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The role of macropores and multi-resolution soil survey datasets for distributed surface–subsurface flow modeling

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SUMMARY

Distributed watershed-scale modeling is often used as a framework for exploring the heterogeneity of runoff response and hydrologic performance of the catchment. The objective of this study is to apply this framework to characterizing the impacts of soil hydraulic properties at multiple scales on moisture storage and distributed runoff generation in a forested catchment. The physics-based and fully-coupled Penn State Integrated Hydrologic Model (PIHM) is employed to test a priori and field-measured properties in the modeling of watershed hydrology. PIHM includes an approximate representation of macropore flow that preserves the water holding capacity of the soil matrix while still allowing rapid flow through the macroporous soil under wet conditions. Both phenomena are critical to the overall hydrologic performance of the catchment. Soils data at different scales were identified: Case I STATSGO soils data (uniform or single soil type), Case II STATSGO soils data with macropore effect, and Case III field-based hydropedologic experiment revised distributed soil hydraulic properties and macropore property estimation. Our results showed that the Case I had difficulties in simulating the timing and peakflow of the runoff responses. Case II performed satisfactorily for peakflow at the outlet and internal weir locations. The distributed soils data in Case III demonstrated the model ability of predicting groundwater levels. The analysis suggests the important role of macropore flow to setting the threshold for recharge and runoff response, while still preserving the water holding capability of the soil and plant water availability. The spatial variability in soil hydraulic properties represented by Case III introduces an additional improvement in distributed catchment flow modeling, especially as it relates to subsurface lateral flow. Comparison of the three cases suggests the value of high-resolution soil survey mapping combined with a macropore parameterization can improve distributed watershed models.

1. Introduction

Subsurface lateral flow has been widely recognized as important to the generation of stormwater runoff (Alaoui et al., 2011; McGuire and McDonnell, 2010; Tromp-van Meerveld and McDonnell, 2006a,b), to the study of preferential flow (Thomas et al., 2013; Graham and Lin, 2011; Lin, 2010; Vogel et al., 2010), and to the evaluation of nutrient fluxes (Dhillon and Inamdar, 2013; Hwang et al., 2012; Zhang et al., 2011). However, direct observation of the occurrence and distribution of subsurface lateral flow at the hillslope scale has been constrained by temporal dynamics and spatial heterogeneity. To gain an improved conceptual understanding, mathematical models for vadose zone hydrology were developed to explore the hillslope scale hydrological processes (Hopp and McDonnell, 2009; Kabat et al., 1997; Lehmann et al., 2007; Mirus and Loague, 2013).

The issue related to upscaling measured hydraulic parameters from use in catchment scale modeling applications are being tested more frequently than ever, mostly because of the capability of integrated environment models in the understanding of water resources and quality in subsurface and surface water systems. Early modeling applications proved that the effective soil hydraulic parameters could adequately describe the lumped hydrological behavior (Feddes et al., 1993; Kabat et al., 1997). However, the effective soil hydraulic parameters for modeling studies are difficult to obtain from aggregation of soil types (Kabat et al., 1997). Only a few studies have reported the effects of soil spatial variability on hydrological response to input resolution of spatial data. Mirus et al. (2011) argued that reducing the representation of spatially variability of soil hydraulic properties did not affect the dominant runoff generation processes, and the reduced spatial

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complexity could still retain the ability to simulate the overall hydrograph and runoff pattern. This conclusion raises the question of the resolution of soil hydraulic properties for watershed modeling.

Another important issue for distributed catchment modeling is the representation of preferential flow. In forested catchments, preferential flow through macropores such as root holes, cracks or pipes in soils, or through dissolutions features, joints, and fractures in bedrock can lead to large and fast infiltration and recharge to groundwater (Aubertin, 1971; Anderson et al., 1997). Even though the macroporous volume is small relative to the soil matrix, the volumetric transport capacity can be significant to the overall flow (Watson and Luxmoore, 1986). The critical pore size at which infiltration can be classified as macropore flow has been discussed in Beven and Germann (1982). Several studies have focused on approximating the macropore flow contributions to subsurface flow (Hutson and Wagenet, 1975; Gerke and van Genuchten, 1993; Mohanty et al., 1997; Vanderkwaak, 1999). It has been found that modeling with a macropore flow concept yields improvements than without macropores (Tromp-van Meerveld and Weiler, 2008; Van Schaik et al., 2010; Beven and Germann, 2013).

This study compares the effects of multi-resolution soil data from national databases, and in situ field observations on the overall hydrologic performance of the Shale Hills Catchment. According to State Soil Geographic (STATSGO) Data uniform soil type is applied at Shale Hills Catchment. To obtain higher resolution soil information we used the results of Baldwin (2011). In the experiment, catchment-wide maps of saturated moisture content, depth to bedrock, and slope value were used to delineate map units with similar soil moisture patterns. The multi-resolution soils data led to three model scenarios: Case I: STATSGO data without macropore effect; Case II: STATSGO data adding macropore effect; and Case III: hydropedologic functional units data with macropore effect. This study employed a fully coupled physics-based integrated model: Penn State Integrated Hydrologic Model (PIHM) to evaluate the effects of spatial soil pattern on subsurface flow and overall catchment model performance.

