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Pattern similarity based soil moisture analysis for three seasons on a steep hillslope

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ABSTRACT

Soil moisture is an important factor for understanding hydrological and solute transport processes at the hillslope scale. The selection of representative points for soil moisture measurement has been explored to investigate temporal variation of average soil moisture with minimum costs and maximum stability. The optimal selection of soil moisture monitoring points has been reevaluated to address hillslope hydrological processes and the impacts of seasonal differences. An alternative method to select soil moisture measurement points was developed to adequately represent immediate soil moisture response patterns to sequential rainfall events. To address the seasonal features of rainfall events and their impacts on soil moisture redistribution along the hillslope, field soil moisture data were collected at 49 points for three seasons over periods of 25 days with bi-hourly monitoring intervals. For effective characterization of soil moisture variation, soil moisture datasets were classified using cluster analysis based on Euclidean similarity. Points delineated using the proposed method not only provide better stability of average soil moistures but also adequately represent the response patterns of soil moisture to rainfall events on the hillslope.

1. Introduction

Soil moisture is a critical hydrological component in various water transport processes such as evapotranspiration, infiltration, exfiltration and lateral flow at the hillslope scale (Brocca et al., 2007; Corradini, 2014; Rodriguez-Iturbe and Porporato, 2004; Tromp-van Meerveld and McDonnel, 2006). The lateral and vertical distributions of soil moisture play an important role in determining the impacts of hydrometeorological drivers (e.g., rainfall), topography and vegetation on the redistribution of soil moisture (Gao and Shao, 2012a; Lawrence and Hornberger, 2007; Zhang et al., 2006). The variation of soil moisture is more dynamic and more sensitive to external drivers (e.g., rainfall, solar radiation, and wind speed) in shallower soil layers than in deeper soil layers. Interactions between soil moisture and various environmental factors (e.g., rainfall and evapotranspiration) and associated hillslope hydrological processes (e.g., vertical, lateral, and return flow) cause spatial and temporal variations of soil moisture distribution at the hillslope scale (Korsunskaya et al., 1995; Rosenbaum et al., 2012).

To better understand the variation of soil moisture, optimal selection of soil moisture monitoring points has previously been explored (Kim, 2009; Western et al., 1999). Geostatistical analysis has been used in a number of approaches to estimate the spatial patterns of soil moisture variability at the hillslope and catchment scales (Korres et al., 2015; Rosenbaum et al., 2012). However, the costs of collecting reliable information on soil moisture variation patterns can be prohibitive (Liang et al., 2014). Identification of representative points for soil moisture measurements is essential to reduce the number of measurement points required, and thus reduce costs, as well as to investigate temporal variations of soil moisture at the hillslope scale (Penna et al., 2013).

Temporal stability has been widely used as a parameter for selecting representative points to provide temporal characterization of soil moisture variation for designated grid cells (Kachanoski and de Jong, 1988; Vachaud et al., 1985). Temporal stability may vary with soil depth, soil properties, land use and hydrometeorological conditions (Biswas and Si, 2011; Gao and Shao, 2012b; Gao et al., 2015; Li and Shao, 2014; Penna et al., 2013). Most studies of temporal stability have been performed using datasets collected at daily or weekly intervals (Junquira Junior et al., 2017; Zhang et al., 2016). Statistically highest stability has been an important criterion for determining the representative

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point for the spatially averaged soil moisture of a given area (Penna et al., 2013). However, because of the prompt and continuous variation of soil moisture caused by rainfall events and its highly nonuniform and nonlinear response patterns along a hillside, statistical approaches for selecting representative points may not adequately represent the spatial features of soil moisture variation in terms of hillslope hydrological processes (Gao and Shao, 2012a; Gwak and Kim, 2016; Kim, 2012). Furthermore, the variation patterns and formation of peak soil moisture are strongly associated with the terrain characteristics and soil water retention capacity of the location of measurements (Grayson et al., 1997; Korsunskaya et al., 1995; Tromp-van Meerveld and McDonnel, 2006).

To characterize distinct soil moisture responses to rainfall events, a feature-based approach for time series can be employed. The Euclidean distances between soil moisture time series can be used for shape-based comparison because they represent the difference between soil moisture series collected at the same time (Sohrabinia et al., 2014; Van Arkel and Kaleita, 2014). The dissimilarity distance between datasets can be used to classify time series of soil moisture and to form clusters with similar variation patterns associated with rainfall.

For this paper, we have explored the following research issues. An alternative method for determining soil moisture monitoring points was proposed based on the soil moisture response features associated with hydrological processes. Soil moisture response characteristics for different soil depths and seasons were then investigated. Clusters for soil moisture variation were delineated by applying the hierarchical clustering method through evaluating dissimilarity between soil moisture datasets. The temporal variation patterns of soil moisture along the hillside were characterized addressing primary hydrological processes, and the representative point for each clustered dataset was determined. The representative points identified using a well-established temporal stability method and the newly proposed clustering method were compared during three seasons, and this approach was evaluated not only for its capability of representing the variation of mean soil moistures but also for its strength in addressing process-based hydrological explanations.

