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High-resolution space–time quantification of soil moisture along a hillslope using joint analysis of ground penetrating radar and frequency domain reflectometry data

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SUMMARY

We combined ground-penetrating radar (GPR) and frequency domain reflectometry (FDR) to assess the space–time variability of soil moisture along a hillslope. Time-lapse GPR and FDR measurements were conducted weekly during the period 23/03–08/06/2011 along a cultivated hillslope in the Belgian loam belt. A full-wave GPR model, a soil dielectric mixing model and the Debye equation were combined to directly estimate soil moisture from GPR measurements. Measured GPR data were well reproduced by the full-wave GPR model, resulting in a relatively good agreement between the GPR and FDR-derived soil moisture. Subsequently, we merged the soil moisture obtained from both techniques in a data fusion framework and we investigated its spatial and temporal variability. The results indicate that there was a high correlation between the spatial variability of soil moisture and topography as well as between its temporal variability and rainfall. A temporal stability analysis showed that soil moisture at the footslope is higher and more stable than that at the summits and backslopes. The proposed approach appears to be promising for assessing soil moisture at the hillslope scale with a relatively high space–time resolution.

1. Introduction

Soil moisture has long been acknowledged as an important factor to understand hydrological and meteorological processes. In catchment hydrology, soil moisture controls the separation of precipitation into evaporation, runoff and infiltration. Hence, the spatial variability of soil moisture largely influences on the accuracy of flow estimation (Zehe et al., 2005). In soil hydrology, quantitative knowledge of soil moisture is essential for estimating soil hydraulic properties, i.e., retention curve and hydraulic conductivity functions, which are subsequently used to predict soil moisture profiles and calculate groundwater recharge (Entekhabi et al., 1994; Ines and Mohanty, 2008). Soil moisture is also a crucial factor that controls the partitioning of radiation energy into latent and sensible heat fluxes, and consequently, near-surface temperature and precipitation (Seneviratne et al., 2010). As a result, a timely and accurate knowledge of soil moisture is essential for hydrometeorological modeling and prediction. However, assessing soil moisture is not trivial due to its complexity and high variability, which requires an advanced monitoring system with a high spatial and temporal resolution.

Given the importance of soil moisture, numerous techniques have been developed for characterizing this variable across a range of spatial scales. Excellent reviews on these techniques are presented in Rubin and Hubbard (2005), Robinson et al. (2008) and Vereecken et al. (2008). At small scale, contact-based sensing techniques (e.g., time domain reflectometry and capacitance probes) are useful. These techniques provide relatively accurate soil moisture with a high temporal resolution. However, their small supporting volume makes them time-consuming, poorly representative and labor-intensive. In conditions where hard or stony soil is present, measurements using these techniques may even be impossible (Robinson et al., 2012). At watershed and basin scales, soil moisture is usually obtained by remote sensing techniques (e.g., synthetic aperture radar (SAR), soil moisture and ocean salinity mission (SMOS), advanced scatterometer (ASCAT)). These techniques provide soil moisture data with a large extent but their space–time resolution is often too coarse to account for the high space–time dynamics of hydrological processes. In addition, only information on the few top centimeters of soil is provided. Their accuracy is also strongly affected by vegetation and surface roughness (Wagner et al., 2007; Verhoest et al., 2008).

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Hillslope is a fundamental unit of landscapes and, therefore, understanding hillslope hydrology is crucial for upscaling soil water dynamics and hydrological processes to larger scales (Vereecken et al., 2007). However, studies of hillslope hydrology are hindered by unavailability of high spatial resolution soil moisture information over the whole hillslope area. At this scale, it is impractical to use contact-based techniques and the use of air- or space-borne remote sensing is not appropriate. In that respect, geophysical techniques (e.g., electromagnetic induction (EMI) and GPR) are ideal to fill the scale gap between the local scale and the watershed scale. EMI is a non-invasive technique which measures bulk soil electrical conductivity. Because soil moisture largely contributes to the bulk soil electrical conductivity, the spatial and temporal variation of soil moisture can be assessed by using EMI measurements. Sherlock and McDonnell (2003) and Meerveld and McDonnell (2009) observed that EMI-derived electrical conductivity and locally measured soil moisture were well correlated. They concluded that EMI was useful for hillslope or catchment hydrological studies because it could relatively quickly provide spatially distributed soil moisture data over a large area with a reasonable degree of accuracy. Robinson et al. (2012) used time-lapse EMI measurements to monitor moisture dynamics in time and space in a semi-arid oak savanna hillslope. They observed that EMI-derived electrical conductivity quickly increased after rainfall events and that the spatial pattern of soil moisture depended not only on topography but also on soil texture distribution. However, in addition to soil moisture, EMI is sensitive to other soil properties like clay content, salinity and organic matters. This causes difficulties to separate contribution of soil moisture to soil bulk electrical conductivity from those of other properties, thereby strongly limiting the accuracy of soil moisture determination using EMI (Sudduth et al., 2003; Rodriguez-Perez et al., 2011).

