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Land-surface hydrology with cosmic-ray neutrons: principles and applications

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Abstract: Soil moisture plays the critical role in land-surface processes. But it is not well understood, in part because of its strong spatial variability that makes difficult obtaining representative measurements. The recently developed cosmic-ray soil moisture probe provides the means for such representative measurements and therefore has the potential to provide useful area-average data for land-surface hydrology.
Key Words : cosmic-ray neutrons, soil moisture, land surface hydrology, measurement method

1. Introduction

Soil moisture is the most important part of the water and energy cycle (Fig. 1). It plays a critical role in weather and seasonal climate forecasting and in linking water, energy and biogeochemical cycles over land. But our understanding of water at the land surface is poor, in part because of the mismatch between the scales at which processes above and below the land surface are observed, parameterized and modeled. In the well-mixed atmospheric boundary layer that scale is from hectometers to tens of kilometers. Below the surface, states and fluxes are usually measured at a point. To remove the mismatch, the subsurface must be characterized at the scale comparable to that above the land surface. I call it the useful scale and define it as a range 100 m – 1000 m that broadly matches the needs of future high-resolution land-surface and hydrological models (Wood et al., 2011; Maxwell et al., 2015).

Area-average water states and fluxes are difficult to measure at the useful scale. Point measurements are not representative because of strong spatial heterogeneity (e.g., Fig. 1 in Zreda et al., 2012) and must be upscaled, which is impractical. Scale-integrating methods for soil moisture, such as satellite microwave methods, usually measure over large areas (10 km – 50 km), integrate meteorological, topographic and other factors, and must be downscaled, which is uncertain.

The cosmic-ray method (Zreda et al., 2008, 2012; Desilets et al., 2010), with the hectometer footprint (Desilets and Zreda, 2013; Köhli et al., 2015), integrates out small-scale variations, but is not affected by large-scale variability. It is, therefore a good scale integrator of soil moisture for land-surface and hydrological studies. In this review, I discuss the principles of the cosmic-ray method, the instruments for measuring cosmic-ray neutrons, the methodology for converting neutron data to moisture and some applications to land-surface hydrology.

2. The principle of the cosmic-ray method

The cosmic-ray method (Zreda et al., 2008, 2012; Desilets et al., 2010) takes advantage of the extraordinary sensitivity of cosmogenic low-energy, moderated neutrons of energy between 1 eV and 1000 eV to hydrogen present in materials at the land surface. Most neutrons on earth are cosmogenic (Fig. 1). Primary cosmic-ray protons collide with atmospheric nuclei and unleash cascades of energetic secondary neutrons that interact with terrestrial nuclei and produce fast (evaporation) neutrons at the land surface. The fast neutrons that are produced in air and soil travel in all directions within the air-soil-vegetation continuum and in this way an equilibrium concentration of neutrons is established. The equilibrium is shifted in response to changes in the water present above and below the land surface, for example in soil. Adding water to soil results in more efficient moderation of neutrons by the soil, causing a decrease of fast neutron intensity above the soil surface, where the measurement is made. Removing water from the soil has the opposite effect. The resultant neutron intensity above the land surface is inversely proportional to soil water content (Zreda et al., 2008, 2012).

The measurement volume is a quasi-cylinder with the diameterof a few hectometers (also called the footprint) and

