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Simulation of soil moisture on a hillslope using multiple hydrologic models in comparison to field measurements

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SUMMARY

Soil moisture in a hillslope is simulated using three multi-dimensional hydrologic models: a 3D surface–subsurface integrated model and two 2D distributed hydrologic models, MIKE-SHE and WEP, which adopt the Richards equation at different levels of approximation. High-resolution topographic data (1 m in horizontal accuracy), soil depth, hydraulic conductivity, porosity, and soil characteristics obtained from the literature and in-situ measurements were used as prior information for modeling. Numerical simulations were compared with multiple TDR sensor measurements from different locations and depths. Using available input data, the models had limited ability to reproduce the soil moisture dynamics shown in field measurements. The 3D model estimated the spatial diversity of the infiltration process of soil water movement more accurately than the distributed hydrologic models, MIKE-SHE and WEP. Suitable model parameters and correlations among them were estimated through Monte Carlo simulation using the 3D model. Parameters selected through the Monte Carlo method were used to simulate soil moisture variations at measurement sites. Relatively high correlations were found among the van Genuchten model parameters and the bottom boundary condition (bed rock). An increasing pattern of correlation between porosity to the downstream direction was found, which shows connectivity between parameter correlation and identifiability. Simulation results imply that multi-dimensional modeling of soil moisture in a hillslope may benefit from ensemble-based simulations that consider inherent uncertainty from model parameters and structures.

1. Introduction

Soil moisture, a critical factor in hydrologic systems, plays a key role in synthesizing interactions among soil, climate, hydrologic response, solute transport, and ecosystem dynamics (Kirchner et al., 2000; Rinaldo et al., 2011; Rodríguez-Iturbe and Porporato, 2004). The spatial and temporal distribution of soil moisture at a hillslope scale is essential for understanding hillslope runoff generation processes (Blume et al., 2009; Brocca et al., 2012; Kim, 2014, 2009; Lee et al., 2007; Redding and Devito, 2008; Western and Grayson, 1998).

Soil moisture is controlled primarily by soil properties such as water retention characteristics and surface cover under relatively dry conditions (Cantón et al., 2004; Delleur, 1998). Topography plays a key role in maintaining soil moisture at intermediate levels of soil saturation (Anderson and Burt, 1978; Kim and Kim, 2007; Western and Grayson, 1998; Wilson et al., 2004). Soil water movement in a hillslope can be governed by vertical drainage to weathered bedrock and subsequent generation of lateral flow over bedrock (Haga et al., 2005; Kim, 2009; Uchida et al., 2003). Unsaturated zone dynamics and generation of lateral flow can be explained through pressure variations (Lu et al., 2011; Lv et al., 2013; Torres et al., 1998; Uchida et al., 2004). Sources of headwater catchment runoff have been investigated under storm flow conditions (McGlynn and McDonnell, 2003) and normal low flow periods (Uchida et al., 2003).

Most soil moisture variation models solve well-known governing equations which describe water movement in vadose zone, or overland flow (i.e., Richards equation and St. Venant equations) (An and Yu, 2014; Rodríguez-Iturbe and Porporato, 2004; Simunek and Van Genuchten, 2008). The physically-based distributed hydrology model, MIKE-SHE based upon the Richards equation, has used measured soil moisture data in the calibration procedure (Jayatilaka et al., 1998; Mertens et al., 2004). A distributed hydrologic model with water and energy transfer processes (WEP) that

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implemented a generalized Green-Ampt model for the soil moisture transfer process was applied to simulate soil moisture content and other hydrologic variables for different types of catchments (Jia et al., 2006, 2005, 2001). The 3D surface–subsurface integrated model, with improved numeric flexibility for computing soil moisture flux with the Richards equation, has been used to simulate soil moisture for several benchmark cases (An and Yu, 2014).

Over recent decades, important advances in simulation models have improved our understanding of soil moisture dynamics. Binley and Beven (1992) simulated a heterogeneous Darcian headwater stream with a 3D model and parallel computing. Bronstert and Bárdossy (1999) used a physically based hydrologic model to investigate the effects of runoff generation on a loessy small catchment. Corradini et al. (2000) proposed and evaluated a general model for local infiltration–redistribution–reinfiltration in a two-layered soil profile. Several studies have evaluated the applicability of multi-dimensional models for simulating soil moisture variability at various spatio-temporal scales (Cornelissen et al., 2014; Herbst and Diekkrüger, 2003; Mahmood and Vivoni, 2011; Rößler and Löffler, 2010; Tavakoli and Smedt, 2013; Zehe et al., 2010; among others). A review of soil moisture modeling research was recently published in a Special Issue of Journal of Hydrology "Determination of Soil Moisture" (see Corradini, 2014; Romano, 2014). However, despite these previous efforts, current knowledge is still insufficient to accurately model soil moisture dynamics in a hillslope. Additionally, few studies have compared distributed hydrological models that use intensive field monitoring of soil moisture and in-situ measurements of hydraulic properties for simulating soil moisture variation on a mountainous hillslope. The ability to address the existence and impact of lateral flow and vertical drainage flux, which fluctuates spatially and temporally during storm events and consequential low flow periods, varies with the limitations of a model's assumptions.

