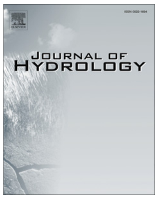
Journal of Hydrology 551 (2017) 47–55

Contents lists available at ScienceDirect

Journal of Hydrology

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



Research papers

Environmental controls on the spatial variability of soil water dynamics in a small watershed

Wei Hu[a,*], Henry Wai Chau[b], Weiwen Qiu[a], Bingcheng Si[c,d]

[a] *New Zealand Institute for Plant & Food Research Limited, Private Bag 4704, Christchurch 8140, New Zealand*
[b] *Department of Soil and Physical Sciences, Lincoln University, Christchurch 7647, New Zealand*
[c] *University of Saskatchewan, Department of Soil Science, Saskatoon, SK S7N 5A8, Canada*
[d] *College of Hydraulic and Architectural Engineering, Northwest A&F University, Yangling 712100, China*

ARTICLE INFO

Article history:
Received 8 March 2017
Received in revised form 26 May 2017
Accepted 26 May 2017
Available online 29 May 2017

Keywords:
Empirical orthogonal function
Controlling factor
Soil moisture
Topography
Spatial variability
Temporal stability

ABSTRACT

Soil water content (SWC) in the root zone is controlled by a suite of environmental variables. Complication arises from the cross-correlation between these environmental variables. Therefore, there is still a poor understanding on the controls of root zone SWC dynamics due, in part, to a lack of an appropriate method to untangle the controls. The objective of this study was to reveal the dominant controls of root zone soil water dynamics in a small watershed using an appropriate method based on empirical orthogonal function (EOF). For this purpose, SWC of 0–0.8 m layer in a small watershed on the Chinese Loess Plateau was used. The space-variant temporal anomaly (R_{tn}) of SWC, which is responsible for the spatial variability of soil water dynamics, was decomposed using the EOF. Results indicated that 86% of the total variations of R_{tn} were explained by three significant spatial structures (EOFs). Sand content and grass yield dominated the EOF1 of R_{tn} and elevation and aspect dominated EOF2 and EOF3 of R_{tn}, respectively. Moreover, their effects on soil water dynamics were time-dependent. The EOF analysis showed that three independent groups of factors (i.e., soil and vegetation dominated earth surface condition, elevation related near surface air humidity, and aspect regulated energy input) may drive the variability in soil water dynamics. Traditional correlation analysis, however, indicated that SWC was greater at higher elevation and sun-facing slopes, which distorted the soil water dynamics controls. Although original SWC-based partial correlation basically supported our findings, the results highly depended on the controlling factors selected. This study implied that R_{tn} rather than original SWC should be preferred for understanding soil water dynamics controls.

1. Introduction

Soil water content (SWC) in the root zone controls the water and energy partition between the boundary of soil and atmosphere (Famiglietti et al., 1998). It is of critical significance for a range of hydrological processes including infiltration, evapotranspiration, and drainage (Mohanty and Skaggs, 2001; Western et al., 2004). Knowledge of controls on SWC dynamics is crucial to understanding hydrological processes and developing models for SWC prediction (Grayson et al., 1997; Brocca et al., 2010).

The SWC controls have received increasing attention in the pedological and hydrological communities. A range of environmental factors such as soil properties, vegetation, and topography have been identified to be the dominant factors (Western et al., 1999; Gómez-Plaza et al., 2001; Martínez-Fernández and Ceballos, 2003; Hu et al., 2010; Gao et al., 2011; Wang et al., 2012, 2015; She et al., 2013; Vereecken et al., 2014). Usually, finer textured soils can store more soil water (Vachaud et al., 1985; Hu et al., 2010); larger vegetation coverage usually corresponds to less water storage because of the higher water demand (Hupet and Vanclooster, 2002; Biswas et al., 2012); and sites with a higher elevation and sun-facing slope are usually drier than sites with lower elevation and shaded slopes (Nyberg, 1996; Qiu et al., 2001; Chaplot and Walter, 2003; Brocca et al., 2007).

