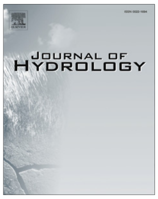
Journal of Hydrology 512 (2014) 27–38

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Towards soil property retrieval from space: Proof of concept using in situ observations

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ARTICLE INFO

Article history:
Received 14 September 2013
Received in revised form 24 December 2013
Accepted 11 February 2014
Available online 1 March 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Magdeline Laba, Associate Editor

Keywords:
Surface soil moisture
Soil hydraulic parameter retrieval
JULES
Land surface modeling

SUMMARY

Soil moisture is a key variable that controls the exchange of water and energy fluxes between the land surface and the atmosphere. However, the temporal evolution of soil moisture is neither easy to measure nor monitor at large scales because of its high spatial variability. This is mainly a result of the local variation in soil properties and vegetation cover. Thus, land surface models are normally used to predict the evolution of soil moisture and yet, despite their importance, these models are based on low-resolution soil property information or typical values. Therefore, the availability of more accurate and detailed soil parameter data than are currently available is vital, if regional or global soil moisture predictions are to be made with the accuracy required for environmental applications. The proposed solution is to estimate the soil hydraulic properties via model calibration to remotely sensed soil moisture observation, with in situ observations used as a proxy in this proof of concept study. Consequently, the feasibility is assessed, and the level of accuracy that can be expected determined, for soil hydraulic property estimation of duplex soil profiles in a semi-arid environment using near-surface soil moisture observations under naturally occurring conditions. The retrieved soil hydraulic parameters were then assessed by their reliability to predict the root zone soil moisture using the Joint UK Land Environment Simulator model. When using parameters that were retrieved using soil moisture observations, the root zone soil moisture was predicted to within an accuracy of 0.04 m^3/m^3, which is an improvement of $\sim$0.025 m^3/m^3 on predictions that used published values or pedo-transfer functions.

1. Introduction

The moisture content of soil is a key variable that controls the exchange of water and energy fluxes between the land surface and the atmosphere. This is because evaporation and transpiration are a function of the variability in soil moisture. Hence it plays a vital role in most environmental processes (Seneviratne et al., 2010), especially in the development of weather systems. Of the few important hydrological variables that can be directly observed, soil moisture has been declared as an Essential Climate Variable by the Global Climate Observing System (GCOS-107, 2006) and is therefore a reportable land surface parameter for contributing members. Because of the high spatial variability shown by soil moisture, monitoring very high resolution temporal changes globally, or even regionally, is not straightforward from both a logistical and an economic point of view. Both active and passive remote sensing methods are utilized in soil moisture monitoring, including the Advanced Microwave Scanning Radiometer-2 (AMSR2; C- and X-band) (Imaoka et al., 2010), Advanced Scatterometer (ASCAT; C-band) (Albergel et al., 2009) and Soil Moisture and Ocean Salinity (SMOS; L-band) (Kerr et al., 2010). However, current satellites are able to provide only the information for the top 1–5 cm, and consequently, there is still a great reliance on the soil moisture evolution predicted by land surface models (LSMs) to obtain soil moisture information for the top 1 m of soil, commonly referred to as the root zone.

LSMs are normally used to provide a boundary condition to weather and climate models, delivering the land surface feedbacks to the atmosphere. Hence, coupled land surface-atmosphere schemes must be able to predict the energy, water, and carbon exchanges, with explicit representation of vegetation and soil types. Yet, LSMs are often used uncoupled from atmospheric models and therefore require meteorological input data such as precipitation, temperature, radiation and so on, as well as parameters that represent the vegetation and soil of that area (Abramowitz et al., 2007). Soil hydraulic properties play a pivotal role as inputs to the LSM, regulating such things as infiltration and runoff. These parameters are normally derived from empirical equations that add value to basic information like field morphology, texture,

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http://dx.doi.org/10.1016/j.jhydrol.2014.02.031
0022-1694/© 2014 Published by Elsevier B.V.

structure and pH, by translating them into estimates of other more difficult to measure soil properties, like the soil hydraulic properties. Yet, pedo-transfer functions cannot be extrapolated beyond the specific constraints, in terms of geomorphic region or soil type, under which it was developed (McBratney et al., 2002). Therefore, extrapolation over large areas yields crude estimates of soil hydraulic properties with large standard deviations (Vereecken et al., 1990; Vereecken et al., 1989), the accuracy of which deteriorates with the extent of the extrapolation, and thus adversely affects the accuracy of the model simulations. Thus, soil moisture estimates using LSMs typically suffer from physical parameterization, based on low-resolution and/or erroneous soil property information (Grayson et al., 2006). For example, De Lannoy and Reichle (2012) addressed the soil moisture biases of the GEOS-5 land data assimilation system by revising the global soil properties and soil hydraulic parameters that are used in the Catchment LSM through comparison against available in situ soil moisture measurements.

