Journal of Hydrology 495 (2013) 150–161

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Spatial pattern of soil moisture and its temporal stability within profiles on a loessial slope in northwestern China

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ARTICLE INFO

Article history:
Received 4 December 2012
Received in revised form 25 April 2013
Accepted 4 May 2013
Available online 10 May 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief.

Keywords:
Spatial pattern
Soil moisture profile
The Loess Plateau
Temporal persistence
Vegetation types

SUMMARY

Temporal stability of spatial distributions of soil moisture are usually observed after repeated surveys of soil moisture across an area. To understand how temporal stability of soil moisture varied with soil depth under the combined influences of vegetation and local topography, we collected soil moisture data at intervals of 10 cm within 1-m profiles on a loessial slope in China in four plots (61 m × 5 m) under different types of vegetation (Korshinsk peashrub, KOP; purple alfalfa, ALF; natural fallow, NAF; millet, MIL). Measurements of soil water content were made by neutron probes on 15 occasions between 2010 and 2012. Soil moisture distributions in both the vertical and horizontal dimensions were investigated to describe its spatial pattern and to lay the groundwork for better understanding its temporal stability characteristics. The results indicated that: (1) soil moisture presented different vertical but similar horizontal trends in the four plots, with significant correlations of soil moisture occurring primarily among adjacent soil layers irrespective of vegetation types, mostly in soil profiles under KOP and ALF and less frequently in soil profiles under NAF and MIL; (2) based on Spearman rank correlation coefficients, with increasing depth temporal stability generally increased under KOP and MIL, but first increased and then decreased under ALF, and increased after the first three measurements under NAF; (3) based on the relative difference technique, points with extreme moisture tended to remain representative at more depths than did points with average moisture and their time stability increased with increasing soil depth; and (4) the correlation between MRD (mean relative differences) and the wetness index weakened with soil depth. The relationship between SDRD (the standard deviation of MRD) and the wetness index varied nonlinearly with soil depth. Vegetation type, soil depth and the wetness index, in descending order of influence, had significant effects on the temporal stability of soil moisture. Among selected soil properties, saturated hydraulic conductivity, bulk density and soil organic carbon all significantly affected the SDRDs. These observations are expected to add valuable information to the theory of temporal stability and for the practices of soil moisture management.

1. Introduction

When repeated surveys of soil moisture at fixed points across an area of interest are conducted, soil water contents at some points are often consistently higher than, equal to or lower than the areal mean (Guber et al., 2008; Pachepsky et al., 2005; Zhou et al., 2007). This phenomenon has been called the temporal stability of soil moisture (Vachaud et al., 1985), and is a reflection of the temporal persistence of soil moisture within a spatial distribution pattern (Kachanoski and De Jong, 1988; Schneider et al., 2008; Zhou et al., 2007). Applying this concept enables an assessment of the status of soil moisture in an area to be made using a relatively small number of observational points (Gao et al., 2011; Jacobs et al., 2004; Martínez-Fernández and Ceballos, 2005), which reduces time and labor costs as compared to sampling randomly at many points. This technique is also useful for providing missing soil-moisture data caused by the malfunction of probes or by other observational problems (Dumedah and Coulibaly, 2011; Pachepsky et al., 2005). Moreover, a field can be subdivided into areas with different conditions of soil moisture according to their temporal

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0022-1694/$ - see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhydrol.2013.05.001

stability characteristics. For each such area, a particular plant species can be planted according to their adaptability to the moisture conditions, and soil water management practices such as mulching (De Souza et al., 2011) and irrigation (Starr, 2005) can be optimized. Given the great potential of these applications, the temporal stability of soil moisture has received much attention since Vachaud et al. (1985) proposed the concept.

Across study areas of various sizes, many environmental factors are linked to the temporal stability of soil moisture. Vachaud et al. (1985) considered soil texture, especially clay content, to be the main explanatory variable for the temporal stability of soil moisture. Locations with gentle slopes consistently exhibited time-stable features, but other landscapes, such as depressions, hilltops and steep slopes, were less time stable (Jacobs et al., 2004). Schneider et al. (2008) reported that the vegetative cover and the management of grazing in a steppe ecosystem affected the temporal stability of soil moisture. In addition to soil properties, topography and vegetation, the depth of observation is an important aspect in the study of the temporal stability of soil moisture (Martínez-Fernández and Ceballos, 2003; Starks et al., 2006). The temporal stability of soil water storage was consistently lower in shallow soil layers than in deeper layers in a wheat field in Carolina, based on the successively increasing magnitudes of the rank correlation coefficients for depths of 15, 23, 30 and 46 cm (Nielsen et al., 2000). Guber et al. (2008) drew a similar conclusion from the index of temporal stability calculated at depths of 10, 30 and 50 cm in agricultural fields in Maryland. In three layers (0–1, 1–2 and 2–3 m) of a deeper soil profile on a hillslope on the Loess Plateau of China, the temporal stability of soil water storage increased with increasing soil depth, using a relative-difference technique (Gao and Shao, 2012). However, similar results were not obtained on another hillslope in the same watershed (Hu et al., 2010), where the temporal stability of soil water content was less at 0.2 m than at depths of 0.6 and 0.8 m. Employing the same two indices used by Hu et al. (2010), i.e. the standard deviation of relative difference (SDRD) and the mean absolute bias error, Gao et al. (2011) found no change in temporal stability with soil depth in sloping jujube orchards on the Loess Plateau. Similarly, observational depth did not significantly affect the distribution of soil moisture in an Australian catchment, based on ranked mean relative differences (MRDs) of soil moisture in the 0–60 and 0–30 cm soil layers (Grayson and Western, 1998). Hence, the variation in temporal stability in soil moisture within a profile remains unknown and thus requires further study, especially by observing a sufficient number of sampling depths at regular intervals in the soil profiles.