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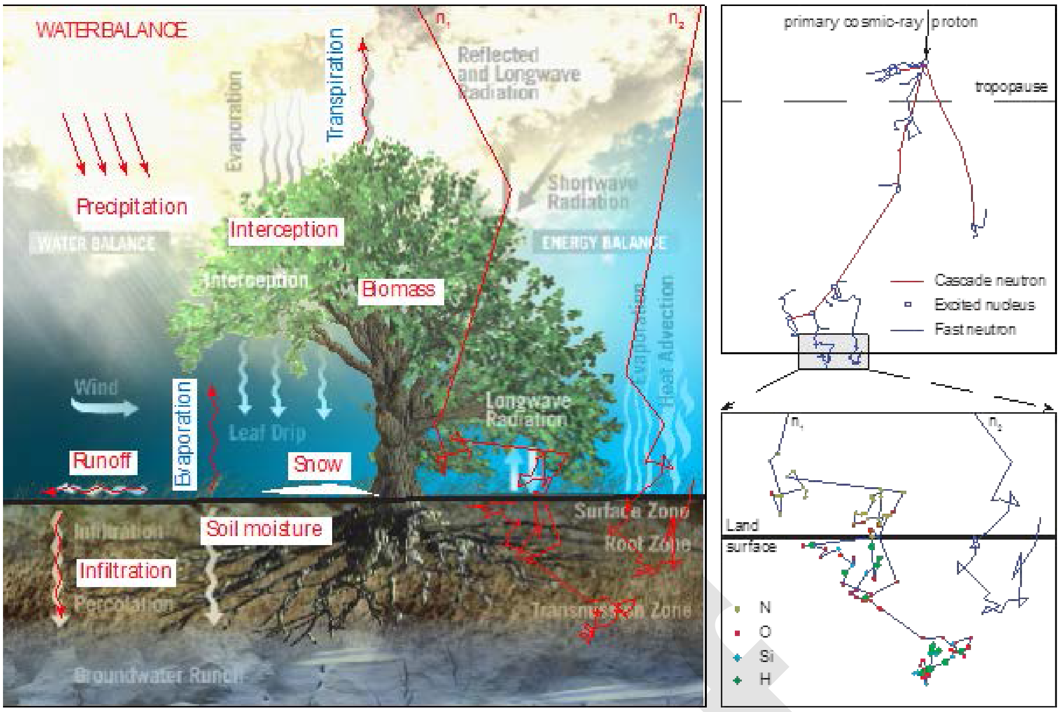

Fig. 1 Left: Water mass balance at the land surface; red labels indicate pools and fluxes measurable using cosmic rays. Right: Cosmic-ray neutron interactions with air and soil. Tracks of two neutrons are shown in the lower panel. Neutron n1 was absorbed in soil and removed from the pool of neutrons measurable by cosmic-ray probe above the surface; neutron n2 went back to the atmosphere and is measurable there. These tracks are copied onto the left panel (red lines). Background image — European Space Agency (ESA).

Fig. 2 Footprint of the COSMOS probe located at the Rietholzbach site, Switzerland (cosmos.hwr.arizona.edu/Probes/StationDat/018/index.php). The white dashed line with the radius of 300 m is the footprint estimated using Desilets and Zreda (2013); the footprint estimated by K~~oe~~hli et al. (2015) would be smaller. Red dots located on three smaller, yellow circles at radii of 30 m, 80 m and 200 m show the locations of calibration samples.

a depth of a few decimeters (Desilets et al., 2013; Köhli et al., 2015). The footprint increases with increasing altitude (decreasing pressure), and decreases with increases of each of the following: air pressure, absolute humidity of air, soil moisture and vegetation density. The measurement depth decreases strongly with increasing soil moisture.

Because of the large size of the footprint, it usually contains many sources of water, in addition to soil water. Fig. 2 shows an estimated footprint for the cosmic-ray probe at the Rietholzbach site in Switzerland. The visible sources of water include soil (including water in pore spaces, in minerals and in organic matter), vegetation (grass, crops, trees), small creeks and man-made infrastructure (buildings, roads). The largest source of water is soil, but the other reservoirs, especially vegetation, may be important and they should be assessed independently.

Neutron measurements can be made using stationary or roving probes. The former provide time series of moisture over the hectometer footprint, the latter gives moisture for swaths of land along driving routes.

3. Instruments

Low-energy cosmogenic neutrons are measured using proportional counters (Knoll, 2000), which are sensitive to thermal neutrons (median energy of 0.025 eV), shielded by a layer ofplastic that shifts the energy sensitivity of the counter to neutrons of the desired energy (>1 eV). The cosmic-ray probe (Fig. 3) is powered using a solar panel paired with a rechargeable battery and is equipped with an Iridium satellite modem or a cellular modem for real-time telemetry. It can be operated almost anywhere in the world, except areas with insufficient day light. A stationary neutron probe of this type is implemented in the Cosmic-ray Soil Moisture Observing System (Fig. 4), or COSMOS (Zreda et al., 2012; cosmos.hwr.arizona.edu); therefore, it is sometimes called "COSMOS probe". The instrument is described in Zreda et al. (2012). A mobile COSMOS detector is a bigger version of the stationary probe, additionally equipped with a GPS system for real-time positioning (Chrisman and Zreda, 2013).