Some of previous studies on SWC controls is easier to understand, whereas others are rather involved. For example, Qiu et al. (2001) observed greater SWC on the south-facing slope than the north-facing slope on the Chinese Loess Plateau in 1999 because of higher precipitation on the south-facing slope. Hébrard et al. (2006) found that none of the local factors (e.g., aspect, slope, and soil texture) were correlated to the SWC pattern, suggesting

---

* Corresponding author.
E-mail address: wei.hu@plantandfood.co.nz (W. Hu).

http://dx.doi.org/10.1016/j.jhydrol.2017.05.054
0022-1694/© 2017 Elsevier B.V. All rights reserved.

that another local factor may have masked their effects. Gao et al. (2011) also noticed that SWC could be negatively correlated to cos (aspect) and positively correlated to slope during wet periods. Shi et al. (2014) observed a positive correlation between SWC and slope, which is attributed to the coincidence of areas with steeper slope and areas at lower elevations. Therefore, there is a lack of consensus on the effects of environmental factors on SWC dynamics. This is because environmental factors are usually cross-correlated and correlation analysis between cross-correlated environmental factors and the original SWC data may not be able to identify the true controls. Unfortunately, most above mentioned studies did not remove the effects of others before determining the influences of an environmental factor on SWC. Although partial correlation analysis was used to unveil the effect of one factor by controlling the effects of others (Zhao et al., 2007), the selection of the controlling factors can be sometimes subjective and empirical.

The patterns of soil water dynamics may be better reflected by the temporal change in SWC than the original SWC itself. Therefore, it is expected that controls on spatial variability of temporal change in SWC may provide more insights into the physical mechanism of soil water dynamics (Hu and Si, 2016). As stated above, however, previous studies on SWC controls usually focused on spatial patterns of original SWC and few considered the spatial patterns of temporal changes in SWC.

Recently, spatio-temporal SWC was decomposed into a temporal mean (i.e., time-stable pattern, $M_{\hat{t}n}$) and a temporal anomaly (A_{tn}), which is directly related to soil water dynamics (Mittelbach and Seneviratne, 2012; Brocca et al., 2014; Gao et al., 2015; Rötzer et al., 2015). Mittelbach and Seneviratne (2012) indicated that the climate forcing affected both time-stable pattern of SWC and spatial variations in soil water dynamics at a spatial extent of approx. 31,500 km^2. Based on previous studies (Mittelbach and Seneviratne, 2012; Vanderlinden et al., 2012), Hu and Si (2016) decomposed the A_{tn} further into a space-invariant temporal anomaly ($A_{t\hat{n}}$) and a space-variant temporal anomaly (R_{tn}). The R_{tn} is responsible for spatial variability of soil water dynamics and was further decomposed into the sum of product of spatial structures (EOFs) and temporally-varying coefficients (ECs) using the empirical orthogonal function (EOF) (Perry and Niemann, 2007; Joshi and Mohanty, 2010). Hu and Si (2016) concluded that this decomposition was beneficial to spatial SWC prediction in the hummocky landscape with a sub-humid continental climate where significant snowmelt runoff and rainfall runoff happens in the spring and summer, respectively. However, the advantage of EOF -based analysis for determining soil water dynamics controls has not been demonstrated because Pearson correlation analysis indicated that both $M_{\hat{t}n}$ and significant EOFs of R_{tn} were controlled by the same factors (i.e., soil properties and topography) (Hu and Si, 2016). This was because topography-regulated surface runoff (i.e., non-local control) determined both spatial patterns of SWC and its dynamics in that area. Due to the $M_{\hat{t}n}$ being more related to the "static" pattern and R_{tn} more related to the "dynamic" pattern, we expected that the controls of $M_{\hat{t}n}$ and R_{tn} may not be exactly the same at other sites especially where soil water is more local controlled. Therefore, an improved understanding of controls on the soil water dynamics may be obtained by correlating environmental factors with the spatial structures of temporal anomaly. Related studies, however, are not available with the exception of Hu and Si (2016). The empirical orthogonal function was used to reveal the SWC controls, but most studies focused on spatial anomaly (Perry and Niemann, 2007; Joshi and Mohanty, 2010; Ibrahim and Huggins, 2011). Furthermore, the relative importance of different factors on the soil water dynamics at different times has not been explored.

