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Temporal stability and variability of field scale soil moisture on mountainous hillslopes in Northeast Asia

Chanyang Sur, Yong Jung, Minha Choi *

Water Resources and Remote Sensing Laboratory, Department of Civil and Environmental Engineering, College of Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea

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A B S T R A C T

Soil moisture is a crucial component in the hydrologic cycle. The analysis of soil moisture variability is challenging because soil moisture is dependent on physical factors such as: antecedent precipitation, soil texture, land cover, and topography. This study investigated soil moisture variability, validated the utility of temporal stability analysis for measuring areal mean soil moisture, and identified factors that were strongly related to temporal stability characteristics at small mountainous sites in Northeast Asia. Soil moisture contents were measured at different depths using time domain reflectometers at two fields in the center of Korea. Time series analyses showed that slope played a substantial role on soil moisture distribution. The Chi-square test identified Gumbel distribution as an optimal soil moisture distribution. The mean and the standard deviation of soil moisture showed an upper convex shape and the variability of soil moisture was highest at moderate mean soil moisture conditions (~15–20%) at 10, 30, and 60 cm in the study sites. Temporal stability analysis revealed the representativeness of the average volumetric soil moisture contents with errors of ±4.91% and ±2.35% for the fields of Sulma and Chongmi river basins, respectively. Analysis of variance and Tukey's honestly significant difference tests showed that the slope and soil texture, particularly clay, had an impact on the temporal stability characteristics of soil moisture for the study sites, the land cover had no significant impact. Temporally stable locations for soil moisture were determined with the milder slope and higher clay contents at the study sites.

1. Introduction

Soil moisture is an important variable to control the exchange of the water and energy between the land surface and the atmosphere. It is a substantial hydrologic component and its accurate estimation is essential to predict energy and hydrological processes at various spatial scales. For example, antecedent soil moisture conditions are the most critical hydrologic variables to predict flood events (Merz and Blöschl, 2009; Norbiato et al., 2008). Aside from flood predictions, the soil moisture information cannot be ignored in many hydrologic applications such as the estimation of infiltration, surface storage, and evapotranspiration (Brocca et al., 2009; Choi and Jacobs, 2007; Jacobs et al., 2003; Javelle et al., 2010).

There are several ways to measure soil moisture contents from field to global scales using various types of measurement systems. For the field measurements, scoop tool for gravimetric sampling, cosmic ray neutrons, time domain reflectometry, and impedance probes are widely used (Grayson and Western, 1998; Zreda et al., 2008). In recent, remote sensing instruments including passive and active microwave systems on aircraft or satellite have been utilized for large area measurements (Jackson et al., 1995, 1999, 2010; Pietroniro and Prowse, 2002). However, remote sensing data tend to have a major difficulty in understanding hydrology due to coarse spatial scales.

To overcome this major limitations of the remote sensing data, spatio-temporal variability of in-situ soil moisture within the remote sensing footprints has been routinely conducted (Choi and Jacobs, 2007; Cosh et al., 2005; Jacobs et al., 2004, 2010; Mohanty and Skaggs, 2001). The variability information of in-situ soil moisture can be used to validate and downscale the remote sensing products. The variability of soil moisture is dependent on several physical factors such as antecedent precipitation, land surface slope, soil texture, and soil cover (Mohanty and Skaggs, 2001). Each factor has different influences on soil moisture contents. For instance, precipitation directly affects total amount of soil moisture. Land surface slope and soil texture influences rainfall-runoff with various infiltration rates, water holding capacities, and redistribution behavior depending on porosity distribution.

* Corresponding author at: Department of Civil and Environmental Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea. Tel.: +82 2 22200324; fax: +82 2 22204322.
E-mail address: mchoi@hanyang.ac.kr (M. Choi).

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The relationships between mean soil moisture and variability have been intensively studied to identify reasonable statistical distributions, determine optimal locations of the measurements (i.e., minimize the number of sampling sites), and calibrate soil moisture dynamics models. Reasonable statistical soil moisture distributions were sought by the several methods such as Chi-square test and Probability Plot Correlation Coefficient (PPCC) test. Brocca et al. (2007) have applied the Chi-square test for evaluating of soil moisture distributions in hilly and rolling sites, concluding that the region followed a normal distribution pattern. The PPCC test was also employed by Choi and Jacobs (2007) and Jacobs et al. (2010) and the normal and log-normal distributions were identified as reasonable statistical distributions.

The mean soil moisture using the minimal measurements has been estimated by Vachaud et al.'s (1985) temporal stability concept, which was, the spatial patterns of soil moisture preserved with temporal variables. The mean soil moisture value of a given site might be represented efficiently with minimum number of ground-based soil moisture measurements (Cosh et al., 2005; Grayson and Western, 1998; Jacobs et al., 2004; Mohanty and Skaggs, 2001). Thus, the sampling regime of a few ground-based soil moisture measurements is necessary to characterize a given site.

Several previous studies have estimated the temporal stable characteristics associated with physical factors of various regions (Brocca et al., 2007, 2010; Choi and Jacobs, 2011; Jacobs et al., 2010; Mohanty and Skaggs, 2001). They all demonstrated that several few temporally stable locations captured the mean soil moisture contents with reasonable error ranges within the remote sensing footprints. However, these temporal stability characteristics were varied by different physical factors.

