Journal of Hydrology 531 (2015) 534–542

Contents lists available at ScienceDirect

Journal of Hydrology

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

Can shallow-layer measurements at a single location be used to predict deep soil water storage at the slope scale?

Lei Gao [a], Yujuan Lv [a], Dongdong Wang [b], Muhammad Tahir [a], Xinhua Peng [a,*]

[a] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, 71 East Beijing Road, Nanjing 210008, PR China
[b] College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing 210095, PR China

ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 31 October 2015
Accepted 2 November 2015
Available online 7 November 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renato Morbidelli, Associate Editor

Keywords:
Temporal persistence
Soil water prediction
Hillslope hydrology
Humid area

SUMMARY

Knowing the amount of soil water storage (SWS) in agricultural soil profiles is important for understanding physical, chemical, and biological soil processes. However, measuring the SWS in deep soil layers is more expensive and time consuming than in shallower layers. Whether deep SWS can be predicted from shallow-layer measurements through temporal stability analysis (TSA) remains unclear. To address this issue, the soil water content was measured at depths of 0–1.6 m (0.2-m depth intervals) at 79 locations along an agricultural slope on 28 occasions between July 2013 and October 2014. SWSs values were then calculated for the 0–0.4, 0.4–0.8, 0.8–1.2, 1.2–1.6, and 0–1.6 m soil layers. The SWS exhibited strong temporal stability, with mean Spearman's ranking coefficients (r_s) of 0.83, 0.92, 0.83, and 0.79 in the 0–0.4, 0.4–0.8, 0.8–1.2, and 1.2–1.6 m soil layers, respectively. As expected, the most temporally stable location (MTSL1) accurately predicted the average SWS of the corresponding soil layer, and the values of absolute bias relative to mean (ARB) were lower than 3% for all of the investigated soil layers. Using TSA, deep-layer SWS information could be predicted using a single-location measurement in the 0–0.4 m soil layer. The mean ARB values between the observed and predicted mean SWS values were 2.9%, 4.3%, 3.9%, and 2.7% in the 0.4–0.8, 0.8–1.2, 1.2–1.6, and 0–1.6 m soil layers, respectively. The prediction accuracy of the spatial distribution generally decreased with increasing depth, with linear determination coefficients (R^2) of 0.93, 0.79, 0.72, and 0.84 for the four soil layers, respectively. The proposed method could further expand the application of the temporal stability technique in the estimation of SWS.

1. Introduction

Soil water storage (SWS) affects physical, chemical, and biological soil processes (Schjonning et al., 2003). For agricultural soils, spatial and temporal SWS information is important for the development of precision agriculture (Marques da Silva and Silva, 2008), the prediction of soil erosion (Baptista et al., 2015), and the control of agricultural pollutants (Kibet et al., 2014). Detailed characterization of the SWS profile could provide a better understanding of these processes (Blöschl and Sivapalan, 1995). However, information on the SWS of an area, particularly in the deep soil layers, is difficult to capture because of its strong spatio-temporal variability.

The concept of temporal stability was first proposed by Vachaud et al. (1985) and provides a powerful tool for estimating the spatial mean of the SWS in an area. Temporal stability assumes that the spatial patterns of SWS persist over time, although the mean values may vary considerably. Thus, identifying the most temporally stable location (MTSL) for predicting the SWS spatial average has been one of its most important applications. Many successful examples are available from diverse climate zones, including humid (Brocca et al., 2010), semi-humid (Hu et al., 2013), and semi-arid climates (Martínez-Fernández and Ceballos, 2003).

