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Configuration of the relationship of soil moistures for vertical soil profiles on a steep hillslope using a vector time series model

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SUMMARY

Variation in soil moisture content throughout soil profiles during several sequential rainfalls represents the internal hydrological response on a hillslope scale. A multiplex TDR system has been operating on a mountainous hillslope to obtain the time series of soil moisture along two transects in the study area. The soil moisture modeling conducted in this study highlights our understanding of the inter-relationships between soil moistures at identical spatial locations, but at different depths. A sequential procedure was used for the time series modeling to delineate an appropriate model for application to all monitoring points. The feedback relationship of soil wetness between two different depths was expressed with the proposed vector autoregressive model. Based on the successful modeling of 31 coupled soil water histories, the vertical distributions of the stochastic model throughout the study area were obtained. The distribution of the delineated models implied a spatial distribution of the hydrological processes, such as vertical infiltration for the upper soil layers and some of the lower soil layers (38 out of 62 models), lateral redistribution and subsurface flow over bedrock mostly for the lower soil layers (24 out of 62 models) on the steep hillslope. With the use of the resultant models, applications were proposed to improve the data acquisition system, i.e. gap filling for missing data and limited prediction for an ungauged location.

1. Introduction

Soil moisture is a critical variable of the hydrological state in determining hydrological processes such as runoff response, water energy interaction (i.e. evapotranspiration), transport of solute, groundwater and eco-hydrological dynamics (Ambroise, 2004; Brolsma and Bierkens, 2007; Chen and Hu, 2004; Hotta et al., 2010; Montaldo et al., 2001; Rodriguez-Iturbe and Porporato, 2004; Tromp-van Meerveld and McDonnell, 2006). The spatial and temporal distributions of soil moisture have been studied over a wide range of scales such as 0.46, 0.47 and 0.57 ha (Penna et al., 2009), 10.5 ha (Western et al., 1999) and between 5 and 60 ha (Wilson et al., 2004) and those along hillslopes may indicate the internal hydrological process for the generation of runoff (Hilberts et al., 2007; Hopp and McDonnell, 2009; Lin et al., 2006).

The movement of water in a soil layer is governed, not only by the matrix flow, but is also controlled by the preferential flow (Ireson et al., 2006; Lepore et al., 2009; Mathias et al., 2006). However, the difficulty in predicting the hydrological process is mainly associated with the heterogeneity of the soil (Allaire et al., 2009). The activity of earthworms, soil cracks, flow over distinct soil layers and hydrophobicity are all responsible for the complexity of flow in the soil media of a natural system. Several mechanisms exist for the generation of a flux faster than the matrix flow in a soil layer, such as crack flow, burrow flow, finger flow, soil interface lateral flow and macropore flow (Blake et al., 1973; Gish et al., 2005; Greco, 2002; Rezanzhad et al., 2006; Weiler and McDonnell, 2007; Zehe and Flüher, 2001; Zhu and Lin, 2009).

Time domain reflectometry (TDR) has been the most reliable method for *in situ* soil moisture measurement (Cosh et al., 2005; Zehe et al., 2010). Further developments in vertical TDR probing (Greco and Guida, 2008), wireless sensor networking (Bogena et al., 2007) or ecological measurements such as stem water content (Hernandez-Santana et al., 2008) and litter moisture (Canone et al., 2009) also indicate extensive applications of TDR. Soil moisture measurements were used for the characterization of spatial variability (Western et al., 1999; Petrone et al., 2004; Zehe et al., 2010). The stochastic features of the soil moisture dynamics were studied both in a probabilistic approach (Ridolfi et al., 2003) and time series modeling of measurements at the hillslope scale (Kim and Kim, 2007; Kim, 2009a). However, the stochastic structure between measured soil moistures had not been studied and coupled soil moistures can be understood through systematically analysis

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of the intensive time series measurements. The interaction between vertically adjacent soil moistures may be mutual, rather than being a uni-directional function, not only because of the heterogeneous flux pattern, but also due to hystereisis in the soil tension and water content, and the pressure wave transmission (Abdul and Gillham, 1984; Weiler and McDonnell, 2007).

This paper addresses two questions via soil moisture monitoring and modeling. First, what is the hydrological process along the two transects and on the downslope part of hillslope in the context of the delineated model structure? More specifically, what advantage can be gained using a vector model over other simpler approaches, such as univariate or multivariate models? Secondly, how can the results of modeling be used to support better data acquisition for missing data or to improve the redundancy of soil moisture monitoring?

2. Study area

The study area was a hillslope on the Gamak Mountain, located in the north-western part of South Korea. The hillslope is the headwater of the tributary stream, Sulmachun (Fig. 1), which is connected to the Imjin River. The average annual rainfall in this area has been approximately 1500 mm/year over the last 10 years, and the minimum and maximum temperatures are −10 and 35 °C, respectively. The vegetation in this study area is primarily composed of a mixture of *Polemoniales* and shrubby *Quercus*. The slope of study area (Fig. 1) varies between 20° and 35°. A previous soil moisture study has been conducted on the hillside adjacent to the study area (Kim and Kim, 2007; Kim, 2009b). In fact, extensive survey work and redesign of the monitoring program were performed to address the monitoring network along multiple transects.

