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Downscaling near-surface soil moisture from field to plot scale: A comparative analysis under different environmental conditions

Paolo Nasta [a,*], Daniele Penna [b], Luca Brocca [c], Giulia Zuecco [d], Nunzio Romano [a]

[a] Dept. of Agricultural Sciences, AFBE Division, University of Napoli Federico II, Portici, Napoli, Italy
[b] Dept. of Agricultural, Food and Forestry Systems, University of Florence, Italy
[c] Research Institute for Geo-Hydrological Protection, National Research Council, Perugia, Italy
[d] Dept. of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro, Italy

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ABSTRACT

Indirect measurements of field-scale (hectometer grid-size) spatial-average near-surface soil moisture are becoming increasingly available by exploiting new-generation ground-based and satellite sensors. Nonetheless, modeling applications for water resources management require knowledge of plot-scale (1–5 m grid-size) soil moisture by using measurements through spatially-distributed sensor network systems. Since efforts to fulfill such requirements are not always possible due to time and budget constraints, alternative approaches are desirable. In this study, we explore the feasibility of determining spatial-average soil moisture and soil moisture patterns given the knowledge of long-term records of climate forcing data and topographic attributes. A downscaling approach is proposed that couples two different models: the Eco-Hydrological Bucket and Equilibrium Moisture from Topography. This approach helps identify the relative importance of two compound topographic indexes in explaining the spatial variation of soil moisture patterns, indicating valley- and hillslope-dependence controlled by lateral flow and radiative processes, respectively. The integrated model also detects temporal instability if the dominant type of topographic dependence changes with spatial-average soil moisture. Model application was carried out at three sites in different parts of Italy, each characterized by different environmental conditions. Prior calibration was performed by using sparse and sporadic soil moisture values measured by portable time domain reflectometry devices. Cross-site comparisons offer different interpretations in the explained spatial variation of soil moisture patterns, with time-invariant valley-dependence (site in northern Italy) and hillslope-dependence (site in southern Italy). The sources of soil moisture spatial variation at the site in central Italy are time-variant within the year and the seasonal change of topographic dependence can be conveniently correlated to a climate indicator such as the aridity index.

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1. Introduction

Near-surface soil moisture (θ) is a key indicator of hydrological response and a linking variable in the relationships among climate, soil, topography, and vegetation (Western et al., 2004; Wilson et al., 2004). Local knowledge of soil moisture dynamics is crucial for improving water management strategies and setting up optimal use of available water resources (Romano, 2014; Vereecken et al., 2015). Hydrological processes such as evapotranspiration and surface runoff are highly nonlinear and are controlled by near-surface soil moisture which, in turn, necessitates its inherent variability to be properly described over a variety of spatio-temporal scales (Blume et al., 2009; Swarowsky et al., 2011; Mittelbach and Seneviratne, 2012; Penna et al., 2013; Poltoradnev et al., 2016). Several studies report local and nonlocal biophysical controls affecting soil moisture patterns across different spatial scales (Famiglietti et al., 2008; Joshi and Mohanty, 2010; Zhao et al., 2011; Brocca et al., 2012; Shin and Mohanty, 2013; Qiu et al., 2014; Zucco et al., 2014). The relations between soil moisture and the readily available digital terrain data assumed as basic key-controlling factors have been extensively investigated (Beaudette et al., 2013; Hu and Si, 2014; Qu et al., 2015; Schröter et al., 2015). Other biophysical factors, such as soil properties, vegetation characteristics, and anthropogenic disturbance (e.g. tillage), additionally enhance the spatio-temporal variability of soil moisture patterns (Jonard et al., 2013; Gaur and Mohanty, 2013; Dimitrov et al., 2015).

* Corresponding author at: Department of Agricultural Sciences – Division of Agricultural, Forest and Biosystems Engineering, University of Naples Federico II, Via Università 100, Portici, Italy.
E-mail address: paolo.nasta@unina.it (P. Nasta).

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Indirect measurements of soil moisture are becoming either intermittently accessible (low temporal resolution, >1 day) or continuously available (high temporal resolution, ≤1 day) at the field (e.g. cosmic ray technology, measurement circle with diameter of about 500–600 m) to the regional scale (e.g. remote sensing, pixel dimension of 10–40 km) (Romano, 2014; Brocca et al., 2017; Mohanty et al., 2017). Many applications, such as water resources planning, soil management, subsurface contaminant transport, precision agriculture, just to mention a few, require spatially distributed information of plot-scale soil moisture (e.g. meter grid size, 1–5 m). A large number of near-real-time on-site measurements (e.g. wireless sensor networks) is necessary in order to develop optimal prevention, mitigation, and adaptation strategies for soil erosion control, flood forecasting, afforestation programs after wildfires, and assessment of contaminant transport to the groundwater (Meyles et al., 2003; Cosh et al., 2004; Hoehn et al., 2017). However, such dense-information systems require excessive costs, time, and efforts for their installation and maintenance. Before installing a sensor network, it is extremely useful to infer whether or not soil moisture patterns are controlled by either radiation-related or flow-related topographic variables. This is prognostic information enabling the sensors to be optimally positioned in a field plot. Therefore it is necessary to develop suitable methods for capturing these smaller scale insights while having data available at larger spatial scales (spatial scale transfer approach). Solving this top-down spatial scale mismatch forms part of the so-called downscaling problem, which, in brief, involves the use of auxiliary data to retrieve the desired fine-scale fluctuations and heterogeneities of a certain variable given its spatially-averaged values at a larger scale (Vereecken et al., 2008; Vereecken et al., 2014; Pachepsky and Hill, 2017; Peng et al., 2017).

