Geoderma 170 (2012) 195–205

Contents lists available at SciVerse ScienceDirect

Geoderma

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

Field scale spatiotemporal analysis of surface soil moisture for evaluating point-scale in situ networks

Gary C. Heathman [a,*], Michael H. Cosh [b], Eunjin Han [c], Thomas J. Jackson [b], Lynn McKee [b], Scott McAfee [a]

[a] National Soil Erosion Research Laboratory, USDA-ARS, West Lafayette, IN 47907, USA
[b] Hydrology and Remote Sensing Laboratory, USDA-ARS, Beltsville, MD 20705, USA
[c] Graduate Student, Purdue University, Civil Engineering Department, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 17 March 2011
Received in revised form 25 October 2011
Accepted 9 November 2011
Available online 24 December 2011

Keywords:
Soil moisture
Field scale
Point-scale
Temporal stability
In situ

ABSTRACT

Soil moisture is an intrinsic state variable that varies considerably in space and time. From a hydrologic viewpoint, soil moisture controls runoff, infiltration, storage and drainage. Soil moisture determines the partitioning of the incoming radiation between latent and sensible heat fluxes. Although soil moisture may be highly variable in space and time, if measurements of soil moisture at the field or small watershed scale are repeatedly observed, certain locations can often be identified as being temporally stable and representative of the an area average. This study is aimed at determining the adequacy of long term point-scale surface soil moisture measurements in representing local field scale averages which may ultimately serve as in situ locations for the calibration and validation of remotely sensed soil moisture. Experimental data were obtained by frequency-domain reflectometry (FDR) sensors permanently installed in two agricultural fields, AS1 and AS2 (2.23 and 2.71 ha, respectively) at a depth of 5 cm. Twenty additional FDR sensors, spaced 35 m apart, were installed horizontally at a depth of 5 cm in each field with automated data collection being transmitted every 30 min from July 15 through September 20, 2009. Additionally, meteorological data were obtained from existing weather stations in each field. The FDR sensors revealed persistent patterns in surface soil moisture within each field and identified sites that were temporally stable. The locations that were optimal for estimating the area-average field water contents were different from the permanent sensor locations in both fields. Permanent sensor data showed approximately 4 and 10% mean relative differences for fields AS1 and AS2, respectively, with relatively large standard deviations. Thus, minimum offset values could be applied to the temporally stable field sites to obtain representative field average values of surface soil moisture. However, use of permanent sensor data for offset estimates gave poor results. These findings are of relevance for applications of geospatial surface soil moisture data assimilation in hydrologic modeling when only point-scale observations are available, as well as, remotely sensed surface soil moisture calibration and validation studies.

Published by Elsevier B.V.

1. Introduction

Soil moisture comprises only 0.15% of the liquid freshwater on Earth, but it is a major component of soil hydrology, meteorology, and agriculture (Western et al., 2002). From a hydrologic viewpoint, soil moisture is the main source of memory that controls runoff, infiltration, storage and drainage. In meteorology, soil moisture determines the partitioning of the incoming radiation between latent and sensible heat flux and plays a crucial role in the land surface and atmospheric feedback system. From an agricultural aspect, soil moisture controls irrigation scheduling and yield forecasting. Implicit in the above mentioned is recognition that the land surface and atmosphere, as well as ground water storage, are inextricably linked to the soil water content; therefore, detailed information of the soil water content and its spatio-temporal dynamics are necessary for sustained agricultural production, soil resource conservation, as well as efficient management of water resources in streams and reservoirs (Starks et al., 2003; Starks et al., 2006).

At present, point scale ground-based measurements of soil moisture are typically obtained using periodic gravimetric sampling, neutron attenuation, time-domain reflectometry (TDR), or frequency-domain reflectometry (FDR). Typically, the large spatial and temporal variability of soil moisture is not well represented with these methods. At large scales however, remote sensing techniques have demonstrated that spatial and temporal characterizations of surface soil moisture fields can be estimated to augment sparsely distributed point measurements from in situ networks (Njoku et al., 2002). Several in situ studies have been designed to determine the footprint scale mean values to validate remotely sensed soil moisture products (Cosh et al., 2004, 2006; Njoku et al., 2002). The validation has not

* Corresponding author. Tel.: +1 765 494 8683; fax: +1 764 494 5984.
E-mail address: gary.heathman@ars.usda.gov (G.C. Heathman).

0016-7061/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.geoderma.2011.11.004

been without errors due to limited sample size and the mismatch between field studies and the sensor footprint which may limit practical application of remotely sensed soil moisture products. The need for better estimates of surface, as well as profile soil moisture, has heightened interest in a combination of techniques that evaluate the spatial and temporal characteristics of surface soil moisture.

Although surface soil moisture is highly variable, if measurements of soil moisture at the field or small watershed scale are repeatedly observed, certain locations can often be identified as being temporally stable and representative of the an area average (Vachaud et al., 1985) . Temporal stability has also been termed as rank stability, temporal persistence, or time-stable in describing the persistence of spatial patterns and characteristic behavior of soil moisture (Mohanty and Skaggs, 2001; Pachepsky et al., 2005). In this paper we will consistently use the term temporal stability as it pertains to the time invariant association between spatial location and the classical statistical parametric values. Temporal stability can therefore be considered as the persistence of the spatial pattern of soil moisture in an area over time.

