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Soil moisture prediction of bare soil profiles using diffuse spectral reflectance information and vadose zone flow modeling

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ABSTRACT

Soil hydraulic property information of the vadose zone is key to quantifying the temporal and spatial variability of soil moisture, and for modeling water flow and contaminant transport processes in the near surface. This study deals with exploring the feasibility of using diffuse soil spectral information in the visible, near-infrared and shortwave infrared range (350–2500 nm) to estimate coarse-scale soil hydraulic parameters and predict soil moisture profiles using a topography-based aggregation scheme in conjunction with a 1D mechanistic water flow model. Three different types of parametric transfer functions (so-called spectrotransfer functions, STFs; pedotransfer functions, PTFs; and spectral pedotransfer functions, SPTFs) were aggregated from the point scale to 1 km^2 pixel size. to provide coarse scale estimates of van Genuchten-Mualem (VGM) hydraulic parameters. The coarse scale hydraulic parameters were evaluated by simulating soil water dynamics of the 1 km^2 pixels across the Zanjanrood River sub-watershed (ZRS) in northwest Iran. Resultant soil water states were compared with ground-truth measurements and advanced synthetic aperture radar (ASAR) estimates of soil water content. The topography-based aggregation scheme was found to provide effective values of the VGM hydraulic parameters across the ZRS study site. The coarse scale STFs performed best in terms of simulating surface, near-surface and subsurface soil water dynamics, followed by the coarse scale SPTFs and PTFs, which performed similarly. The average simulated soil water contents of the surface layer closely correlated with ASAR estimates during relatively wet periods. Simulated subsurface soil water dynamics matched well with the ground-truth measurements. These findings indicate the feasibility of using spectral data to predict VGM hydraulic parameters and, ultimately, to predict soil water dynamics at the larger scales.

1. Introduction

Profile soil moisture, as a key dynamic state variable, plays a central role in weather and climate predictions from the regional to the global scale by controlling the exchange and partitioning of water and energy fluxes between the land surface and the atmosphere (Vereecken et al., 2008; Kornelsen and Coulibaly, 2014). Accurate knowledge of profile soil moisture at various spatial and temporal scales is also important for strategic management of water resources (Vereecken et al., 2016). Soil moisture status and fluxes vary considerably in both space and time due to inherent variations in the soil hydraulic properties (Montzka et al., 2011), precipitation rates (Koster et al., 2004; Rosenbaum et al., 2012), topographic features (Joshi and Mohanty, 2010; Jana and Mohanty, 2012b; Schröter et al., 2015), and vegetation characteristics (Famiglietti et al., 1998; Guar and Mohanty, 2013).

A range of in-situ and remote soil water sensing techniques have been developed, tested, and used with varying levels of success during the past several decades (Vereecken et al., 2014). In-situ techniques are generally confined to short-term field experiments or point-scale sensor installations that are representative over a relatively small spatial scales since soil water is subject to considerable spatial heterogeneity (Greifeneder et al., 2016). Indirect estimates of soil moisture can be obtained using active (Ulaby et al., 1996; Baghdadi et al., 2012; Jagdhuber et al., 2013; Kornelsen and Coulibaly, 2013) and passive (Jonard et al., 2011; Montzka et al., 2013; Dimitrov et al., 2014, 2015) microwave remote sensors that have had the greatest success in estimating soil moisture in a spatially and temporally consistent behavior. These methods provide surface soil moisture estimates of only the top few centimeters (0–5 cm) of a soil profile (Kerr, 2007). The somewhat low spatial

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resolution (several tens of kilometers) of passive microwave measurements has prompted research on downscaling to expand applicability (Pellenq et al., 2003; Merlin et al., 2008). However, non-invasive geophysical methods, such as ground penetrating radar (GPR) (Weihermuller et al., 2007; Jonard et al., 2011), electromagnetic induction (EMI) (Robinson et al., 2012), and electrical resistivity tomography (ERT) (Vanderborght et al., 2013), have been used to bridge the gap between point and satellite measurements of soil moisture.

Soil-vegetation-atmosphere-transfer (SVAT) models are commonly used to numerically simulate state variables such as soil moisture, as well as for estimating energy-mass exchange fluxes. The performance of SVAT models is usually confined by uncertainty of the driving forces and its parameters. While soil hydraulic properties are very important in distributed SVAT models, they are mostly observed only at the point scale or generalized to soil maps. A major challenge when running these models at a larger scale is obtaining accurate model inputs and physically realistic hydraulic parameter values. Aggregation of soil hydraulic properties from field to watershed or regional scales is critical for SVAT model performance at these scales (Zhu and Mohanty, 2002a, 2002b; Vereecken et al., 2007; Jana and Mohanty, 2012a, 2012b, 2012c; Vereecken et al., 2016). Hence, a need exists for upscaling schemes that enable one to convert point scale data to much larger extents.

Coarse scale characteristics of the soil hydraulic parameters are governed predominantly by soil texture and structure (especially at the field scale), and topography (especially at watershed scales and beyond) (Jana, 2010). Topography plays a key role in soil classification. Several studies have shown that topography-based scaling algorithms are able to capture much of the variations in soil hydraulic parameters required to generate equivalent flows and soil moisture states in a coarsened domain (Wilson et al., 2004; Jana and Mohanty, 2012a, 2012b).

