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Spatial-temporal variability of soil moisture: addressing the monitoring at the catchment scale

Jacopo Dari, Renato Morbidelli[1], Carla Saltalippi

Dept. of Civil and Environmental Engineering, University of Perugia, via G. Duranti 93, 06125 Perugia, Italy

Christian Massari, Luca Brocca

National Research Council, Research Institute for Geo-Hydrological Protection, via Madonna Alta 126, 06128 Perugia, Italy

Abstract

Soil moisture plays a fundamental role in the mass and energy balance between the land surface and the atmosphere, making its knowledge essential for several hydrological and climatic applications. The aim of this study is to extend the current knowledge of soil moisture spatial-temporal variability at the catchment scale (up to 500 km^2). The main implication is to provide guidelines to obtain soil moisture values representative of the mean behaviour at the medium-sized river basin scale, which is useful for remote sensing validation analysis and rainfall-runoff modeling. To this end, 23 measurements campaigns were carried out during a time span of 14 months at 20 sites located within the Upper Chiascio River Basin, a catchment with a drainage area of about 460 km^2 in the Umbria Region (central Italy). The data set allowed the analysis of both soil moisture temporal stability and its dynamics. On the basis of statistical and temporal stability approaches, it was investigated how factors such as climatic regime and geomorphology influence soil moisture behaviour. For the investigated area, the spatial variability of soil moisture was higher in dry periods with respect to wet periods, mainly due to the rainfall pattern characteristics during different periods of the year. Soil moisture values recorded during wet periods showed a better correlation than those recorded during dry periods. The maximum number of required samples, to obtain the mean areal soil moisture with an absolute error of 3% vol/vol, was found equal to 12. The temporal stability analysis showed that during wet periods just one "optimal" measurement point can provide values of soil moisture representative of the catchment-mean behaviour, while during dry periods the number of "optimal" measurement points became equal to two. Therefore, at the adopted spatial scale the use of a single measurement point can lead to significant errors. From the perspective of soil moisture dynamics, the decomposition of the spatial variance showed that the contribution of the time-invariant component (temporal mean of each site) was predominant on respect to the total spatial variance of absolute soil moisture data, for almost the whole observation period. Results provided guidance to optimize soil moisture sampling by performing targeted measurements at a few selected points representative of the catchment-mean behaviour.

[1] Correspondence to: renato.morbidelli@unipg.it

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1. Introduction

Soil moisture is of paramount importance for many hydrological processes (Brocca et al., 2017a). Its knowledge is relevant in several fields which include rainfall-runoff partitioning (Blöschl and Sivapalan, 1995; Brocca et al., 2010b; Koster et al., 2010; Mirus and Loague, 2013), landslide forecasting (Brocca et al., 2012a), soil nutrient cycling processes (Schjonning et al., 2003), drought monitoring and agriculture (Crow et al., 2012; Champagne et al., 2015). The spatiotemporal variability of soil moisture content raises many challenges to its definition at various scales. Small-scale variations, due to geomorphological characteristics and soil properties, such as the saturated hydraulic conductivity, occur in the spatial range of a few tens of meters and in the temporal range of a few days (Western et al., 2004). Large-scale variations affect very extensive areas, such as whole basins (>100 km^2), and are also caused by atmospheric forcings.

Practically, ground based measurements and remote sensing techniques can be used to characterize at each scale the spatiotemporal variation of soil water content. Ground based measurements such as time domain reflectometry, neutron probes, capacitance probes and gravimetric analyses provide detailed information on the soil moisture values when careful calibration of devices is available (Romano, 2014). However, these techniques are time consuming, very expensive and provide information only in selected points. To overcome this issue, the use of sensors on board of satellite platforms has been spreading over the past few decades (Fang and Lakshmi, 2013; Brocca et al., 2017b). This technology allows to remotely sense various meteorological data, including soil moisture, over large domain but is limited by the low spatial resolution, ranging from 1 km (e.g., Sentinel-1, Bauer-Marschallinger et al.,

2018) to 40 km (e.g., SMAP, Entekhabi et al., 2010) and by the inherent bias of the measurement thus requiring an accurate on-site verification prior their use within model and applications. For these reasons, traditional measurement methods are necessary and still widely used. However, given the high costs, an effort is required to identify soil moisture sampling optimization schemes for reducing the number of measurements as few as possible in accordance with the desired accuracy and the site characteristics.

Several authors investigated the possibility to optimize the sampling scheme through specific soil moisture field campaigns in experimental areas characterized by dimension up to few square kilometers by using the statistical analysis (Bell et al., 1980; Famiglietti et al., 1999; Brocca et al., 2007; Wang et al., 2008), the temporal stability analysis (Vachaud et al., 1985; Grayson and Western, 1998; Martinez-Fernandez and Ceballos, 2005; Brocca et al., 2009; Zhou et al., 2013), or both (Jacobs et al., 2004; Choi and Jacobs, 2007; Brocca et al., 2010a; Hu et al., 2010; Brocca et al., 2012b; Baroni et al., 2013; Liao et al. 2017; Lai et al., 2017; Lai et al., 2018). Recently, Mittelbach and Seneviratne (2012), considering a very large scale (the entire Switzerland area), showed that the spatial variability of soil moisture is predominantly determined by a time-invariant component and that statistical and temporal stability analysis can lead to different results by considering temporal anomalies rather than absolute soil moisture values. Mittelbach and Seneviratne (2012) concluded their analysis encouraging further studies at different scale to investigate the spatio-temporal characteristics of temporal soil moisture anomalies in addition to assessments of those of absolute soil moisture.

All these studies highlighted that soil moisture spatial variability increases with the extension of the investigated area and that soil moisture patterns show a significant temporal stability, thus making just one optimal measurement point able to represent the areal mean behaviour. However, at the catchment scale, for large areas, especially during seasons with strong propensity for the development of convective rainfall systems, as stated in terms of optimal sampling scheme for the small scale could fail.

