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Soil moisture spatial variability in experimental areas of central Italy

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Summary The knowledge of soil moisture spatial variability is an important issue for hydrological and climatic studies. This paper investigates the soil moisture spatial pattern obtained from spot measurements carried out in different experimental plots located in small basins of Central Italy. The near-surface volumetric soil moisture content was measured using a portable time domain reflectometer (TDR) over regular grids whose areas ranging in extension from 9 to 8800 m². The sampling in each site was periodically repeated in order to investigate the moisture pattern as function of wetness conditions. The statistical properties of the measurements and the relation of the statistical parameters with the field-mean soil moisture content were analyzed. The results states that the probability distribution can be assumed normal for soil moisture in flat areas and for normalized soil moisture in gentle slope areas. A general decreasing trend of variance with increasing mean moisture content was observed. Moreover, considering the relationship between the field-mean water content and the coefficient of variation an optimal measurements number ranging from 15 to 35, in the worse case, was found for the study areas. The higher number was required for the site with more significant relief. These results were also confirmed through the geostatistical analysis and the correlation with the topographical attributes. Specifically, the correlation lengths were found increasing with the mean areal slope and the mean drainage direction and ranging between 10 and 15 m. This is corroborated through geostatistical analysis showing that the natural logarithm of the specific upslope area was the best spatial predictor for near-surface soil moisture when the water volume in the soil is higher. On this basis, the surface and subsurface lateral redistribution of water can be surmised fundamental in spatial organization of soil moisture.

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Introduction

The knowledge of soil moisture in the upper soil layer is of up most importance to assess the hydrological response of a catchment. In particular, the flood formation process in the Mediterranean area is strictly linked to the spatial variability of the soil moisture antecedent the rainfall event (Aronica and Candela, 2004). To characterize this variability even for a small catchment, remote sensing data should be used (Pietroniro et al., 1994; Pietroniro and Prowse, 2002), but their temporal resolution is unsuitable for flood prediction and mainly for flash floods. Moreover, these data are indirect measurements of soil moisture that must be verified through accurate on-site measurements. For this reason, in practice, the spatial pattern of soil moisture has to be inferred through ground point measurements and rainfall-run-off data.

Generally, the analysis of the soil moisture measurements is carried out for two different scales: the meteorological scale (large areas) and the small catchment scale (small areas). As noted by Entin et al. (2000), the variance of the soil moisture spatial pattern is expected to be due to a small scale component dominated by soil type, topography and vegetation and a large scale component due to atmospheric quantities such as precipitation and evapotranspiration. Because of the different processes operating at a single scale, the results obtained for the meteorological scale can not be coupled with those of the smaller scale (Vinnikov et al., 1996; Yoo et al., 1998; Cosh et al., 2004). The contribution of the infiltration and the lateral soil moisture redistribution processes makes the small scale variability of more interest for the hydrological studies on flooding and erosion in medium and small catchments.

For small areas, several studies have been reported in literature differing with the sampling scheme and the methodologies used for assessing spatial variability. The sampling scheme (randomly, regular grid or transect) and the density of measurements were linked to the aim of the analysis and mainly to financial resources. In fact, the classical methods for ground point measurements (time domain reflectometry, gravimetric techniques and neutron probes) are time consuming and, hence, they were not generally used for routinely monitoring large areas. Famiglietti et al. (1998) reviewing 20 small scale near-surface soil moisture variability experiments assessed that most of them were plagued with low sampling frequency in space, time or both. Therefore, the necessity to identify a procedure for determining the optimal number of samplings in order to accurately estimate the mean moisture content is fundamental. This can be achieved through the knowledge of the statistical properties of the observed quantities in areas with different topographical, soil type and land use characteristics.

The methodologies used to assess the soil moisture spatial variability can be grouped as

- (a) Statistical analysis, aimed to define the probability density function of the sampled soil moisture and to characterize its variability through the coefficient of variation.

- (b) Geostatistical analysis, aimed to describe the variance between the point values sampled in a spatial field as a function of their distance and to assess if the soil moisture pattern is continuous in space or erratic.
- (c) Regression analysis, aimed to assess the factors influencing the soil moisture variability (topography, soil type, and land use) by using one or more observed patterns.

Most of the published studies considered more than one sampling scheme and more than one methodology. However, the results were different according to the study area, and this makes their use in other climatic regions questionable.

