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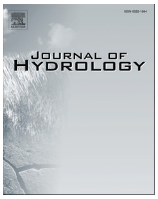

Connectivity and topographic thresholds in bi-hourly soil moisture measurements along transects on a steep hillslope

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SUMMARY

Observation of temporal variations in soil moisture along transects is important when examining hydrological processes on a hillslope. Although there is substantial interest in characterizing catchment hydrology through an investigation of hydrologic connectivity, few attempts have been made to explore hydrologic connectivity within soil layers using soil moisture observations. Mathematical relationships among soil moisture differences are reproducible when Granger causality is defined within the context of hydrological connectivity because the process based transfer functions facilitate soil moisture predictions. Soil moisture time series along two transects on a steep hillslope were obtained using a multiplexed time domain reflectometry system during the growing season in June 2008 and 2009. The transfer function relationships between multiple soil moisture differences were delineated to determine a representative point for reliable time series modeling, and to establish the spatial pattern of areal clusters that will enable model identification and prediction. The impact of hillslope topography on the modeling of coupled soil moisture was highlighted by configuring the threshold behavior of model predictability. Results showed that soil moisture temporal relationships can be used for the prediction of volumetric soil moisture, within a specific area associated with representation point. Reliable relationships among soil moistures were apparent for points having greater upslope areas between 400 m^2 and 1000 m^2.

1. Introduction

Soil moisture is an important factor controlling and determining the spatial and temporal distribution of hydrological processes at the hillslope scale (Blume et al., 2009; Kim, 2009; Redding and Devito, 2008). Soil moisture measurements have frequently been used to identify spatial and temporal variations in saturation patterns (Anderson et al., 1997; Buttle et al., 2004; Haga et al., 2005; Kim, 2012a; Western and Grayson, 1998). An understanding of soil moisture fluctuations and their interaction with hillslope hydrological processes enables us to configure flowpaths, residence time, connectivity and the distribution of spatial saturation patterns (Keith et al., 2010; Spence et al., 2010; Torres et al., 1998; Tromp-van Meerveld and McDonnell, 2006; Uchida et al., 2006; Western et al., 2001).

Another issue of increasing interest in mountainous catchment research is the connectivity between hydrological processes. The hydrological connectivity between hillslopes and stream flows (McGuire and McDonnell, 2010) has recently been explored to determine (i) topographic and geologic controls on runoff generation (Jencso and McGlynn, 2011), (ii) threshold relationships between soil moisture and stream flow (Burke and Kasahara, 2011), and (iii) modeling infiltration patterns and flow path resistance at semiarid hillslopes (Smith et al., 2010). In addition, pipeflow connectivity can act as an important hydrological mechanism in humid temperate hillslopes (Jones et al., 1997; Uchida et al., 1999). Connected patterns, which can be detected by ground penetrating radar (Holden, 2004), strongly affect temporal variations in soil moisture (Hopp and McDonnell, 2009). However, the rigorous testing of hydrological connectivity using field measurements within the vadose zone on a hillslope has rarely been performed, although most studies implicitly assume that the scale of water transition is identical to the spatial extent of the regolith, and therefore use such an assumption in physics-based models (e.g., HYDRUS) (Jana and Mohanty, 2012; Kampf, 2011; Kohne et al., 2011).

Historically, time stability analysis has been used to characterize the spatial and temporal variability of soil moisture (Chen, 2006; Grayson and Western, 1998; Heathman et al., 2012; Vauchaud et al., 1985). Temporal stability analysis has also been used to identify locations that represent the spatial average of soil moisture for satellite images validation (Brocca et al., 2012; Loew and Schlenz, 2011), water storage evaluation (Gao et al., 2011)

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and infilling of missing soil moisture (Dumedah and Coulibaly, 2011). However, statistical approaches that do not use hydrological processes may suffer from a lack of physical interpretation.

The impact of topography on hillslope hydrological processes has been explored in many studies (Dunne and Black, 1970; Anderson and Burt, 1978; McGlynn and McDonnell, 2003; McGuire et al., 2005). An accumulation of subsurface flow is often found in relatively high upslope accumulation areas, namely the upslope area, (Dunne and Black, 1970; Harr, 1977; Anderson et al., 1997; Beven, 1978; Jencso et al., 2009), and can be calculated through digital terrain analysis (Quinn et al., 1991; Seibert and McGlynn, 2007).

Time domain reflectometry (TDR) and its derivatives are useful in monitoring the volumetric water content of the soil layer (Katsura et al., 2008; Western and Grayson, 1998; Western et al., 2001; Zehe et al., 2010b). Recently, temporal variations of spatially distributed soil moisture at the hillslope scale have been analyzed in numerous ways, for example, soil moisture stochastic dynamics for a hillslope (Ridolfi et al., 2003), and spatial covariance structures (Zehe et al., 2010b) and univariate or vector analyses (Kim and Kim, 2007; Kim, 2011). A causality analysis between coupled soil moistures appears useful in understanding hydrological processes for a point-scaled soil moisture series (Kim, 2012b). In this paper the connectivity of soil moisture refers to the granger causality which can be defined as “the predictability between two soil moisture time series indicating whether one time series could be better predicted using present and past information of the two time series rather than using only one soil moisture series” (Granger, 1969). However, few studies have explored soil moisture relationships from a process-based perspective and these relationships can be extensively investigated to determine soil moisture connectivity and reproducibility in soil moisture prediction. Furthermore, the impact of topography on the development of soil moisture connectivity appears to be related to threshold issues in hillslope hydrological systems (Zehe and Sivapalan, 2009; Zehe et al., 2010a).

