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Calibration of a catchment scale cosmic-ray probe network: A comparison of three parameterization methods

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SUMMARY

The objective of this work was to assess the accuracy of soil water content determination from neutron flux measured by cosmic-ray probes under humid climate conditions. Ten cosmic-ray probes were set up in the Rur catchment located in western Germany, and calibrated by gravimetric soil sampling campaigns. Aboveground biomass was estimated at the sites to investigate the role of vegetation cover on the neutron flux and the calibration procedure. Three parameterization methods were used to generate site-specific neutron flux – soil water content calibration curves: (i) the N_0-method, (ii) the hydrogen molar fraction method (*hmf*-method), and (iii) the COSMIC-method. At five locations, calibration measurements were repeated to evaluate site-specific calibration parameters obtained in two different sampling campaigns. At two locations, soil water content determined by cosmic-ray probes was evaluated with horizontally and vertically weighted soil water content measurements of two distributed in situ soil water content sensor networks. All three methods were successfully calibrated to determine field scale soil water content continuously at the ten sites. The *hmf*-method and the COSMIC-method had more similar calibration curves than the N_0-method. The three methods performed similarly well in the validation and errors were within the uncertainty of neutron flux measurements despite observed differences in the calibration curves and variable model complexity. In addition, we found that the obtained calibration parameters N_{COSMIC}, N_0 and N_S showed a strong correlation with aboveground biomass.

1. Introduction

Soil water content is a key variable in the global hydrologic cycle. Important hydrologic processes such as evapotranspiration are controlled by root zone soil water content in case of water limitation (Jung et al., 2010; Denmead and Shaw, 1962). This is generally the case in (semi-)arid environments and may also occur in temperate regions during summer time. Therefore, agricultural production can be limited by soil water availability, which raises the need for irrigation in large parts of the world to sustain food supply (Siebert et al., 2005). Furthermore, climate and weather conditions are influenced by mass and energy fluxes between the land surface and the atmosphere (Shukla and Mintz, 1982). To better understand hydrologic processes on relevant scales, soil water content measurements are important for validating and calibrating hydrologic models (Brocca et al., 2012), and land surface and climate models (Koster et al., 2004). Recent publications emphasize the need for soil water content measurements at the field scale to derive process variables and parameters (Vereecken et al., 2008; Crow et al., 2012). However, high spatial variability and temporal dynamics of soil water content pose a challenge for soil water content measurements at relevant scales.

Current state-of-the-art methods for soil water content measurements include point measurements using electromagnetic sensors or gravimetric sampling, sensor networks, geophysical measurements, and air- and space-borne remote sensing (Vereecken et al., 2008). The main limitation of electromagnetic soil water content sensors and gravimetric sampling is that they only provide information for a small volume of soil ($\sim 10^{-3}$ m^3). Given the high spatial variability of soil water content, a large number of point measurements is required to provide adequate information on soil water content at larger scales (Crow et al., 2012). Therefore, wireless sensor networks were developed that allow continuous monitoring of soil water content at a large number of locations (Schaefer et al., 2007; Bogena et al., 2010; Dorigo et al., 2011). Although sensor networks achieve a high temporal resolution, the spatial extent of sensor networks is still relatively small (<1 km^2).

Soil water content derived from space-borne remote sensing techniques is based on the use of active and passive microwave sensors with the advantage of global coverage (Kerr, 2007). However, L-band passive microwave sensors (e.g. Soil Moisture and

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Ocean Salinity satellite (SMOS)) are only sensitive to soil water content of the upper few cm of the soil, and additional information on vegetation characteristics and surface roughness is needed to estimate soil water content from measured brightness temperature (Kerr et al., 2012). C-band active microwave measurements have an even smaller penetration depth and are strongly affected by vegetation and surface roughness (Jackson and Schmugge, 1989). The accuracy of future soil water content products of the upcoming Soil Moisture Active Passive Mission (SMAP) will also be limited by vegetation cover, and may also suffer from radio frequency interference (Entekhabi et al., 2010).

Geophysical techniques, such as ground penetrating radar (Eppstein and Dougherty, 1998; Huisman et al., 2003) and electromagnetic induction (Sheets and Hendrickx, 1995; Akbar et al., 2005), show promising results to overcome the existing gap between continuous point measurements in time and temporally sparse but global remote sensing data (Robinson et al., 2008), although they are labor-intensive when large-scale surveys (>1 km^2) are required.

