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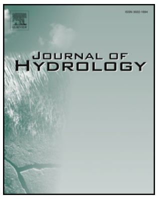

Research papers

Rock fragment and spatial variation of soil hydraulic parameters are necessary on soil water simulation on the stony-soil hillslope

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ABSTRACT

Whether the spatial variation and influence of rock fragment contents (RFCs) on soil hydraulic parameters (SHPs) should be jointly considered in the soil water simulation have been less investigated in previous studies. In this study, we tested whether considering these factors were necessary in the soil water simulation on a representative stony-soil hillslope located in Taihu Lake Basin, China. Five schemes of SHPs in HYDRUS-3D model were established. They were (i) MultiRFHet: spatially varied SHPs extracted from Durner's multimodal retention function based on the observed soil water retention data; (ii) RosHom: spatially uniformed SHPs derived from ROSETTA; (iii) RosHet: spatially varied SHPs derived from ROSETTA; (iv) RosRFCHom: spatially uniformed SHPs derived from ROSETTA and adjusted by RFCs; (v) RosRFCHet: spatially varied SHPs derived from ROSETTA and adjusted by RFCs. Results indicated when the spatial variation and influence of RFCs on SHPs were both considered (MultiRFHet and RosRFCHet), acceptable accuracies (Nash-Sutcliffe efficiency or NSE ≥ 0.58 for MultiRFHet and > 0.17 for RosRFCHet) were achieved in simulating the soil water storage (SWS) variation. Since the MultiRFHet required the calibration by the observed soil water retention data, RosRFCHet was a good alternative in the simulation. On the contrary, the SHPs acquired without considering neither the RFCs nor the spatial variation yielded unacceptable simulation results (NSE general < 0). This demonstrated that spatial variation and influence of RFCs on SHPs should be included in the SWS simulation on this stony-soil hillslope, although it had limited effect in subsurface flow simulation.

1. Introduction

With superiority in time and economic costs and in deriving continuous hydrological processes over space and time, three-dimensional (3D) physically-based modeling has been widely adopted in hydrological researches (e.g., Herbst et al., 2006; Vereecken et al., 2015; Baroni et al., 2017). Numerous models have been developed and applied in different areas over the last decades (e.g., Fiori and Russo, 2007; Fang et al., 2016; Baroni et al., 2017). Sources of uncertainties affecting the model simulation (e.g., model structure, input parameters and dependent variables) have also been investigated and determined (Fu et al., 2015; Vereecken et al., 2015). Among these sources, uncertainty of soil hydraulic parameters (SHPs) was recognized as one of the major obstacles for achieving the optimal simulations (Chirico et al., 2007; Baroni et al., 2017).

Traditional approaches in acquiring the SHPs include direct measurement and indirect estimation. Direct laboratory or field measurements of SHPs are costly and time-consuming, thus restrict the availability of high spatial resolution SHP data for model simulation (Chirico et al., 2007; Vereecken et al., 2010). Thereby, indirect methods especially the pedotransfer functions (PTFs) have been developed to estimate the SHPs from easily measurable soil physical and chemical properties (Wösten et al., 2001; Vereecken et al., 2010), for example the HYPRES (Wösten et al., 1999) and Vereecken (Vereecken et al., 1989). However, previous studies have demonstrated that applying existing PTFs always introduced substantial uncertainty when they were used outside the datasets they developed (Chirico et al., 2007; Liao et al., 2014). Reliable approaches are needed to cost-effectively estimate the SHPs in areas with different geological, pedological and meteorological backgrounds, for example the stony soil areas.

Stony soils are soils containing over 30% in volume of rock fragments (soil particles > 2 mm) as defined by Tetegan et al. (2011). Due to soil development processes and actions of mankind as well as soil erosion, stony soils are worldwide distributed. For example, in Western Europe, stony soils account for 30% of soil resources, and account for 60% in the Mediterranean region (Poesen and Lavee, 1994). In China,

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mountains composed of stony soils account for 18% of the national area (Ma and Shao, 2008). Therefore, comprehensively and accurately revealing the hydrological processes of upstream stony-soil hillslope is critical for the protection of the downstream ecosystems.

Rock fragment content (RFC) affected the SHPs and consequently affected the hydrological processes in stony soils (Cousin et al., 2003; Ma et al., 2010; Coppola et al., 2013). As rock fragments could reduce pore volume available for containing water and increase the tortuosity of water flow, the water content and hydraulic conductivities of stony soils generally decreased with increasing RFC (Baetens et al., 2009; Hlaváčiková et al., 2016). Rock fragments have an obvious influence on the stony soils' water retention, especially in the low suction region (Ravina and Magier, 1984; Baetens et al., 2009). The widely used van Genuchten-Mualem model (van Genuchten, 1980; Mualem, 1976) cannot characterize the low suction region of the soil water retention characteristic of stony soils (Vereecken et al., 2010; Assouline and Or, 2013). Recently, several dual-porosity functions have been developed for structured soils (Šimůnek et al., 2003; Arora et al., 2011) and can be used to derive SHPs of stony soils (Ma and Shao, 2008). The one proposed by Durner (1994) (multimodal retention function, abbreviated as MultiRF in this study) is promising since it requires less parameters that are relatively easy to be obtained (Šimůnek et al., 2003; Parajuli et al., 2017). Besides, as existing PTFs did not consider the RFC, empirical functions to modify the PTFs have been built to predict the SHPs in stony soils based on the SHPs of fine earth and RFCs (Bouwer and Rice, 1984; Brakensiek et al., 1986). However, doubts emerged with the applications of these empirical functions (e.g., Ma et al., 2010; Novák et al., 2011). Investigations are still needed to verify performances of the dual-porosity functions and modified PTFs in the soil water simulations for stony soils.