Some existing downscaling methods are based on knowledge of several terrain attributes, which are often easily obtained from already available digital elevation models (DEMs) (Perry and Niemann, 2007; Korres et al., 2010; Busch et al., 2012; Coleman and Niemann, 2012; Werbylo and Niemann, 2014). Coleman and Niemann (2013) proposed the Equilibrium Moisture from Topography (EMT) model to downscale spatial-average soil moisture values by exploiting information on topographic attributes only. The EMT model was subsequently upgraded by including spatial information about soil and vegetation characteristics (Ranney et al., 2015) across different spatial scales (Cowley et al., 2017; Hoehn et al., 2017). This physically-sound model provides metrics to define the dominant type of topographic indexes in explaining the spatial variation of soil moisture patterns. In other words, radiation-related and flow-related topographic variables determine whether hillslope dependence or valley dependence is the dominant organization type. Under the above circumstances, we also define temporal instability of soil moisture patterns as the seasonal (intra-annual) change of topographic dependence. If a soil moisture data set exhibits temporal instability, we question the role of climatic seasonality. Our main hypothesis is that valley pattern (flow-related topographic index) should be dominant in the humid season whereas hillslope pattern (radiative-related topographic index) should be more important during the dry season.

The above-mentioned downscaling procedures rely on the availability of spatial-average soil moisture data. If this is not the case, such as when future scenarios need to be developed or there is a lack of historical time series, we hereby propose to obtain surrogate values through the use of a simplistic hydrological model. Bucket-filling models estimate soil moisture by using long records of boundary forcing data and a few lumped parameters for soil and vegetation characteristics (Laio et al., 2001; Bergström and Lindström, 2015; Castillo et al., 2015).

In this study, we adopt the bucket model proposed by Guswa et al. (2002) and we name it as "Eco-Hydrological Bucket" (EHB) in the remainder of the paper. The experimental field mimics a bucket requiring boundary forcing, i.e., precipitation and potential evapotranspiration, as input data. Our investigation aims to couple the EHB and EMT models in order to relate boundary forcing data to spatial-average soil moisture which, in turn, is used with readily-available topographical attributes for estimating spatially distributed soil moisture values. The major goal of the present paper is twofold: *i*) to calibrate and test the performance metrics of the proposed downscaling approach at three sites located in northern, central, and southern Italy under different climatic and topographical conditions; *ii*) to relate climatic seasonality to the dominant type of topographic dependence affecting temporal instability (if detected) of simulated soil moisture patterns.

The paper is organized as follows: Section 2 briefly describes the three experimental sites and the model set-up whereas Section 3 presents calibration and validation of the EHB and EMT models. In Section 4 we analyze the topographic dependence of soil moisture patterns and their relationship with seasonal values of a climate indicator (Aridity Index, AI). The conclusive remarks are finally presented in Section 5.

2. Methods and experimental works

2.1. Data sets in the three experimental sites

The three test sites are located in Italy along an ideal transect that crosses different local climatic zones (Fig. 1). Terrain attributes were retrieved from the available digital elevation models (DEM) with different resolutions (see Table 1).

The first site known as "Piramide" (hereinafter PIR) is positioned along a divergent-convex hillslope in the lower part of the Rio Vauz catchment which belongs to the Italian Dolomites (the Veneto Region in northern Italy) (Penna et al., 2009; Penna et al., 2011; Penna et al., 2013). The size of the field is 0.46 ha, the elevation range is 1936–1986 m a.s.l., and the dominant land use is alpine grassland. Mean annual precipitation is 1.02 m, half of which consists in snowfall (the snow-free period spans from May till October). The climate is typically alpine. Soil depth assessed through depth-to-refusal measurements was on average 1.1 m. The highest content in organic matter was found in the first 0.10 m of the soil profile and soil porosity ranged from 45% to 70.5% (Penna et al., 2015). Recurrent field campaigns were carried out in the summer season of 2005, 2006 and 2007 in order to measure surface soil moisture on a grid of 26 points by using a portable time domain reflectometry device (TDR300, Spectrum Technologies Inc., USA) connected to probes with metallic rods 0.12 m long.

The second site called "Ingegneria" (hereinafter ING) is located in the Upper Tiber Valley in the Region of Umbria (central Italy). A detailed description of this experimental area can be found in Brocca et al. (2007) and Brocca et al. (2009). The climate is sub-continental Mediterranean with mean annual rainfall of about 0.83 m. Land use is grassland, and soil texture of the uppermost soil layer is silty clay loam. Surface soil moisture values were measured in 14 measurement campaigns (February to May 2004) by following a regular grid of 50 points. Near-surface soil moisture was determined by using a portable TDR unit (Soilmoisture Equipment Corporation TRASE® TDR) connected to probes with metallic rods 0.15 m long.

The third site is a small catchment located near the village of Monteforte Cilento in the Region of Campania (southern Italy) (Nasta et al., 2013). It is denoted by the acronym MFC1 and belongs to the Upper Alento River Catchment (Nasta et al., 2009; Nasta et al., 2017). The climate is sub-humid Mediterranean with hot-dry summers and mild-wet winters. The MFC1 catchment is divided into private landholdings with different land uses (arable

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