Recently, passive neutron sensors, so called cosmic-ray probes (CRP), were proposed to measure soil water content at the field scale (Zreda et al., 2008). The general measurement principle is similar to that of active neutron probes. Soil water content monitoring using passive neutron probes relies on the determination of the time-variable fast neutron flux near the earth surface. High energy protons from space, or primary cosmic rays, serve as natural radiation source. Proton interaction in the Earth's atmosphere with terrestrial atoms produces high energy neutrons, so called secondary cosmic rays. Subsequent collision and moderation of secondary cosmic rays with terrestrial nuclei produces fast neutrons in the atmosphere. Only fast neutrons are then effectively moderated and absorbed by hydrogen. Therefore, the fast neutron flux shows a strong inverse correlation with the abundance of hydrogen atoms in the upper soil layer and thus can be used to determine soil water content (Zreda et al., 2008). The most attractive feature of the cosmic-ray probe is the relatively large measurement volume. Because of the large mean free path in air traveled by fast neutrons before collisions, the horizontal footprint has an approximate radius of about 300 m around the cosmic-ray probe at sea level or somewhat less depending on air density (Desilets and Zreda, 2013). The effective measurement depth varies as a function of soil water content between ~12 cm for moist soils up to 70 cm for dry soils (Franz et al., 2012).

Recently, the use of cosmic-ray probes for soil water content sensing has increased considerably. Several methods are now available to estimate soil water content from the fast neutron flux: (i) a site-specific shape-defining function (N_0-method) (Desilets et al., 2010), (ii) a universal calibration function (*hmf*-method) (Franz et al., 2013b) and (iii) a COsmic-ray Soil Moisture Interaction Code (COSMIC operator) (Shuttleworth et al., 2013). All three parameterization methods were calibrated with the Monte Carlo Neutron-Particle eXtended model (MCNPx) (Pelowitz, 2005). The MCNPx model is a state-of-the-art particle transport model developed mainly at the Los Alamos National Laboratory. The site-specific N_0-method is the computationally simplest method requiring only one calibration parameter for soil water content estimation. However, it requires intensive soil sampling to adequately estimate this calibration parameter. The universal calibration function was developed to overcome the necessity of local calibration campaigns in case of logistic or practical difficulties, and to allow measurements with a moving cosmic-ray probe (Chrisman and Zreda, 2013). However, bulk density, lattice water and aboveground biomass need to be measured or derived from maps if these variables cannot be measured directly within the footprint. The COSMIC operator was developed to reproduce the time-costly modeling of neutron soil water interaction processes with the MCNPx code. The COSMIC code also requires site-specific calibration of three parameters. Input and calibration requirements are therefore similar to the N_0-method.

All three methods are parameterized based on an imperfect representation of reality in the MCNPx model, and are, therefore, subject to uncertainties in user-defined model parameterization, initial and boundary conditions. It has also been reported that the three methods differ in how neutron detection by the CRP is modeled. Initial modeling work assumed that only fast neutrons are detected by the polyethylene-shielded detector. However, very recently it was realized that a larger part of the detected neutrons (about 30%) may also come from the thermal energy range (D. Desilets and T.E. Franz, personal communication). Documentation of these aspects is limited in previous publications and can therefore not be analyzed in further detail in this paper. Clearly, the availability of three different methods to estimate soil water content from cosmic-ray probe measurements raises the question how well each of the three parameterization methods performs under various soil, meteorological, and vegetation conditions.

Within this context, the main objective of this study is to compare the three available methods of soil water content determination from cosmic-ray probe measurements at several test sites against independent in situ soil water content measurements. The test sites are located in the Rur catchment in western Germany and are part of the Terrestrial Environmental Observatories (TERENO) infrastructure (Zacharias et al., 2011). The test sites are particularly well suited for an intercomparison study because of their low altitude and the fact that they are located close together within 0.63° latitude. Additionally, the test sites have different types of vegetation cover, a wide range in mean annual precipitation (from 743 to 1401 mm), and two of the test sites are equipped with distributed in situ soil water content sensor networks. Two of the parameterization methods (*hmf*-method and the COSMIC operator) were developed to reproduce measured neutron flux data from measured soil water content (Shuttleworth et al., 2013; Franz et al., 2013b). In this study, these two methods are used inversely for soil water content determination along with the N_0-method. Repeated gravimetric in situ sampling campaigns and the two distributed sensor networks are used to evaluate the reliability of the three methods.

2. Materials and methods

2.1. Site description and instrumentation

The Rur catchment is situated in western Germany and covers an area of 2354 km^2 (Fig. 1). It is part of the TERENO project that established four terrestrial observatories in Germany (Zacharias et al., 2011; Bogena et al., 2012). The Rur catchment exhibits distinct gradients in topography, land use, and climate. The elevation ranges from 15 m in the lowland region in the North up to 690 m in the hilly region in the South. The lowland region is characterized by intensive agriculture, whereas the southern part is mainly covered by forest and grassland. The total land use distribution in the catchment is 14% coniferous forest, 17% deciduous forest, 32% grassland, and 34% crop land (mainly wheat, maize, sugar beet and barley). In the northern part of the Rur catchment, the mean annual precipitation and potential evapotranspiration are about 700 mm and 600 mm, respectively. At the higher altitudes in the southern part of the catchment, mean annual precipitation increases to 1200 mm and the potential evapotranspiration decreases to less than 500 mm (Bogena et al., 2005).

Ten cosmic-ray probes (type CRS1000, HydroInnova LLC, 2009) were installed in the Rur catchment at a height of 1.5 m (Fig. 2). Five probes are equipped with two neutron detectors to measure