Journal of Hydrology 516 (2014) 21–36

Contents lists available at ScienceDirect

Journal of Hydrology

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

Scaling of surface soil moisture over heterogeneous fields subjected to a single rainfall event

Richa Ojha [a,*], R. Morbidelli [b], C. Saltalippi [b], A. Flammini [b], Rao S. Govindaraju [a]

[a] School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA

[b] Department of Civil and Environmental Engineering, Perugia University, Via Duranti 93, 06125 Perugia, Italy

ARTICLE INFO

Article history:
Available online 3 February 2014

Keywords:
Soil moisture
Scaling curves
Infiltration
Sharp-front models
Field-scale

SUMMARY

Determining surface soil moisture evolution over a range of scales remains a challenge because of multi-scale heterogeneity exhibited by soils. Measurement techniques are not in accordance with the scales at which information on soil moisture is needed. In situ point measurements are expensive and provide information only at a few select points. On the other hand, the spatial resolution of remote sensing data is too coarse for hydrologic applications. Currently, surface soil moisture evolution for heterogeneous fields subjected to rainfall conditions is achieved by a computationally intensive numerical solution of the Richards equation. To describe surface soil moisture evolution at local- and field-scale in an efficient manner, reference scaling curves are developed in this study based on a sharp front approximation and by adopting a log-normally distributed spatial hydraulic conductivity field. These scaling curves facilitate the determination of temporal evolution of surface soil moisture at any unmeasured location in the field, and can be used to obtain the field-scale surface soil moisture evolution for a single rainfall event. The scaling curves are computationally straight forward, and reduce the need for extensive soil moisture measurements at numerous locations in the field. Comparisons with experimental and numerical simulation results show that the proposed scaling curves hold promise for describing mean surface soil moisture evolution at the field-scale.

1. Introduction

Surface soil moisture is a key variable for understanding various hydrological processes, as it strongly influences the streamflow response to rainfall at the watershed scale. It also plays an important role in weather and climate prediction studies because of its control on processes that lead to flooding and soil-atmosphere interaction (Vereecken et al., 2008). Accurate prediction of the spatial and temporal variation of surface soil moisture at large scales is necessary to improve hydrologic and climatic modeling (Brocca et al., 2010).

The spatial and temporal variability of soil moisture poses numerous challenges to its characterization at various scales. Broadly, remote sensing and ground based measurements are used to quantify the spatial and temporal variation of surface soil moisture. Ground based measurements rely on using time domain reflectometry (Robinson et al., 2003), capacitance probes (Bogena et al., 2007), neutron probes, and gravimetric methods. These methods provide precise information on soil moisture if accurate calibration of the measuring instrument is available (Western et al., 2002). However, these measurements are expensive, time consuming, and provide information at a few select points. Moreover, interpreting the spatial and temporal patterns of soil moisture at different scales from few measurements at large separation times and distances is a very challenging task (Grayson and Western, 1998).

Remote sensing techniques provide surface soil moisture estimates, over large areas using sensors operating in microwave bands that are not influenced by solar radiation and cloud cover. Remote sensing methods include passive microwave radiometers (Crosson et al., 2005), synthetic aperture radars (Western et al., 2004), scatterometers (Blumberg et al., 2006), and thermal methods (Sugiura et al., 2007). Synthetic aperture radars are touted as one of the best options to obtain soil moisture data at high resolutions (<20 m) for bare soil surfaces (Baghdadi et al., 2008). However, signals from these radars are strongly influenced by terrain and topographical features, and are difficult to interpret. Therefore, coarse resolution scatterometers and microwave radiometers are used to obtain soil moisture data and are of less use to hydrologic studies (Wagner et al., 2007).

Limitations associated with ground based measurements and remote sensing techniques make it difficult to obtain accurate assessment of spatial and temporal variation of soil moisture at

* Corresponding author. Tel.: +1 765 494 2256.
E-mail address: rojha@purdue.edu (R. Ojha).

http://dx.doi.org/10.1016/j.jhydrol.2014.01.057
0022-1694/

resolutions of interest to hydrologic studies (Vereecken et al., 2008). Several authors have tried overcoming the limitations of ground-based measurements by trying to determine the optimal number of measurement points that yield best estimates of mean soil moisture profile for different scales (Bell et al., 1980; Famiglietti et al., 1999, 2008; Fernandez and Ceballos, 2005; Starks et al., 2006; Brocca et al., 2007, 2010; Choi and Jacobs, 2007; Morbidelli et al., 2012). Brocca et al. (2007) used a statistical approach to estimate the optimal number of required measurement locations as a function of field mean moisture content, for areas ranging from 400 to 10,000 m^2. Famiglietti et al. (2008) analyzed over 36,000 in situ soil moisture samples for Southern Great Plains, and concluded that optimal number of sampling locations for areas of 0.64 km^2 and 2500 km^2 are 18 and 30, respectively, to estimate mean soil moisture within 3% error. Temporal stability analysis, introduced by Vachaud et al. (1985), has also been used to optimize sampling locations (Gomez-Plaza et al., 2000; Tallon and Si, 2003; Starks et al., 2006; Brocca et al., 2009). Starks et al. (2006) performed temporal stability analysis across a 610 km^2 watershed in Oklahoma. They identified two temporally stable measurement locations out of eight to be representative of the mean field moisture. Brocca et al. (2009) identified the location at which soil moisture measurements accurately represented field-mean soil moisture by using temporal stability analyses. Although these studies have been able to identify the optimal number of sampling locations, a major drawback is that the results are site specific. It is not possible to perform direct comparisons among the results because of differences between experimental areas, sampling schemes, and study periods (Brocca et al., 2009, 2010).