The Loess Plateau is an area of the world suffering most from severe soil erosion. The terrestrial ecosystems of the Loess Plateau, due to their fragility, may exhibit early ecological responses to global climate change (Wang et al., 2011). On the Loess Plateau, loessial slope is a fundamental geomorphic type and is characterized by severe rain erosion and an urgent need for revegetation. The soil moisture profile of loessial slopes may deteriorate under the influence of planted vegetation (Chen et al., 2008; Wang et al., 2010), which was intended to prevent the loss of soil and water by influencing the hydrological processes on the slope. The length of the slope is an important factor controlling the hydrological processes (McCool et al., 1989; Moore and Burch, 1986). The relatively short lengths documented in earlier studies of these hydrological processes were not comparable in size to actual field conditions in this region (Fu et al., 2009). To address this issue, four adjacent plots with different types of vegetation, were established on a longer loessial slope (61 m) with similar gradients (12–14°) in 2003. Zeng et al. (2011) examined the temporal-spatial variability of soil moisture and the ability of the revegetation types to control erosion in the initial period (2004–2007). The distribution of moisture and nutrients in the soil during the intermediate period (2008–2009) and the depletion of soil moisture since the establishment of the different vegetation types have also been investigated (Fu et al., 2009, 2010, 2012). The type of revegetation combined with the time since revegetation occurred greatly influenced the temporal-spatial features of the soil moisture in various layers along the slope. As part of the effort to understand the response of soil moisture to vegetation restoration on loessial slopes, Jia and Shao (2013) investigated the temporal stability of water storage in the upper 1 m layer of the soil profiles between 2010 and 2011. Aside from that study, the temporal stability of soil moisture in the plots has been little studied. Moreover, the spatial distribution patterns of soil moisture, whether vertically in profiles or horizontally across the landscape, are still poorly understood.

The temporal stability of soil moisture is scale-dependent in terms of the extent of the study area (Brocca et al., 2009; Vanderlinden et al., 2012). Smaller spatial areas usually respond to smaller variations in topography and soil properties and are thus convenient for providing more detailed information on temporal stability. This study aimed to further understand the temporal stability of soil moisture within soil profiles on loessial slopes. The specific objectives of this study are: (1) to investigate the distribution patterns of soil moisture as a basis for subsequent analysis, (2) to detect variation in temporal stability in soil profiles and (3) to understand the mechanisms controlling temporal stability of soil moisture under the combined influences of vegetation type, soil depth and topography. These objectives are expected to resolve the spatial pattern and temporal stability of soil moisture, with the goal of helping to improve the management of soil water on loessial slopes.

2. Materials and methods

2.1. Study area and experimental layout

This study was conducted on a loessial slope within the Liudaogou catchment of Shenmu County in Shaanxi Province, China. The study area is located in the transitional belt between the Loess Plateau and the Mu Us desert, 38°46′–38°51′N and 110°21′–110°23′E, and covers an area of 6.89 km^2. The terrain is undulating, with an elevation ranging from 800 to 2600 m a.s.l. In the catchment, a series of deep gullies are widely distributed together with large tracts of sloping land. The regional climate is classified as moderate semiarid with an annual mean temperature of 8.4 °C and a mean annual precipitation of 437 mm. Most of the rainfall occurs during the growing season, with 70% of the annual rainfall occurring from June to September.

In 2003, four adjacent plots, 5 m $\times$ 61 m, were established on a uniform loessial slope (12–14°) facing northwest (Fig. 1a). To facilitate measurement of soil water content, 11 aluminum probe access tubes were installed at equal intervals of 5 m along the midline of each plot. Fig. 1b shows the numbered tube positions in the plots (Jia and Shao, 2013). One plot was planted with Korshinsk peashrub (KOP) and one with purple alfalfa (ALF), one was natural fallow (NAF) and one was a millet field (MIL). The soil in all plots is Aeolian loess. The size distribution of the soil particles indicated a loamy texture (USDA system), with 44.1–47% sand, 41.8–43% silt and 10.6–13.3% clay. Detailed information about the plots can be found elsewhere (Fu et al., 2009, 2010, 2012; Jia and Shao, 2013; Zeng et al., 2011).

2.2. Measurement of soil moisture

Soil moisture is a common synonym of soil water (Chesworth, 2007). Neutron probes, a nondestructive but indirect tool commonly used for repetitive measurement of volumetric water