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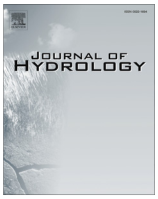

Time series modeling of soil moisture dynamics on a steep mountainous hillside

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SUMMARY

The response of soil moisture to rainfall events along hillslope transects is an important hydrologic process and a critical component of interactions between soil vegetation and the atmosphere. In this context, the research described in this article addresses the spatial distribution of soil moisture as a function of topography. In order to characterize the temporal variation in soil moisture on a steep mountainous hillside, a transfer function, including a model for noise, was introduced. Soil moisture time series with similar rainfall amounts, but different wetness gradients were measured in the spring and fall. Water flux near the soil moisture sensors was modeled and mathematical expressions were developed to provide a basis for input–output modeling of rainfall and soil moisture using hydrological processes such as infiltration, exfiltration and downslope lateral flow. The characteristics of soil moisture response can be expressed in terms of model structure. A seasonal comparison of models reveals differences in soil moisture response to rainfall, possibly associated with eco-hydrological process and evapotranspiration. Modeling results along the hillslope indicate that the spatial structure of the soil moisture response patterns mainly appears in deeper layers. Similarities between topographic attributes and stochastic model structures are spatially organized. The impact of temporal and spatial discretization scales on parameter expression is addressed in the context of modeling results that link rainfall events and soil moisture.

1. Introduction

Soil moisture, a critical hydrological variable, significantly affects infiltration, evapotranspiration, runoff, solute transport, and ecosystem dynamics (Clark and Gedney, 2008; Blume et al., 2009; Teuling et al., 2010; Feng et al., 2012; Corradini, 2014). At the hillslope scale, water content of the surface soil plays an important role in rainfall runoff and erosion processes (Haga et al., 2005). The spatial and temporal distribution of soil moisture (Vereecken et al., 2014) and soil pore pressure largely controls water movement in unsaturated zones and the generation of lateral subsurface storm flows (Uchida et al., 2004; Tsutsumi et al., 2005).

Following Beven and Kirkby (1979) topographically based hydrologic model, a number of researchers (e.g., Whitfield et al., 2006; Huang et al., 2008) included a topographic index in the description of the hydro-meteorological processes when predicting soil vegetation-atmosphere interactions. Specifically, the impact of terrain topography on soil wetness has been accounted for through the delineation of a topographic wetness index, $\ln(a/\tan B)$, where a is the upslope contributing area and $\tan B$ is local slope, using a surface digital elevation model (Quinn et al., 1991). Basic assumptions for topographic wetness index based modeling include a steady state approximation of saturation tendency with the hydraulic gradient as a local slope and the downward transmissivity expressed as an exponential function (Beven and Kirkby, 1979) or a more general power function (Ambroise et al., 1996). In principle, *in situ* soil moisture data can be used to check the validity of basic hydrologic modeling philosophy and its extensive developments (Walter et al., 2002; Whitfield et al., 2006; Huang et al., 2008; Jana and Mohanty, 2012). The spatial relationship between saturation tendency and topographic attributes (Pradhan et al., 2008; Vincendon et al., 2010) has been evaluated within the larger context of the impact of rainfall on soil moisture.

Many studies have used the Richards and St. Venant equations to model soil moisture and overland flow, respectively, at the hillslope scale (Jayatilaka et al., 1998; Mertens et al., 2004; Simunek and van Genuchten, 2008; An and Yu, 2014). The applicability of multi-dimensional models to represent spatial and temporal variations of soil moisture has been evaluated (Mahmood and Vivoni, 2011; Tavakoli and Smedt, 2013; Cornelissen et al., 2014). However, accurate data relative to the spatial distribution of hydraulic

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parameters, macropores and preferential flow pathways are extremely difficult to obtain under field conditions. In order to improve understanding of hydrological responses *in situ*, monitoring the variations in soil moisture is vital.

One of objectives in time series model can be a better understanding of the process with hydrologic meaning (Young, 2013). Modeling of chemical tracers and $\delta^{18}O$ values were attempted by combining a nonlinear component and linear transfer functions (Iorgulescu et al., 2005, 2007). Studying the structure of a time series model that has rainfall as the input and soil moisture content pattern as the output may lead to an understanding of the characteristics of the temporal response of soil moisture to a given hydrometric driver (e.g., rainfall). In this context, the Box–Jenkins transfer function (Box and Jenkins, 1976; Salas et al., 1988) with noise modeling, and its modifications, were used to interpret subsurface hydrologic and water quality parameters (von Asmuth et al., 2002; Jones and Smart, 2005). Univariate and multivariate models were applied for point-scaled soil moisture contents measured via Time Domain Reflectometry (TDR) (Kim and Kim, 2007; Kim, 2009a, 2014a,b). However, the configuration of the soil moisture variation pattern for rainfall events was not explored in the context of the structure of time series model. Furthermore, the seasonal differences of soil moisture response patterns can be elucidated even in similar wetness condition.

In this context, we hypothesize that the response pattern of soil moisture to sequential rainfall events can be identified through modeling and the resulting stochastic structure between rainfalls and water content and this can reveal soil moisture controls such as soil hydraulic structure, topography and eco-hydrological processes. Furthermore, the mathematical description in soil moisture redistribution near installed TDR sensors may provide a deterministic basis for the transfer function which includes noise modeling.

