Journal of Hydrology 527 (2015) 1034–1044

Contents lists available at ScienceDirect

Journal of Hydrology

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

Scale-dependence of temporal stability of surface-soil moisture in a desert area in northwestern China

Pingping Zhang [a,b], Ming'an Shao [a,b,c,*], Xingchang Zhang [a,b]

[a] Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources, Yangling 712100, China
[b] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling 712100, China
[c] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographical Science and Natural Resources, Chinese Academy of Sciences, Beijing 100101, China

ARTICLE INFO

Article history:
Received 23 April 2015
Accepted 10 May 2015
Available online 16 May 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Sampling scales
Re-sampling method
Temporal stability
Soil moisture
Desert ecosystems

SUMMARY

Soil moisture is an important component in hydrological cycles but is highly variable in space and time. As a tool for optimal soil and water management and effective field monitoring, the analysis of temporal stability has recently received increasing interest. The scale dependence of temporal stability, however, has received little attention. We measured surface-soil (0–6 cm) moisture at 187 sampling locations in a desert region (40 km^2) in northwestern China approximately every two weeks from April to October 2012 with a Theta Probe, for a total of 13 sampling campaigns. We grouped the samples by re-sampling analysis under six sampling spacings and six different sizes of sampling area (extents) to analyse the changes in the characteristics of temporal stability at the various sampling scales and to test the accuracy of the field-mean moisture content estimated by measurements at a limited number of locations at each sampling scale. Increasing the spacing had little influence on the temporal stability of both the overall spatial pattern and the individual locations, whereas increasing the extent tended to increase the temporal stability of the overall spatial pattern but to decrease the temporal stability at the individual locations. The characteristics of temporal stability were susceptible to changes in scale when extent was small. Exponential and power equations could well express the relationships between most of the parameters of temporal stability and sampling scale. The number of identified representative locations (RLs) was influenced by sample size and was more sensitive to changes in sample size caused by extent than by spacing. At all sampling scales, the sets of selected RLs accurately estimated the field mean for the entire study period by using offset estimates, and the estimate accuracy was not affected by sampling scale. Increasing the spacing did not change the influence of topography and soil properties on temporal stability, whereas increasing the extent tended to intensify the influence of relative elevation and soil organic carbon content but to weaken the influence of saturated hydraulic conductivity on temporal stability. This study contributes to our understanding of the dependence of temporal stability of soil moisture in desert ecosystems on sampling scale and will help the integration of information from different spatial scales and the design of optimal sampling sizes and strategies for similar studies.

1. Introduction

Surface-soil moisture is a key component of the hydrological cycle (Choi and Jacobs, 2007; Heathman et al., 2012). It plays an active role in controlling the exchange of water and energy between the land surface and the atmosphere (Vereecken et al., 2007; Sur et al., 2013; Vereecken et al., 2014). In arid desert environments, it also acts as a key factor limiting the growth of vegetation (Thornes, 1985), and its dynamics largely control the spatial and temporal distribution of vegetation and the restoration and reconstruction of degenerated ecosystems (Berndtsson et al., 1996; Rodriguez-Iturbe et al., 1999). Soil moisture, however, is highly variable in space and time across different scales, so characterising the behaviour of soil moisture can be challenging (Vereecken et al., 2007).

The analysis of the temporal stability of soil moisture is receiving increasing interest. This concept was first introduced by Vachaud et al. (1985) and is a reflection of the temporal persistence of the spatial structure (Kachanoski and Jong, 1988). This method can identify representative temporally stable locations that can predict the field-mean soil moisture over long periods and can thus

* Corresponding author at: Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China. Fax: +86 29 87012210.

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

http://dx.doi.org/10.1016/j.jhydrol.2015.05.015
0022-1694/© 2015 Published by Elsevier B.V.

help to optimise soil and water management and effective field monitoring (Martínez-Fernández and Ceballos, 2003). Variable soil moisture at a location is due to the operation and interaction of underlying hydrological processes at different spatial scales, so the spatial variability of soil moisture is often a function of scale (Famiglietti et al., 2008). Kachanoski and Jong (1988) thus extended the concept of temporal stability with an analysis of spatial coherence and indicated that the temporal stability was also strongly scale dependent. An adequate understanding of this scale dependence is the basis for the integration of information from different spatial scales (Western and Blöschl, 1999) and would be extremely beneficial for developing efficient and effective strategies of soil sampling for the validation of remote-sensing techniques and the application of some climate and hydrological models (Starks et al., 2003; Mittelbach and Seneviratne, 2012).