In order to provide a physical interpretation for soil moisture time series analysis, this paper introduces a mathematical development based on the input-storage-output relationship for the transfer function between coupled soil moistures. The structure of soil moisture connectivity is implemented into the modeling platform and the influence of rainfall is intentionally excluded to facilitate the test of soil moisture connectivity. A systematic procedure for conducting the time series analysis is presented to model soil moisture differences. The analysis of soil moistures measurements taken during the growing season in June 2008 and 2009 addresses the following research questions: first, how the connectivity of hydrological processes can be expressed in soil layers along the hillslope; and second, whether there is a topographic threshold behavior in the performance of the soil moisture model, and how controls, such as topography and rainfall, explain the model's performance.

2. Materials and methods

2.1. Study area and hydrometric monitoring

The study area is a steep mountainous hillslope with granite bedrock, located within the Sulmachun catchment basin in north-western South Korea (shown in Fig. 1). The Sulmachun watershed was designated as a hydrologic monitoring watershed since 1980, and time series of hydrologic responses (rainfall and streamflow) as well as meteorological variables (wind speed and relative humidity) have been measured in this area for the past 20 years. The mean annual rainfall is approximately 1500 mm, and the temperature varies between −15 and 35 °C, with a mean annual temperature of approximately 11 °C. The areal extent of the study area is approximately 4000 m^2, and the angle of the slope varies between 20° and 35°. Soil depths vary between 25 cm and 90 cm from the hilltop to the downslope area, respectively. The predominant soil textures within the study area are loamy sand and sandy loam, and the primary hillslope vegetation is a mixture of *Polemoniales* and shrubby *Quercus*, with no systematic vegetation structure identified over the small scale of the hillslope.

To obtain the topography and determine the spatial distribution of soil depth, an extensive field surveying took place in 2007 using a Theodolite (DT-208P, TOPCON) with approximately 1000 iron pole insertions. The deepest penetration depth obtained with 4 to 5 iron pole insertions was recognized as the soil depth for each surveying point. Refined Digital Elevation Models (DEMs) with resolutions of 0.5 m both for the surface and bedrock layers were established (Fig. 1). Before designing the soil moisture monitoring network, the spatial distribution of water accumulation was evaluated. An algorithm using multiple flow in 8 directions (MD8) (Quinn et al., 1991), and an infinite directions (MD∞) (Seibert and McGlynn, 2007) were used to compute the saturation tendency from the DEM. Both the MD8 and MD∞ schemes were then used to calculate the upslope contributing area and the topographic wetness index, $\ln(a/\tan\beta)$, where a is the upslope area per unit width and $\tan\beta$ is the local topographic slope. Based on an analysis and the frequency distribution of the wetness index, soil moisture sensors were placed so that flow patterns could be configured along transects A and B (Kim, 2009). Depending upon the soil depth, two or three TDR waveguides were carefully inserted in an upslope direction to minimize disturbance (SoilMoisture, 2005). Sensors were inserted at depths of 10, 30 and 60 cm, and the number of soil moisture monitoring points along transects A and B were 15 and 21, respectively. The soil moisture measurements obtained during June 2008 and 2009 were used for analysis because of the excellent data acquisition rate and similar hydro-meteorological conditions (e.g. temperature, canopy and rainfall) between the two periods.

2.2. Soil moisture transfer function between two points along a hillslope

Soil water inflow into a point can be expressed as the summation of the upper vertical flow and upslope lateral flow, while the outflow component can be partitioned into the lower vertical flow and the downslope lateral flow. Therefore, the rate of soil moisture variation in a soil cube can be approximated as:

$$d\theta/dt = I(t) - O(t) \tag{1}$$

where the inflow, $I(t)$, can be split into mean inflow, $\bar{I}(t)$, and a perturbation component, $I'(t)$, from the upper and upslope directions, and outflow, $O(t)$, can be partitioned into mean outflow, $\bar{O}(t)$, and a perturbation component, $O'(t)$, to the lower and downslope directions of the hillslope. The mean inflow and outflow components are comprised of gravity driven vertical and downslope flows, potential flux and evapotranspiration associated with stationary features located near the measurement point, such as local slope, soil texture and depth. Perturbation components are related to the pressure wave transmission or to the lateral pipe flow induced by rainfall events (Torres et al., 1998; Uchida et al., 1999).

Soil moisture can be expressed by a storage function as follows:

$$\theta = f(I, dI/dt, d^2I/dt^2, \ldots, O, dO/dt, d^2O/dt^2, \ldots) \tag{2}$$

The soil moisture difference $d\theta$ can be expressed as:

$$d\theta = \theta_{t+1} - \theta_t = a_1 I + a_2 dI/dt + \cdots + b_1 O + b_2 dO/dt + \cdots \tag{3}$$