Therefore, the main objective of this paper, aimed at the determination of an optimal soil moisture sampling scheme, is to investigate the soil water content behaviour at a scale in which the rainfall spatial variability may play an important role. For this purpose, the analysis carried out in this paper is based on a long measurement period which has been divided into wet and dry sub-periods in order to explore the influence of convective and frontal rainfall systems on soil moisture variability. At the same spatial scale, on the basis of the methodology proposed by Mittelbach and Seneviratne (2012), the secondary objective of this paper is to evaluate the roles of the time-invariant contribution of the temporal anomalies in the determination of the spatial variability of soil moisture.

2. Materials and Methods

2.1 Study area

The soil moisture measurements were carried out in 20 experimental sites located in the Upper Chiascio River Basin, which is an inland area in the Umbria Region with a drainage area of approximately 460 km^2 (Fig. 1). The basin was mainly characterized by an Apennine climate with an altitude between 320 and 1550 m a.s.l. and a mean slope of 24%. The mean annual temperature was 13.0 °C and the mean annual precipitation was 1050 mm, generally with the highest monthly values recorded in the autumn and winter seasons.

insert here Fig. 1

2.2 Soil moisture measurements

The selection of the 20 experimental sites for the monitoring of soil moisture was based on the necessity to have heterogeneity in terms of land use, topography, texture and vegetation cover. With this choice (site number and position) we tried to represent the entire catchment considering also the necessity to conduct each measurement campaign in the same day.

As shown in Table 1, the distribution of soil texture classes of the measurement points was fairly uniform with most of the sites located in silty clay loam and clay loam (respectively 30% and 35% of the total) soils. The terrain of the experimental sites was mostly flat, with 70% of the measurement points placed in flat areas and 30% in hilly areas. With regard to land use, the area where the experimental sites are located was predominantly cultivated, with small wooded areas and semi-natural environments. The sampling scheme adopted was designed to have a number of measurement points and measurement campaigns that can catch the soil moisture spatial and temporal variability. In fact, experimental sites were located on an extended area and the measurement campaigns were prolonged to capture the alternation between dry and wet periods. The 23 monitoring campaigns covered a time span ranging from March 2014 to May 2015 and were distanced between them for about two weeks each. During each field campaign, four measures were carried out at each of the 20 monitored sites and the mean value was considered as the reference value to be stored in the database. The soil moisture was measured through a portable unit using two wire connector-type Time Domain Reflectometry probes (TDR) of the Soil Moisture Equipment Corporation - TRASE® TDR, which provides a soil moisture measurement representative for a soil layer depth of 15 cm. To obtain the volumetric soil moisture once the dielectric constant is measured, the standard calibration curve was used (Skaling, 1992). The equipment has a quoted error within ± 2% vol/vol. Except for the texture classes given in Table 1, a detailed characterization of the study soils is delayed for future developments, which could also highlight further aspects of interest.

insert here Table 1

2.3 Rainfall data

The rainfall pattern that affected the study basin during the measurement period was analysed in order to separate dry from wet periods. The daily rainfall data recorded by 14 rain gauges located within the area of interest was collected and spatially averaged by using the Thiessen Polygon method.

2.4 Statistical analysis

The main statistical features of the soil moisture data set were determined and analysed in terms of spatial and temporal variability.

Let us denote θ_{ij} the soil moisture measured at site i (i = 1,...,N) during the sampling day j (j = 1,…,M), with N = 20 and M = 23; the spatial mean referred to each sampling day, $\bar{\theta}_j$, is given by:

$$\bar{\theta}_j = \frac{1}{N}\sum_{i=1}^{N} \theta_{ij} \quad (1)$$

in a similar way, the temporal mean for each measurement point, $\bar{\theta}_i$, is calculated by:

$$\bar{\theta}_i = \frac{1}{M}\sum_{j=1}^{M} \theta_{ij} \quad (2)$$

The coefficient of variation for each sampling day, CV_j, is obtained from the relation:

$$CV_j = \frac{\sigma_j}{\bar{\theta}_j} = \frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\theta_{ij}-\bar{\theta}_j\right)^2}}{\bar{\theta}_j} \quad (3)$$

where σ_j is the "spatial" standard deviation. For each site, the coefficient of variation in time, CV_i, and the temporal standard deviation, σ_i, can be defined analogously.

The number of required samples for estimating the mean value within a specific absolute error, NRS, can be obtained from the knowledge of σ_j through the following implicit relation (Wang et al., 2008):

$$NRS = t^2_{1-\frac{\alpha}{2},NRS} \left(\frac{\sigma_j^2}{AE^2}\right) \quad (4)$$

where $t^2_{1-\frac{\alpha}{2},NRS-1}$ is the value of the Student's t-distribution at the confidence level 1-α/2, NRS is the number of the degrees of freedom and AE indicates the absolute error considered, expressed in volumetric soil moisture (% vol/vol).

2.5 Temporal stability

The temporal stability analysis, introduced by Vauchad et al. (1985), allows to identify the measurement points where the observed values of soil moisture are representative of the mean soil moisture of the entire monitored area. This is extremely important because it permits to install a small number of probes in a few selected points for retrieving the average soil moisture over a large area. Furthermore, the knowledge of the temporal persistence of soil moisture patterns provides support in determining the frequency of measurements under different wetness conditions. The temporal stability analysis is carried out using the relative differences method, which is described below. Considering the spatial mean for each sampling day previously introduced, the relative difference, δ_{ij}, referring to site i and sampling day j is calculated by:

$$\delta_{ij} = \frac{(\theta_{ij} - \bar{\theta}_j)}{\bar{\theta}_j} \quad (5)$$

For each measurement point i, the mean, $\bar{\delta}_i$, and the standard deviation, $\sigma(\delta_i)$, of the relative differences can be obtained by:

$$\bar{\delta}_i = \frac{1}{M}\sum_{j=1}^{M} \delta_{ij} \quad (6)$$

$$\sigma(\delta_i) = \sqrt{\frac{1}{M-1}\sum_{j=1}^{M}\left(\delta_{ij} - \bar{\delta}_i\right)^2} \quad (7)$$

The $\bar{\delta}_i$ quantifies how much the soil moisture recorded at a sampling point departs from the mean spatial value during the measurement period; the $\sigma(\delta_i)$ is an index of the temporal variability. The "representative" sites of the mean value in time are characterized by lower values of $|\bar{\delta}_i|$ and $\sigma(\delta_i)$.

Jacobs et al. (2004) defined a single metric to identify the best sampling point, the index of time stability, ITS, that combines the $\bar{\delta}_i$ and its $\sigma(\delta_i)$. It can be calculated, for each site, as follows:

$$ITS_i = \left[\bar{\delta}_i^2 + \sigma(\delta_i)^2\right]^{1/2} \quad (8)$$

It is noteworthy that originally in Jacobs et al. (2004) this index was called root mean square error (RMSE). In this study, the wording ITS (Zhao et al., 2010; Penna et al., 2013) is employed instead of RMSE in order to disambiguate the index of time stability from the common definition of the RMSE. According to this method, "optimal" measurement points are characterized by low values of the ITS; the main advantage of the ITS approach is that it allows to identify representative sampling sites by considering just one parameter.

2.6 Decomposition of soil moisture spatial variance

The soil moisture dynamics were studied on the basis of the approach introduced by Mittelbach and Seneviratne (2012). According to this method, the spatial variance of soil moisture data can be decomposed in the following three components:

$$\sigma^2\left(\theta_{ij}\right) = \sigma^2(\bar{\theta}_i) + \sigma^2\left(A_{ij}\right) + 2\mathrm{cov}\left(\bar{\theta}_i, A_{ij}\right) \quad (9)$$

where $\sigma^2(\bar{\theta}_i)$ is the spatial variance of the temporal mean, $\sigma^2(A_{ij})$ is the spatial variance of the temporal anomalies, A_{ij}, which quantify how much each observed value deviates from the temporal mean and can be calculated as:

$$A_{ij} = \theta_{ij} - \bar{\theta}_i \tag{10}$$

The third component of the right side in Eq. (8) is the spatial covariance between the temporal mean soil moisture of a site and the temporal anomaly.

2.7 Data processing

The observed data were analysed both in their completeness and by considering partial sets based on temporal and spatial criteria. Specifically, the values of soil moisture recorded during wet and dry periods were compared, as well as those observed in flat and hilly areas. The separation between dry and wet periods was determined by analysing the rainfall measurements occurred in the experimental area in the measurement period. For each day in which a measurement campaign was carried out, it was calculated the mean of the daily rainfall recorded by 14 rain gauges installed thereabout the experimental sites. This operation was repeated for the five days previous each measurement campaign; the spatial averages were then summed obtaining the values of API5 referred to each sampling day. The periods in which these values were found higher than a mean threshold value were classified as “wet”, otherwise as “dry”.

3. Results

3.1 Statistical analysis

The time series of soil moisture values observed at each site, their spatial mean and the average rainfall over the study area during the measurement period are shown in Fig. 2; the spatial mean soil moisture responds to the precipitation input with sudden increments after significant events and slow decrements in the absence of precipitation. Two wet and two dry periods have been identified in the time interval of interest.

insert here Fig. 2

The spatial mean, the spatial standard deviation and the coefficient of variation of the soil moisture obtained during each measurement campaign are contained in Table 2. It also shows the associated value of API5 (the average value considering 14 rain gauges) and its coefficient of variation, CV API5. The behaviour of the CV API5 values reported in Table 2 evidences the different rainfall patterns during the various periods of the year. In presence of prevailing convective systems, mainly observed during dry periods, the average CV API5 is equal to 1.03, while with prevailing frontal systems, typically observed during wet periods, this value become 0.63.

insert here Table 2

As expected, for both soil moisture and API5, the values of the coefficient of variation of the soil moisture obtained during each measurement campaign were lower during the wet periods. In fact, during the dry season, the average CV_j of soil moisture was equal to 0.21, while for the wet season it was equal to 0.16. Globally, i.e. by considering the entire data set, the average value of CV_j was equal to 0.19. This is an index of the low variability of soil moisture field during the wet periods, when the investigated area is interested by spatially uniform rainfall systems; during the dry period, instead, the soil moisture field is less uniform, as a response to isolated convective rainfall systems, that determine significant spatial differences in the soil moisture values.

The decreasing trend between CV_j and $\bar{\theta}_j$ is shown in Fig. 3. This behaviour indicates a lower variability of absolute soil moisture under increasing wetness conditions and it is consistent with the behaviour observed in most of the previous analogous studies (e.g., Bell et al., 1980; Famiglietti et al., 1999, 2008; Brocca et al., 2010a; Brocca et al., 2012b) conducted in smaller areas.

insert here Fig. 3

The assumption that the relationship between CV_j and $\bar{\theta}_j$ is represented by an exponential law allows to establish the maximum NRS for estimating the mean soil moisture value with a specific absolute error (AE) as a function of the average wetness conditions. By using Eq. (4), the NRS values were calculated for an AE equal to 3% and 4% (see Fig. 4). By assuming the relation between CV_j and $\bar{\theta}_j$ as exponential, Eq. 4 provides NRS as a function of the mean soil moisture within a certain level of confidence. For instance, by considering a confidence interval of 95%, to obtain the average soil moisture with an AE of 3%, a maximum NRS of 12 was required. This value was found for a mean soil moisture of ~30% vol/vol and was the maximum of the curve shown in Fig. 4, obtained by fitting the values calculated with Eq. 4 by considering the entire set of soil moisture measurements.

insert here Fig. 4

Brocca et al. (2012b), on the basis of soil moisture data recorded during a time span of about one year over two areas with a smaller extension (178 and 242 km^2) but comparable to those of interest in this study, found a maximum NRS value up to 3 (AE=4%). Obviously, with the increase of the AE, the NRS decreases, reaching the value of 7 for absolute an error of 4%. This method allows to plan a reliable in situ monitoring with respect to a fixed accuracy, also at a catchment spatial scale.

3.2 Temporal stability analysis

In order to check out which sites are the most suitable to obtain the benchmark soil moisture, i.e. the areal mean calculated considering all the 20 sites, the relative differences method was applied. For this purpose, the values of $\overline{\delta}_i$, $\sigma(\delta_i)$ and ITS were considered and compared. The application of the ITS method to values of $\overline{\delta}_i$ and $\sigma(\delta_i)$ that vary in ranges quite different from each other could provide unreliable results if the aim is to identify a measurement point temporally stable and representative of the mean soil moisture for the entire study area. Without any standardisation, it could happen that an experimental site shows a low value of ITS because of a low value of $\sigma(\delta_i)$ but a relatively high value of $\overline{\delta}_i$, thus making that point temporally stable but distant from the areal mean soil moisture. In this case, the recorded values should be scaled in order to obtain the areal mean. Because of this, the identification of "optimal" measurement point was here addressed by comparing temporal stability analysis with correlation analysis, always keeping in mind that the final aim is to identify temporally stable sites that could also provide a soil moisture value representative of the catchment-mean behaviour. This procedure was applied for the entire data set and considering the partition between wet and dry periods, in order to highlight the influence of climate conditions on soil moisture variability. Distinguishing between values observed in flat areas from those in hilly areas, it was also possible to evaluate the geomorphological characteristics that experimental sites should have to be considered as optimal measurement sites.

The most representative site of the entire study basin, in terms of mean soil moisture, was the number 8 of Fig. 1. Fig. 5a shows the good determination coefficient (R^2 equal to 0.837) between the values found at site 8 and the areal mean soil moisture. Fig. 6a shows the rank ordered mean relative difference, with the corresponding standard deviation, for each experimental site; on the same chart, also the ITS associated to each measurement point is shown. Site 8 showed good characteristics in terms of temporal stability as $|\bar{\delta}_i|$ was close to zero and $\sigma(\delta_i)$, represented by the vertical bar, was very low. The ITS values were minimal for sites 8 and 1, but the latter showed a significant value of $|\bar{\delta}_i|$.

By considering the entire data set, the values of $\sigma(\delta_i)$ varied between a minimum and a maximum of 7.6% and 19.7% (in absolute value), respectively. In particular, for the site number 8, values of $|\bar{\delta}_i| = 0.003$, $\sigma(\delta_i) = \pm 9.7\%$ and ITS = 9% were found.

insert here Fig. 5

insert here Fig. 6

The same analyses were also carried out separately during wet and dry periods, and results are shown in Fig.s 5b-c and 6b-c. In the dry periods, the site where the soil moisture values were closer to the average of the study basin was the number 16, with R^2 equal to 0.725 (Fig. 5b), which also showed good characteristics in terms of temporal stability, i.e., low values of $|\bar{\delta}_i|$, $\sigma(\delta_i)$ and ITS, even if these values are worse than those relative to sites 8 and 1. Conversely, during the wet periods, the site 8 was the optimal one, with R^2 equal to 0.857 (Fig. 5c) and the lowest values of $|\bar{\delta}_i|$, $\sigma(\delta_i)$ and ITS. While there is no doubt that during the wet periods the site

8 was the “optimal” one, for the dry periods further evaluations are needed; together with site 8, site 16 could be chosen as “optimal” for this period because it showed the best determination coefficient with the spatial mean and consequently a $|\bar{\delta}_i|$ closer to zero. For this site the ITS wasn't the lowest one because of a $\sigma(\delta_i)$ higher than other sites (i.e., site 1). This is probably due to a few values recorded during the transition periods, when the catchment is not yet in uniform wetness conditions. It can be observed that both sites 8 and 16 were located in flat areas. Also if not statistically significant, this interesting indication could be the object of future developments.

In the spatial correlation triangle shown in Fig. 7, the generic box identified by the i-th line and j-th column expresses the correlation between the values of soil moisture measured during the i-th campaign and those measured in the j-th campaign. Higher correlations are represented with darker cells. It can be seen that the values of soil moisture measured during campaigns carried out in wet periods were highly correlated each other, while lower values were obtained between campaigns carried out during dry periods. Relatively high correlations were also observed between measurement campaigns belonging to wet periods distant in time (about 5 months). The spatial correlation between measurements carried out during wet periods reached values of 0.94 and always remained larger than 0.71. Another aspect of interest was that, in accordance with previous studies (Mohanty and Skaggs, 2001; Cosh et al., 2004; Martinez-Fernandez and Ceballos, 2005; Brocca et al., 2012b), in most cases measurements campaigns during the transition periods were those that show the lower correlation values. Finally, campaigns taken during different dry seasons were occasionally negatively correlated with each other. These results provided useful information for optimize a soil moisture monitoring. For instance, with the objective to validate soil moisture estimation from remote sensing, transition periods should be avoided or, alternatively, an adequate number of sampling points should be adopted.

insert here Fig. 7

The same analysis was carried out with data separated by site geomorphology. Measurements in flat sites provided values of soil moisture positively correlated with each other over time and significantly higher than those observed in hilly sites, where the correlation was high solely between adjacent measurement campaigns (see Fig. 8). During the wet periods, there was an increase in the spatial correlation between the average soil moisture over hilly areas and the areal mean value; the same happened with the average water content over flat areas.

insert here Fig. 8

3.3 Decomposition of soil moisture spatial variance

The analyses previously described, aimed to identify the most representative sites of the mean-catchment soil moisture behaviour, were carried out in terms of absolute values of soil moisture. However, some studies (e.g., Mittelbach and Seneviratne, 2012; Brocca et al., 2014) suggested that the temporal anomalies (the absolute soil moisture minus the seasonal mean) can show a different behaviour with respect to the absolute values. On the basis of this new perspective, Fig. 9 shows the time evolution of the terms that contribute to the determination of spatial variance of soil moisture according to Equation 9. In most cases the dominant contribution was the one related to the temporal mean. The influence of temporal anomalies was higher during dry periods and in some cases larger than that related to the temporal mean. These results were in line with what previously mentioned about the lower stability of soil moisture values observed during the dry season. During the wet periods, the contribution of the covariance was often close to zero, while the time-invariant term was dominant.

insert here Fig. 9

4. Discussion

4.1 Statistical and temporal stability analyses

The combination of statistical and temporal stability analysis allowed us to highlight that, also at the large scale (up to 500 km^2), soil moisture field showed temporal stability properties. In fact, considering the whole data set, soil moisture measurements in site 8 represented the areal mean with R^2 equal to 0.837 and RMSE equal to 2.4% vol/vol. During the wet periods, the performances of the same experimental site rose, with a higher determination coefficient and a smaller root mean square error (R^2 equal to 0.857 and RMSE equal to 1.2% vol/vol). During the dry periods, there was a loss in the accuracy of the estimation. The mean of the values recorded in the “optimal” measurement points (sites 8 and 16) for this period was able to reproduce the catchment-mean behaviour with R^2 equal to 0.846 and RMSE equal to 1.6% vol/vol. Considering a third experimental site during the dry periods, no significant advantage was gained. In fact, involving also the measurements detected in site 1, that showed good temporal stability properties, the areal mean was reproduced without an increase in R^2 and with a restrained decrease in the RMSE, reaching the value of 1.2% vol/vol. These results allow us to affirm that a single "optimal" measurement point should be enough during the wet periods, while during the dry periods a couple of selected sites could be necessary. In order to optimize the soil moisture monitoring over the investigated area, not only the number and the location of “optimal” measurement points, but also the frequency of sampling, is of paramount. The lower variability of soil moisture during the wet periods suggests that during wet seasons the sampling can be addressed less frequently than in dry and transition (between dry to wet and vice versa) periods, when the lower temporal persistence of the soil moisture field makes necessary to sample more frequently. This result is in accordance with previous studies (Zhao et al., 2010). The lower correlation obtained during the dry periods and thus the “lower” temporal stability was also confirmed by $\sigma(\delta_i)$ observed in the two periods: it ranged between 3.6% and 12.6% during the wet periods and between 8.1% and 23% during the dry ones.

At the scale considered in this paper, climatic factors address the soil moisture behaviour in the same way for different morphological conditions. In fact, soil moisture values recorded in flat sites were more correlated with the areal mean than those found in hilly areas, both for the dry and wet seasons. Although the different number of flat and hilly sites may influence this result, it is equally true that a drainage slower than in the inclined slopes associated with the absence of horizontal fluxes may explain this phenomenon, making this morphologic feature relevant for the identification of optimal measurement points, especially at the catchment scale considered in this paper, characterized by high possibility to find a variable geomorphology.

Finally, we remark that the magnitude of CV_j values was in agreement with results obtained in previous studies characterized by similar conditions (Famiglietti et al., 1999; Western and Blöschl, 1999). More specifically, a comparison with studies conducted in central Italy (Brocca et al., 2007, 2009, 2010a, 2012b) showed how the average value of CV_j increases with the size of the investigated area, assuming values equal to: (i) 0.06-0.08 at local scale (1-500 m^2), (ii) 0.10 at small plot scale (501-5000 m^2), (iii) $\approx$ 0.15 at plot scale (5001-100,000 m^2) and (iv) $\approx$ 0.20 at small catchment scale (50-240 km^2). In this work, the experimental area was larger than those examined in the above-mentioned studies, and the heterogeneity of topography and land use was more significant. Therefore, we expect to find a higher value of CV_j that however is consistent (~0.20) with the values observed for areas equal to 240 km^2. Consequently, at least in central Italy, it might be assumed that the average value of CV_j equal to ~0.20 represents an upper limit of the expected spatial variability of soil moisture observations. This result is very important when a distributed rainfall-runoff model has to be used.

4.2 Decomposition of soil moisture spatial variance

Considering the entire measurement period, in accordance with Mittlebach and Seneviratne (2012) and Brocca et al. (2014), the component due to the temporal mean provided the highest contribution (61%) to the total variance, also if the spatial variability of temporal anomalies can never be neglected. During the wet periods the landscape and soil characteristics such as texture and land cover exert a large influence on the soil moisture spatial distribution, larger than the contribute related to the climatic factors which mainly impact the anomaly term. This can be also associated to the type of precipitation systems that affect the Mediterranean area which are synoptic during the winter season and more convective all through the summer. During the transition periods, the gap between the contribution of the temporal mean and of the anomalies decreased in favour of the latter as also demonstrated in a recent study (see i.e. Gao et al., 2015) and the climatic factors become significant likely due the alternation of warm and cold days determined by weather variability. During the summer months (June, July and August) the contributions of temporal mean and anomalies reached the maximum annual values with first still dominating the second but less than during the wet season. This result reinforces what previously mentioned about the analysis of the correlation between the measurement campaigns in relation to the lower reliability of soil moisture surveys carried out during the dry and especially transient periods. Moreover, another important aspect to be considered for the analysis of the time-variant and time-invariant component is the spatial scale. Results depends on the spatial heterogeneities of time-invariant components such as soil texture and vegetation that are expected to be less variable at smaller spatial scale. In this study, we have performed the analysis at basin scale, 500 km², that is much smaller than the region investigated in Mittlebach and Seneviratne (2012), 31500 km², and much larger than those considered in Gao et al. (2015), 0.6 km². As expected, we have obtained that the time-invariant component is less (more) important than in Mittlebach and Seneviratne (2012) (Gao et al., 2015), with results similar to those found in Brocca et al. (2014) who analysed different networks at different spatial scales.

5. Conclusions

Soil moisture measurements carried out in 20 experimental sites in the Upper Chiascio River Basin for a period longer than one year have been used to investigate the soil moisture behaviour at a spatial scale (~500 km^2) in which the rainfall spatial variability may play an important role. Based on results obtained from statistical and temporal stability analyses, as well as from the decomposition of the soil moisture spatial variance, the following conclusions can be drawn:

1. The maximum number of required samples (NRS), considering an absolute error (AE) of 3% vol/vol and intermediate wetness conditions, is equal to 12.
2. Soil moisture exhibits greater variability during dry and transition periods. In fact, the average coefficient of variation for the dry season is equal to 0.21, while for the wet one it is equal to 0.16.
3. Also for areas up to 500 km^2, the soil moisture field exhibits temporal stability. More specifically, during wet periods, one "optimal" measurement site allows estimating the areal mean value with a good agreement (R^2 = 0.857 and RMSE = 1.2% vol/vol), while during dry periods a couple of representative sites becomes necessary. In this way, the catchment-mean pattern is reproduced with R^2 = 0.846 and RMSE = 1.6% vol/vol. The most representative sites are located over flat areas. This last result, distinctive of the

large scale adopted in this paper, is mainly due to the rainfall pattern characteristics during different periods of the year.

4. The total spatial variance of absolute soil moisture data is predominantly determined by the time-invariant component, due to the temporal mean of each site. However, during the summer season and the transition periods, the gap between the contribution of the temporal mean and of the anomalies significantly decreases.

These results represent a useful support to optimize any soil moisture sampling over areas with dimension up to 500 km^2. Further analyses, aimed to investigate deeper layers or to assess the effects of different land uses and soil properties on the spatiotemporal variability of soil moisture in the study basin, are still needed.

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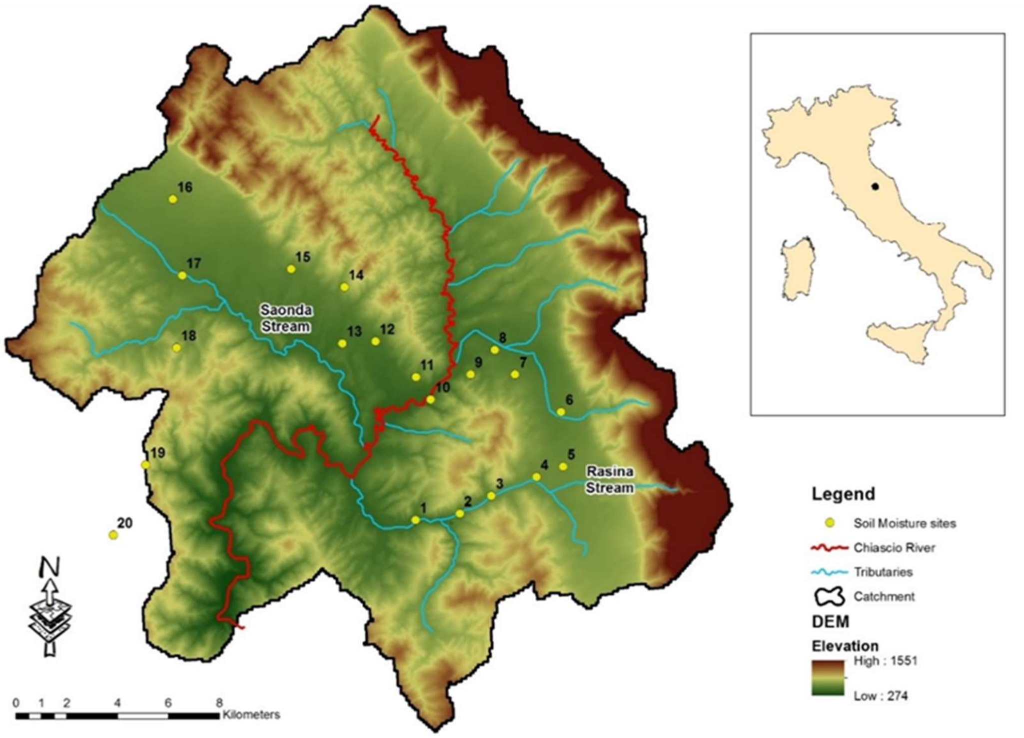
Table 1 Soil texture (according to the USDA classification), land use, terrain and altitude of the 20 selected measurement points (a.s.l.: above sea level).

Site	*Soil texture*	*Land use*	*Terrain*	*Altitude (m a.s.l.)*
1	Silty clay loam	Agricultural	Flat	380
2	Silty clay loam	Agricultural	Flat	405
3	Silty clay loam	Agricultural	Flat	436
4	Silty clay loam	Agricultural	Flat	457
5	Loam	Agricultural	Flat	452
6	Clay loam	Agricultural	Flat	428
7	Loam	Agricultural	Flat	436
8	Silt loam	Agricultural	Flat	396
9	Clay loam	Forest and semi-natural	Hilly	453
10	Clay	Forest and semi-natural	Hilly	380
11	Silt loam	Forest and semi-natural	Hilly	408
12	Silty clay loam	Agricultural	Flat	400
13	Silt loam	Forest and semi-natural	Flat	409
14	Clay loam	Agricultural	Flat	497
15	Clay loam	Agricultural	Flat	431
16	Clay loam	Artificial surfaces	Flat	459
17	Silty clay loam	Agricultural	Flat	422
18	Clay loam	Agricultural	Hilly	553
19	Loam	Agricultural	Hilly	575
20	Clay loam	Forest and semi-natural	Hilly	624

Table 2 Statistic parameters (mean, $\bar{\theta}_j$, standard deviation, σ_j, and coefficient of variation, $CV_j(\theta)$) of the observed soil moisture and average values of API5 calculated for each sampling day, considering 14 rain gauges, with the corresponding coefficient of variation, CV API5.

	Date - (progressive number)	$\bar{\theta}_j$ (%)	σ_j (%)	CV_j (ϑ)	API5 [mm]	CV API5
Wet	26/03/14 - (1)	33.09	5.44	0.16	20.60	0.48
	14/04/14 - (2)	32.84	5.26	0.16	15.61	0.57
	08/05/14 - (3)	32.71	4.96	0.15	21.96	0.26
Dry	04/06/14 - (4)	26.92	6.20	0.23	10.23	0.70
	20/06/14 - (5)	25.84	5.25	0.20	37.28	1.63
	02/07/14 - (6)	25.07	4.20	0.17	14.14	0.19
	06/08/14 - (7)	30.34	3.95	0.13	11.58	0.77
	20/08/14 - (8)	20.65	5.49	0.27	0.04	1.61
	09/09/14 - (9)	24.15	5.53	0.23	0.15	1.08
	24/09/14 - (10)	25.81	3.89	0.15	5.12	0.91
	09/10/14 - (11)	21.16	5.46	0.26	0.08	1.11
	23/10/14 - (12)	24.72	4.75	0.19	3.33	0.53
	04/11/14 - (13)	25.09	5.43	0.22	0.04	1.43
Wet	21/11/14 - (14)	33.94	5.28	0.16	83.48	0.22
	05/12/14 - (15)	36.42	5.02	0.14	29.98	0.26
	18/12/14 - (16)	37.06	4.83	0.13	12.17	0.37
	28/01/15 - (17)	36.29	5.78	0.16	9.16	0.77
	11/02/15 - (18)	35.78	5.08	0.14	17.23	0.36
	10/03/15 - (19)	36.67	6.80	0.19	25.72	0.43
	24/03/15 - (20)	35.11	6.84	0.19	1.82	2.57
Dry	13/04/15 - (21)	25.71	5.56	0.22	0.00	-
	08/05/15 - (22)	21.05	5.79	0.27	0.00	2.09
	29/05/15 - (23)	29.12	4.84	0.17	8.67	0.38



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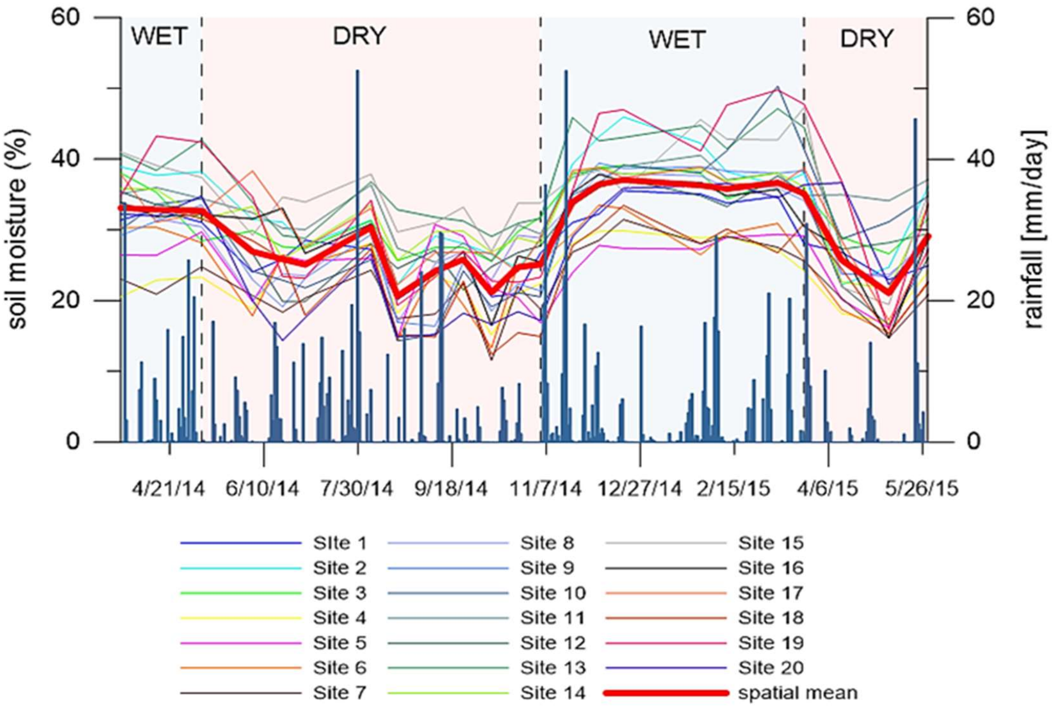

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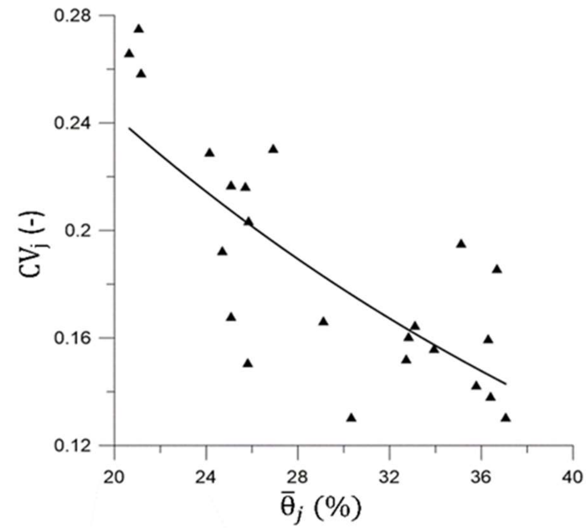

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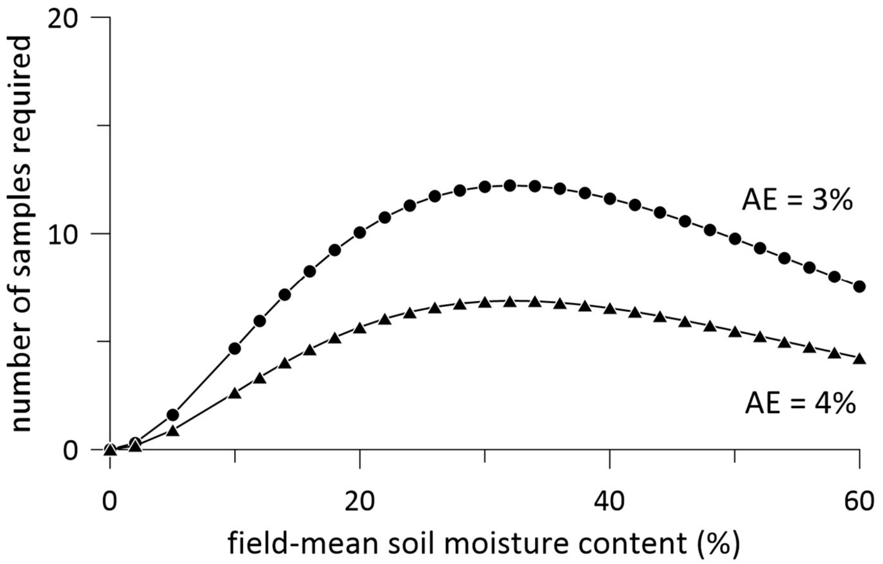

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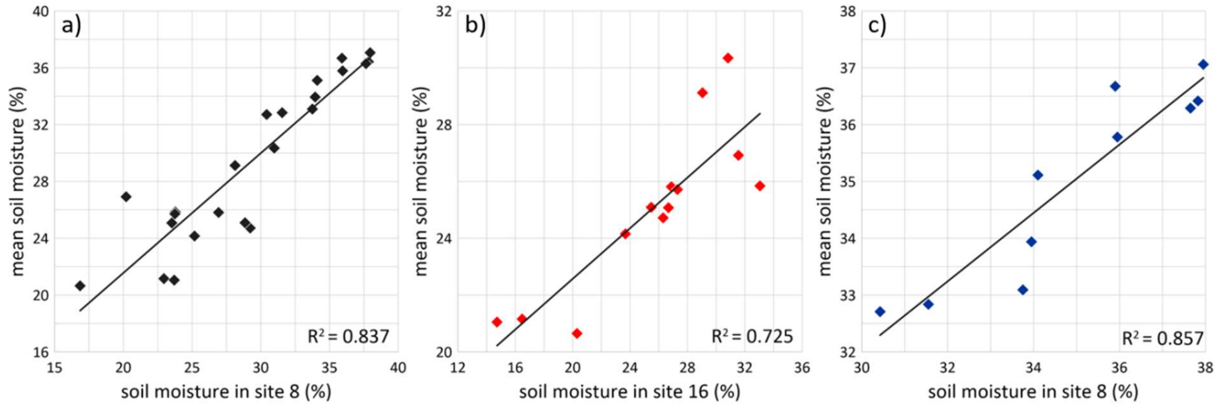