In this study, we identified the best temporally stable soil moisture sampling points to represent the areal mean for mountainous terrain because few previous studies have been conducted on this land cover type in East Asia. The temporal stability of the soil moisture was further analyzed with physical variables such as soil texture, land cover, and land slope to identify which physical variables were critical.

2. Material and methods

2.1. Study area and datasets

Sulma and Chongmi river basins are located near the center of Korean Peninsula. The sizes of Sulma and Chongmi regions are 8.5 km^2 and 569 km^2, respectively (Fig. 1). The Sulma River basin has a 5.8 km long meandering river and is located in the mountainous terrain with an average slope of 40% (Kim et al., 2007). The Sulma River basin has six rain gauges, two water level measurement locations, and one weather station. These locations record information on precipitation, water flow amount, water quality, and weather records every 10 min. The major soil texture in the Sulma region is a gneiss complex with well-developed fault planes and foliated structures. Land cover is forested with over 90% of the area consisting of 20 to 30 year old needle- and broad-leaf trees. *Quercus variabilis* (i.e., Cork Oak), *Quercus mongolica*, and *Quercus serrata* (i.e., Konara Oak) are the dominant species on the West side of the watershed. The East side of the watershed has *Pinus koraiensis* as a major species (Korea Institute of Construction Technology, 2006; Kwon et al., 2009). The Chongmi River basin is a larger watershed. This river basin contains a 60.8 km river and is also located in a mountainous region with a variety of slopes ranging from 0% to 30%. The region consists mostly of farming fields, however, the study area is near to mountainous zone with mixed forest. The length of the river basin perimeter is 185 km, the average width of the river is 9.53 m, and the highest elevation is 676 m. This part of the study area is located in the International Hydrological Programme (IHP) supported by United Nations Educational, Scientific and Cultural Organization (UNESCO) (Yi et al., 2010). Three water level locations are currently operating and five rain gauges are actively running. The major soil texture of this region is sandy loam and the surface soil depth ranges from 30 to 100 cm. Land cover is shrub, and weeds are widely spread. From a geological perspective, these locations have plenty of small stratifications, particularly the Sulma River region. We studied one section of the Sulma and Chongmi river basin watersheds as shown in Fig. 1 (~670 m^2 and ~880 m^2 for the Sulma and Chongmi river basins, respectively). The characteristics of the test sites in Sulma catchment, which is small-scale, and Chongmi, which is meso-scale, had the same characteristics with whole catchment (Kim et al., 2007). Table 1 summarizes the details of the Sulma and Chongmi river basins.

Soil moisture data from time domain reflectometer (TDR) sensors were measured from March 7 to December 11, 2008 (197 days) and from June 11 to December 5, 2008 (176 days). These soil moisture contents were measured at two-hour intervals for the Sulma and Chongmi river basins, respectively.

The TDR sensors were installed vertically into the soil layer without disturbing soil structures. These measurements were then converted to daily soil moisture contents. Horizontal measurements were conducted at 19 and 18 locations with 11,229 and 9504 total samples for the Sulma and Chongmi river basins, respectively (Fig. 1). The TDR works well in the field because of high measurement accuracy for soil moisture

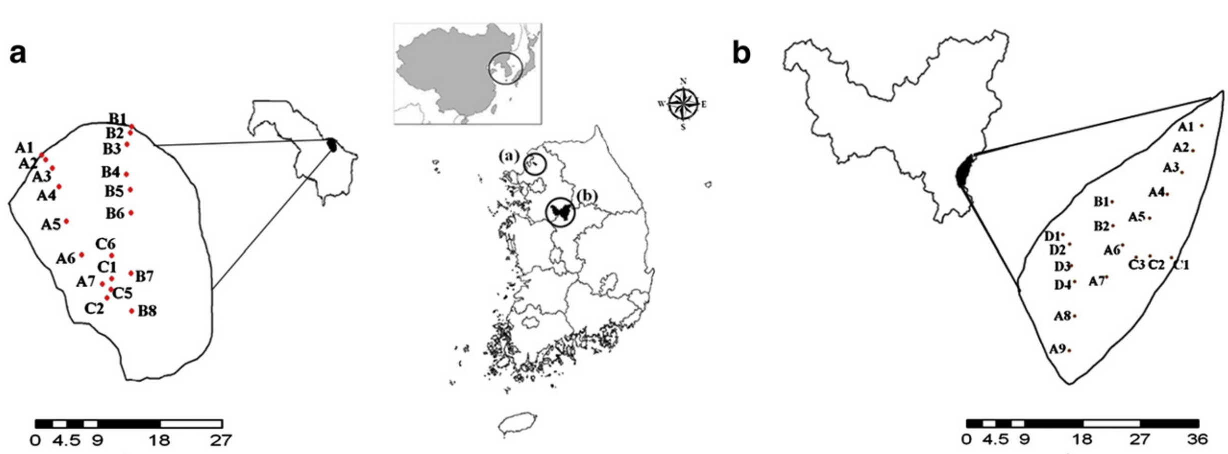

Fig. 1. Study fields indicated as filled circles within a) Sulma River basin (observation locations: A1–A7, B1–B8, C1–C2, and C5–C6) and b) Chongmi River basin (observation locations: A1–A9, B1–B2, C1–C3, and D1–D4).