Catena 132 (2015) 29–36

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

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

Lei Gao [a], Mingan Shao [b,*], Xinhua Peng [a], Dongli She [c]

[a] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, 71 East Beijing Road, Nanjing 210008, PR China
[b] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China
[c] Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China, Ministry of Education, College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, PR China

ARTICLE INFO

Article history:
Received 25 September 2014
Received in revised form 11 March 2015
Accepted 22 March 2015
Available online 28 April 2015

Keywords:
Profile soil water content
Controlling factor
Hillslope hydrology
Rainwater replenishment depth
Semi-arid area

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.

* Corresponding author.
E-mail address: mashao@ms.iswc.ac.cn (M. Shao).

http://dx.doi.org/10.1016/j.catena.2015.03.022
0341-8162/

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 ($\overline{SWC_i}$):

$$\overline{SWC_i} = \frac{1}{M}\sum_{j=1}^{M} SWC_{ij} \tag{1}$$

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

$$\overline{SWC_j} = \frac{1}{N}\sum_{i=1}^{N} SWC_{ij} \tag{2}$$

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