Journal of Hydrology 364 (2009) 311–327

Contents lists available at ScienceDirect

Journal of Hydrology

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

Hillslope scale soil moisture variability in a steep alpine terrain

Daniele Penna *, Marco Borga, Daniele Norbiato, Giancarlo Dalla Fontana

Department of Land and Agroforest Environments, University of Padova, Agripolis, viale dell'Università, 16, Legnaro IT-35020, Italy

ARTICLE INFO

Article history:
Received 11 April 2008
Received in revised form 19 September 2008
Accepted 8 November 2008

Keywords:
Soil moisture
Hillslope hydrology
Scaling
Alpine region

SUMMARY

In this study we analyse space–time variability of soil moisture data collected at 0–6, 0–12 and 0–20 cm depth over three hillslopes with contrasting steep relief and shallow soil depth in the Dolomites (central-eastern Italian Alps). The data have been collected during two summer seasons (2005 and 2006) with different precipitation distribution. Analysis of soil moisture data shows that different physical processes control the space–time distribution of soil moisture at the three soil depths, with a marked effect of dew on the 0–6 cm soil depth layer. The range of skewness values decreases markedly from the surface to deeper layers. More symmetric distributions, characterised by relatively low skewness, are found for mid-range soil moisture contents, while highly skewed distributions (generally with more log–normal shape) are found at dry and wet conditions. Scatter plots drawn for the whole data set and the analysis of the correlation coefficients suggest a good persistence of soil moisture with depth: the highest degree of correlation was observed between data collected at 0–12 and 0–20 cm.

Examination of correlation between soil moisture fields and topographical attributes shows that, notwithstanding the steep relief and the humid conditions, terrain indices are relatively poor predictors of soil moisture spatial variability. The slope and the topographic wetness index, which are found here the best univariate spatial predictors of soil moisture, explains up to 42% of the time-averaged moisture spatial variation.

A negative relationship between the soil moisture spatial mean and the corresponding spatial standard deviation is found for mean water contents exceeding 25–30%, while a transition to a positive relationship is observed with drier conditions. Overall, soil moisture variability shows the highest values at moderate moisture conditions (23–29%) and reduced values for wetter and drier conditions for all depths. A negative linear relationship between mean soil moisture content and the coefficient of variation was observed.

A soil moisture dynamics model proved to successfully capture the soil moisture variability at the hillslope scale. The simulated time series of hillslope-averaged soil moisture are in good agreement with the observed ones. Moreover, the model reproduces consistently the observed relationships between soil moisture spatial mean and corresponding variability.

Introduction

Soil moisture plays a central role in the global water cycle by controlling the partitioning of water and energy fluxes at the earth's surface and constitutes the physical linkage between soil, climate and vegetation (Albertson and Montaldo, 2003; Pan et al., 2003; Rodríguez-Iturbe and Porporato, 2004). At the point scale soil moisture is crucial for the infiltration process (Bronstert and Bárdossy, 1999; Raats, 2001) and plant dynamics (Porporato et al., 2004). At the hillslope and catchment scale, the spatial and temporal distribution of soil moisture controls the flood formation process (Borga et al., 2007). At the regional and continental scale, soil moisture controls water distribution through land surface atmosphere feedback mechanisms (Koster et al., 2004).

Due to soil heterogeneity, atmospheric forcing, vegetation and topography, soil moisture is variable in space and time. Understanding and characterizing this variability is one of the major challenges within hydrological sciences. Information characterizing space–time variability of soil moisture is important to understand the contribution of soil moisture variability at smaller scales towards the effective soil moisture observed at larger scales or its role in the parametrization of, e.g., climate and watershed models (Famiglietti et al., 1999; Ryu and Famiglietti, 2005). As such, this information can provide guidelines for the design of field experiments and for the efficient use of remote sensing estimates.

Characterization of space–time soil moisture variability has been attempted by analysing the trends of spatial soil moisture

---

* Corresponding author. Tel.: +39 049 8272700; fax: +39 049 8272686.
E-mail address: daniele.penna@unipd.it (D. Penna).

