Journal of Hydrology 489 (2013) 148–159

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

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

The role of vegetation and soil properties on the spatio-temporal variability of the surface soil moisture in a maize-cropped field

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ARTICLE INFO

Article history:
Received 6 June 2012
Received in revised form 4 March 2013
Accepted 9 March 2013
Available online 19 March 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Soil moisture
Spatio-temporal variability
Controlling factors
Principal component analysis
Geostatistics
Agricultural field

SUMMARY

Soil moisture dynamics are affected by complex interactions among several factors. Understanding the relative importance of these factors is still an important challenge in the study of water fluxes and solute transport in unsaturated media. In this study, the spatio-temporal variability of surface soil moisture was investigated in a 10 ha flat cropped field located in northern Italy. Soil moisture was measured on a regular 50 × 50 m grid on seven dates during the growing season. For each measurement campaign, the spatial variability of the soil moisture was compared with the spatial variability of the soil texture and crop properties. In particular, to better understand the role of the vegetation, the spatio-temporal variability of two different parameters – leaf area index and crop height – was monitored on eight dates at different crop development stages. Statistical and geostatistical analysis was then applied to explore the interactions between these variables. In agreement with other studies, the results show that the soil moisture variability changes according to the average value within the field, with the standard deviation reaching a maximum value under intermediate mean soil moisture conditions and the coefficient of variation decreasing exponentially with increasing mean soil moisture. The controls of soil moisture variability change according to the average soil moisture within the field. Under wet conditions, the spatial distribution of the soil moisture reflects the variability of the soil texture. Under dry conditions, the spatial distribution of the soil moisture is affected mostly by the spatial variability of the vegetation. The interaction between these two factors is more important under intermediate soil moisture conditions. These results confirm the importance of considering the average soil moisture conditions within a field when investigating the controls affecting the spatial variability of soil moisture. This study highlights the importance of considering the spatio-temporal variability of the vegetation in investigating soil moisture dynamics, especially under intermediate and dry soil moisture conditions. The results of this study have important implications in different hydrological applications, such as for sampling design, ranking stability application, indirect measurements of soil properties and model parameterisation.

1. Introduction

Soil moisture is a key variable controlling hydrological and energy fluxes at different spatio-temporal scales. It influences the partitioning of rainfall into infiltration and runoff as well as the partitioning of net radiation into sensible heat and latent heat fluxes. Soil moisture controls the subsurface water drainage and thereby the leaching of chemicals to the groundwater. Because of the heterogeneity of soils, atmospheric forcing, vegetation and topography, soil moisture is extremely variable over time and space and the characterisation of this variability is still one of the major challenges within the hydrological sciences (Vereecken et al., 2007).

During the last few decades, an increasing number of studies have focussed on the estimation of the soil moisture using different approaches, considering explicitly the spatio-temporal variations of soil moisture (Robinson et al., 2008; Vereecken et al., 2008). These studies have covered plot, field and small catchment scales using point measurements (Western et al., 2002; Zehe et al., 2010), or larger scales (large catchments and whole planet) using remote sensing observations (see, for instance, SMOS mission in Kerr et al., 2001; SMAP mission in Entekhabi et al., 2010; gravity change detection GRACE in Tapley et al., 2004). Recent promising methodologies have also aimed at detecting soil moisture at an intermediate scale (Zreda et al., 2008; Rivera Villarreyes et al., 2011; Christiansen et al., 2011). Because of practical limitations, only the near surface soil moisture was detected in most of these studies (see review in Brocca et al., 2007; Choi et al., 2007). Only a few studies have taken into account the soil moisture variability

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0022-1694/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.03.007

at different soil depths (e.g., Hupet and Vanclooster, 2002; De Lannoy et al., 2006; Bogena et al., 2010).

With respect to the dynamics of soil moisture variability, some studies have reported that the variability increases with decreasing average moisture content (e.g., Famiglietti et al., 1999; Hupet and Vanclooster, 2002). Other studies have reported an opposite trend (e.g., Western et al., 1998), or that detecting a trend is impossible (e.g., Hawley et al., 1983; Charpentier and Groffman, 1992). More recently, improvements in the instruments and methodologies that are available, as well as comparisons of different data sets, have allowed more general conclusions to be reached and the apparent contradictions detected in the past literature to be explained. In particular, the spatial variability of soil moisture in humid and semi-humid climates has been shown to be greater during dry periods. On the contrary, in semi-arid environments, the spatial variability increases as the soil moisture pattern increases. This behaviour implies that, starting from a very wet soil state, the standard deviation of the soil moisture increases with decreasing mean soil moisture, it reaches a maximum value at a critical mean moisture content and then decreases during further drying. Consequently, the coefficient of variation tends to decrease with increasing mean soil moisture, indicating that a larger number of samples is needed to characterise the mean moisture value under dry conditions (Hupet and Vanclooster, 2002; Ryu and Famiglietti, 2005; Choi et al., 2007; Brocca et al., 2007; Lawrence and Hornberger, 2007; Famiglietti et al., 2008; Wang et al., 2008; Penna et al., 2009). Although many studies have utilised soil moisture measurements that are carried out at the soil surface ($\sim$0–10 cm), their results corroborate theoretical studies obtained by stochastic simulation analysis of water flow in heterogeneous soils (Roth, 1995; Harter and Zhang, 1999; Vereecken et al., 2007).