Soil water content is a crucial factor for vegetation construction on the Chinese Loess Plateau which is characterized by the arid and semi-arid environment (Zhang et al., 2015). Influences of environmental factors on SWC distribution have been widely explored in this area (Qiu et al., 2001; Gao et al., 2011; Wang et al., 2012, 2015; She et al., 2013), but soil water dynamics controls are not fully understood because of cross-correlation of environmental factors. Therefore, the objective of this study was to elucidate the dominant controls of root zone SWC dynamics at a small watershed on the Chinese Loess Plateau using the EOF analysis and to demonstrate the advantages in understanding soil water dynamics controls using the EOF method. For this purpose, spatio-temporal SWC of 0–0.8 m was first decomposed into three components (i.e., $M_{\hat{t}n}$, $A_{t\hat{n}}$, and R_{tn}). Soil water dynamics controls were then determined by correlating significant spatial structures of R_{tn} with environmental factors. Finally, the relative importance of each environmental factor to the variance of R_{tn} was determined.

2. Materials and methods

2.1. Data

Datasets from LaoYeManQu watershed (110°22′ E, 38°47′ N) in the Chinese Loess Plateau were investigated (Fig. 1). This study area (20 ha in size) is located in a cold semi-arid climate (Bsk) zone (Peel et al., 2007). Soils are dominated by Calcaric Arenosol and Calcaric Regosol (FAO, 1988).

At each of the 124 sampling locations, volumetric SWC measurements at depths of 0.2, 0.4, 0.6, and 0.8 m were obtained on 20 occasions from 11 June 2007 to 23 July 2008 by a neutron probe. The SWC was measured approximately fortnightly except in the winter when SWC of the root zone did not change much as soils were frozen. Some SWC measurements were also made a few days after big rainfall events (e.g., SWC was measured on 21 June after 80 mm rainfall during 14–18 June in 2008). We recognized that SWC spatial patterns of surface layer immediately after big rainfall events were not captured by our measurements, but SWC spatial patterns of the root zone were much less affected by the lagged measurement. Therefore, our measurements basically portrayed the temporal variations in soil water conditions of the root zone, whereas not all SWC spatial patterns especially those related to runoff were captured. Because soil water dynamics can be understood as a cumulative change in SWC compared to the time-stable pattern, soil water dynamics controls for a given sampling time should be independent of the sampling frequency.

A range of soil, topography, and vegetation properties were collected at each location (Hu et al., 2009, 2010). Only the properties that have been normally recognized to affect soil water patterns were selected in this study. These include sand (>0.05 mm) content, bulk density, organic carbon content for the surface 0–0.1 m, elevation, cos(aspect), tan (slope), grass biomass, shrub and wood biomass yield, and total biomass yield. Sand content was calculated from the soil particle size fractions evaluated by the MasterSizer2000. Bulk density was measured by the gravimetrical method from undisturbed soil samples of 0.05 m in diameter and height. Organic carbon content was determined by the dichromate oxidation method (Nelson and Sommer, 1975). Elevation was measured every 1–3 meters for the whole watershed with a differential, kinematic GPS to construct a digital elevation map with a resolution of 1 m × 1 m, from which cos(aspect) and tan (slope) were derived by the ArcMap 9.2. On September 2008, above ground grass was collected from an area of 1 m × 1 m and oven dried to obtain grass biomass yield. Shrub and wood biomass yield over areas of 5 m × 5 m was determined by combined sampling and visual estimation. All the biomass yield over areas of