Upscaling techniques could use just a few measurements to make field-scale inferences, thus eliminating the need for intensive measurements in the field. While scaling in the unsaturated zone mostly refers to relating soil hydraulic properties to media properties, in case of surface soil moisture the focus has been on transferring information across scales. Aggregation involves integrating local-scale behavior to infer spatial and temporal distributions at larger scales (Western et al., 2002; Crow et al., 2012). Woods et al. (1995) used the representative elementary area (REA) concept based on self-similarity to understand how soil moisture scales over a catchment area. Blöschl et al. (1995) questioned the existence of a fixed REA suggested by Woods et al. (1995), and inferred that REA would vary between storms as it is strongly controlled by the correlation length scales of precipitation. Vandenbygaart and Protz (1999) used the REA concept to study soil morphology, and concluded that REA is site-specific, and needs to be determined for each study. A shortcoming of these studies has been the lack of general guidelines to identify REA. Further, the aggregated response at larger scales is assumed to be a linear integration which is seldom true in heterogeneous media (Hemakumara, 2007).

Many studies have used statistical and geo-spatial concepts to scale soil moisture with varied success (Hawley et al., 1983; Bárdossy and Lehmann, 1998; Western et al., 1998a,b; Anctil et al., 2002; Bi et al., 2009; Lakhankar et al., 2010). Standard geostatistical techniques such as regularization and variogram analysis are initially used to identify the spatial structure of soil moisture variation, and further interpolation techniques such as co-kringing and external drift kringing are used to obtain soil moisture estimates at larger scales. While geostatistical methods are very popular, they are suited for organized soil moisture data, i.e. large amounts of spatially distributed soil moisture data are needed (Bárdossy and Lehmann, 1998). A common assumption in geostatistical methods is that the variable is spatially correlated, not a necessary valid assumption for soil moisture (Grayson and Blöschl, 2000).

Hydrologic models, based on mass and energy balance, have also been used to address scaling issues related to soil moisture (Western et al., 2002). Among the available models, Variable Infiltration Capacity (VIC) and TOPMODEL have been used frequently (Wood et al., 1992; Kalma et al., 1995; Liang et al., 2003; Crow et al., 2005). However, it is well known that all hydrologic models are simplified representations of reality, mostly focus on key processes that dominate the response at scales of interest, and often ignore other processes or use simplified representations (Western et al., 2002; Crow et al., 2005). Despite the numerous approaches available for aggregation of surface soil moisture, major limitations exist in terms of data requirements; current existing studies are site specific and require fairly demanding calibration and validation exercises.

Scaling methods based on similar media concept have the potential to model the surface spatial and temporal variation of vadose zone processes while accounting for natural variability. The key to such methods lies in developing a reference solution that can be scaled for different soil properties by developing scale factors based on dimensional analysis (Zhang et al., 2004). This technique has been used to model spatial and temporal evolution of soil hydraulic properties, infiltration and drainage (Warrick et al., 1977; Shouse et al., 1992; Warrick and Hussen, 1993; Zhang et al., 2004). Subsequent efforts have been directed towards scaling approaches that are more macroscopic and empirical in nature based on the concept of functional normalization (Russo and Bresler, 1980; Sposito and Jury, 1985). Studies based on functional normalization approach derive scale factors through least-squares regression analysis, thus relating properties of two different physical systems in some empirical way (Kozak and Ahuja, 2005).

Developing a scale-invariant form of the Richards equation using Lie groups would greatly aid in describing flow under different initial and boundary conditions in a wide range of heterogeneous unsaturated soils (Sposito, 1990; Haltas and Kavvas, 2010; Sadeghi et al., 2012). Initial attempts towards scaling of Richards' equation were made by Reichardt et al. (1972) for horizontal infiltration of water into a uniform, initially air-dry homogeneous soil column. Similar media concept has been utilized to develop scale factors for time, pressure head, hydraulic conductivity and soil water diffusivity. Warrick and Amoozegar-Fard (1979) scaled the 1-D Richards equation using similar media concept for a constant head boundary condition. Kutilek et al. (1991) formulated an invariant form of the Richards equation for two specific classes of problems: vertical infiltration into a homogeneous soil for constant flux at the surface, and vertical infiltration into a soil with a thin seal layer and positive pressure head at the seal surface. Warrick and Hussen (1993) developed a scaled form of the Richards equation for constant initial and boundary conditions and for both head and flux specified boundary conditions. The scaled equation was invariant to hydraulic conductivity and air-entry pressure. Wu and Pan (1997) developed a scaled equation for three-dimensional axisymmetric Richards equation in a cylindrical coordinate system to describe infiltration process from a finite ponding source for a ring infiltrometer. Sadeghi et al. (2011) developed a scaled form of the Richards equation for soil water redistribution process by assuming similarity in soil–water content profile and water flux density curves.

The above-mentioned studies have used specific scaling factors and suggest transformations to obtain an invariant form of the Richards equation for specific initial and boundary conditions under the strong assumption that similarity conditions are preserved. These similarity conditions are defined based on microscopic scale geometry, shape of soil hydraulic functions or linear variability (Sadeghi et al., 2012). The natural heterogeneity exhibited by field soils does not conform to these assumptions. Further, when a field soil is subjected to rainfall or irrigation, the boundary