Based on the above contents, the objectives of the paper are:

- to make a peer review of the background on the near surface soil moisture spatial variability for the small scale studies;
- to analyze the soil moisture data collected in different sites of an interior region in Central Italy, in order to determine their statistical properties and to investigate their spatial structure also in relation with topography;
- to address the issue concerning the minimum spot measurements number to estimate the mean water content in a given area within a threshold of error.

Background analysis

In this section, previous studies on spatial variability of near surface soil moisture content, θ , at small catchment scale are reviewed, with particular emphasis to the more recent contributions. For each study, Table 1 reports some synthetic characteristics of the area investigated, the statistical properties of the soil moisture samplings and the measurement method.

As regards the statistical distribution of θ , its knowledge is important because several hydrological, ecological and atmospheric processes are nonlinearly related to soil moisture. Although most of the previous studies did not investigate the statistical distribution, several authors analyzing spot measurements over grids and transects located mainly in flat areas (Hills and Reynolds, 1969; Bell et al., 1980; Hawley et al., 1983; Vachaud et al., 1985; Francis et al., 1986; Munoz-Pardo et al., 1990; Nyberg, 1996; Anctil et al., 2002 and Buttafuoco et al., 2005) found the soil moisture content normally distributed. However, Loague (1992) noted that only the soil moisture sampled along linear transects was normally distributed, on the contrary of that sampled over a grid of points. In an intensive soil moisture campaign carried out in 1997 for the Southern Great Plains hydrology experiment (SGP97), Famiglietti et al. (1999) analyzed more than 11,000 impedance probe measurements of soil moisture. They ascertained that the distribution of θ evolved from negatively skewed/non-normal under very wet conditions, to normal in the midrange of mean moisture content, to positively skewed/non-normal under dry conditions. From a deep inspection of Table 1 and referring

Table 1 Main characteristics of previous studies on soil moisture variability

Authors	Location	Land use	Soil	Slope (%)	Area (m ²)	Method	Depth (cm)	NS	NSP	Argt	SP (m)	M (%)	CV	NOR (%)
Bell et al. (1980)	Jefferson Kansas	Agric	Silt-loam	0	16E4	Grav	15	29	19	G+I	90	16.6	0.11	100
	Finney Kansas		Clay	0	16E4		15	8	36	G	60	20.3	0.10	
	Phoenix Arizona		Clay-loam	2	16E40		15	24	19–35	G+I	30–133	29.3	0.08	
	Hand S. Dakota		Loam	5	16E4		10	10	36	G	60	18.4	0.17	
Hawley et al. (1983)	Oklahoma, USA C3	Bare soil	Silty-loam	0.3	17.9E4	Grav	0–15	4	16	I	50	25.1	0.21	100
	Oklahoma, USA C4	Bare soil		0.3	12.1E4				16			24.1	0.23	
	Oklahoma, USA C5	Winter wheat		0.3	5.1E4				16			29.3	0.16	
	Oklahoma, USA C6	Winter wheat		0.3	5.3E4				15–16			22.9	0.18	
Vachaud et al. (1985)	Oklahoma, USA R5	Pasture		4	9.6E4				33–92			28.0	0.20	
	Oklahoma, USA R6	Pasture w.m.		4	11E4				25			29.0	0.18	
	Oklahoma, USA R7	Pasture w.m.		4	7.8E4				25			24.6	0.16	
	Oklahoma, USA R8	Pasture p.m.		4	7.5E4				32–38			26.6	0.23	
	Grenoble France	Grass	sand + silty-clay	0	2000	NWM	100	24	17	G	10	31.3	0.17	100
	Sevilla Spain	Agric	?	?	?	NWM		8	9	I	Random	?	?	?
	Mornag Tunisia	?	Sand + silt + clay	0	100	Grav		2	19	T	5	?	?	100
	Medjez el bab Tunisia	?	Sand + silt + clay	0	1E4	NWM		3	25	G	20	?	?	100
Munoz-Pardo et al. (1990)		Agric	Sandy-loam	0	1.2E4	Grav	100	3	81	G	12.5	16.6	0.14	100
Loague (1992)	R5 Oklahoma, USA	Agric	Silt-loam	3	9E4	Grav	10	1	157	G	25	30.0	0.10	0
					250				50	T	5	30.0	0.10	100
					100				50	T	2	34.0	0.06	100
	Lucky Hills Arizona	Range land	Sandy-loam	20	4.4E4	TDR	15	4	33	G	30	?	?	?
Whitaker (1993)					260			4	52	T	5	?	?	?
					245			4	49	T	5	?	?	?
					4.4E4			4	134	G+T	18.1	11.7	0.19	?
					4.4E4			4	134	G+T	18.1	9.6	0.16	?
Nyberg (1996)					4.4E4			4	134	G+T	18.1	8.7	0.16	?
					4.4E4			4	134	G+T	18.1	11.7	0.15	?
					250			1	258	T	1	11.1	0.11	?
					1			1	51	I	0.14	12.1	0.19	?
Famiglietti et al. (1998)	Gardsjon Sweden	Forest	Sandy-silty	20	0.04	TDR	15	1	20	I	0.045	22.4	0.09	100
					1			1	35	I	0.17	22.3	0.14	100
					100			1	36	I	1.7	20.9	0.36	100
					6300			2	70	I	9.5	26.4	0.38	100
Famiglietti et al. (1998)					6300			2	60	G	10.2	31.2	0.34	100
	Rattlesnake hill, TX, USA	Grass	Gravelly-clay + clay	5.3	200	Grav	5	88	21	T	10	36.6	0.21	?