A detailed understanding of soil moisture dynamics would have several implications for hydrological research and in soil moisture sampling design. In particular, several studies have suggested the possibility of identifying locations where soil moisture contents is either consistently higher or lower than the mean value in the study area. This phenomenon has been called time or temporal stability (Vachaud et al., 1985), temporal persistence (Kachanoski and de Jong, 1988), and rank stability (Tallon and Si, 2003) in spatial patterns of soil moisture. By ascertaining the existence of time stability, the number of field observations that are necessary may be reduced considerably. At best, it is possible, with a single initial measuring campaign, to identify a small number of locations that may be used to estimate mean values and the variance over the whole area of the characteristic parameters of the water transport process (Comegna and Basile, 1994). In this context, the temporal stability of soil moisture patterns may have profound implications for sampling design, comparisons of hydrological models and water management, as reported in several studies (e.g., Kachanoski and de Jong, 1988; Grayson and Western, 1998; Gómez-Plaza et al., 2000; Mohanty and Skaggs, 2001; Grant et al., 2004; Jacobs et al., 2004; Petrone et al., 2004; Martínez-Fernández and Ceballos, 2005; Starr, 2005; Lin, 2006; Guber et al., 2008; Williams et al., 2009; Zhao et al., 2010).

However, some previous studies have failed to find locations where soil moisture patterns can be considered stable because different controls operate on the spatial soil moisture (e.g., Teuling and Troch, 2005; Wilson et al., 2005; Teuling et al., 2006). On the field or small catchment scale in fact, the variability is expected to result from a small scale component that is dominated by soil type, topography and vegetation variables (e.g., Merz and Plate, 1997; Entin et al., 2000). Because of the strong interactions between the driving variables, the results are site-specific, and thus general conclusions regarding the driving forces of the variability cannot be made.

Several authors have reported that the spatial distribution of soil moisture patterns is related directly to topographic characteristics (Qiu et al., 2001; Western et al., 2004; Brocca et al., 2007; Penna et al., 2013), vegetation (e.g., Gómez-Plaza et al., 2000; Hupet and Vanclooster, 2002; Schume et al., 2003) or soil properties (Grant et al., 2004; Hebrard et al., 2006; Vereecken et al., 2007). Some studies have indicated that the spatial variability of soil moisture is controlled by soil and vegetation, even if the sites considered are characterised by marked topographic structures (Wilson et al., 2004; Penna et al., 2009). Other authors have noted the difficulty of identifying any single controlling variable and have indicated that a more complex interaction among the factors in the system determines the spatial variability of soil moisture (e.g., Zhao et al., 2010; Zhu and Lin, 2011). Other studies have reached similar conclusions, highlighting observations that the spatial distribution of soil moisture, in particular in semi-arid areas, cannot be predicted by a single variable (i.e., vegetation or soil) and that the relative importance of the controlling variables changes when different sites are considered (Williams et al., 2003; Schneider et al., 2011).

Some general behaviours can be defined from previous research considering that the relative importance of the controlling variables depends directly on the state of the system, i.e., on average soil moisture. Grayson et al. (1997) defined two main soil moisture conditions and demonstrated that, in areas where precipitation continually exceeds evapotranspiration (i.e., humid and semi-humid regions), the topography upslope of a given point is the dominant variable. The authors called this phenomenon "non-local control". Furthermore, in areas where evapotranspiration continually exceeds precipitation (i.e., semi-arid regions), spatial soil moisture patterns reflect the soil and vegetation distribution, and only local terrain (areas of high convergence) influences these patterns. The authors called this phenomenon "local control". Advances in the theoretical understanding of these empirical findings have been made by Albertson and Montaldo (2003), who showed that the temporal evolution of soil moisture variability is driven by the sum of the covariances between soil moisture and different fluxes. In a simulation study, Teuling and Troch (2005) showed that the spatial variability of soil moisture is due to the variability in vegetation when the mean soil moisture is relatively dry. However, when the mean soil moisture is relatively wet, the spatial variability is explained mainly by the soil variability.

These results were corroborated by the analysis of experimental data. Considering wet, medium and dry conditions, Gómez-Plaza et al. (2001) showed, for example, that in semi-arid areas, the controls are affected by a strong seasonal variation. This effect is particularly evident in the presence of vegetation influencing the spatial variability of soil moisture. Similar conclusions were made by Teuling et al. (2006) and Pan and Wang (2009). In general, the spatial distribution of soil moisture is found to be more unstable when spatio-temporal dynamics of the vegetation are present (Gómez-Plaza et al., 2000; Zhao et al., 2011). However, even if the role of vegetation is investigated with increasing attention, in most of the field studies mentioned above, the vegetation was characterised using qualitative measures (e.g., visual estimation) or by conducting measurements on a single date to represent the values for the entire season. Using this approach, correlations derived from a single measurement of vegetation properties do not capture the seasonal variations. This lack of seasonal representativeness was recognised in most of the papers mentioned previously as the reason for the relatively low correlation between soil moisture and vegetation properties. For this reason, some authors have indicated that further research should explicitly consider the vegetation dynamics during the entire monitoring period (e.g., Teuling et al., 2006; Zhao et al., 2010).