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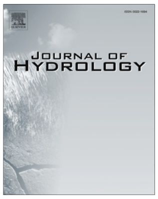

Can soil water measurements at a certain depth be used to estimate mean soil water content of a soil profile at a point or at a hillslope scale?

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SUMMARY

Profile soil water contents (θ) are important for scheduling irrigation, determining root water uptake and energy partition between sensible and latent heat. Soil water content measurements for deep soil profiles are time consuming and costly. The objective of this study was to test whether θ at a certain depth at a point can be used to estimate profile θ at a point or at a hillslope scale by time stability analysis. A total of 37 datasets of θ from 0.1 m to 3.8 m depths were collected by a neutron probe at 28 locations over four years on a representative hillslope in the Chinese Loess Plateau. Time stability of vertical patterns of θ was assessed by Spearman's rank correlation analysis. Soil water contents of the first two years were used to identify the time stable depth using mean absolute bias error, and θ of the second two years were used to validate if the time stable depth identified and associated mean relative difference can be used to predict mean θ of a soil profile at a point or at a hillslope scale. Results showed that vertical patterns of θ were time stable. The prediction error for mean θ varied with sampling locations and soil profile depths. At the most time stable location (location 4) in terms of vertical patterns, mean θ of soil profiles (i.e., 0–1.0 m, 0–2.0 m, 0–3.0 m, and 0–3.8 m) was predicted well by the most time stable depth, with absolute bias relative to mean <0.05 at a point scale and <0.10 at a hillslope scale. Further application of this approach in the Canadian Prairies site indicated that mean θ of 0–1.0 m soil profile at a point or a transect scale was predicted well by the most time stable depth at almost all the locations. This study verified that soil profile θ at both point and hillslope (or watershed) scales can be predicted with the θ measurements at the most time stable depth.

1. Introduction

Soil water content (θ) of a soil profile not only determines the water and energy fluxes between soil and atmosphere (Famiglietti et al., 1998), but also plays a crucial role in vegetation growth (Yang et al., 2012). However, θ at the landscape scale is very difficult to obtain because of its spatio-temporal variability (Dobriyal et al., 2012). It is even more so for θ measurements in deep soil profiles because it is generally more expensive and labor intensive.

Efforts have been made on estimating soil water contents of root zone (e.g., 0–1.0 m below the ground) at different scales. Most of these methods were based on physically-based models with near-surface θ measurements, either observed *in situ* or with remote sensing (Ragab, 1995; Calvet and Noilhan, 2000; Das and Mohanty, 2006; Sabater et al., 2007; Albergel et al., 2008; Manfreda et al., 2013). Conceptual and semi-analytical models were also developed to predict time evolution of soil profile θ in homogeneous or layered soils (Corradini et al., 2000; Morbidelli et al., 2011, 2013). While there has been some success in using these models to estimate root zone θ, the accuracy heavily depends on the understanding of soil hydrological processes. Furthermore, other soil or vegetation parameters are always required, which calls for more measurements.

In spite of spatio-temporal variability, repeated measurements have indicated the existence of time (or temporal) stability of the spatial patterns of θ in horizontal direction (Vachaud et al., 1985; Cosh et al., 2004; Brocca et al., 2009; Hu et al., 2009; Joshi et al., 2011). The time stability concept has been used to upscale θ of an area from measurements of a time stable location from the same (Starks et al., 2006; De Lannoy et al., 2007; She et al., 2012) or different areas (Gao et al., 2012; Hu et al., 2013).

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Nomenclature

$\overline{\theta'_j}$	predicted mean θ of a soil profile at a point (or hillslope) scale at time j
$\delta_j(i)$	relative difference of θ at depth (or location) i at time j
$\overline{\theta_j}$	spatial mean θ of a soil profile at a point (or hillslope) scale
$\overline{\delta_j}$	temporal mean of $\delta_i(i)$
$\theta_j(i)$	θ measurement at depth i (or mean θ of a soil profile at location i) at time j
CR	slow neutron count ratio
m	number of sampling dates in the calibration period
MABE	mean absolute bias error
MABE_H	mean absolute bias error in horizontal direction
MABE_V	mean absolute bias error in vertical direction
MRD	mean relative difference
MRD_H	mean relative difference in the horizontal direction
MRD_V	mean relative difference in the vertical direction
MTSD	most time stable depth
MTSL	most time stable location
n	number of depths (or sampling locations)
q	number of sampling dates in the validation period
R	Spearman's rank correlation coefficient
RBIAS	absolute bias relative to mean
RBIAS_V	absolute bias relative to mean in the vertical direction
RBIAS_H	absolute bias relative to mean in the horizontal direction
R_H	Spearman's rank correlation coefficient in the horizontal direction
R_V	Spearman's rank correlation coefficient in the vertical direction
SD	standard deviation
SDRD	standard deviation of relative difference
θ	soil water content

Soil water contents vary with depth due to the heterogeneity of environmental factors such as water and energy input and soil texture (Wang et al., 2013). Meanwhile, soil water contents at different depths undergo temporal change to different extents, which may alter the vertical patterns of θ. To date, however, few studies assessed whether these changes were significant enough to destroy the time stability of vertical patterns of θ. We hypothesize that the varying vertical patterns of θ are time stable enough to have time stable depths which can be used to predict mean θ of a soil profile at a point and at a hillslope scale.