Practical methods for estimating soil moisture continuously over time and relatively large spatial areas likely involve a combination of remote sensing and modeling (Entekhabi et al., 1999; Vereecken et al., 2014). Recent studies have demonstrated that profile soil moisture could be estimated well by assimilation of remotely sensed surface soil moisture data into a hydrological model (Das et al., 2008a; Ines and Mohanty, 2008a, 2009; Montzka et al., 2011; Han et al., 2013, 2014; De Lannoy and Reichle, 2016; Vereecken et al., 2016). Despite the important role of surface and subsurface soil moisture in hydrological and meteorological predictions, detailed spatial and temporal modeling of profile soil moisture at the large scale is often still lacking.

During the past few decades, visible, near-infrared and shortwave infrared (Vis-NIR-SWIR) reflectance spectroscopy has been shown to be an effective alternative to conventional in-situ or laboratory methods for providing rapid, noninvasive and cost-effective estimates of a wide range of soil properties. Many studies have shown the capability of laboratory scale Vis-NIR-SWIR (400–2500 nm) spectrometry to accurately estimate basic soil properties such as the soil particle size distribution, organic carbon content, water content, and clay mineralogy (Gomez et al., 2008; Lopez et al., 2013; Minasny et al., 2008, among many others). These properties are at the same time key input parameters for many pedotransfer functions (PTFs) for estimating the unsaturated soil hydraulic properties (Vereecken et al., 2010). Despite extensive literature on predictions of basic soil properties from Vis-NIR-SWIR data, more research is needed to more directly and reliably estimate the soil hydraulic properties. A few studies recently analyzed the potential of soil spectral information in the Vis-NIR-SWIR region to estimate soil hydraulic properties using point (Janik et al., 2007; Minasny et al., 2008; Lagacherie et al., 2008; Babaeian et al., 2015b) and parametric (Santra et al., 2009; Babaeian et al., 2015b) transfer functions. These studies provided soil hydraulic parameters at point scale. While some scale mismatch between mostly point measurements of the soil hydraulic parameters and hydrological models appears to be unavoidable, a better understanding of the required upscaling process is very much needed.

While the advantages of PTFs have been demonstrated for quantifying soil hydraulic properties (e.g., Vereecken et al., 1989; Schaap et al., 2001; Homaee and Farrokhian Firouzi, 2008; Ghorbani Dashtaki et al., 2010; Khodaverdiloo et al., 2011), they are rarely implemented in hydrologic models where a broad definition and application of soil types still dominate simulations of soil moisture. Parametric PTFs provide soil hydraulic parameters that could be used directly in hydrological models. Guber et al. (2009) compared a number of published PTFs and the HYDRUS-1D model (Šimůnek et al., 2005) to simulate water flow in a soil profile.

The spectral behavior of a soil is a dynamic soil property that can undergo rapid changes because of changes in soil composition due to, for example, agricultural activities, soil erosion and biological processes. Using spectral data as PTF input provides an effective way of including the temporal processes in hydrological models. Babaeian et al. (2015a, 2015b) recently derived and validated the accuracy of spectrotransfer functions (STFs) and spectral pedotransfer functions (SPTFs) to predict the unsaturated soil hydraulic properties. STFs relate the hydraulic properties directly with spectral reflectance parameters, while SPTFs use additional basic soil data such as the particle size distribution and bulk density.

In this paper we present a study to test the effectiveness and robustness of coarse-scale derived parametric PTFs, STFs, and SPTFs by studying surface, near-surface and subsurface soil water dynamics in a semi-arid region, the Zanjanrood River sub-watershed (ZRS), in northwestern Iran. The accuracy of simulated surface soil water states is tested against estimates from microwave satellite imagery. Our primary objective was to assess coarse scale values of the van Genuchten-Mualem soil hydraulic parameters (van Genuchten, 1980) to simulate surface, near-surface and subsurface soil water dynamics at the 1 km × 1 km domain/pixel size, while incorporating the influence of the local topography into the aggregation algorithm. Reference soil water states for comparison were obtained from the advanced synthetic aperture radar (ASAR) through the IEM algorithm developed by Rahman et al. (2008). Our findings will help to assess the value of air- and space-borne hyperspectral data for studying the spatio-temporal dynamics of profile soil water contents.

2. Materials and methods

2.1. Study area

The Zanjanrood River sub-watershed (ZRS), located in the northwestern part of Iran, was selected as the test area for our study. The ZRS area of approximately 250 km^2 was chosen for its variety in terrain and land use characteristics, soil type and soil distribution patterns (Fig. 1). The topography consists of level to slightly undulating slopes varying approximately from 0 to 4%, with elevations ranging from approximately 1380 to 2160 m above mean sea level. The climate is semi-arid, with an average annual precipitation of 320 mm. The maximum (43 °C) and minimum (−30 °C) yearly temperatures occur in August and January, respectively, while the average yearly temperature is about 11 °C. Soil texture varies from clay to sandy loam, with the majority of soils classified as clay loam and loam. Rain-fed agriculture with a land cover of wheat (75%) and poor rangeland (25%) dominate land-use in the area. Using Arc GIS FishNet tool (ESRI), the entire ZRS was divided into a grid of 1 km × 1 km pixels to match the ASAR (global mode) pixels. We selected 20 pixels across the study area for analysis so that they represent different locations, soil types, topographies and land uses (see Fig. 1). A summary of various geophysical attributes of the selected pixels are given in Table 1.

2.2. Numerical simulations

The HYDRUS-1D software package was used to simulate vertical water flow in the soil domains (Šimůnek et al., 2005). HYDRUS-1D