The spatial variations of SHPs also affect the simulation of soil water dynamics. The SHPs show spatial variations at different scales and detailed characterizing these variations is a crucial challenge over large areas (Herbst et al., 2006; Baroni et al., 2017). As the discrepancy between scales at which SHPs were measured or predicted and at which hydrological model ran, the upscaling procedure was inevitable, and thus the uncertainty of spatial variations of SHPs generated (Vereecken et al., 2007). To date, many scientists have focused on revealing the uncertainty of spatial variation of SHPs on simulating hydrological process (e.g., Herbst et al., 2006; Fiori and Russo, 2007). For example, Sciuto and Diekkrüger (2010) investigated the impacts of the SHPs' spatial variations on the water balance and found the spatial resolution has a larger impact on the soil moisture than the aggregation of the soil properties. Baroni et al. (2017) quantified the impact of different types of uncertainties that arose from the unresolved soil spatial variability on simulated hydrological states and fluxes. However, previous studies were generally conducted through virtual experiment, only a few of them based on exact characterizing the actual spatial variation of SHPs of the study regions (e.g., Jin et al., 2015; Fang et al., 2016).

The objectives of this study were to test the hypotheses that considering (i) the influence of rock fragments on SHPs and (ii) the spatial variation of SHPs improve the soil water simulation on the stony-soil hillslope. Specifically, the MultiRF was adopted to extract the SHPs by fitting observed soil water retention data. We also investigated whether adjusting the ROSETTA derived SHPs by RFC and adopting spatial variation of SHPs would be necessary.

2. Materials and methods

2.1. Study hillslope

This study was conducted on a hillslope (31°21′N, 119°03′E) (has an area of about 0.4 ha) in the hilly area of Taihu Lake Basin, China (Fig. 1). Green tea (*Camellia sinensis* (*L.*) *O. Kuntze*) is the dominated plant on the study hillslope. The adjacent hillslope is dominated by Moso bamboo (*Phyllostachysedulis (Carr.) H. de Lehaie*). The data of both the tea and bamboo hillslopes were used to assess the relationships between the SHPs and soil/terrain properties. However, soil water dynamics were only simulated on the tea hillslope since a trench were opened along the boundary of tea and bamboo hillslopes to separate them into two hydrological units. The downslope boundary of the tea hillslope was near a pond. Detailed descriptions of this study hillslope can be found in Liao et al. (2016).

2.2. Data collection

Automatic monitoring systems were installed at four sites on the tea hillslope (TG01, TG02, TG03 and TG04) and four sites on the bamboo hillslope (BF01, BF02, BF03 and BF04) (Fig. 1). At each site and each depth (10- and 30-cm), three EC-5 paired with three MPS-6 sensors (Decagon Devices Inc., Pullman WA, USA) were circled installed to monitor the soil water content and matrix potential respectively. The averages of the measured values of the three EC-5 and MPS-6 sensors were respectively used as the final soil water content and matrix potential data at each site and depth. The rock fragments on this hillslope are usually small (< 1 cm in diameter) and comparatively homogenously distributed in the soil. Therefore, although these sensors were installed in the fine-textured soils, their measuring volumes included both the fine-textured soils and rock fragments. The final measured data by these sensors could reflect the soil water content and matrix potential of the stony soils. Sensors were calibrated for each soil depth and before installation. Before installing these sensors, soil profiles were opened and three soil horizons (A, B and C) were observed within each profile (Liao et al., 2016). After all sensors were installed, the profiles were carefully backfilled. A weather station (Decagon Devices Inc., Pullman WA, USA) was established to record the meteorological data (Fig. 1). Two rain gauges were equipped respectively above and below the canopy of the tea plant to monitor the gross rainfall and throughfall on the tea hillslope (Fig. 5). As the ratio (about 75%) of the monitored throughfall to the gross rainfall (1821 mm) during from 29 March 2016 to 28 March 2017 was in the ranges of previous studies, which with approximate leaf area index (e.g., Siles et al., 2010; Zheng et al., 2018). Thus, we think the monitored throughfall by one rain gauge was acceptable. All measurements (soil water content, matrix potentials, and meteorological data) were collected every 5 min. The daily averaged of these measured data were used in the following analyses.

Soil samples at 0- to 20-cm and 20- to 40-cm depth intervals were collected using a hand auger at 39 sites on the tea hillslope and at the four automatic monitoring sites on the bamboo hillslope (Fig. 1). Three subsamples were collected for each depth interval at each site and then fully mixed. These samples were air dried, weighted, ground and sieved through a 2 mm polyethylene sieve. Particles > 2 mm were weighed to determine the RFC. Soils passed through the 2 mm polyethylene sieve were used to determine the contents of clay (< 0.002 mm), silt (0.002–0.05 mm) and sand (0.05–2 mm), as well as the contents of soil organic matter (SOM) (Liao et al., 2016). In addition, the depths to bedrock (DB) of all 43 sites (39 on the tea hillslope, 4 on the bamboo hillslope) were determined when taking soil samples using a hand auger (Fig. 1).

A high-resolution (1 m) digital elevation model (DEM) was derived from a 1:1000 contour map. Terrain attributes including elevation, slope, plane curvature (PLC), profile curvature (PRC), and topographic wetness index (TWI) were determined from this DEM in ArcGIS 10.0 (ESRI, Redlands, CA). The statistics of terrain attributes and soil properties of the tea hillslope are shown in Table 1.

2.3. The predictions of SHPs

Scheme I: spatially varied SHPs extracted from the MultiRF based on the observed soil water retention data (MultiRFHet)

Twelve groups of soil water retention data were derived in this study (Fig. 2). They were TG01-10 (10 indicated the 10 cm depth),