2. Materials and methods

2.1. Study area

The study area is a steep hillslope in the Sulmachun watershed in northwestern South Korea (Fig. 1). The area of the watershed is about 8.5 km^2, 95% of which is forest covered. Hydrometeorological data (e.g., rainfall, streamflow, temperature, and humidity data) have been collected over the past 25 years at seven hydrologic monitoring stations (Fig. 1). The mean annual rainfall for the last five years was approximately 1636 mm with a standard deviation of 268 mm, and 70% of the total rainfall occurred during the Asian monsoon season between June and August. The mean annual evaporation was approximately 420 mm, which was estimated with the eddy-covariance method using data obtained from a flux tower 50 from the study area. The temperature varied between −15 and 35 °C. The elevation of the hillslope ranges between 200 and 260 m above sea level, and the surface slope varies between 20° and 35°. The hillslope bedrock consists of gneissic granite, and fracture development is negligible. Leptosol is the dominant soil type and Cambisol was found at greater depths (IUSS Working Group WRB, 2015). Based on analysis of 15 soil samples, the predominant soil textures were sandy loam and loamy sand. The mean bulk density of the soil samples was 1.36 g/cm^3, and the porosity varied between 25% and 49%. The depth of the soil ranged between 25 and 95 cm, and the depth of the root zone was approximately 20 to 30 cm. Generally, the soil depth was deeper farther downslope. Vegetation within the study area is a mixture of *Polemoniales,* shrubby *Quercus,* and a coniferous canopy of *Pinus densiflora.*

An automatic rain gauge system located 50 m from the study area was used to measure rainfall, as shown in Fig. 1. The average rate of potential evapotranspiration (PET) was estimated for the spring and autumn periods as 4.9 mm/day and 1.35 mm/day, respectively, based on meteorological data such as net radiation, wind velocity, air temperature and relative humidity measured at 10-min intervals. Leaf area indices (LAIs) for the corresponding seasonal periods were measured using an LAI-2000 device (LI-COR, 2004). LAIs for November 5 and 19 were 1.06 and 0.98, respectively, whereas those for May 15 and 28 were 2.98 and 3.97, respectively.

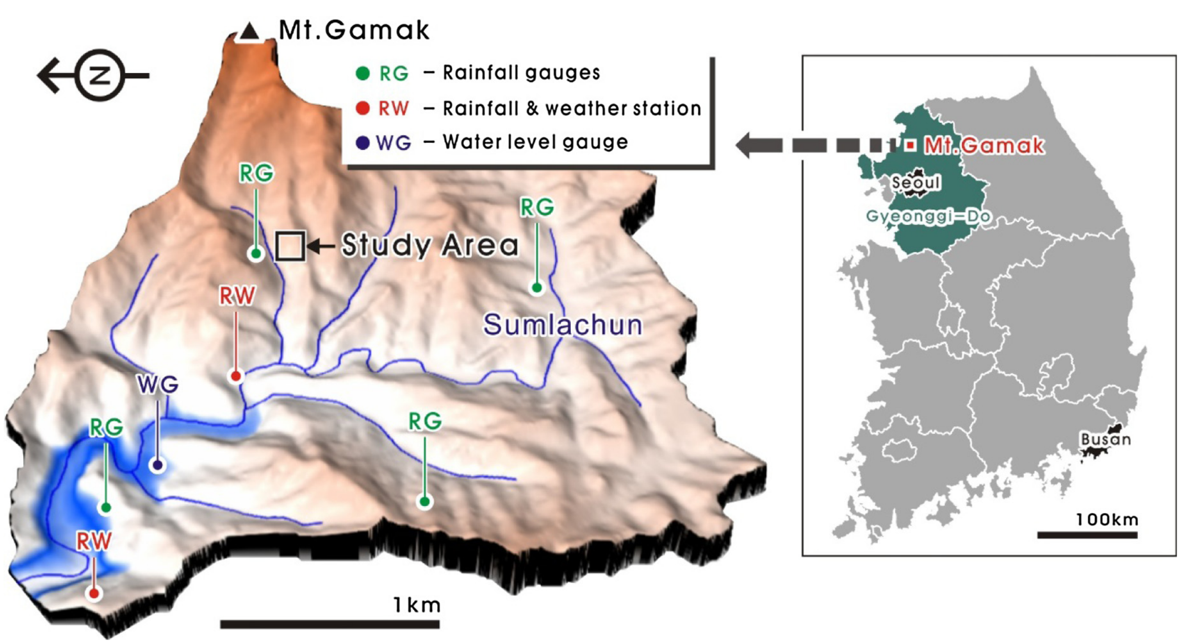

Fig. 1. The Sulmachun catchment and the study area.