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Multivariate analysis of soil moisture history for a hillslope

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SUMMARY

In this study, the spatial distribution of measured soil moisture was analyzed on the platform of multivariate modeling. Soil moisture time series for two seasons were selected and used for analysis to reveal similarities and differences in soil moisture responses for a few rainfall events. The development of a soil moisture transport process that considers the representative element volume and uncertainty of soil media provides the hydrological basis for time series modeling. The systematic procedure of Box–Jenkins with noise modeling was used to delineate the final models for all monitoring points. The physical basis of mass balance and the continuity in inflow contribution, as well as statistical criteria, were used in the model selection procedure. Heuristic approaches provide the spatial distribution of selected models along the transect of a hillside. Comparative analysis for two different depths and seasons provide an understanding of the variation in soil moisture transfer processes at the hillslope scale. Differences in soil moisture models for both depths and seasons are associated with eco-hydrological processes. The relationships between distributed topographic features and modeling results were explored to configure dominant hydrological processes for each season.

Introduction

Soil moisture, a key variable in the runoff response mechanisms and hydrological processes within the vadose zone at the hillslope scale (Beven, 2002; Ambroise, 2004) also controls the partitioning of energy and water related to evapotranspiration, solute transport, and ecosystem dynamics (Georgakakos, 1996; Rodriguez-Iturbe and Porporato, 2004). Knowledge of the spatial and temporal distributions of soil moisture is important in understanding eco-hydrological processes at the hillslope scale (Ridolfi et al., 2003; Kim and Kim, 2007). For example, the dynamics of unsaturated zones and the generation of lateral subsurface storm flows are heavily dependent on the spatial and temporal distribution of soil moisture and soil pore pressure (Torres et al., 1998; Uchida et al., 2004). Similarly, downslope flux through preferential pathways is a dominant process for transport water toward the lower parts of hillslopes in humid areas (Uchida et al., 2005; Hewlett and Hibbert, 1963).

Understanding the spatial and temporal distribution of soil moisture along hillslopes could be critical for configuring the internal hydrological behavior and eco-hydrological processes of hillsides (Hilberts et al., 2007; Lin et al., 2006; Tromp-van Meerveld and McDonnell, 2006). In this study, the soil moisture responses for sequential rainfall events on hillslope are characterized by rigorous modeling.

In situ monitoring of soil moisture is a challenging task in hydrology (Topp, 2003). For a point scale measurement, the most reliable technique seems to be a Time Domain Reflectometry (TDR) (Walker et al., 2004), which requires the designing of a delicate monitoring system to obtain time history of soil water content with consideration of the topographic feature of the study site (Kim et al., 2007). A multiplex TDR system (Soil Moisture Equipment Corp., 2005) was used for the intensive monitoring of the soil moisture time series and the results were expressed as the spatial distribution of the temporal variation of soil moisture along the hillslope. The relationship between rainfall and soil moisture needs to be addressed, take into account a representative moisture sensor, the average wetness of a soil cube and the uncertainty associated with the soil matrix.

A systematic approach is required to explain the spatial distribution of a multiple time series acquired from field measurements. The transfer function modeling approach and its modifications have been widely used to understand and forecast streamflow variations (Castellano-Mendez et al., 2004; Salas et al., 1988). Time series modeling has been widely used in the interpretation of other hydrologic data, such as water quality variables, groundwater levels and streamflow nitrate analysis (Astatkie and Watt, 1998; Salas et al., 1988; Worrall et al., 2003). In this paper, the Box–Jenkins transfer function with noise modeling is employed to analyze the relationship between rainfall inputs and the soil moisture time series as outputs (Box and Jenkins, 1976).

In this study, the following research questions will be addressed with the modeling results: (1) How can the measured soil moisture

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be addressed within the framework of a time series model considering the Representative Elementary Volume (REV) and uncertainty of porous media? (2) What is the soil moisture response distribution for a sequential rainfall input along a hillslope, on the platform of multivariate modeling approach? (3) In terms of seasonal and depth variations, what are the differences in the soil moisture models? (4) How could the distribution of models be addressed in conjunction with several topographic surrogates for the hillslope hydrological processes? (5) What is the corresponding explanation for the each model in the context of hydrologic behavior during a few sequential rainfall events?

The implications of hydrological processes in modeling procedures, such as model evaluation and refinement, may provide better understanding for eco-hydrological processes as well as providing hydrologically meaningful modeling results.