Therefore, the first objective of this study is to assess the applicability of multiple hydrologic models (the 3D model, MIKE-SHE, and WEP) for simulation of soil water movement in a steep hillslope of a mountainous catchment. These three models adopt the Richards equation with different levels of approximation to simulate soil moisture dynamics. Our aim is to evaluate reproducibility of a Richards equation-based model in comparison with an intensive field monitoring of soil moisture in a hillslope. Another objective of this study is to estimate suitable model parameters and assess their uncertainty using a Monte Carlo simulation for the 3D model. Parameter identifiability and impacts of correlation will be discussed through analysis of ensembles from the Monte Carlo simulation. The scope of this study is limited to evaluating the uncertainty of prior information such as model parameters and the boundary condition of the 3D model. Intensive soil moisture monitoring data collected with a delicate multiplex TDR system (Soil Moisture Equipment Corp., 2003) were used for simulation evaluation.

Section 2 presents material and methods including study area, measurement of soil moisture and in-situ soil hydraulic conductivity, multiple hydrologic models, input setup, and evaluation methods. Section 3 contains results from three hydrologic models and the Monte Carlo simulation using the 3D model. Section 4 concludes the paper.

2. Materials and methods

2.1. Study area

The study area is a hillslope in the Sulmachun catchment, located at the headwaters of the Imjin River in northern South Korea (Fig. 1(a)). The area is about 3200 m^2, with a mean annual precipitation of 1500 mm/year, and a minimum and maximum temperatures of −10 and 35 °C, respectively. The land cover is a mixture of *Polemoniales* and shrubby *Quercus*, and the slope varies between 30° and 45°, as shown in Fig. 1(a). Gneiss composites underlain by granite bedrock are the primary geological feature. Soil depth varies between 10 and 80 cm, but is mostly distributed between 15 and 45 cm. Further information about the study area can be found in Kim and Kim (2007). Considering the relatively small size of the study area, vegetation is assumed to be uniform. Soil sample particle analysis indicated no systematic difference in soil texture distribution along the hillslope. Refined Digital Elevation Models (DEM), with a 0.5 m resolution for surface and bedrock (1 m resolution used in modeling after resampling), were produced from topographic information using a Theodolite (DT-208P, TOPCON), as well as by direct measurements using iron poles.

2.2. Soil moisture measurement

A soil monitoring system recorded rainfall events and soil moisture conditions for six points and two soil depths using a delicate multiplex TDR system (Soil Moisture Equipment Corp., 2003). This information was used to evaluate the soil moisture models (see Fig 1(b)). Wave guides were inserted horizontally, heading in an upslope direction, at depths of 10 and 30 cm, without disturbing the soil layer. Soil moisture was recorded hourly from May 1, 2004 through May 25, 2004. An Automatic Rain Gauge System (ARGS, Eijkelkamp), located 50 m from the study area, was used to monitor rainfall history, as shown in Fig. 1(a). Average rate of potential evapotranspiration (PET) for autumn and spring was estimated at 1.35 mm/day and 4.9 mm/day, respectively, by the Penman–Monteith combination method, as well as by utilizing meteorological data such as net radiation, wind velocity, air temperature, and relative humidity obtained from a weather station at 10 min time intervals (see Fig. 1(a)). Detail information about soil moisture measurements can be found in Kim (2009).

2.3. In-situ measurement of hydraulic characteristics

In-situ hydraulic properties measured with a tension infiltrometer, (Ankeny et al., 1988) were used as the hydrological model parameters. Tension infiltrometers have been widely used due to their applicability in the field and strength in evaluating preferential flow (Jarvis, 2007). As a preliminary experimental procedure, each designated point was cleaned to a depth of 10 cm and covered with 5 mm of fine, saturated sand. If the local slope is greater than 20%, then the experimental error associated with the surface slope can be significant (Bodhinayake et al., 2004). The membrane disk and the sand layer should be sufficiently attached to confirm that the experimental practice satisfies the assumption underlying the measurement with the balance of an appropriate tension pressure (Sullivan et al., 1996). This field work also satisfies the requirement of local slope. The order of tension pressure was −8, −6, −3, −1 and 0 cm, since a reverse order may lead to the hysteresis effect (Reynolds and Elrick, 1991). Additionally, infiltration measurements were continued until steady-state conditions were reached under each tension, which generally occurred between 10 and 30 min. Both unsaturated and saturated hydraulic conductivities were estimated using two assumptions, which are Wooding's equation (Eq. (1), Wooding, 1968) and Gardner's equation (Eq. (2), Gardner, 1958).

$$Q = \pi \cdot r^2 K(h)\left(1 + \frac{4}{\pi \cdot r\alpha}\right), \tag{1}$$

$$K(h) = K_S \cdot \exp(\alpha \cdot h), \tag{2}$$