A series of studies on time stability of θ have been conducted in our study area with different purposes. Hu et al. (2009) explored the effects of neutron probe calibration procedures on identification of the most time stable location (MTSL) for mean θ estimation, and indicated that spatial variability of soil properties such as bulk density and soil organic carbon content should be taken into account in neutron probe calibration. Subsequently, Hu et al. (2010b) developed a new index termed mean absolute bias error (MABE) to identify the MTSL for mean θ evaluation, and the performance of MABE was found to be better than the standard deviation of relative difference (SDRD). With both MABE and SDRD indices, Hu et al. (2010a) explored the impacts of soil depth, soil texture, and land use on time stability of θ, and they observed the significant effect of soil depth and soil texture. After comparing the performance of seven time stability indices for identifying the MTSL, Hu et al. (2012) found that MABE and root-mean-squared differences are the best. The above studies were conducted within the measurement extent, while Hu et al. (2013) applied the time stability concept to estimate mean θ in an area using the measured θ at the MTSL in an adjacent or distant area. However, little is known on if there are vertical time-stable patterns in soil profile and if it is possible to use θ measurements at one depth of a point to predict mean θ of a soil profile at a point or at a hillslope scale.

Therefore, the objectives of this study were to: (1) assess if there is the time stability of vertical patterns of θ, and (2) test if θ at a certain time stable depth can be used to predict mean θ of a soil profile at a point and at a hillslope scale. We used a θ dataset from a hillslope in the Chinese Loess Plateau in this study. A dataset from a transect in the Canadian Prairies was used for further validation.

2. Materials and method

2.1. Study area

This study was conducted on a hillslope (average slope of 19°) of the Liudaogou watershed in the Chinese Loess Plateau (110°22′E, 38°49′N). The climate is cold semi-arid (Bsk) (Peel et al., 2007) with mean annual temperature of 8.4 °C, precipitation of 437 mm, and potential evapotranspiration of 785 mm. The dominant soils are Inceptisols with texture of sandy loam (Soil Survey Staff, 2010). The selected hillslope is convex with slope length of 280 m, running southeast-northwest. Vegetations in this hillslope are common in the Chinese Loess Plateau. At the top 100 m, vegetation is dominated by the bunge needlegrass (*Stipa bungeana Trin.*) with scattered korshinsk peashrub (*Caragana korshinskii Kom.*). Alfalfa (*Medicago sativa L.*) was planted about 40 years ago at the bottom 180 m, and now it is replaced by the bunge needlegrass as a result of the "Grain for Green" project launched by the Chinese central government.

2.2. Data collection

A total of 28 sampling locations with intervals of 10 m were setup along the middle of the hillslope. From the top to the bottom of the slope, the sampling locations were referred to location 1 (#1) to location 28 (#28) consecutively (Hu et al., 2010b). At each sampling location, an aluminum neutron probe access tube with 4 m long was installed in the fall of 2004. Neutron counting measurements were taken at 0.1 m depth intervals from the depth of 0.1 m to the depth of 1.0 m, and at 0.2 m intervals from 1.2 m to 3.8 m. Site specific calibration equation was used to convert the neutron count to θ. The θ measurements were collected monthly with a few exceptions. A total of 37 datasets of θ measurements were collected from October 2004 to October 2008.

2.3. Data analysis

Spearman's rank correlation coefficient (R) was used to assess the time stability of vertical patterns (or horizontal patterns) of θ between measurement dates with the whole datasets of θ (Vachaud et al., 1985). The closer R is to 1, the more stable the vertical (or horizontal) patterns of θ between different dates will be. For differentiation, R will be expressed as R_V (or R_H) in terms of vertical (or horizontal) direction.

The whole datasets were roughly divided into two even groups in terms of measurement span, i.e., calibration (22 datasets obtained from October 2004 to September 2006) and validation (15 datasets obtained from October 2006 to October 2008) groups. The calibration datasets were used to identify the MTSD (or MTSL) using the MABE. The validation datasets were used to test the possibility to use soil water measurements at a certain depth to estimate mean θ of a soil profile at a point or at a hillslope scale.