Journal of Hydrology 448–449 (2012) 100–111

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Characterization of annual soil moisture response pattern on a hillslope in Bongsunsa Watershed, South Korea

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ARTICLE INFO

Article history:
Received 31 August 2011
Received in revised form 12 April 2012
Accepted 17 April 2012
Available online 4 May 2012
This manuscript was handled by Philippe Baveye, Editor-in-Chief, with the assistance of Nunzio Romano, Associate Editor

Keywords:
Soil moisture
Variability
Hillslope hydrology
Terrain analysis

SUMMARY

Annual time series for spatially distributed soil moisture measurements are useful for identifying water distribution control factors on a hillslope scale. In this intensive 1-year field study of soil moisture on a permanent channel initiation point hillslope, high resolution digital elevation models (DEMs) of surface and bedrock, were used to analyze time series of soil moisture spatial distributions for 19 terrain indices. In linear correlations, observed soil moisture patterns were best explained by local slope and distance to channel. In nonparametric analyses, contributing area and topographic wetness index provided significant correlations to soil moisture. Terrain based modeling hypotheses were tested on time scales between 2 h and 32 days. Soil moisture time series response patterns were classified into distinct patterns based on genetic calibration of recession models and hydrologic implications. Relatively high predictability of soil moisture via topographic characteristics is attributed to high-resolution soil moisture and terrain data.

1. Introduction

Spatial and temporal variations in soil moisture are key characteristics for understanding hydrological processes on a hillslope scale, because soil moisture is significantly associated with infiltration, evapotranspiration, and vegetation dynamics (Albertson and Montaldo, 2003; Brolsma and Bierkens, 2007; Clark and Gedney, 2008; Rodriguez-Iturbe and Porporato, 2004; Teuling et al., 2006; Tromp-van Meerveld and McDonnell, 2006; Wilson et al., 2005). The addition of soil moisture measurements can improve the accuracy of estimated model parameters (Huang et al., 2008; Usuga Loaiza and Pauwels, 2008), rainfall runoff response predictions for a representative elementary watershed (Lee et al., 2007; Reggiani et al., 1999), as well as flood formation process predictions (Borga et al., 2007). The subsurface storm flow, an important component in the generation of hillslope runoff, is also significantly affected by both temporal and spatial soil moisture distributions (Freer et al., 2002; Montgomery and Dietrich, 2002).

Soil moisture can be determined using an eco-hydrologic controller, such as vegetation impact, as well as by hydro-meteorological, topographic, and geologic drivers. On a hillslope, the redistribution of soil moisture will depend on a number of conditions, such as topography, relative wetness, and vegetation cover (Canton et al., 2004; Teuling and Troch, 2005; Wilson et al., 2005). The impact of topography on soil water content is more pronounced in humid and temperate climates (Anderson and Kneale, 1980; Wilson et al., 2005).

In order to predict variations in soil moisture, relationships between the spatial distributions of soil moisture and terrain indices has been explored using a number of different approaches (Baggaley et al., 2009; Blyth et al., 2004; Penna et al., 2009; Tenenbaum et al., 2006; Western et al., 1999; Wilson et al., 2005). The wetness index (Beven and Kirkby, 1979), as a terrain factor, is the most commonly used method. Impacts of terrain attributes on other environmental variables, such as soil properties (Leij et al., 2004; Seibert et al., 2007) or vegetation (Kakembo et al., 2007), have also been explored. The field of hydrological digital terrain analysis has been complicated by the difficulty in obtaining an accurate estimation of an upslope contributing area (O'Loughlin, 1986; Quinn et al., 1991; Tarborton, 1997; Kim and Lee, 2004; Erskine et al., 2006; Seibert and McGlynn, 2007).

Increasing numbers of field observations of soil moisture are being reported from many research activities (Brocca et al., 2007; Canton et al., 2004; Famiglietti et al., 2008; Kim, 2009b; Zehe et al., 2010). Point scale soil moisture measurement methods, such as time domain reflectometry (TDR), have allowed the spatial scale (<100 m) of the point measurement range to be extended (Robinson et al., 2003, Vereecken et al., 2008). In addition, the incorporation of wireless sensor networks and frequency domain reflectometry (FDR) increase measurement potential for larger spatial scales (Bogena et al., 2010). Remote sensing methods still need improvements in

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http://dx.doi.org/10.1016/j.jhydrol.2012.04.030

their accuracy for small scale analysis and depth of penetration depth for deep soil layers. Scale issues relating to soil measurement and models have been reviewed by Vereecken et al. (2008) and Western et al. (2002).

Studies of spatial predictions of soil moisture have provided comparisons between topsoil point-scale measurements and terrain representations at various DEM resolutions (0.5 m–50 m) that were created from light detection and ranging (LIDAR) data (Baggaley et al., 2009; Blyth et al., 2004; Erskine et al., 2006; Sorensen and Seibert, 2007; Tenenbaum et al., 2006). The impact of topographic attributes on variations in soil moisture is not fully evaluated due to the inconsistent resolution of factors, such as terrain data, heterogeneity of soil texture, and vegetation on a watershed scale. Differences in spatial resolution of point measurements and model, as well as temporally uneven soil moisture measurements, will also affect the evaluation (Wilson et al., 2005).