Remotely sensed soil moisture measurements can be used to address this soil hydraulic property estimation problem. However, most work to date has focused on utilizing synthetic simulations (Ines and Mohanty, 2008; Montzka et al., 2011), or observations on engineered soils (Burke et al., 1997a,b, 1998; Camillo et al., 1986; Ines and Mohanty, 2008; Santanello et al., 2007) (for a more detailed review of these studies refer to Bandara et al. (2013b)). Using a data assimilation approach, where model dynamics and remote sensing observations are merged, Qin et al. (2009) estimated both soil moisture and soil parameters simultaneously. They retrieved the soil texture and the soil porosity, concluding that the former contained large uncertainties when using different initial soil texture values, while the retrieval of soil porosity had relatively small uncertainties. Using an Ensemble Kalman Filter, Li and Ren (2011) explored the ability to calibrate the parameters of the van Genuchten–Mualem model through inverse modeling. They estimated three, four and five parameters and identified that the estimates of the two most important variables, saturated hydraulic conductivity and the shape parameter α, were improved. Moreover, they concluded that there were "many unsatisfactory estimates for the other three parameters". Pollacco and Mohanty (2011) showed that the high non-uniqueness of the inverted soil hydraulic parameters is due to their inter-correlation. Therefore, they proposed that a more accurate way of obtaining the saturated hydraulic conductivity and the air entry matric potential would be to scale them from point measurements. However, this was based on a numerical study for homogeneous soils, that this methodology would not be feasible for a large scale study under natural conditions.

Importantly, only a limited number of studies have focused on estimating soil hydraulic properties from soils under transient flow or naturally occurring boundary conditions. For example, the study by Dane and Hruska (1983) determined the hydraulic conductivity and soil water characteristic curves of soils undergoing drainage with the initial and boundary conditions known. Their methodology was initially tested for an engineered soil with known soil hydraulic characteristics, followed by a homogeneous clay loam soil. They concluded that the method should be applicable to heterogeneous soils, provided that both the boundary conditions and the water content profiles are well defined for each layer. However, this has not been tested, as prior knowledge of both the boundary conditions and the water content are rarely available in practice.

Using a measured time-series of soil water content at three different depths under natural boundary conditions, Ritter et al. (2003) estimated effective soil hydraulic properties utilizing the inverse parameter estimation method. Their study showed that when using laboratory determined soil hydraulic properties to simulate the water balance at field scale, inaccurate results were produced, and a 'trial and error' optimization did not yield objective results, leading to a poor fit of measured data. Consequently, they identified that efficient parameter estimation can be obtained only when an optimization algorithm is combined with the numerical model, demonstrating the feasibility of the inverse modeling approach to soil hydraulic property estimation of a soil column. Ritter et al. (2003) concluded that additional experimental data (drainage conditions, prior information of soil parameter data and so on) were needed to identify realistic parameters due to the ill-posed problem. An alternative approach, using a water injection experiment to derive effective soil parameters at field scale, has been tested by Ye et al. (2005) and Yeh et al. (2005). They applied spatial moments to 3-D snapshots of a moisture plume under impermanent flow conditions, to estimate the 3-D effective unsaturated hydraulic conductivity tensor. The effective hydraulic conductivities compared well with laboratory measured unsaturated hydraulic conductivity values. They concluded that the ratio of horizontal to vertical spreading of the plume, at varying moisture contents, confirmed the existing stochastic theories. Additionally, they also identified that the principal directions of the spatial moments varied as the moisture plume evolved through local heterogeneity, a feature that had hitherto not been recognized in the theories.

Despite these studies, all have focused on retrieving the soil hydraulic conductivity at saturation, and largely ignored the other soil hydraulic parameters. Consequently, the work presented in this paper focuses on retrieving all the important soil hydraulic parameters (Clapp and Hornberger exponent, hydraulic conductivity at saturation, soil matric suction at air entry, volumetric fraction of soil moisture at saturation, critical point, and wilting point), as shown in Table 1. In a former study (Bandara et al., 2013b), the authors developed a methodology for estimating the soil hydraulic properties of a heterogeneous soil column in a synthetic twin-experiment framework. According to this methodology, the soil hydraulic parameters were derived by calibrating an LSM to soil moisture observations, such as those which would be available from satellite observations. This study advances that work by applying the methodology to a field application with heterogeneous soil column under natural conditions. Given that this is a proof of concept study, it uses the more accurate and detailed in situ point measurements as opposed to satellite remotely sensed data. Satellite observed soil moisture observations were not used at this early stage due to their coarse resolution and the difficulty to validate results at those scales This study uses the Joint UK Land Environment Simulator (JULES) as the land surface model (Best et al., 2011; Clark and Harris, 2009; Clark et al., 2011), together with the Particle Swarm Optimization (PSO) method that is based on the complex collective behavior of individuals in decentralized, self-organizing systems, falling within the category of 'swarm intelligence' (Kennedy and Eberhart, 1995), and are discussed in detail under Section 3 of this paper.

2. Site and data description

The work presented in this paper focuses on three sites, Y2 (34.6548 S, 146.1103 E), Y5 (34.7284 S, 146.2932 E) and Y7 (34.8518 S, 146.1153 E). These sites are located near Yanco, New South Wales, Australia (as shown in Fig. 1), and form part of the OzNet soil moisture monitoring sites (Smith et al., 2012); http://www.oznet.org.au. The soil of the Yanco region is duplex, with horizon A being approximately 0.30 m deep. The dominant horizon A soil type at each location is loam, sandy loam and loam (Australian Bureau of Rural Science), respectively. The soil moisture has been measured continuously at depths of 0–0.05 m, 0–0.30 m, 0.30–0.60 m, 0.60–0.90 m (as shown in Fig. 2a) as the average over 30 min intervals using vertically installed Campbell Scientific