean and the standard deviation of the relative differences are given by:

$$\overline{\delta}_i = \frac{1}{m}\sum_{j=1}^{m} \delta_{ij} \qquad [4]$$

$$\sigma(\delta_i) = \sum_{j=1}^{m}\left(\frac{\delta_{ij} - \overline{\delta}_i}{m-1}\right)^{1/2} \qquad [5]$$

where m is the number of sampling occasions. Obviously, a “stable” location in time is characterized by a low value of $\sigma(\delta_i)$.

3. Spearman non-parametric test. This index was used to characterize the persistence of soil water content spatial pattern with time (Brocca et al., 2009), defined by:

$$r_s = 1 - \frac{6\sum_{j=1}^{m}\left(R_{ij} - R_{ij'}\right)^{2}}{n\left(n^2 - 1\right)} \qquad [6]$$

where R_{ij} is the rank of the soil water content observation S_{ij} at location i at time j and $R_{ij'}$ is the rank of the soil water content observation at the same location, but at time j'. n is the number of observations.

4. Pearson´s correlation analysis. Relationships between SWC temporal stability and land use, soil texture, and terrain-based attributes were determined by Pearson´s correlation analysis. A total of 13 explanatory variables (land uses, topographic variables, and soil textures) were used after making the following changes: Land use (shrubland, orchard, grassland, forage land, fallow land and cropland) was transformed into six independent “dummy” variables (0 for absence and 1 for presence); aspect, taken as a compass bearing, was transformed into Cosine (aspect); elevation was defined as relative to the outlet elevation (1,051 m). For each of these transformed variables, relationship between SWC and mean relative difference and associated variance is evaluated using Pearson’s correlation coefficient.

Conclusions

In conclusion, while the spatial pattern of SWC for the experimental catchment was inconsistent over time, some sites exhibited temporal stability across the whole time period analyzed. Such persistent locations that catch well with mean catchment behaviors prove a smaller survey design that is less expensive to implement and provides reasonable characterization of mean processes. Temporal stability of SWC patterns was stronger during dry periods, and was found to increase with soil depth. The representative locations of dry conditions were always more stable. There is a clear trend whereby the temporal stability of SWC, indicated by the rank correlation coefficients, declined with increasing mean SWC. The results obtained here also show that temporal stability was weaker during the transition periods between dry and wet soil moisture status, in which the profile was being recharged markedly. Measurements at Catchment average SWC monitoring (CASWCM) sites were used to represent the catchment scale SWC average and shown to be accurate indicators of the mean SWC. The selected CASWCM sites were situated in land use types of grassland and under forage, which together occupied 38% of the surface area of the catchment. The phenology of the vegetation played a significant role in the temporal stability of the spatial patterns of SWC. Land use may be a good criterion for locating SWC measurement locations for catchment mean estimation. Future work should focus more on the detailed analysis of the seasonal character of temporal stability on areas with changing land cover.

Acknowledgements

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