In this study, spatial patterns of soil moisture time series were measured on a hillslope. The selection of the study area took into account the presence of a permanent channel initiation inside the hillslope. A constant water table at the downslope boundary may indicate that the study area has various hillslope processes from hilltop to channel. Soil moisture was monitored between September 2005 and September 2006. Based on soil moisture time series data and digital terrain measurements obtained from manual surveying, the following issues relating to soil moisture distributions are addressed: (1) determination of the dominant terrain attribute and how its linear and nonparametric correlations with soil moisture patterns can vary during the study period to explain soil moisture on a hillslope with a permanent channel initiation point; (2) evaluation for one of basic Topmodel hypotheses (Beven and Kirkby, 1979) over a wide range of time scales; and (3) characterization of temporal features of soil moisture responses in terms of mathematical modeling, evolutionary computation, and using control factors with hydrologic implications during the recession period.

2. Methodology

2.1. Study area

The study area is located in Gwangneung Forest in Pochun-si, Gyeonggi-do, Korea. The Gwangneung forest is part of the Bongsunsa Watershed (Fig. 1), in the Han River Basin located in the northwestern part of South Korea (37°45′25.37″N and 127°9′11.62″E). Average annual precipitation is 1400 mm, with more than 65% of annual rainfall occurring between June and August. The annual mean temperature is 11.5 °C. A long-term soil moisture monitoring system was installed on a hillslope, taking into consideration operational limitations of the wired TDR system in terms of spatial scale (<100 m). The hillslope area (Fig. 1) is approximately 2100 m^2. Soil texture of 20 samples was mainly composed of a sandy loam and loam with a mixture of sand (65–43%), silt (29–46%) and clay (6–11%). The soil texture distribution was horizontally uniform, based on particle analysis of 20 samples using the soil texture triangle (Davis and Bennett, 1927). The Bongsunsa Watershed is underlain by weathered gneiss and schist, with an eastern aspect. Average soil porosity at a 10 cm depth was about 50% with porosity decreasing with soil depth. Soil depth ranged between 50 and 100 cm. Average slope of the monitored hillside was 19°. The study area is primarily covered by a mixture of *Carpinus sp.* and shrubby *Quercus sp.* The fluxes of H_2O and CO_2 have been measured since 2005 (Hong et al., 2008). No notable pattern in the spatial distribution of the vegetation communities was observed. Visual inspection also indicates an abundance of macropores in the topsoil that decreased with soil depth.

2.2. Soil moisture monitoring system

Understanding the distribution of saturation tendency along a hillslope transect can be useful for determining an appropriate sensor position with the limited capacity of a point scaled monitoring device. Measurement points were located along several designated transects, Fig. 1, based on the spatial distribution of the upslope area, soil depth, valid detection range for the waveguide, and the location of the MiniTRASE system with four multiplexer control boards (Model 6022 and 6020B05). At each sensor point, three coated buriable waveguides (6005CL, length of 20 cm) were inserted parallel to the upslope direction at depths of 10, 30, and 60 cm, without disturbing the soil structure. Location and insertion depth of the sensor were adjusted along the corresponding transect when the designated location was sufficiently close to a large canopy or bedrock depth was less than 60 cm. Cable length ranged between 10 m and 40 m. Bulk densities of 21 soil samples ranged from 1 to 1.5 g/m^3, which indicates calibration is not required (Tomer et al., 1999; Quinones et al., 2003). Soil moisture time

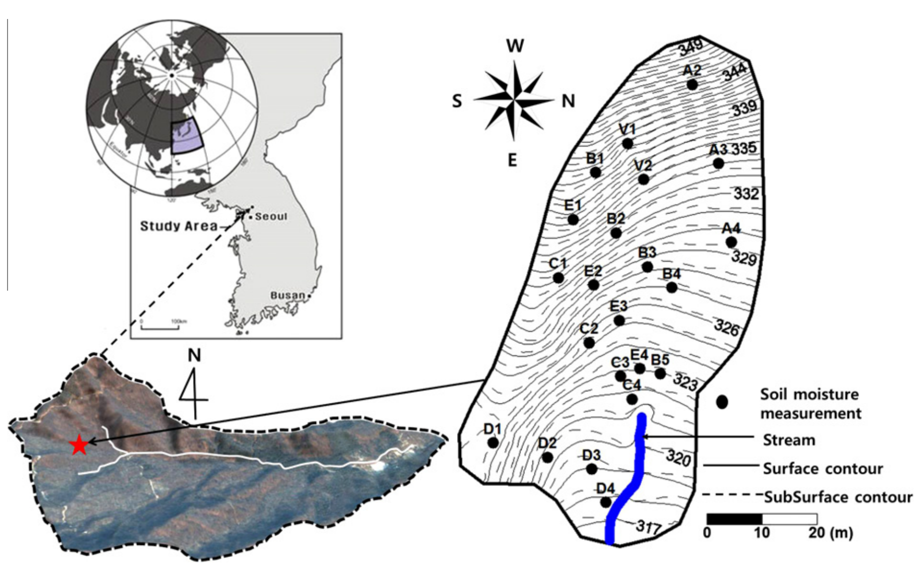

Fig. 1. Location of the study area in Bungsunsa catchment; Surface and bedrock topographies and monitoring locations are indicated as dark black circles.