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Estimation of soil water storage using temporal stability in four land uses over 10 years on the Loess Plateau, China

Bingxia Liu [a,c], Ming'an Shao [b,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, Shaanxi, China
[b] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A & F University, Yangling 712100, Shaanxi, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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SUMMARY

An understanding of the temporal stability of soil water storage (SWS) in deep soil profiles is critical to optimize monitoring strategies and to predict the status of soil water on the Loess Plateau. This study tested and validated the feasibility of estimating mean SWS over multiple years by the SWSs at selected locations. The SWSs in 0–1, 1–2, 2–3, and 3–4 m layers were collected using neutron probes at 11 sites in each of four land-use types: cropland (CL), grassland (GL), fallow land (FL), and shrubland (SL). The most time-stable locations (MTSLs) for the various layers and the location at mid-slope for each land use were selected on 20 sampling occasions during a calibration period from July 2004 to December 2005. A validation data sets from January 2006 to October 2013 was used to test the length of time the estimates of mean SWS remained valid. The SWSs in SL and GL decreased with plant growth, and the temporal variations were larger in SL and GL than in FL and CL. The temporal stability of the SWSs was high for all soil layers in four land uses, with the rank correlations over the threshold of significance ($\alpha = 0.05$) over 10 years. The degree of temporal stability of SWSs was ranked as CL > FL > GL > SL, and the temporal stability of SWSs in SL and GL decreased with increasing lengths of observation period, as indicated by lower mean Spearman's correlations for all soil layers. The MTSLs selected from the calibration period could accurately estimate mean SWSs for diverse layers under four land uses with estimation errors less than 10% over eight years. The study verified that a single location at mid-slope of each land use could be sampled in order to reduce the required number of samples and save time and labor while maintaining a high accuracy of prediction over multiple years.

1. Introduction

Soil water is a critical variable in studies of hydrological processes and the soil–plant–atmosphere continuum, especially in arid and semi-arid regions. It is the most limiting factor for the production and restoration of vegetation on the Loess Plateau of China (Xia, 2008; Gao et al., 2011; Jia and Shao, 2013a), controlling the patterns of the spatial and temporal distributions of vegetation. Obtaining accurate soil water data at landscape scales economically, however, is difficult due to the strong temporal–spatial variability of soil water (Dobriyal et al., 2012). Soil moisture also varies with soil depth due to the heterogeneity of environmental factors and soil properties (Wang et al., 2013). Conventional monitoring of soil water involves *in situ* point measurements at fine resolution in both space and time, which is expensive, time-consuming and labor-intensive. The accurately estimation of soil water storage (SWS) by monitoring the optimal locations is thus essential for managing water resources efficiently.

Despite the strong spatiotemporal variability of soil water, previous studies have indicated that the spatial patterns of soil water are time-stable, that is, the rank of soil water at sample locations does not change with time, at a high probability (Brocca et al., 2009, 2010; Hu et al., 2010a, b; Joshi et al., 2011). Vachaud et al. (1985) first found that the spatial patterns of soil water changed slightly with time and that field-averaged soil water was persistent over time even though observed at specific locations. Kachanoski and de Jong (1988) defined the stability of soil moisture over time as the temporal stability of the spatial pattern. The temporal stability of soil water has since been extensively applied to identify time-stable sites that represent the field mean soil water conditions (Martínez-Fernández and Ceballos, 2005; De Lannoy et al.,

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

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2007), to model hydrologic variables (Brocca et al., 2009; Minet et al., 2011; Zehe et al., 2010), and to optimize the measurement of soil water (Cassel et al., 2000; Heathman et al., 2009).

The temporal stability of soil water is affected by many factors, such as length of observation period (Martinez et al., 2013) and type of land use or vegetation (Ruiz-Sinoga et al., 2011; Jia et al., 2013). Jia and Shao (2013b) reported that re-vegetation types had significant effects on the temporal stability of SWS within the 0–1 m profile, and further confirmed that the vegetation cover and aboveground biomass were the main factors affecting the temporal stability of soil water. A model used by Martinez et al. (2013) indicated that season and length of observation period impacted the determination of temporal and spatial variability over one year. Studies, though, have mainly focused on short-term measurements of soil moisture (Cosh et al., 2006; Schneider et al., 2008), with only a few studies evaluating the temporal stability of soil moisture for periods longer than three years of observation periods (Martínez-Fernández and Ceballos, 2003; Gao and Shao, 2012; Jia et al., 2013).

