Journal of Hydrology 498 (2013) 254–264

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

Hillslope scale temporal stability of soil water storage in diverse soil layers

Xiaoxu Jia [a], Ming'an Shao [a,b,*], Xiaorong Wei [a], Yunqiang Wang [a,c]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China
[b] Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China
[c] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710075, China

ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form 16 April 2013
Accepted 25 May 2013
Available online 21 June 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Soil water storage
Temporal stability
Representative location
Hillslope hydrology
The Loess Plateau

SUMMARY

Knowledge of the soil water storage (SWS) of soil profiles on the scale of a hillslope is important for the optimal management of soil water and revegetation on sloping land in semi-arid areas. This study aimed to investigate the temporal stability of SWS profiles (0–1.0, 1.0–2.0, and 2.0–3.0 m) and to identify representative sites for reliably estimating the mean SWS on two adjacent hillslopes of the Loess Plateau in China. We used two indices: the standard deviation of relative difference (SDRD) and the mean absolute bias error (MABE). We also endeavored to identify any correlations between temporal stability and soil, topography, or properties of the vegetation. The SWS of the soil layers was measured using neutron probes on 15 occasions at 59 locations arranged on two hillslopes (31 and 28 locations for hillslope A (HA) and hillslope B (HB), respectively) from 2009 to 2011.

The time-averaged mean SWS for the three layers differed significantly ($P < 0.05$) between HA and HB and was greatly affected by topography and vegetation. Temporal–spatial analyses showed that the temporal variation of SWS decreased with increasing soil depth, while the spatial variation increased on both hillslopes. Comparisons of the values for SDRD and MABE and the number of time-stable locations with SDRD and MABE < 5% among various depths indicated that temporal stability increased with an increase in soil depth. The representative sites identified for each hillslope (two on HA and one on HB) accurately estimated the mean SWS for the three soil layers ($R^2 \geqslant 0.95$, $P < 0.001$). SWS on the scale of a hillslope was strongly time stable, and the temporal–spatial patterns of SWS were highly dependent on sampling depth. The temporal stability of SWS patterns was controlled by soil texture, organic carbon content, elevation, and properties of the vegetation in the study area, which was characterised by diverse or complex terrains and plant cover. Such effects, however, might vary across hillslopes due to different conditions of wetness and patterns of land use. This study provides useful information on the profiles of mean SWS on the scale of a hillslope, which is necessary for improving the management of soil water on sloping land on the Loess Plateau.

1. Introduction

Soil water storage (SWS) of soil profiles is critical for understanding a number of hydrological and biological processes (Western et al., 2004; Choi and Jacobs, 2007; Brocca et al., 2009). It is also an important parameter for the rational management of water resources and adoption of vegetational restorations, especially in semi-arid and arid areas, such as the Loess Plateau in China (Hu et al., 2009, 2010a; Gao et al., 2011). Soil moisture is variable in space and time due to soil heterogeneity, climatic forcing, vegetation and topography, but it also shows a somewhat strong temporal stability of spatial pattern (Vachaud et al., 1985; Comegna and Basile, 1994; Mohanty and Skaggs, 2001; Martínez-Fernández and Ceballos, 2005; Brocca et al., 2009, 2010; Hu et al., 2009; Zhao et al., 2010). The concept of temporal stability was first proposed by Vachaud et al. (1985) and is defined as the time-invariant association between spatial location and classical statistical parameters of a given soil property. Kachanoski and de Jong (1988) later expanded the definition of the stability of soil moisture over time as a description of the temporal persistence of spatial pattern. One of the most useful applications of the concept of temporal stability is the potential to identify representative locations that could rapidly and effectively represent the mean SWS of the entire study area of interest. Various studies have recently confirmed and

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China. Fax: +86 29 87012210.
E-mail address: mashao@ms.iswc.ac.cn (M. Shao).

0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.05.042

supported this application of temporal stability (Gómez-Plaza et al., 2000; Grayson et al., 2002; Cosh et al., 2008; Hu et al., 2009; Zhao et al., 2010; Brocca et al., 2012).

The concept of temporal stability has been broadly applied in various types of land uses, such as grassland (Vachaud et al., 1985; Schneider et al., 2008; Zhao et al., 2010), cropland (Martínez-Fernández and Ceballos, 2003; Guber et al., 2008), and forests (Lin, 2006), and over different climatic zones, such as semi-arid (Gómez-Plaza et al., 2000; Hu et al., 2010a; Zhao et al., 2010), semi-humid (Brocca et al., 2009, 2010; Heathman et al., 2009), and humid (Jacobs et al., 2004) zones. This concept has also been applied to the study of soil moisture on the Loess Plateau, where the water content is the most crucial factor for the restoration of vegetation (Hu et al., 2009, 2010a,b; Gao et al., 2011; Gao and Shao, 2012; Jia and Shao, 2013). Most studies on the temporal stability of soil moisture on the Loess Plateau have focused on the surface soil layer, and only few of them (Hu et al., 2010b; Gao and Shao, 2012) have addressed the entire soil profile. The Loess Plateau is known for its complex terrains, patterns of land use, and soil types, which can lead to large spatial variations of soil water (Hu et al., 2009; Wang et al., 2012). Because the restoration of vegetation must be implemented on relatively small scales (e.g. hillslopes or small watersheds) due to the high variability of soil water, studies of the temporal stability of SWS for various soil layers on the scale of a hillslope can be very important for the optimal management of soil water on the Loess Plateau, especially during the restoration of vegetation (Hu et al., 2010a). Information characterising the temporal stability of the SWS profile on the scale of a hillslope is also helpful for developing more efficient and effective sampling strategies and predictive models for monitoring water in such areas with large variabilities of soil, terrain, and vegetation (Zhao et al., 2010).