In previous studies, the SWS spatial average was typically predicted from the MTSL of the corresponding soil layer. For example, Hu et al. (2010) successfully predicted the mean SWS at soil depths of 3.0–4.0 m by using SWS measurements of the 3.0–4.0 m MTSL. Data for deeper soil layers are more difficult to obtain than data from shallow layers. Put-in-and-read devices are often used to measure the soil water contents (SWCs) of shallow soil layers, e.g., 0–0.06 m (Schneider et al., 2008) or 0–0.2 m (Penna et al., 2013). Although the SWC of a deep soil layer could be monitored using a portable probe, increasing the time resolution would be difficult, and the measurement could not be completed quickly, e.g., just before a rainfall event, over a large study area. The use of automatic measurement devices for deep MTSLs could considerably reduce costs; however, installation in the deep soil layer

* Corresponding author. Tel.: +86 25 86881198; fax: +86 25 86881000.
E-mail address: xhpeng@issas.ac.cn (X. Peng).

http://dx.doi.org/10.1016/j.jhydrol.2015.11.002
0022-1694/

would greatly disturb the soil and destroy its temporal stability. These issues would be resolved if the SWS in the deeper soil layers and throughout the soil profile could be predicted by observing a single, shallow layer.

A limited number of studies have explored the feasibility of predicting SWS from the MTSLs of other soil layers. For example, Penna et al. (2013) found that MTSLs could be good indicators of other soil layers at the hillslope scale, but the deepest soil layer investigated in their study was only 0.2 m. At greater soil depths, Hu and Si (2014) found that the vertical patterns of SWC at 0–1.4 m in a humid continental climate and those at 0–3.8 m in a cold semi-arid climate were time-stable and that the mean SWC of the profile could be predicted using data from a particular soil depth. Although these authors proved the feasibility of predicting profile SWC based on measurements from a certain soil layer, the layer used was the most time-stable in the vertical direction, which is not necessarily a shallow soil layer. Hu and Si (2014) explored the feasibility of predicting mean profile SWC with shallow soil layer data and found that shallow soil layer data could only predict the mean SWC at limited depths, e.g., 0.1 m for 0–0.2 m and 0.4 m for 0–0.9 m. One possible reason for this low prediction accuracy may be that the mean SWC of a slope was estimated using TSA twice. The SWC at the most time-stable depth was used to predict the mean SWC of the MTSL, followed by calculating the mean SWC of the slope. The processes of the first TSA could be saved if the locations in the shallow soil layers could directly predict the mean SWC or SWS in the deeper soil layers (or the entire soil profile), which would decrease the uncertainty introduced by the TSA. In this study, we hypothesized that a single-location measurement from a shallow soil layer could be used to predict the SWS of deeper soil layers or the entire soil profile on an agricultural slope.

Thus, the objectives of this study were (1) to test the temporal stability of SWS in a red soil area in China and (2) to validate the hypothesis that the SWS of a deep layer or the entire soil profile, including the mean values and the spatial distribution, could be predicted based on a single-location measurement from a shallow soil layer.

2. Materials and methods

2.1. Study area

The studied slope (~5°) is located in Yingtan, Jiangxi province, China, and is 4 km from the Yingtan Ecological Experimental Station, Chinese Academy of Sciences (28°15′N, 116°55′E) (Fig. 1). The study area covers an area of 3.1 ha, ranges in elevation between 43 and 50 m, and has a typical warm and humid subtropical monsoon climate with a mean annual temperature of 17.8 °C. The mean annual precipitation (1795 mm) mainly comprises precipitation from April to June (wet period), and the mean annual potential evapotranspiration (1229 mm) mainly comprises evaporation between July and September (dry period). These meteorology data were measured or calculated from 45 years of climatology data from the Yingtan weather station (1954–1999).

The soils in the study area are red soils, which are widespread in China and cover an area of 102 million ha. In the present study area, red soils are mainly derived from Quaternary red clay and are classified as ultisols based on the USDA Soil Taxonomy classification system (Soil Survey Staff, 2010). The soils in the upper 1.0 m layer are clay loam based on the USDA classification system (i.e., in the 0–0.1 m soil layer, the sand, silt and clay proportions are 40.0%, 26.9% and 33.1%, respectively). Detailed information regarding the soil properties is presented in Table 1. The slope is located in a rainfed, intensively agricultural area, in which crops (79%) and citrus (19%) are the primarily land use types (Fig. 1).