0022-1694/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2008.11.009

variability with spatial mean moisture content. Empirical analyses found that, generally, the standard deviation increases during drying from a very wet stage, reaches a maximum value at a specific or critical mean moisture content and then decreases during further drying (Famiglietti et al., 2008). Western et al. (2003) provided a qualitative interpretation of why variance peaks at intermediate moisture contents by making use of the combined results from several field campaigns. In their interpretation, differences in behaviour in humid and semiarid regions are related to differences in the patterns of controlling processes. They found that the location and magnitude of the variance peak changed between catchments. Depth appeared to have only a small effect on the relationship. In the last 10 years, a number of studies have attempted to examine quantitatively how different processes act to either increase or decrease the spatial variability of soil moisture. By using the similar media concept, Salvucci (1998) showed how variability in soil texture leads to different soil moisture variability states in different limiting cases. Albertson and Montaldo (2003) showed how covariances between soil moisture and fluxes, originating from variability in soil moisture, forcing and/or land surface properties, can lead to either an increase or decrease in soil moisture variability. Teuling et al. (2005) developed a simple soil moisture dynamics model and showed how vegetation, soil and topography controls interact to either create or destroy spatial variance. By accounting for effects of spatial variability in soil and vegetation characteristics, in combination with atmospheric forcing (precipitation and potential evapotranspiration), different observed relations between spatial mean soil moisture and its variability can be explained in this way. Using stochastic analysis of the unsaturated Brooks–Corey flow in heterogeneous soils, Vereecken et al. (2007) showed that parameters of the moisture retention characteristic and their spatial variability determine to a large extent the shape of the soil moisture variance–mean water content relationship. They found that the standard deviation of soil moisture peaked between 0.17% and 0.23% for most textural classes and that the peak value was controlled by the parameters which describe the pore size distribution of soils. The theoretical results obtained by Vereecken et al. (2007) correspond well with Ryu and Famiglietti (2005) who experimentally found that the soil moisture variance–mean water content relationship tends to peak around a value of 0.2%.

These studies generally examined soil moisture variability for gentle topographies. Examples are provided by the Tarrawarra and Mahurangi experiments (Western and Grayson, 1998, 2000, 1999, 2004; Wilson et al., 2003, 2004) and SGP97, SGP99, SMEX02 and SMEX03 (Famiglietti et al., 1999; Mohanty and Skaggs, 2001; Choi and Jacobs, 2007). Few field studies have examined variability of soil moisture patterns in steep terrain and high altitude (above tree line) conditions (Grant et al., 2004). In general, the spatial variability of soil moisture in mountainous regions is expected to be high relative to other landscapes due to heterogeneous conditions of surface and bedrock topography, soil characteristics, wind patterns, interaction between evaporation, condensation and precipitation. Moreover, it is expected that the soil moisture spatial variability in humid and steep conditions with shallow soils (more favourable to lateral flow occurrence) exhibits a stronger relationship with topographic variables than in more gently sloping landscape (Grayson and Western, 2001).

The main objective of this study is to characterise the variability of field scale soil moisture for three hillslopes characterised by contrasting steep relief and shallow soil depth located in the high mountainous Vauz river basin (Dolomites, central eastern Italian Alps). Soil moisture data were collected over three depths: 0–6, 0–12 and 0–20 cm. The three hillslopes show marked differences in topography, representing concave, planar and convex structure. Because of the relative small area, we do not expect significant differences in precipitation, relative air humidity, temperature and other climatic variables. This allows to isolate the effects of topography and soil depths on space–time variability of soil moisture fields. The hillslopes considered may be deemed representative of pedological, topographic, climatic conditions frequently met in pasture areas of the Dolomites.

Based on these data, this study (1) characterises the statistical properties of the soil moisture measurements with varying soil depth and hillslope topography, and investigates the correlation between soil moisture measurements collected at various soil depths; (2) examines the influence of topographic variables on soil moisture spatial variability; (3) investigates the relationship between mean moisture content and spatial variability and (4) analyses the suitability of applying a soil moisture variability dynamics model to reproduce the observed spatial mean moisture content – spatial variability relationship. The use of a water balance model to characterise the spatial and temporal organization of soil moisture fields is appealing, since this could reduce the need for ground based measurements significantly in numerous applications. The model applied here (Teuling and Troch, 2005) accounts for variations in soil and vegetation properties but not for redistribution due to lateral flow. It is therefore interesting to evaluate the quality

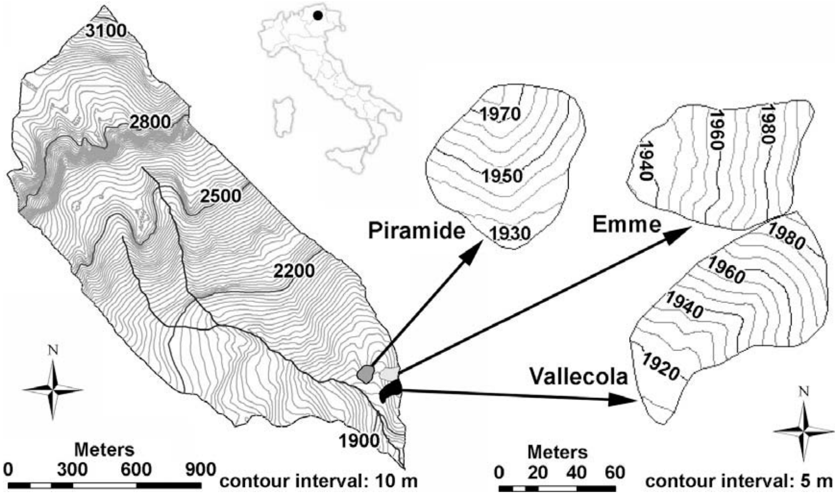

Figure 1. Rio Vauz catchment and location of the three hillslopes.