Gneiss composites, underlined by granite bedrock, are the primary geological features and the depth of the soil layer varies from 25 to 95 cm. The porosity at a depth of 10 cm was about 50% and this decreased in deeper layers. Considering the relatively small size of the study area (11,000 m^2), the spatial variability in the vegetation can be neglected (Kim, 2009b). A particle analysis of soil samples indicated that the soil composition percentages of sand, silt and clay ranged between 55% and 75%, 25% and 45% and 2% and 5%, respectively, and there was no systematic difference in the soil texture distribution along the hillslope (Kim and Kim, 2007; Kim, 2009b). Refined Digital Elevation Models (DEM) for the surface and bedrock, with a resolution 0.5 m, were obtained after an intensive topographical survey (540 points) of the study area using a theodolite (DT-208P, TOPCON) and via direct and multiple measurements of the soil depth using iron poles.

3. Methods and materials

3.1. Field data acquisition of soil moisture

A soil monitoring system was installed and operated over a few sequential rainfall events during mid-September to the end of October 2007. Based on digital elevation models, the spatial distribution of the flow was evaluated assuming the soil wetness was primarily governed by the terrain on the humid hillslope (Wilson et al., 2004; Quinn et al., 1991; Anderson and Kneale, 1980). Monitoring locations were determined for the two transects, transects A and B, from the hilltop to a natural and variable channel initiation point and the hydrologically *active* area, region C, located downslope of the study area. Fig. 2 shows the locations of the monitoring points, as well as the topographic wetness index, ln (*a*/tan *β*), where '*a*' is the upslope area and 'tan *β*' is the local slope estimated, using the MD8 algorithm (Quinn et al., 1991).

The hydrological process involved in the vertical soil profile can be configured by investigating the interactions between the soil moisture responses at different depths. In this study, the soil moisture along two transects of a mountainous hillside was intensively monitored. Reliable *in situ* measurements, using a multiplex TRASE-TDR system (Soil Moisture Equipment Corp., 2005) were employed to obtain the soil moisture as a multiple time series. Depending on the soil layer depth, 2–3 sensors were installed at the monitoring points to configure the vertical profile and subsequent redistribution of the soil moisture. Wave guides were inserted horizontally, heading in an upslope direction at depths of 10, 30 and 60 cm, without disturbing the soil layer.

Temporal variations in the soil moisture content were recorded bi-hourly for the modeling period between September 18 and October 8 2007, and for an extended period between October 9 and 25 2007. An Automatic Rain Gauge System (ARGS), located 50 m from the study area, was used to measure the rainfall, as shown in Fig. 1. During the modeling period, rainfalls of 38.6,

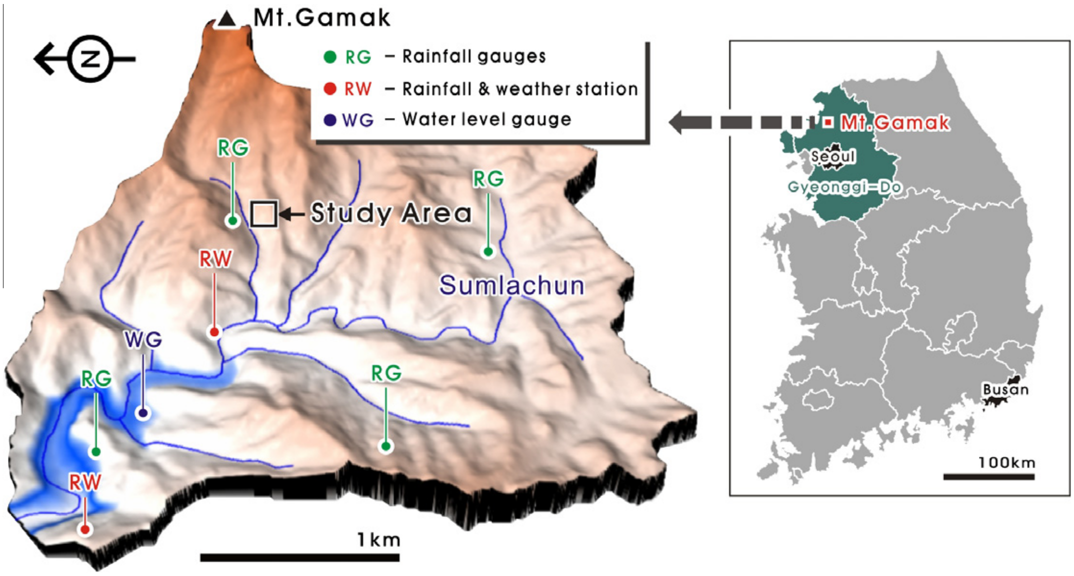

Fig. 1. The Sulmachun catchment and the study area.