(continued on next page)

Western et al. (1998)	Tarrawarra Australia	Grass	Silt-loam	8	10.5E4	TDR	30	13	500	G	15	35.0	0.11	?
Fitzjohn et al. (1998)	Guadalajara central Spain	Forest	Gravel + silty-clay	22	3675	TDR	15	3	170	G	5	16.2	0.37	?
Famiglietti et al. (1999)	SGP97 LW03	Range land	Loamy-sand	10	64E4	Grav-IP	6	23	49	G	100	13.9	0.58	8.7
	SGP97 LW13	Range land	Loam	10	64E4			25	49			21.2	0.27	56.0
	SGP97 LW21	Winter wheat	Silty-loam	0	64E4			17	49			18.6	0.40	70.6
	SGP97 ER05	Range land	Silty-loam	10	64E4			20	49			34.5	0.16	95.0
	SGP97 ER13	Winter wheat	Silty-loam	0	40E4			23	27			26.1	0.19	78.3
	SGP97 CF04	Winter wheat	Silty-loam	0	64E4			23	49			27.4	0.22	82.6
Gómez-Plaza et al. (2001)	Murcia Spain	Grass-burnt	Loam	29	300	TDR	15	14	16	T	20	7.8	0.45	?
		Grass-burnt		30	300				16			8.9	0.39	?
		Grass-unburnt		31	200				11			11.1	0.40	?
Walker et al. (2001)	Nerrigundah Austr.	Grass	Loam	11	6E4	TDR	15	12	238	G	20	25.9	0.21	?
Anctil et al. (2002)	Canada	Agric	Organic soil	0	750	Grav	5	2	90	T	8	31.8	0.17	100
Hupet and Vanclooster (2002)	Louvain Belgium	Agric	Silt-loam	0	6300	TDR-NMM	0–125	60	28	G	15	30.0	0.09	100
Williams et al. (2003)	Guadalajara central Spain	Pine	Cambisol	30	4.4E4	TDR	15	4	767	G	5	49.5	0.29	?
		Oak	Cambisol	38	3.9E4				184			15.0	0.25	?
		Scrub	Regosol	40	3.0E4				143			11.5	0.42	?
		Olives ab.	Calcisol	12.5	4.2E4				186			10.0	0.39	?
		Olives cult.	Calcisol	14	3.3E4				149			35.0	0.40	?
		Cultivated	Regosol	12	7.7E4				350			9.5	0.54	?
Chaplot and Walter (2003)	Armorican Massif France	Grass	Loam	5	3.8E4	TDR	10	16	149	G	10	38.8	0.45	?
Meyles et al. (2003)	Dartmoor UK	Grass	Sand	13	12.000	Grav	0–120(3)		112		Random	?	?	?
Fernandez and Ceballos (2003)	Duro basin Spain	Agric	Sandy-loam	8	12.9E7	TDR	20	19	140	G	10	57.9	0.11	?
Petrone et al. (2004)	Quebec Canada	Agric	Peat	0	1200	TDR	15	3	336	G	2	77.7	0.40	?
				0	9E4			3	57	G	30	74.7	0.44	?
				0	254			2	508	T	0.5	?	?	?
Western et al. (2004)	Tarrawarra 1 Austr.	Grass	Silt-loam	8	10E4	TDR	30	8	145	G	30	31.5	0.12	?
	Tarrawarra 1 and 2 Austr.		Silt-loam	8	45E4			8	470		40	30.5	0.13	?
	Point Nepeau Austr.		Sand	8	13E4			6	589		15	10.3	0.30	?
	Carran's New Zeal.		Silt-loam + clay	14	5E4			6	485		10	36.6	0.16	?
	Satellite Station New Zeal.		Clay-loam	16	60E4			6	368		40	40.8	0.06	?
	Clayden's New Zeal.		Clay	14	13E4			6	273		20	42.0	0.07	?
Buttafuoco et al. (2005)	South Italy	Pine forest	Sandy-loam	30	567	TDR	45	9	152	G	3	20.6	0.20	100
	Sila Massif													