Methodology

The study site

The study area is located inside the Korean National Arboretum (KNA), which belongs to the Gwangneung Forest, Pochun-si, Gyeonggi-do, Korea. The Gwangneung forest is part of the Bongsunsa Watershed (Fig. 1), which is connected to the Han River basin. The latitude and longitude of the study area are 37°45′25.37″N and 127°9′11.62″E, respectively. The average annual precipitation was 1,332 mm from 1982 to 2004. The Bongsunsa watershed is underlaid by weathered gneiss and schist with eastern aspect and the dominant soil texture is sandy loam. The soil depths range between 0.4 and 0.8 m. Hillsides with slopes 10–20° account for 80% of the total area, while maximum slope was 51°. This catchment is primarily covered by a mixture of *Carpinus* sp. and shrubby *Quercus* sp. The annual mean temperature at the site is 11.5 °C. A study site was selected to install the long-term soil moisture monitoring system, taking into consideration the required operational conditions for multiplex Time Domain Reflectometry (TDR) system. The average slope of the soil moisture monitoring hillside is 19° and the soil texture is composed of mixture of sand (53.2%), silt (39.2%) and clay (7.6%). Average soil porosity at a 10 cm depth is about 50% due to intensive development of root and biological activity. Visual inspection also indicates the abundance of macropores.

The monitoring scheme

In order to consider the impact of topography in designing the soil moisture monitoring system, a procedure for the monitoring scheme installation was performed as described in Kim et al. (2007). The digital terrain model was obtained through an intensive surveying for 320 points using Deodolite (DT-208P, TOPCON). The polar coordinates drawn by surveying were converted into Cartesian coordinates by a coordinate convert algorithm. The depth to the bedrock was also measured with multiple insertions of an iron pole at all corresponding points. On the basis of the acquired coordinate information, intensive Digital Elevation Models (DEMs) for surface and subsurface topography were acquired with a resolution of 0.5 m (Figs. 1 and 2).

In order to obtain the spatial distribution of soil moisture measurement points, digital terrain analysis was performed to estimate topographic wetness index and the contributing area (O'Callaghan and Mark, 1984; Quinn et al., 1991). The assumption for this approach is that, as the wetness index for a certain point becomes greater, the possibility for a greater concentration of flowpaths is also increased. Based on the spatial distribution of soil, the measurement points were determined as shown in Fig. 2. The monitoring points were determined according to a preliminary estimation of soil wetness based on terrain analysis, selected transect lines, and the manual adaptation on installing waveguides depending on field conditions, such as the existence of a tree. Further details for the design of the soil moisture monitoring system can be found in Kim et al. (2007).

The main TDR system connects waveguides to all measuring points. Soil moisture and rainfall data were collected during May and September in 2007. Rainfall data was collected using an Automatic Rain Gauge System (ARGS), installed at the top of the canopy, located 300 m downstream from the study area, as shown in Fig. 1. Rainfalls of 4.8 mm, 13.3 mm, 16.9 mm, 59 mm, 15.3 mm and 43.1 mm were recorded on May 1, 8, 11, 15, 17 and 23, 2007, and rainfall of 13.5 mm, 57 mm, 27.5 mm, 77 mm, and 23 mm were recorded for September 5, 14, 17, 18, and 27, 2007, respectively. Mean rainfall rates for May and September periods were 5.08 mm/day and 6.6 mm/day, respectively. The mean equilibrium evapotranspiration during May and September was estimated as 2.0 mm/day and 2.02 mm/day, respectively (Slatyer and McElroy, 1961).

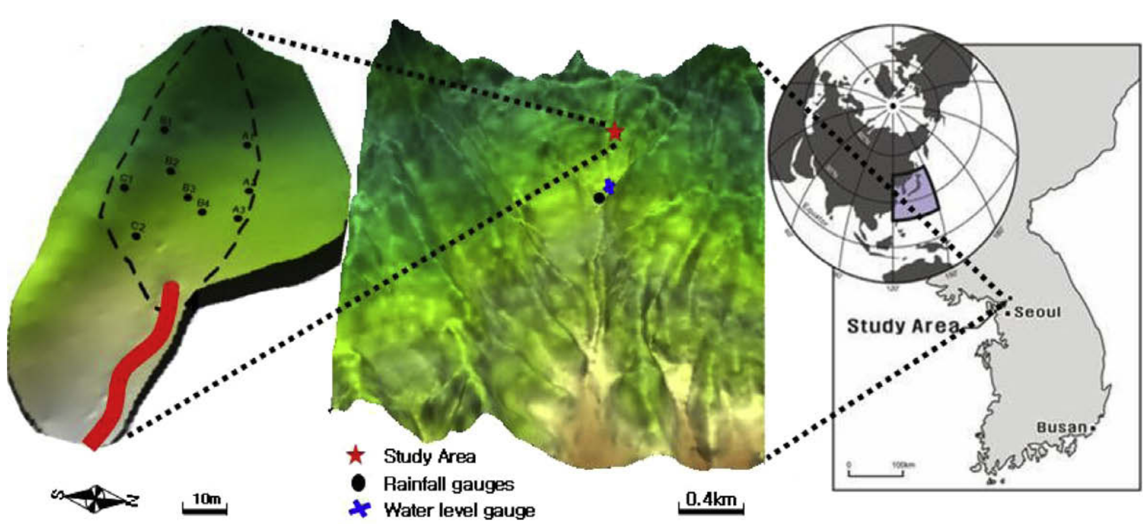

Fig. 1. The location of the Bongsunsa Watershed and the study area.