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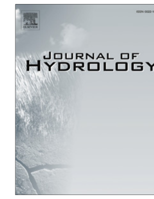

Research papers

Footprint radius of a cosmic-ray neutron probe for measuring soil-water content and its spatiotemporal variability in an alpine meadow ecosystem

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A B S T R A C T

Cosmic-ray neutron probes (CRNPs) have footprint radii for measuring soil-water content (SWC). The theoretical radius is much larger at high altitude, such as the northern Tibetan Plateau, than the radius at sea level. The most probable practical radius of CRNPs for the northern Tibetan Plateau, however, is not known due to the lack of SWC data in this hostile environment. We calculated the theoretical footprint of the CRNP based on a recent simulation and analyzed the practical radius of a CRNP for the northern Tibetan Plateau by measuring SWC at 113 sampling locations on 21 measuring occasions to a depth of 30 cm in a 33.5 ha plot in an alpine meadow at 4600 m a.s.l. The temporal variability and spatial heterogeneity of SWC within the footprint were then analyzed. The theoretical footprint radius was between 360 and 420 m after accounting for the influences of air humidity, soil moisture, vegetation and air pressure. A comparison of SWCs measured by the CRNP and a neutron probe from access tubes in circles with different radii conservatively indicated that the most probable experimental footprint radius was >200 m. SWC within the CRNP footprint was moderately variable over both time and space, but the temporal variability was higher. Spatial heterogeneity was weak, but should be considered in future CRNP calibrations. This study provided theoretical and practical bases for the application and promotion of CRNPs in alpine meadows on the Tibetan Plateau.

1. Introduction

Soil water is an important component of the terrestrial hydrological cycle. Soil water accounts only for 0.05% of the fresh water on Earth, but it sustains terrestrial biological existence and production and the stable development of terrestrial ecosystems (Vereecken et al., 2015). Soil water is also a key state variable, controlling the exchange of vapor and energy between land and atmosphere and thus has a critical influence on ecological and hydrological processes, such as surface runoff, rainwater infiltration and evapotranspiration (Vereecken et al., 2014).

The Tibetan Plateau is the highest geographical unit on Earth, with a mean elevation >4000 m a.s.l. Meadows developed in this high, cold and oxygen-deficient environment are fragile and sensitive to climate change. The ecological environment of the Tibetan Plateau has changed profoundly in recent decades due to the dual influence of climate change and human activity (Zhang et al., 2015b). It became warmer and wetter during 1982–2001, which has increased vegetation coverage and net primary productivity. The plateau, however, had a warming and drying trend during 2001–2011 due to a change in the rainfall pattern (Zhang et al., 2015a). Soil water has become especially important for the restoration and healthy development of degraded meadows.

Soil water has been extensively studied on the Tibetan Plateau in recent decades, mainly by probe in situ observation and remote sensing in regional scale studies, respectively (Zhu and Shao, 2015). Studies at hectometer scales, however, are rare, but could serve as bridges for scale transformation and could provide accurate non-point data for calibrating the results of remote-sensing

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inversion. Cosmic-ray neutron probes (CRNPs) are an effective tool for hectometer-scale measurements of soil-water content (SWC), filling the gap between point observation and remote-sensing inversion, and has the advantages of being automatic and non-destructive. CRNPs have been evaluated and successfully applied in many kinds of ecosystems, including farmland (Han et al., 2015), forest (Heidbüchel et al., 2016; Nguyen et al., 2017), grassland (Peterson et al., 2016), desert (Schreiner-McGraw et al., 2016) and even alpine (Schattan et al., 2017) ecosystems. The application has also been evaluated on the "third pole" of the earth – the Tibetan Plateau (Zhu et al., 2016, 2017). Zhu et al. (2016, 2017) reported a high correlation coefficient (r, 0.938) and low root mean square error (RMSE, 2.1%) for SWCs determined from oven-dried soil samples and SWCs measured by CRNP, demonstrating the good accuracy and applicability of CRNPs in an alpine meadow on the northern Tibetan Plateau.

Identifying the practical range of instruments in different areas is important for maximizing accuracy and developing methods in the ecological, hydrological and geophysical sciences. CRNPs also have footprints. The theoretical footprint of a CRNP is defined as the region that contains 86% of the detected neutrons. Zreda et al. (2008) proposed a theoretical footprint of CRNPs using a neutron-transport model based on the Monte Carlo method. Desilets and Zreda (2013) later reported that the footprint radius of a CRNP was ca. 300 m at sea level using the same model under several simplified assumptions. Köhli et al. (2015) reported radii of 130–240 m at sea level, which were mainly influenced by SWC, air humidity and vegetation, using a refined cosmic-ray neutron source and energy spectrum. As is reported, the radius of a CRNP can also be influenced by elevation (Zreda et al., 2012; Desilets and Zreda, 2013; Köhli et al., 2015). Based on the theory proposed by Zreda et al. (2012) and Desilets and Zreda (2013), the radius of a CRNP was 25% larger at 3000 m a.s.l. than at sea level. Zhu et al. (2016, 2017) also calculated a theoretical radius of ca. 580 m for an alpine-meadow ecosystem at 4600 m a.s.l., nearly two-fold larger than the radius at sea level, which was due to the less probability of neutrons to interact with air molecules in less dense air (Köhli et al., 2015). The radius, however, was only a simple estimate. The new theoretical footprint radius accounting for air humidity, SWC, vegetation and air pressure based on the simulation of Köhli et al. (2015) in the same study area should be updated, and the most probable practical footprint radius also requires further study.