NSP, number of sampling points; NS samplings number; Avg (G, grid; T, transect; I, irregular); SP, sampling spacing; M, mean; CV, coefficient of variation; NOR samplings following normal distribution; ? information not available; Method (NMM, neutron probe; IP, impedance probe; Grav, gravimetric method; TDR, time domain reflectometer).

mainly to the results reported in Famiglietti et al. (1999), θ does not follow the normal distribution in areas characterized by a significant relief. In fact, in these cases the soil water lateral redistribution becomes meaningful as suggested by the connected structure showed by the samplings (Western et al., 1998b).

Another important issue in the statistical analysis concerns the relationship between the variance or the coefficient of variation of θ and its mean areal value. From a practical point of view, the knowledge of this relationship allows: (1) to optimize the number of sampling points to represent with a fair accuracy the field mean (Hills and Reynolds, 1969; Reynolds, 1974; Bell et al., 1980; Owe et al., 1982); (2) to estimate the error associated with a prescribed number of sampling points; (3) to assess the variability of θ within an area once known its remotely sensed mean value; (4) to define the wetness conditions for which the remote sensing monitoring is more accurate (Charpentier and Groffman, 1992). Following Western et al. (2003), Fig. 1 shows the smoothed relationship between mean and variance for the studies reported in Table 1 and based on an adequate number of data. They were grouped in accordance with the relationship trend. In particular, the spatial variability of θ in humid climates is greater for drier soil moisture pattern (see Fig. 1b), whereas in semi-arid environments the spatial variability increases as the soil moisture pattern gets wetter (see Fig. 1a). This corroborates the findings of theoretical studies by Cunningham et al. (1978) and Dunin and Reyenga (1978). For the coefficient of variation-mean relationship a more general pattern was detected, with most of the cases of Table 1 showing a decreasing trend. Moreover, the value of the coefficient of variation was found ranging from 0.05 to 0.58, with higher values for sandy soils and for semiarid climates. We note that these quantities are, in particular, much lower than the corresponding values observed for the saturated hydraulic conductivity (Loague and Gander, 1990; Corradini et al., 1998).

Geostatistical techniques are more and more used to characterize the spatial soil moisture pattern (Vachaud et al., 1985; Warrick et al., 1990; Nyberg, 1996; Bardossy and Lehmann, 1998; Western et al., 1998c; Entin et al., 2000; Anctil et al., 2002; Meyles et al., 2003; Petrone et al., 2004; Western et al., 2004). The central concept of geostatistics is the experimental variogram representing the variance as a function of distance between measurement points. Its main feature is the range defined as the distance at which the variogram levels off (the sill) and beyond which observations appear independent. Directly related to the range, the correlation length is a measure of the spatial continuity of the variable of interest (Western et al., 1998c, 2004). Generally, the correlation length for θ ranges between 0.7 and 650 m, but it is dependent on the scale of the study and on the density of the measurements (Western and Blöschl, 1999). By plotting the values of the range obtained for the studies of Table 1 using the geostatistics, against both the investigated area extension and the spacing between the measurement points, a clear direct proportionality was observed. This implies that the lack of a spatial correlation ascertained in some previous investigations may be due both to a sampling spacing greater than the range and to a small sample size (Western et al., 2004). Instead of the variogram, some authors (Vachaud et al., 1985; Loague, 1992) employed correlogram which, as pointed by Rossi et al. (1992), is more robust when local mean and variance vary substantially as might occur for soil moisture fields. Finally, Western et al. (1998b, 2001) pointed out that the standard geostatistical techniques are not able to capture the spatial connectivity of soil moisture linked to the hydrological behavior of a catchment.