2. Materials and methods

2.1. Site description

The Shale Hills site that we used to test the soil hydraulic properties spatial pattern is a 0.08-km^2 forested watershed managed by the Pennsylvania State University. A program of research using Earth's Critical Zone Observatories (CZOs) has been initiated, and Shale Hills is one the CZOs: the Susquehanna-Shale Hills Critical Zone Observatory (SSHCZO), which focuses on hydrologic flow paths and timescales, as well as the regolith formation, ecosystem dynamics within a small, forested catchment. To date, intensive observed environmental variables have been examined to identify the prominence of hydrologic processes including soil moisture dynamics (Lin and Zhou, 2008; Lin, 2006), subsurface flow pathways (Thomas et al., 2013; Graham and Lin, 2011; Zhang, 2011; Zhang et al., 2014), solute transport (Andrews et al., 2011; Jin et al., 2010; Kuntz et al., 2011), and stream flow generation mechanisms (Lynch, 1976; Lynch and Corbett, 1985). Using field studies as a basis, modeling studies have reported on the antecedent moisture impacted peak flow generation (Qu and Duffy, 2007), land surface energy balance (Shi et al., 2013).

The watershed is situated in the Ridge-and-Valley Appalachians in the Central Pennsylvania (Fig. 1). The climate in Central Pennsylvania represents a humid continental climate. Extreme temperatures have been recorded 39 °C and −29 °C. Precipitation is relatively seasonally uniform. As an experiment site, extensive data sets were examined including topography, soil moisture sampling, soil mapping, streamflow, subsurface flow, and stand characteristics (Baldwin, 2011; Lin, 2006; Meinzer et al., 2013; Zhang, 2011).

The watershed overlies continuous Rose-Hill Shale bedrock with the strike and dip of N54°E and 76°NW (Jin et al., 2010). The bedrock has been set as a no-flow boundary of near surface hydrologic modeling (Qu and Duffy, 2007). The thickness of the soil layer ranges from <0.25 m on the ridge tops and upper side slopes to >2 m in the valley bottom and swales (Lin et al., 2006). Based on field measurements, lateral subsurface flow has been identified as a dynamic part in the watershed hydrologic cycle (Graham and Lin, 2011; Lin et al., 2006). In situ soil moisture measurement suggested that preferential flow is very common in the watershed (Lin and Zhou, 2008). The solute transport tests demonstrated that the preferential flow path is a significant factor controlling transport behavior at the watershed (Kuntz et al., 2011).

The vegetation cover of Shale Hills is a mixture of deciduous forest and evergreen forest. Major species include *Quercus prinus*, *Quercus rubra*, *Quercus alba*, *Tsuga canadensis*, *Carya tormentosa*, *Acer saccharum*, *Carys glabra*, *Pinus sstrobus*, *Pinus virginiana* (Meinzer et al., 2013; Naithani et al., 2013). The rooting zone is extremely shallow, and the majority of the roots are situated in the organic horizon and eluvial horizon (Meinzer et al., 2013; Lin, 2006).

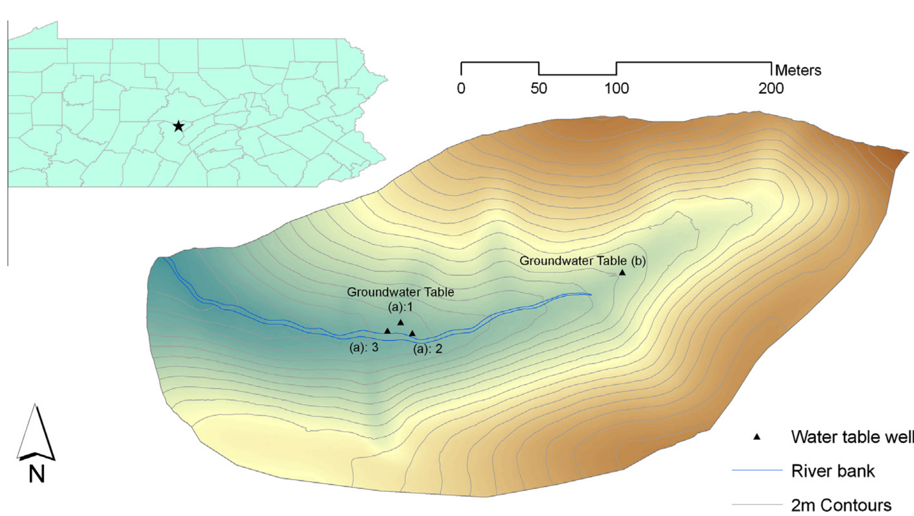

Fig. 1. Location of the Shale Hills Catchment in Pennsylvania.