In this study, we measured SWC in a network of neutron access tubes in an alpine meadow in two consecutive growing seasons on the northern Tibetan Plateau and compared it with SWC measured by a CRNP. The objectives of this study were to: (1) determine the theoretical footprint of the CRNP based on a recent simulation; (2) identify the most probable practical footprint radius of the CRNP in the meadow based on SWC measured by a neutron probe and (3) analyze the temporal variability and spatial heterogeneity of SWC within the CRNP footprint.

2. Materials and methods

2.1. Study area

This study was conducted in an alpine meadow on the northern Tibetan Plateau (31°38′38.58″N, 92°00′51.34″E; Fig. 1a) near Nagqu prefecture at an elevation of ca. 4600 m a.s.l. The study area has a sub-frigid and semi-humid monsoon climate with cold and long winters and cool and short summers. The soil is frozen from October to May, and the growing season is very short, only from June to August. The annual mean air temperature is −0.5 °C, with the lowest monthly mean temperature of −9.5 °C (January) and the highest of 10.4 °C (July). The annual mean rainfall is 455.8 mm, with 64% falling during the growing season. The air is thin due to the high elevation, with a mean pressure of only 58.7 kPa. Vegetation in this area is typical of alpine meadows, with *Kobresia pygmaea* the dominant species and accompanied by *Potentilla* spp., *Leontopodium pusillum*, *Carex moorcroftii* and *Stipa purpurea*, which are all annual herbs. The soil is typical alpine meadows soil and is classified as sandy and sandy clayey loams according to the world soil texture classification. An irregular polygonal fence (Fig. 1b) was built as the boundary of a sample plot to prevent grazing by yaks and goats. The plot was 530–770 m long from southeast to northwest and 480–580 m wide from southwest to northeast and had a total area of 33.5 ha. The terrain was flat, with the largest relative elevation of ca. 11 m. The plot sloped gently from northwest to southeast.

2.2. Experimental design and data acquisition

A cosmic-ray soil-moisture observing system (Probe Science and Technology LLC, Beijing, China) was installed in the middle of the study plot in May 2015 (Fig. 1b and c). The system uses a cylindrical probe (filled with helium gas) to detect neutron density, a datalogger (CR800, Campbell Scientific, Utah, USA) to record the neutrons and meteorological (i.e. air temperature) data and a solar panel and accumulator (12 V) to provide energy. More detailed information about the system is provided by Zhu et al. (2017). The system began operation on 24 May 2015 with a constant data-acquisition step of 1 h. Data for more than two years were obtained. The soil in the study area is thawed from June to August, when SWC varies greatly with precipitation and temperature. CRNP data from 15 June to 2 September 2015 and from 5 June to 1 September 2016 were thus used for analysis in this study.

Point SWC data were collected using a neutron probe (CNC IDR-R). One hundred and thirteen neutron access tubes 75 cm in length were inserted into the soil in a grid of 50 m × 60 m in the plot in early June 2015 (the locations were denoted as L1 to L113), most of the tubes extended 15 cm above the ground and 60 cm into the ground (SWC could thus be measured to a depth of 50 cm) and each access tube was equipped with a removable cap on the top to prevent rain-water entering the tube. Based on prior information of SWC in the field and the depth of detection of the CRNP, data from depths of 10, 20 and 30 cm were only used. All locations except L10, with a measuring depth of only 20 cm, could measure SWC to a depth of 30 cm.

The CRNP was conventionally calibrated (Zreda et al., 2012) during the growing seasons of 2015 and 2016. We chose to collect 48 soil samples based on the special environment of the study area distributed as: (1) four radial distances from the probe: 25, 75, 150 and 250 m; (2) four directions: east, west, south and north and (3) three depths: 10, 20 and 30 cm. This sampling design was repeated on 11 campaigns during the two growing seasons; detailed information has been reported by Zhu et al. (2017). A pit was dug in the first sampling campaign to a depth of 30 cm at each of the 16 locations. Undisturbed soil cores were then collected using cutting rings (100 cm^3) to depths of 10, 20 and 30 cm. Two samples were collected at each depth at each location for a total of 96 undisturbed soil cores for measuring bulk density using the oven-drying method. Volumetric SWC could thus be calculated. SWC hereafter refers to volumetric water content.

2.3. Data processing and analysis

2.3.1. Raw neutron-density correction

The raw neutron density detected by the CRNP contained variations of air pressure, humidity and incoming neutron density (Hawdon et al., 2014; Nguyen et al., 2017), so relevant corrections were needed before the conversion from neutron density to SWC.