Several studies have examined the spatial and temporal stability of soil moisture in the surface layer (0–5 cm) with the purpose of estimating large scale average soil moisture (Cosh et al., 2004, 2006; Jacobs et al., 2004). Among them, the Southern Great Plains 1997 (SGP97) remote sensing experiment was conducted to quantify the spatial variability of soil moisture within selected agricultural fields with spatial dimensions matching the Electronically Scanned Thinned Array Radiometer (ESTAR) L-band passive microwave footprint (Jackson et al., 1999). During the Soil Moisture Experiment 2002 (SMEX02), Cosh et al. (2004) investigated the watershed scale temporal and spatial stability of soil moisture in the Walnut Creek Watershed, Iowa. Their results demonstrated that the soil moisture pattern exhibited both temporal and spatial stability for uniform precipitation events and concluded that representative measurement sites could be used to estimate the watershed scale (~25 km) soil moisture average for long time periods similar to the conditions of the study period. Cosh et al. (2006) reported the results of the Soil Moisture Experiment 2003 (SMEX03) across the Little Washita River Experimental Watershed (LWREW) which was carried out to validate the near-surface soil water content derived from the Advanced Microwave Scanning Radiometer (AMSR-E). Their analysis showed that several of the ground-based network sensors were temporally stable at multiple scales and four sites were identified as representative of the watershed mean.

More recently, Brocca et al. (2010) reported on the spatial–temporal variability of soil moisture and its estimation across scales from field to catchment scale in central Italy. Their primary objective was to determine the optimal soil moisture monitoring design for validation of remotely sensed surface soil moisture and applications in rainfall-runoff modeling. They found that soil moisture temporal variability was more significant than spatial variability in regards to soil moisture monitoring applications based on 35 sampling days and 30 measurements per day within one year. In other words, they surmise that a network of a few soil moisture sensors with fine temporal resolution (e.g., hourly) may be the best option to estimate soil moisture temporal pattern over large areas. Miralles et al. (2010) conducted a study to determine the spatial sampling errors in coarse-scale soil moisture estimates derived from point-scale observations. Their findings revealed that by applying the triple collocation (TC) approach to footprint-scale soil moisture products that estimates of point-to-footprint soil moisture sampling errors could be obtained to within 0.0059 $m^3 m^{-3}$ and enhance the ability to validate satellite soil moisture products using low-density ground networks. A study by Choi and Jacobs (2011) on spatial soil moisture scaling structure during a large scale remote sensing campaign was aimed at providing insights as to what soil moisture characteristics are relevant at both field and watershed scales in terms of temporal stability. They found that based on the role of soil type, topography and vegetation, that soil properties and topography were identified as the most important physical drivers across scales.

The studies mentioned thus far pertain to a range of scales and different observational areas. The assumption is made in most instances that temporal stability analyses for a number of point-scale measurements across multiple scales should reveal locations that are most representative of the overall area-average conditions. Although this may be considered a valid approach at the watershed scale, it does not necessarily provide sufficient information or insight to link point-scale soil moisture measurements to coarser resolution remotely sensed observations. The objective of this study was to determine the adequacy of long term point-scale surface soil moisture measurements in representing local field scale averages in two agricultural fields (2.23 and 2.71 ha) and thus, to better understand and quantify the surface soil moisture spatio-temporal dynamics within each field. This in turn, should improve our efforts to link or upscale point measurements of soil moisture to field scale moisture dynamics on the order of 1–3 ha in size which may provide greater confidence in calibrating and validating remotely sensed observations due to the enhanced area of measurement that is represented in situ.

2. Materials and methods

2.1. Study area, field sites and soil moisture measurements

The environmental monitoring network shown in Fig. 1 is located in the 19,200 ha Upper Cedar Creek Watershed (UCCW) of northeastern Indiana (41° 27′ 38.11777″ N by 84° 58′ 30.09636″ W) which is maintained by United States Department of Agriculture, Agricultural Research Service (USDA-ARS). The watershed scale monitoring network is part of the USDA's nationwide Conservation Effects Assessment Project (CEAP). The predominant land use in the UCCW is agricultural (79%), with major crops of corn and soybeans, and minor crops of winter wheat, oats, alfalfa, and pasture. The area receives approximately 94 cm of annual precipitation and has average daily temperatures ranging from −1 °C to 28 °C. The two field sites used in this study (AS1 and AS2) are part of the network and serve as areas to compare the effects of no-till and rotational tillage practices on runoff, sediment, nutrient and pesticide losses. Both fields are in a corn/soybean rotation with the AS1 field being no-till (NT) and AS2 having rotational tillage (RT) each spring in years when corn is planted. In 2009 both fields were planted in soybeans on April 24.

The majority of soils in the watershed were formed from glacial deposits with slopes ranging from 2 to 10%. The predominant soils within the field sites have been classified as a Glynwood (GnB2) silt loam (Fine, illitic, mesic Aquic Hapludalfs) in the 2.23 ha AS1 field and as a Blount (BaB2) silt loam (Fine, illitic, mesic, Aeric Epiaqualfs) in the 2.71 ha AS2 field (Fig. 2). Both fields have a moderate and uniform slope of approximately 3%. A list of soil properties with depth for each field is given in Table 1 based on soil samples collected from each field.

All in-situ measurements of soil moisture obtained in this work are based on the method of measuring the dielectric permittivity of soil to determine volumetric soil water content (θ_v) using the Hydra Probe II (HP-II) sensor (Topp and Davis, 1985; Topp and Ferre, 2000; Topp et al., 1980). As stated in the manufacture's soil sensor manual (Stevens Water Monitoring Systems, Inc., Portland, Oregon, USA), “the Steven's HP-II sensor is a Frequency Domain Reflectometer (FDR) that measures the behavior of a standing wave generated from the reflection of an electromagnetic wave at a radio frequency of 50 MHz. The HP-II sensor consists of a 4-cm diameter cylindrical head which has four, 0.3-cm diameter tines that protrude 5.8 cm. These are arranged such that a centrally located tine is surrounded by the other three tines in an equilateral triangle with 2.2-cm sides. A 50 MHz signal is generated in the head and transmitted via planar