Fig. 3 Cosmic-ray soil moisture probe installed at Marshall Lake, Colorado, USA. For description of the components, see Fig. 9 in Zreda et al. (2012).

4. Conversion of neutron data to soil moisture

The measured neutron intensity ϕ (in the equation below), normalized for variations in pressure, humidity and solar activity (Zreda et al., 2012), is converted to soil moisture SM using the response function, such as that developed by Desilets et al. (2010):

$$SM = \frac{a_0}{\phi/\phi_0 - a_1} - a_2 \tag{1}$$

where SM is in weigh fraction (g of water per g of dry soil), ϕ_0 is the neutron intensity in air above dry soil (obtained by calibration) and a_0, a_1 and a_2 are fitted constants that define the shape of the calibration function. Modeling conducted by Desilets et al. (2010) gave the following fitting constants for bare soil composed of SiO_2: $a_0 = 0.0808$, $a_1 = 0.372$ and $a_2 = 0.115$. For water content measured in volumetric units (cm^3 of water per cm^3 of soil) both sides of the equation should be multiplied by the dry bulk den-

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Fig. 4 The COsmic-ray Soil Moisture Observing System (COSMOS). The network consists of approximately 100 probes of the type shown in Fig. 2 or similar. The Australian probes displayed here belong to the CosmOz network. Not shown here are other networks that either already exist or that are under construction, most notably the TERENO network in Germany and the COSMOS-UK network in the United Kingdom.

Fig. 5 Collecting soil samples for calibration. Soil samples are collected using a split corer that is pushed into soil, dug out, opened lengthwise, the core is divided into 5-cm long samples and each sample is sealed in a soil tin for shipment to the laboratory. Soil samples are obtained at each of the 18 coring sites shown in Fig. 2.

sity of soil. Other measurements needed for the conversion are atmospheric pressure, atmospheric water vapor, incoming high-energy neutron intensity and temperature. They are used to compute various corrections necessary for the computation of soil moisture from neutron data, as described by Zreda et al. (2012) and other sources.

5. Calibration

Cosmic-ray soil moisture probes have to be calibrated on independently measured area-average soil moisture. This is accomplished by collecting a large number (typically 108) of soil samples (Fig. 5) within the cosmic-ray footprint (Fig. 2), measuring soil water content by independent methods such as oven drying, and computing the area-average soil moisture. Neutron intensity is measured over the duration of sampling. The average soil moisture is then used with the response function, such as the equation given in section 4 above, to obtain a calibration parameter. One calibration data set is sufficient for soils with sparse vegetation, but multiple data sets, obtained at different soil water contents, provide a more accurate calibration and can account for the effects of other pools of water on the response function, such as biomass (Heidbüchel et al., 2015).

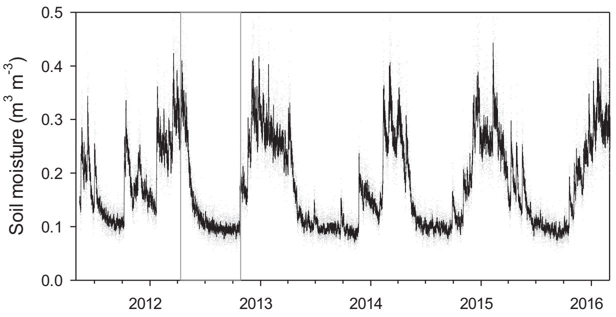

Fig. 6 COSMOS-derived time series of soil moisture from the Tonzi site, California (data from http://cosmos.hwr.arizona.edu/Probes/StationDat/032/index.php). Gray dots show hourly soil moisture; the black line shows 12-hour moving average. Data inside the light gray box in 2012 show a single drying curve that would be used for analysis of infiltration and evapotranspiration (see text for details).