The concept of temporal stability has been applied to up-scale or downscale soil moisture with less effort (Blöschl et al., 2009; de Rosnay et al., 2009; Guber et al., 2008; Hu and Si, 2014). Information on temporal stability has been useful in accurately estimating average soil water from measurements at time-stable points on the Loess Plateau of China, such as identifying the most time-stable locations (MTSLs) of an area (Hu et al., 2009; Jia et al., 2013; She et al., 2012). Gao et al. (2013), Hu et al. (2013) estimated the mean soil water in an area using MTSLs from a different area. Jia and Shao (2013a, b) explored the effects of vegetational type and soil properties on the spatial pattern of temporal stability and applied the temporal stability to estimate mean SWS in 0–1 m soil profiles in our study area. Rolston et al. (1991) reported that selected single sampling locations could be used to predict SWS over two years after an initial analysis of temporal stability because the spatial pattern was fairly persistent for more than one year. The use of the same sampling locations for more than two years, however, increased the error in estimating the average storage. Little information has been attained, though, for the length of time soil moisture at representative points could reliably estimate mean soil water in a study area. In order to obtain a better insight into the temporal stability of SWS in diverse soil layers, this study used neutron-probe data collected from four types of land use, over 68 occasions from July 2004 to October 2013. The specific objectives of this study were: (i) to evaluate the temporal stability of SWSs in various soil layers in 0–4 m profile under four land uses, (ii) to evaluate the effect of the duration of observation periods on the temporal stability of SWS, and (iii) to examine the length of time SWS measured at the selected locations could reliably predict the spatially-averaged SWS in the study area.

2. Materials and methods

2.1. Description of study site

The field measurements were conducted on a hillslope in the Liudaogou watershed (38°46′–38°51′N, 110°21′–110°23′E) in Shenmu County, Shaanxi Province, China (Fig. 1a and b). The watershed covers an area of 6.89 km^2 and the elevation ranges between 1094 and 1274 m. The region has a moderate semiarid continental climate, with a mean annual temperature of 8.4 °C (ranging from −9.7 °C in January to 23.7 °C in July) and a mean annual precipitation of 437 mm. More than seventy percent of the annual precipitation occurs during the growing season (June to September). The distributions of monthly rainfall and mean air temperatures at the study area from 2004 to 2013 are shown in Fig. 2. Amounts of precipitation near the mean annual value of 414 mm fell in 2004, 2009, and 2010, but 2005, 2006, and 2011 were dry years, with rainfalls of 315.1, 290.6, and 303.5 mm, respectively, and the other years were wet years.

A plot (61 m × 5 m) was established in each of four land uses in 2003 on a uniform slope (12–14°) facing northwest (Fig. 1c). The four land uses consisted of three typical vegetative restorations and one crop: Korshinsk Peashrub (shrubland, SL), purple alfalfa (grassland, GL), naturally recovered vegetation (fallow land, FL), and soybean (cropland, CL). The soil in all plots is an Aeolian loess, with a loamy texture (USDA soil textural classification) composed of 45–51% sand, 30–45% silt, and 11–14% clay (Zeng et al. 2011). The background levels of bulk density and hydraulic conductivity of the top 0–0.2 m soil layer on the hillslope were 1.50 g cm^{-3} and 0.94 mm min^{-1}, respectively (Fu et al. 2010).

2.2. Sampling and measurements

Eleven aluminum neutron-probe access tubes, 4 m in length, were installed at regular intervals of 5 m along the midline of each plot (Fig. 1c). Soil moisture was measured with a neutron moisture meter, the CNC 503DR Hydro probe (Beijing Super Power Company, Beijing, China), at increments of 0.1 m between 0 and 1 m and at increments of 0.2 m below 1 m. Soil moisture was measured once a month from July 2004 to September 2007 (twice in July and September 2004), April to October in 2008, 2009, and 2011, and July to October 2010, and approximately every two weeks from May to October in 2012 and 2013. Data were collected from the 11 probes in each plot in the 0–4 m profiles on a total of 82 sampling occasions during the sampling period. Only the data from 68 occasions were analyzed, however, due to missing data or to periods of rain.

Soil moisture samples from 13 sampling occasions within a minimum sampling period of one year have been deemed sufficient to identify representative time-stable locations for estimating mean soil water content (Martínez-Fernández and Ceballos, 2005; Schneider et al., 2008; Hu et al., 2012). Some studies have also indicated that the effect of measurement frequency on the determination of soil water temporal stability and the estimation of mean soil water content was little (Guber et al., 2008; Hu et al., 2012; Vanderlinden et al., 2012). To analyze the temporal stability of SWSs, we thus divided the complete data sets into two groups. Twenty sampling occasions from July 2004 to December 2005 were chosen for calibration, and the other group of 48 sampling occasions from January 2006 to October 2013 was used for validation. The calibration identified the time-stable locations and the MTSLs. The validation data set tested the possibility of using SWS measured at the selected time-stable locations to estimate the mean SWS of a soil profile at the scale of the hillslope.

2.3. Statistical analyses

2.3.1. Assessment of temporal stability

Spearman's rank correlation test (r_s) is a non-parametric test between variables and was used to analyze the temporal stability of soil water spatial patterns. We used r_s to evaluate the effect of the length of observation periods on the determination of temporal stability. The r_s is defined as (Vachaud et al., 1985):

$$r_s(j_1, j_2) = 1 - \frac{6\sum_{i=1}^{n}(R_{ij1} - R_{ij2})^2}{n(n^2 - 1)} \tag{1}$$

where n is the number of sampled locations, R_{ij1} is the rank of the variable SWS measured at location i on day j_1, and R_{ij2} is the rank of SWS at the same location on day j_2. The closer r_s is to one, the more stable the SWS spatial patterns between different sampling dates will be.