Over the last decades, GPR has become a popular geophysical measurement technique that is more and more applied in soil hydrology. GPR was used for soil stratigraphy imaging (Grandjean et al., 2006), aquifer characterization (Tronicke et al., 2004), contamination detection and mapping (Nigel, 2007), soil moisture estimation (Serbin and Or, 2004; Rucker and Ferre, 2005; Minet et al., 2012), water infiltration monitoring (Looms et al., 2008), soil hydraulic characterization (Kowalsky et al., 2005; Lambot et al., 2009), and thawing zones detection in permafrost areas (Westermann et al., 2010). The physical foundation behind these applications of GPR is based on electromagnetic wave propagation in the soil, which is governed by its electromagnetic properties, i.e., the dielectric permittivity ε, the electrical conductivity σ and the magnetic permeability μ. As the dielectric permittivity of water ($\varepsilon_w \approx 80$) is prominently larger than that of the soil matrix ($\varepsilon_s \approx 4-5$) and air ($\varepsilon_a \approx 1$), soil moisture has a dominant influence on soil dielectric permittivity. As a result, soil moisture can be determined by analyzing the GPR reflections (or transmissions).

Several GPR methods have been developed to quantitatively characterize soil moisture. For example, the travel time tomography method determines soil moisture relying on the relationship between the soil dielectric permittivity and wave propagation velocity determined using the ray-based simplification (Huisman et al., 2001; Grote et al., 2003). Redman et al. (2002), Serbin and Or (2004), Rucker and Ferre (2005) used soil surface reflection amplitude obtained from off-ground GPR measurements to estimate the soil surface electrical permittivity. Limitations of these methods are (1) only a part of the GPR waveforms is used to estimate soil moisture; (2) soil moisture estimation depends strongly on the simplifying assumptions with respect to antenna radiative properties and electromagnetic wave propagation in the soil.

With the recent advances in computational technology, there have been an increasing number of studies following the full-wave inverse modeling approach, which accounts for all information in the GPR data to characterize the dielectric medium. One approach is to numerically solve Maxwell's equations by using the finite-difference time-domain (FDTD) (Ernst et al., 2007) or finite-element time-domain (FETD) (Durand and Slodic, 2011) methods. Yet, simultaneously modeling the antenna and medium domains is still challenging for these numerical approaches due to too long computation time in an inversion framework.

In order to avoid the excessive computation time of the numerical approaches, several authors solved analytically Maxwell's equations under specific assumptions. For example, Gentili and Spagnolini (2000) modeled a GPR horn antenna at some distance over a three-dimensional layered medium using an array of frequency independent source dipoles and a feeding line characteristic impedance. However, the interactions between the antenna and medium were not accounted for in this model. Lambot et al. (2004) used data in the frequency domain obtained from an off-ground GPR to estimate soil moisture by far-field full-wave inverse modeling. Wave propagation in soil was described by a planar layered media Green's function. The antenna was characterized by a point source and receiver and its characteristic global, frequency-dependent transmission/reflection coefficients. Compared to the numerical approaches, this approach is much more beneficial in terms of computation time. However, it requires that the distance between the antenna and soil surface is greater than 1.2 the maximum dimension of the antenna aperture to satisfy the far-field assumptions, which limits the GPR intrusion depth and reduces the signal/noise ratio (Tran et al., 2013). Busch et al. (2014) developed a full-wave inversion approach that can work when the antenna is on ground. The electrical field in the frequency domain was calculated by multiplying an unknown source wavelet of a point source by Green's function. As a result, in addition to the soil electrical conductivity and permittivity, this approach requires the estimation of the amplitude and phase of the source wavelet. Lambot and André (2014) generalized the far-field model so that it can be applied to near-field conditions. The model was successfully validated with numerical tests (Tran et al., 2013) and laboratory experiments (Tran et al., 2014) using different types of antennas. Yet, the model has not been validated in field conditions so far.

In many applications, soil moisture data are obtained using different techniques, each having their specific measurement accuracy, resolution, scale and extent (Robinson et al., 2008). The appropriate assessment of the space–time soil moisture variability can rely on an integration of these measurements (Looms et al., 2008). By merging them together, these measurements can constrain each other, and therefore, increase the accuracy and reliability of soil moisture. In this study, in addition to GPR, we also measured soil moisture with a hand-held FDR probe. The theory of FDR is much similar to GPR. To estimate soil moisture, the FDR probe generates an incident signal in the frequency domain and transmits it into soil by a rod array. The reflection signal is controlled by the impedance of the rod array, which varies with the soil dielectric permittivity and correlated soil moisture. Different from GPR, FDR is based on the guided wave technique, and the FDR sensor directly contacts with soil, while GPR exhibits a much more complicated unguided behavior and wave propagation inside the antenna. Like other point measurement techniques, it is difficult for FDR to provide sufficient information to capture the detailed spatial structure of soil moisture over the hillslope area. By contrast, despite suffering from some errors, the spatial structure of soil moisture is well characterized by GPR because GPR can perform many measurements in a short period. In that respect, merging these two measurements allows for a better assessment of the space–time soil moisture dynamics. There are several approaches to perform the combination, e.g., cokriging (Goovaerts, 1998) or