2.2. Soil water storage data collection

At 79 measuring locations, a special polyvinyl chloride access tube (length: 2 m; diameter: 0.05 m) was installed in early 2013. The volumetric SWC (θ) was measured using a size-matched portable probe (time domain reflectometry, TDR, IMKO, Ettlingen, Germany) at each location along the slope (Fig. 1). The measuring accuracy of the probe is 2%, and the repeat accuracy is 0.3% (with the electrical conductivity changing between 0 and 6 dS/m). On 28 occasions between July 2013 and October 2014, SWC data were collected every 0.2 m to a soil depth of 1.6 m. The time interval between the sampling events was approximately 15 days. Overall, 17,696 SWC samples were collected during the study period.

$\mathrm{SWS_{ij}}(k)$, the SWS (mm) of five soil layers at location i , time j, and depth k (m), was calculated from $\theta(i,j,k)$ (%, v/v) with soil depth as follows:

$$\mathrm{SWS_{ij}}(0\text{–}0.4) = [\theta(i,j,0\text{–}0.2) + \theta(i,j,0.2\text{–}0.4] \times 20/10 \quad (1)$$

$$\mathrm{SWS_{ij}}(0.4\text{–}0.8) = [\theta(i,j,0.4\text{–}0.6) + \theta(i,j,0.6\text{–}0.8] \times 20/10 \quad (2)$$

$$\mathrm{SWS_{ij}}(0.8\text{–}1.2) = [\theta(i,j,0.8\text{–}1.0) + \theta(i,j,1.0\text{–}1.2] \times 20/10 \quad (3)$$

$$\mathrm{SWS_{ij}}(1.2\text{–}1.6) = [\theta(i,j,1.2\text{–}1.4) + \theta(i,j,1.4\text{–}1.6)] \times 20/10 \quad (4)$$

$$\mathrm{SWS_{ij}}(0\text{–}1.6) = \mathrm{SWS_{ij}}(0\text{–}0.4) + \mathrm{SWS_{ij}}(0.4\text{–}0.8) + \mathrm{SWS_{ij}}(0.8\text{–}1.2) + \mathrm{SWS_{ij}}(1.2\text{–}1.6) \quad (5)$$

2.3. Temporal stability analysis

The dataset of the 28 sampling occasions was divided into two independent parts. A set of 20 occasions was used as a training set to evaluate the temporal stability of the SWS and identify the MTSL and temporal stability relationship. The other eight occasions were used to validate the prediction accuracy.

A nonparametric Spearman's rank correlation test and mean relative difference techniques were employed to evaluate the temporal stability of the SWS. The first technique was used to determine the persistence of the spatial pattern during the calibration period (Martini et al., 2015; Jia et al., 2015). In this approach, R_{ij} is the rank of the observed $\mathrm{SWS_{ij}}$ at location i on day j among the 79 locations, and R'_{ij} is the rank at the same location but on day j' or at the same location on the same date but at another soil depth. The Spearman's rank correlation coefficient (r_s) is calculated as follows:

$$r_s = 1 - \frac{6\sum_{i=1}^{N}\left(R_{ij} - R'_{ij}\right)^2}{N(N^2-1)} \quad (6)$$

where N is the number of observation locations, which is $N = 79$ in the present study. The r_s values (ranging between −1 and 1) are a measure of the statistical dependence between the SWS on two dates. A value closer to 1 indicates that the spatial pattern is more stable or similar among the different dates.

The relative-difference analysis was used to identify the MTSL and the temporal stability relationship. The difference (Δ_{ij}) between an individual measurement at location i on day j ($\mathrm{SWS_{ij}}$) and the average SWS on the same date from all 79 locations ($\overline{\mathrm{SWS}_j}$) was calculated as follows:

$$\Delta_{ij} = \mathrm{SWS_{ij}} - \overline{\mathrm{SWS}_j} \quad (7)$$

Then, the relative difference (RD_{ij}) was calculated as follows:

$$\mathrm{RD_{ij}} = \frac{\Delta_{ij}}{\overline{\mathrm{SWS}_j}} \quad (8)$$

To provide an estimate of the unbiased difference from the average SWS, the temporal mean relative difference (MRD_i) and its standard deviation (SDRD_i) were defined, respectively, as follows: