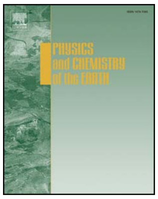
ARTICLE IN PRESS

Physics and Chemistry of the Earth xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

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



Spatial feature analysis of a cosmic-ray sensor for measuring the soil water content: Comparison of four weighting methods

Jingya Cai, Zhiguo Pang*, Jun'e Fu

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

ARTICLE INFO

Keywords:
Soil water content (SWC)
Cosmic ray sensor (CRS)
Spatial feature
Weighting method

ABSTRACT

To quantitatively analyze the spatial features of a cosmic-ray sensor (CRS) (i.e., the measurement support volume of the CRS and the weight of the in situ point-scale soil water content (SWC) in terms of the regionally averaged SWC derived from the CRS) in measuring the SWC, cooperative observations based on CRS, oven drying and frequency domain reflectometry (FDR) methods are performed at the point and regional scales in a desert steppe area of the Inner Mongolia Autonomous Region. This region is flat with sparse vegetation cover consisting of only grass, thereby minimizing the effects of terrain and vegetation. Considering the two possibilities of the measurement support volume of the CRS, the results of four weighting methods are compared with the SWC monitored by FDR within an appropriate measurement support volume. The weighted average calculated using the neutron intensity-based weighting method (Ni weighting method) best fits the regionally averaged SWC measured by the CRS. Therefore, we conclude that the gyroscopic support volume and the weights determined by the Ni weighting method are the closest to the actual spatial features of the CRS when measuring the SWC. Based on these findings, a scale transformation model of the SWC from the point scale to the scale of the CRS measurement support volume is established. In addition, the spatial features simulated using the Ni weighting method are visualized by developing a software system.

1. Introduction

The soil water content (SWC) is a key variable in water and energy cycles (Entekhabi, 1995; Vivoni, 2012). The precise measurement of the SWC over a large range is important in the fields of drought monitoring, irrigation scheduling, hillslope stability analysis, flash flood forecasting and water supply management, among other applications. The cosmic-ray sensor (CRS), which measures SWC based on the interactions between hydrogen and neutrons (Bethe et al., 1940; Knoll, 2000; Shuttleworth et al., 2010; Zreda et al., 2008), is ideal for SWC measurements at the scale of a small watershed, a hydrological model element or an agricultural plot. CRS methods fill the extensive spatial gap between point measurements and satellite remote sensing measurements of SWC (Zreda, 2016). Notably, the former poorly represents large areas due to the high heterogeneity of the SWC (Biswas, 2014; Topp et al., 1980; Vereecken et al., 2008; Vivoni et al., 2008), and the latter, such as that based on microwave remote sensing (Bartalis et al., 2007; Entekhabi et al., 2010; Kerr et al., 2001; Kustas et al., 1998), has an order-of-magnitude footprint of a kilometer and a penetration depth of only a few centimeters.

The method of measuring SWC with CRS is new and has not been widely applied. When first introduced at the regional scale, data must be verified with point-scale measurements, which are generally considered the true values, to confirm the applicability and accuracy of the method in the region. Because of the differences in the spatial scales of point-scale measurements and CRS measurement, a scale transformation is required. Such a transformation relies on the determination of the weight coefficient; thus, weighting methods are applied. Four weighting methods exist: the uniform weighting method (UW method), the geometric weighting method (GW method) (Franz et al., 2012b), the method of discretizing the cumulative fraction of counts (D-CFoC weighting method) (Bogena et al., 2013), and the neutron intensity-based weighting method (Ni weighting method) (Köhli et al., 2015). The UW method, as its name implies, assigns the same weight to the SWC at all positions. It was the first and the most straightforward weighting method; therefore, it is commonly applied despite the advances in CRS applications. The GW method of vertical weighting is so named because it forms a right triangle with weight of the surface soil layer as the horizontal right-angled edge, and the measurement depth as the vertical right-angled edge. Both methods neglect the features of neutron transport and simply assign weights without a theoretical basis. Franz et al. (2012b) compared CRS-based SWC to the weighted SWCfor

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* Corresponding author.
E-mail addresses: jingyacai@126.com (J. Cai), pangzg@iwhr.com (Z. Pang), fuje@iwhr.com (J. Fu).

https://doi.org/10.1016/j.pce.2018.02.001
Received 9 April 2017; Received in revised form 16 September 2017; Accepted 5 February 2018

Please cite this article as: Cai, J., Physics and Chemistry of the Earth (2018), https://doi.org/10.1016/j.pce.2018.02.001

both sands and silts with different soil textures using the UW method and the special GW method (in which the vertical weight changes linearly with depth). They found that the root mean square error (RMSE) and maximum deviation were lower for the GW method than for the UW method at all times, including during infiltration, drainage and evaporation. The D-CFoC weighting method is used to discretize the cumulative weight resulting from the Monte Carlo N-Particle extended (MCNPX) model (Briesmeister, 1997; Pelowitz, 2005), a state-of-the-art particle transport model (Baatz et al., 2014). Bogena et al. (2013) analyzed the relative error in mean SWC and RMSE between the D-CFoC-weighted SWC and the CRS SWC calculated using uncorrected and corrected neutron counts considering the effects of different factors. The relative error and RMSE were all less than 0.30% and 0.04 cm^3/cm^3, respectively, for the neutron counts corrected with arbitrary factors. The Ni weighting method was proposed based on the neutron intensity changes simulated using the Ultra Rapid Adaptable Neutron-Only Simulation (URANOS) software with the Monte Carlo approach. These two methods rely on a physical mechanism derived through simulations of neutron transport. Clearly, the ability of the four weighting methods to upscale SWC from the point to regional and perform scale transformations must be carefully assessed.