The temporal stability of soil moisture has been determined for different purposes over a wide range of scales, from field and hillslope scales to watershed and regional scales. The characteristics of temporal stability, however, can vary greatly between scales. For example, Zhao et al. (2010), Brocca et al. (2009) and Coppola et al. (2011) investigated the temporal stability of the spatial patterns of surface-soil moisture at field scales (225–8800 m^2) and found that the range of mean relative difference (MRD) (Eqs. (1) and (2))was low, generally 20–60%. Grayson and Western (1998) and Cosh et al. (2006), however, reported that the ranges of MRD in 27 and 610 km^2 watersheds were approximately 95% and 170%, respectively. Bosch et al. (2006) reported that the range of MRD exceeded 200% in a 3750 km^2 coastal plain in the United States. The range of MRD thus appears to increase with the size (hereafter, extent) of the study area. Conflicts and divergences, however, have also been reported. For example, Hu et al. (2010) observed that the range of MRD was over 170% in a small watershed (20 ha), whereas Brocca et al. (2012) found that the range of MRD was only approximately 50% in two larger watersheds (178 and 242 km^2). Contradictory results have also been reported for other characteristics of temporal stability, such as the standard deviation of relative difference (SDRD) (Eqs. (3) and (4)) and Spearman's rank correlation coefficient (r_s) (Eq. (5)). Obtaining a clear picture of the characteristics of temporal stability at different scales by simple comparisons of the achieved results is thus difficult, because various studies differ not only in sampling scales but also in environmental conditions, layout of the experiments, and measurement techniques (Vanderlinden et al., 2012). These differences strongly hinder the application of the results to different scales. Systematic study of the effect of scale on the characteristics of temporal stability is thus necessary.

Given the importance of soil moisture in desert ecosystems, the characteristics of the temporal stability of soil moisture at one scale have been preliminarily studied in various desert regions, but little information is available for multiple scales. Whether the temporal stability can be maintained under increasing scale remains unknown. We thus measured surface-soil moisture in a 40 km^2 desert region on 13 occasions from April to October 2012. Re-sampling method was then employed with changing sampling scale (spacing and extent), and the characteristics of temporal stability for each scenario were determined. The objectives of this study were (1) to provide a better understanding of the variation in the characteristics of temporal stability with increasing sampling scales, (2) to test the accuracy of the field-mean moisture content estimated at each sampling scales by using the concept of temporal stability, and (3) to analyse the changes in contributions of topography and soil properties to the temporal stability with changing sampling scales. These objectives could provide a scientific basis for designing efficient sampling schemes, integrating information from different spatial scales, and allowing upscaling in hydrological models.

2. Materials and methods

2.1. Study area and data collection

The experiment was conducted in a desert area in the central reaches of the Heihe River Basin in Gansu Province in northwestern China (Fig. 1). The topography is relatively flat, with an average elevation of ca. 1421 m a.s.l. The area is characterised by an arid desert climate, with a mean annual precipitation of 117 mm, temperature of 7.6 °C, and pan evaporation of 2390 mm. Precipitation is highly variable throughout the year, with nearly 65% falling during July and September. The zonal soil has been classified as a gray-brown desert soil, and the soil texture is quite spatially heterogeneous, ranging from sand to clay. The vegetative cover is approximately 5–15%, and the main species are discontinuous sub-shrubs, such as *Nitraria sphaerocarpa* Maxim. and *Reaumuria soongorica* (Pall.) Maxim.

The study area is approximately 40 km^2 (8 km × 5 km) (39°24′ to 39°28′N and 100°08′ to 100°11′E), bordered by a young oasis to the southwest, a remnant of the Qilian Mountains to the north, and an extension of the Badain Jaran Desert to the southeast (Fig. 1c). Wooden stakes were set on a regular 500 m × 500 m grid throughout the area at a total of 187 locations for measurements of soil moisture. Each location was positioned with a portable Garmin GPS receiver (with a resolution of 3 m). A Theta Probe (Type ML2x, Delta-T Devices, Cambridge, UK) was inserted vertically in the soil to measure the surface (0–6 cm) volumetric soil moisture content approximately every two weeks from 15 April to 15 October 2012, providing a spectrum of moisture conditions ranging from dry to wet. A total of 13 sampling campaigns were conducted. To reduce the possible influence of micro-scale variability, three replicate measurements were conducted within a radius of approximately 10 cm for each location and campaign. Detailed information on the calibration of the probe can be found in Zhang and Shao (2013).

Disturbed and undisturbed soil samples were collected from the 0 to 6 cm soil layer at each location. The disturbed samples were used for measuring soil particle size distribution and soil organic carbon (SOC, g/kg) content. Soil particle sizes were evaluated using the Mastersizer2000 apparatus manufactured by Malvern, and SOC content was measured by using the potassium dichromate-wet combustion method (Nelson and Sommers, 1982). The undisturbed samples were used for determining saturated hydraulic conductivity (Ks, mm/min), using the constant hydraulic head method (Klute and Dirksen 1986), and determining soil bulk density, (BD, g/cm^3) and total porosity (TP, %), using the gravimetrical method.

2.2. Analysis of temporal stability

We evaluated the temporal stability of soil moisture by two statistical approaches. First, the temporal stability of individual locations was determined using an analysis of relative differences (Vachaud et al., 1985). This approach compares the soil-moisture content at a particular location to the mean over the entire study area and determines if it is consistently higher or lower than the mean and the variability of this relationship. The relative difference, δ_{ij}, of the soil-moisture content, θ_{ij}, for each location i is calculated as:

$$\delta_{ij} = \frac{\theta_{ij} - \overline{\theta_j}}{\overline{\theta_j}} \quad (1)$$

where $\overline{\theta_j}$ is the mean soil-moisture content over the entire area on sampling occasion j:

$$\overline{\theta_j} = \frac{1}{N}\sum_{i=1}^{N}\theta_{ij} \quad (2)$$