Vegetation has a significant effect on neutron intensity (Franz et al., 2013a; Bogena et al., 2013) and on the shape (slope) of the calibration function. Thus, measuring soil moisture in the presence of vegetation requires a correction factor (Baatz et al., 2015) or more than one calibration point to define that slope. Heidbüchel et al. (2015) found that two calibration data points are sufficient if the two soil moisture states are very different. (If they are similar, the slope cannot be defined accurately.)

Snow-water equivalent can be measured with cosmic-ray probe (Desilets et al., 2010). Calibration for snow is conducted in a similar way to that for soil moisture, by making independent measurements of snow-water equivalent over the cosmic-ray footprint. But the effect of snow on neutron intensity is not well known and details still have to be worked out.

6. Applications

The cosmic-ray method was originally designed for measuring soil moisture at a fixed location (Fig. 6). Much progress has been made in the past five years. Recent work has shown that the probe can be used for measuring other pools of water, such as snow on the ground and on canopy, water in vegetation, and possibly water on canopy; that it can be used in a moving vehicle to map moisture over large areas; and that it can be used to measure infiltration rates, and possibly hydraulic conductivities, of variably-saturated soils at hectometer scale. These applications are discussed briefly below.

Biomass can be measured with cosmic rays because plants contain significant amounts of water whose presence near the land surface affect the moderation of neutrons and therefore their intensity. The proof-of-concept study involved measurements in a forest and a recently-deforested site nearby (Franz et al., 2013a). The difference in neutron intensities between the sites was converted to biomass water equivalent, and then to dry biomass. The dry biomass was found consistent with allometric measurements at the forested site, showing that the cosmic-ray method is feasible.

Spatial mapping of soil moisture using a mobile probe, or rover, is possible with two recent advances: the development of a larger probe that has high count rate and is equipped with GPS to monitor position as the probe moves; and the development of a universal calibration function (Franz et al., 2013b) that permits conversion of neutron intensity to soil moisture without local calibration. Several rover surveys have been conducted in the past, including a year-long project in Tucson, Arizona, USA, which generated maps of soil moisture for a 1000-km^2 area at 22 different times, permitting mass balance calculations for the entire basin and the entire duration of the experiment. In a recent paper, Franz et al. (2015) combined roving surveys with stationary probes to improve the accuracy of soil moisture determination over a large area.

Infiltration or recharge rate can be inferred from measured soil moisture and mass balance of water in soil. Following a precipitation event, soil moisture slowly decreases over many days (Fig. 6). The drying curve provides information on changes of moisture with time and its temporal derivative gives change of storage. That change is then used in a mass balance equation, which can be converted to infiltration rate. Furthermore, if the hydraulic gradient is known or can reasonably be assumed, that infiltration rate can be converted to unsaturated hydraulic conductivity. Our first study (Karczynski, 2014) showed that cosmic-ray derived effective hydraulic conductivity is consistent with an (upscaled) average of 36 point measurements near the saturation, but that it is much larger than the average at lower levels of saturation. The reasons for that discrepancy have not been elucidated.

In a similar way, area-average precipitation rates can be measured using cosmic-ray probes. The underlying assumption is that all rain water enters the soil where it stays long enough to be measured using neutrons. The difference between neutron-derived soil moisture before and after the rain event equals precipitation amount. Potential problems include surface runoff and fast infiltration; however, both appear to be insignificant at two locations where we conducted proof-of-the-concept experiments.

These and many other results show the utility of the cosmic-ray probe to land-surface studies. The large footprint of the probe averages the small-scale variabilities in states (for example, moisture), fluxes (for example, infiltration rate) and properties (for example, hydraulic conductiv-

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ities), eliminates the needs for upscaling and permits treatment of processes that occur below and above land surfaces at the same useful spatial scale.

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要　　旨

土壌水分は，表層土壌のプロセスにおいて重要な役割を果たす．しかし，土壌水分の空間変動が大きく代表的な測定値の決定が困難であるために，幾分か土壌水分量の把握は難しい．近年に開発された宇宙線による土壌水分計測は，そのような代表的な土壌水分量の平均値を与えるので，表層土壌の水文学において有益な面的平均値の提供を可能にする．

キーワード：宇宙線中性子，土壌水分量，表層土壌水文学，測定方法