We modeled the temporal variation in soil moisture for different locations at two depths to reveal the seasonal difference in soil moisture response in terms of a topographic wetness index. The use of a soil moisture time series modeling approach during sequential rainfall events can address several questions, such as: (1) What is the analytical and deterministic basis for transfer function modeling between rainfall and soil moisture? (2) How can the seasonal difference in soil moisture response be expressed in terms of model structure, given similar average soil moisture and rainfall distribution but a different hydrometeorologic trend? (3) How can the distribution of model structure be explained in conjunction with topographical attributes?

2. Materials and methods

2.1. Study area and soil monitoring system

Soil moisture time series were monitored on a hillside in the Sulmachun catchment, located at the headwaters of the Imjin River in northern South Korea (Fig. 1(a)). Soil moisture was monitored at 11 and 20 monitoring points during autumn and spring, respectively. TDR sensors were inserted horizontally, heading in an upslope direction, at depths of 10 and 30 cm, minimizing the soil layer disturbance (Soil Moisture Corp., 2005). Soil moisture was recorded hourly from November 6 – November 22, 2003 and May 2 to May 22, 2004. The area is approximately 2741 m^2, with mean annual precipitation of 1500 mm/year and minimum and maximum temperatures of -10 and 35 °C, respectively. The study area is primarily covered by a mixture of *Polemoniales* and shrubby *Quercus*, and the slope varies between 30° and 45°, as shown in Fig. 1(b). Gneiss underlain by granite bedrock are the primary geological feature. Soil depths are mostly distributed between 15 and 45 cm, with upper and lower ranges of 10 and 80 cm, respectively. Since the study area occupies a relatively small area, vegetation is assumed to be uniform. Particle analysis of 16 soil samples indicated no systematic difference in soil texture distribution along the hillslope. Using the grain size composition curve average, standard deviation, maximum and minimum of estimated hydraulic conductivities in m/s were $3.12 \cdot 10^{-3}$, $2.69 \cdot 10^{-3}$, $1.42 \cdot 10^{-2}$, and $1.71 \cdot 10^{-4}$, respectively (Kaswnow, 2001), these values do not suggest any impact of preferential flow due to the disturbance of soil structure. Grain size analysis indicated that estimated porosity varied from 0.28 to 0.35. In order to evaluate the actual pore volume of macropores, three undisturbed soil core samples were collected in the study area. Ranges of core sample porosity %, void volume/total volume, were between 45% and 48%. Visual inspection indicates macropore development does not vary structural along the hillslope. Refined Digital Elevation Models (DEM), with a 0.5 m resolution for surface and bedrock, were obtained after an intensive topographical survey of the study area using a Theodolite (DT-208P, TOPCON), as well as by direct measurements (4 insertions for 67 pixels) with iron poles.

In this study, the multiple flow direction algorithm, *MD8*, by Quinn et al. (1991) delineated the contributing area for all points in the study area. Based on digital terrain analysis, the monitoring points were determined in conjunction with the probability distribution function of the contributing area (Freer et al., 2004; Kim, 2009b). Coordinates generated with distance and angle vectors from a known reference position made accurate positioning of TDR sensors possible. Depending on depth of the soil layer, 2 or 3 sensors (10 cm, 30 cm, and 60 cm) were installed at a monitoring point to access vertical profile and subsequent redistribution of soil moisture. An Automatic Rain Gauge System (ARGS, Eijkelkamp), located 50 m from the study area, was used to monitor rainfall, as shown in Fig. 1(a). Rainfalls of 28 mm, 19 mm, and 8 mm were recorded on November 8, 11 and 20, 2003, while rainfalls of 14.5 mm, 33 mm and 15.8 mm were recorded for May 3, 9 and 20, 2004, respectively. Leaf area indices (LAIs), measured by LAI-2000 (LI-COR Bioscience, 2004), for November 5 and 19 were 1.06 and 0.98, while those for May 15 and 28 were 2.98 and 3.97, respectively. The average rate of potential evapotranspiration (PET) for designated periods in both seasons 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 at 10 min time intervals from a weather station (Fig. 1(a)). The difference in elevation between the study area and the weather station is approximately 100 m. Additional information about the study area, equipment and sampling design and implementation can be found in Kim (2009b).

2.2. Mass balance basis of transfer function modeling for hillslope soil moisture

A mathematical description of the soil moisture transfer process at a hillslope-scale with measured precipitation, and soil moisture was developed to provide a mass balance basis for stochastic modeling. Soil moisture (θ) can be partitioned into a mean component of volumetric water content, $\bar{\theta}$, and an additional dynamic term, θ'. The residual component of soil moisture is primarily associated with the heterogeneity of soil structure at the pixel scale. The resolution of a pixel depends on the range of moisture detection and the time scale of data acquisition in the modeling.

If the volume of soil can be approximated as *dxdydz*, where *dx*, *dy*, and *dz* are spatial scales, the soil moisture process in the equation can be expressed as:

$$\frac{d\bar{\theta}}{dt} + \frac{d\overline{q_x}}{dx} + \frac{d\overline{q_y}}{dy} + \frac{d\overline{q_z}}{dz} = 0 \tag{1}$$