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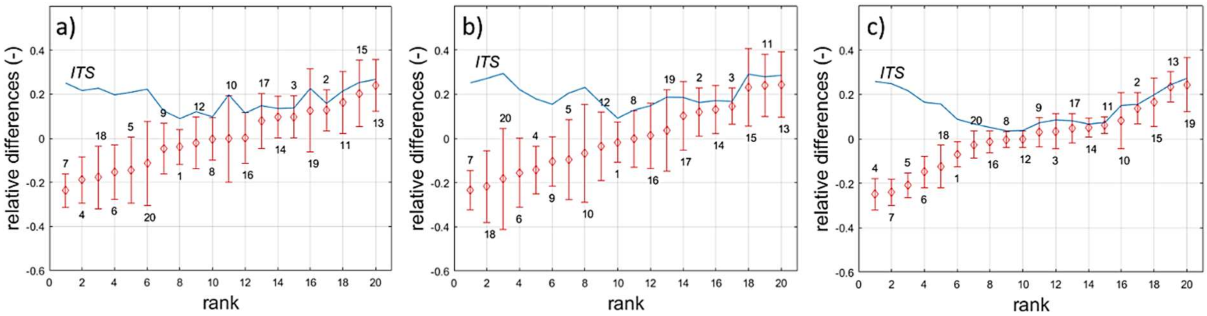

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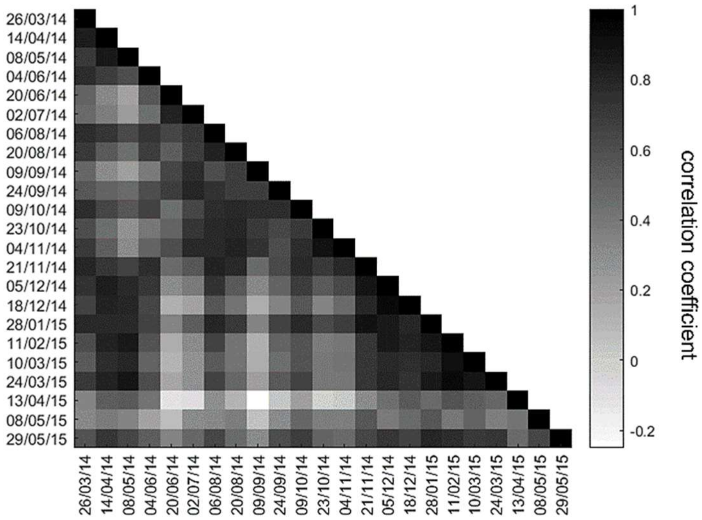
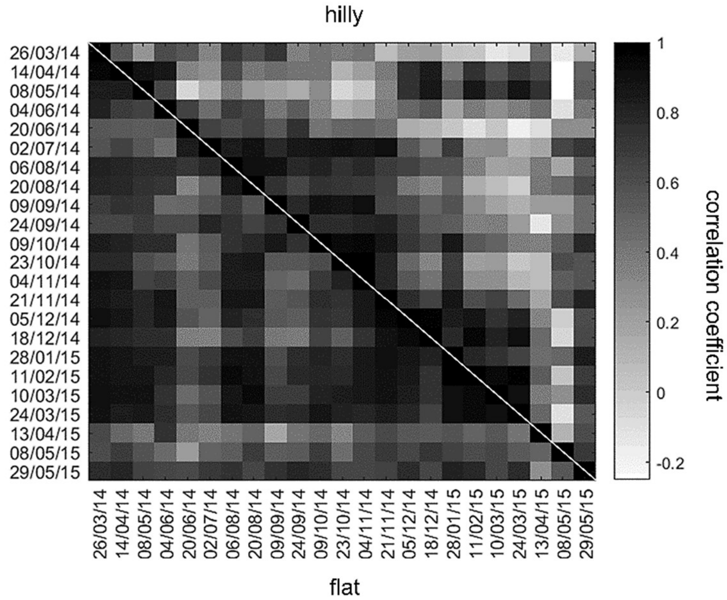


Fig. 7 Correlation triangle of the observed soil moisture values during the measurement campaigns.



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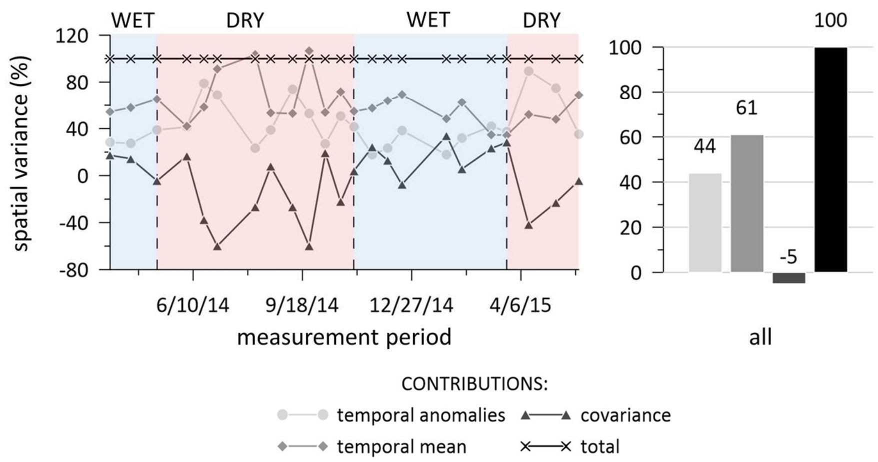

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