The temporal stability of soil moisture has been linked to many factors, such as soil, topography, and vegetation. Elucidating the effects of various factors on the stability of SWS over time is beneficial both for the identification of representative locations and for projecting the temporal stability of areas that have not yet been sampled (Vanderlinden et al., 2011). These factors, however, contribute variously to the identification of representative locations of temporal stability of soil moisture due to differences in the landscapes, land uses, sampling scales, and sampling times. The temporal stability of soil water content in a watershed is mainly controlled by the distribution of soil particle size (Hu et al., 2010a). Gao et al. (2011) suggested that the best locations for estimating the mean soil moisture in sloping jujube orchards should be the locations with relatively high clay contents, relatively gentle slopes, and relatively planar surfaces, agreeing partly with the findings of Grayson and Western (1998) and Jacobs et al. (2004). Gómez-Plaza et al. (2000) identified topographic effects or local topography as the main influences on temporal stability of soil water content on the scale of a transect, as supported by a recent report (Penna et al., 2013) on the scale of hillslopes. The temporal persistence of soil moisture in a relatively flat semi-arid steppe depended on the management of grazing and on the related plant cover (Schneider et al., 2008). Temporal stability is also dependent on soil depth (Martínez-Fernández and Ceballos, 2003; Pachepsky et al., 2005; Guber et al., 2008; Hu et al., 2010b). Soil moisture in deeper layers tends to be more stable (Guber et al., 2008; Gao and Shao, 2012). Furthermore, the determination of the temporal stability of soil moisture can depend on the scale of the study (Kachanoski and de Jong, 1988; Gómez-Plaza et al., 2000; Biswas and Si, 2011). No consistent conclusions have thus been drawn on the factors contributing to temporal stability. In contrast to some studies with relatively uniform soil type, terrain, or vegetation, the relationships between the temporal stability of soil water and the potential contributing factors on the Loess Plateau may be complicated by the complex distribution of soil types, terrains, and plant covers.

Neutron probes have been widely used to measure soil water content (Caysi et al., 2009; Hu et al., 2009, 2010a, 2010b; Gao and Shao, 2012), because they can measure temporal changes at defined positions. Neutron probes yield accurate results (Muñoz-Carpena, 2012) and are non-destructive. They may be used irrespective of the state of the water. The output from neutron probes can be directly related to the soil water content (Chanasyk and Naeth, 1996). The equipment, however, requires extensive soil-specific calibration to obtain reliable data. Several studies have indicated that temporal stability of soil water may be affected by the type of sensor used (Kirda and Reichardt, 1992; Reichardt et al., 1997; Guber et al., 2008). The assessment of temporal stability of soil water using neutron probes, though, has been well demonstrated on the Loess Plateau (Hu et al., 2009, 2010a,b; Gao and Shao, 2012).

Because of the widespread restoration of vegetation on sloping land and the low carrying capacity of soil water for vegetation (Xia and Shao, 2008) in the study area, information on the SWS profiles on the scale of the hillslope is necessary to guide the strategies of revegetation and to optimise the management of water. For a deeper insight on the temporal stability of SWS profiles, this study used neutron probe data collected on two adjacent hillslopes, over 15 occasions from June 2009 to August 2011. The specific objectives of this study were: (i) to gain insight into the temporal–spatial characteristics of SWS for the various soil layers on two adjacent hillslopes, (ii) to analyse the temporal stability of SWS profiles for identifying representative locations that could estimate the mean SWS of a hillslope, and (iii) to investigate the factors that control the temporal stability of SWS profiles on the scale of a hillslope.

2. Materials and methods

2.1. Study site

This study was conducted on two typical hillslopes (HA and HB) of the Loess Plateau in the Liudaogou watershed located in Shenmu County, Shaanxi Province, China (Fig. 1). The Liudaogou watershed is characterised by many deep gullies and undulating loessial slopes. This area lies in a moderate-temperate and semiarid zone with an annual mean precipitation of 430 mm, approximately 77% of which occurs from July to September. The average annual temperature is 8.4 °C, and the mean annual potential evapotranspiration reaches 785 mm. The elevations of the Liudaogou watershed range from 1094 to 1274 m above sea level. The study area is representative of the transitional belt subjected to both wind and water erosion. The soil is a Calcaric Regosol (FAO-UNESCO), developed from low-fertility loess. The soil has weak cohesion, high infiltrability, low water retention, and is prone to erosion. The vegetation has been widely restored in the region during the past decade to remedy the degradation of the soil. This restoration used plants typical of arid land, including purple alfalfa (*Medicago sativa* L.), Korshinsk Peashrub (*Caragana korshinskii* K.), and apricot trees (*Prunus armeniaca*), or recovered abandoned cropland with natural vegetation.

The average slopes of HA and HB are approximately 14° and 19°, respectively. HA and HB are separated by a deep gully. The two hillslopes have received different strategies of vegetational restoration, which have created differences in the patterns of land use and thus in vegetational cover. Restored grassland and forest usually occur as patches in this area. The dominant land uses on HA are grassland occupied by bunge needlegrass (*Stipa bungeana* T.), with some alfalfa (*M. sativa* L.) and *Artemisia scoparia*, and forest with a low planting density of apricot trees. HA also contains some farmland for millet production. HB is mainly covered by abandoned