The main objective of this study is to analyze the spatial features of CRS-based SWC measurements and to establish a scale transformation model of SWC by comparing the four weighting methods. To minimize the effects of the terrain and vegetation, a flat desert steppe with sparse vegetation cover consisting of only grass is chosen for analysis. This test site is particularly well suited for the comparative study. To ensure temporal consistency, simultaneous observations of SWC are made using three methods. The CRS was used to monitor neutrons and log neutron counts continuously for more than two years. During this period, five gravimetric in situ sampling campaigns were conducted to calibrate the CRS. Furthermore, six FDR sensors were evenly distributed within the measurement support volume of the CRS to synchronously monitor the SWC and evaluate the reliability of the four weighting methods.

2. Data and methods

2.1. Study area

The experiment was conducted in the comprehensive experimental base of the Institute of Water Resources for Pastoral Areas operated by the Ministry of Water Resources of China. It is located in the town of Xilamuren, Baotou City, Inner Mongolia Autonomous Region, and covers an area of 150 ha within the Wulanchabu desert steppe region. The terrain is relatively flat, with a maximum elevation of 1690.3 m and minimum elevation of 1585.0 m. The annual average precipitation and temperature are 284 mm and 2.5 °C, respectively. The vegetation is mainly low and sparse grass dominated by homogeneously distributed *Stipa krylovii* and *Leymus chinensis*. Without the effects of human activities and with uniform land surface conditions, the desert steppe provides a favorable environment for the comparative study.

2.2. Measurement support volume of CRS

Before designing the observation procedures, the measurement support volume of the CRS in the study area was estimated.

The measurement support volume is defined as the region within which 86% of the counted neutrons originate (Zreda et al., 2008). It is an axisymmetric three-dimensional region and can be easily positioned according to the location of the CRS which is on the vertical axis of symmetry. The ground footprint of this volume is a circle centered on the CRS. The size of the support volume can be determined based on the footprint radius and measurement depth, corresponding to the horizontal and vertical directions, respectively.

The measurement support volume of the CRS was initially idealized as a cylinder. Desilets and Zreda (2013) analyzed the dependence of the footprint radius on the SWC, atmospheric pressure, humidity and the height of the CRS above the ground. By assuming that the influence on the radius was almost entirely dependent on the air conditions based on consistent theoretical and simulated predictions, they concluded that the footprint radius was inversely proportional to the atmospheric pressure and could be estimated by function (1). In early research using the cylinder approximation, the measurement depth z^* (Franz et al., 2012b; Zreda et al., 2008) was considered uniform in the horizontal direction and strongly dependent on the SWC (function (2)). The range of z^* was between 12 cm for SWC of 0.40 cm^3/cm^3, which is typically in saturated soil, and 70 cm for bone-dry soil, where the SWC is 0. Hereafter, this method of estimating the footprint radius and measurement depth is called the universal method due to its widespread use:

$$R(P) = R_0 \times P_0/P \tag{1}$$

where *R(P)* (m) is the horizontal radius calculated with the universal method at the actual atmospheric pressure P (hPa) and R_O is the corresponding radius at the reference pressure P_O and is approximately 300 m (Zreda et al., 2008) at sea level (P_O = 1013.25 hPa).

$$z^* = \frac{5.8}{\rho_{bd}/\rho_w \times \tau + SWC \times \rho_{bd} + 0.0829} \tag{2}$$

where z^* (cm) is the measurement depth of the CRS; ρ_{bd} (g/m^3) is the bulk density of the soil and is 1.45 g/m^3 in the study area; ρ_w is the density of liquid water and has a default value of 1 g/m^3; τ (Franz et al., 2013) (g/g) is the weight fraction of the lattice water, which is defined as the amount of water released at 1000 °C preceded by drying at 105 °C, in the mineral grains and bound water (ignored in this study because it is below the measurable limit); and *SWC* is the gravimetric SWC (kg/kg).

The historical air pressure monitored by an automatic weather station at the experimental base varies by less than 4%, and the annual average air pressure is approximately 840 hPa. Thus, the measurement radius was estimated as approximately 360 m. In addition, per the historical SWC data from the base, the measurement depth of the CRS is generally less than 40 cm.

Köhli et al. (2015) proposed an improvement for the determination of the measurement support volume of the CRS (hereafter called the improved method) by developing the URANOS software for cosmic-ray neutron analysis based on the Monte Carlo approach. They showed that the radius ranged from 130 m to 240 m, considering not only air pressure but also the SWC, atmospheric humidity and vegetation height (Sect. 2.6.4), which significantly differed from the calculated value based on only air pressure. This result suggests that the influence of the SWC, air humidity and vegetation height cannot be ignored. Additionally, they stated that the measurement support volume is not a perfect cylinder but rather a flat gyroscope (Sect. 3.5). The measurement depth z^* is not uniform but varies slightly with the horizontal distance from the CRS (hereafter called the radial distance). The smaller the radius is, the deeper the depth is. The measurement depth directly below the CRS ranges between 15 cm and 83 cm for various SWC.

Determining the measurement support volume is also the basis of calculating the weighted average SWC. In the four weighting methods of the in situ point-scale SWC, only the last weighting method uses the point-scale SWC within the improved measurement support volume because the improved volume is determined in the process of calculating the weight coefficients of this weighting method. The first three methods use the point-scale SWC in the universal measurement support volume because the universal volume is separately calculated from their weight coefficients and only as the known inputs of weight coefficients calculation. The SWC outside the estimated measurement support volume will be ignored.