At the small catchment scale and the hillslope scale, θ might vary spatially due to soil water lateral redistribution (Beven and Kirby, 1979; Moore et al., 1988; Williams et al., 2003), radiation effects (Moore et al., 1993; Western et al., 1999), heterogeneity in soil characteristics (Hu et al.,

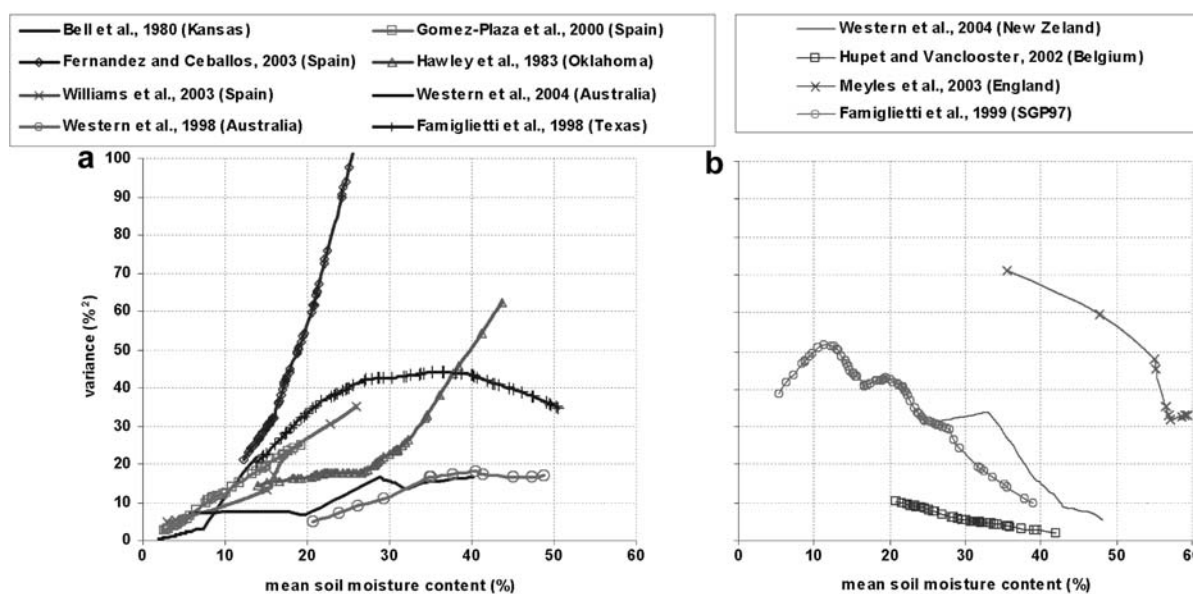


Figure 1 Smoothed relation between mean soil moisture content and variance for different studies on near-surface soil moisture spatial variability for: (a) increasing and (b) decreasing trend.

1997; Famiglietti et al., 1998; Seyfried, 1998) and vegetation characteristics (Qiu et al., 2001; Hupet and Vanclooster, 2002). That is, the topography and land use affect the distribution of water over and within the land surface according with the general soil moisture status (Grayson et al., 1997). As the soil moisture pattern depends on the runoff mechanisms which are seldom parameterized through terrain indices, many authors investigated the relation between the soil moisture spatial pattern and the primary terrain attributes (slope, elevation, aspect or curvature) or the compound topographic indices such as the steady state wetness index of Beven and Kirby (1979). Other attributes were recently analyzed; among them the land elevation above the drainage channel (Crave and Gascuel-Odux, 1997), the downslope gradient (Merot et al., 1995), the bedrock topography (Chaplot and Walter, 2003), and the landscape unit (Park and van de Giesen, 2004; Wilson et al., 2004). The more general and systematic investigations on the role of topography were reported by Famiglietti et al. (1998) and Western et al. (1999). In particular, Famiglietti et al. (1998) explored the temporal pattern of the correlation between topographical attributes, soil properties and soil moisture measured along a profile of length 200 m. They highlighted that under wet conditions, the best correlation exists with porosity and hydraulic conductivity; whereas with relative elevation, aspect and clay content, under dry conditions. Western et al. (1999) analyzed the correlation between topographical attributes and thirteen soil moisture samplings for the Tarrawarra catchment (Australia). The authors, quite consistently with Famiglietti et al. (1998), found that during wet conditions the best predictor of the soil moisture spatial pattern is the specific area, linked to the lateral redistribution process, whereas during dry conditions it is the potential solar radiation index (or aspect), linked to the evapotranspiration process. The combination of these two indices was found generally able to predict the majority of the organized component of the soil moisture spatial variability for the Tarrawarra catchment.

Study area and measurements

The field experiments for spatial variability of soil moisture were carried out on three sites of an inland region of central Italy, located in the Upper Tiber Valley which are indicated henceforth as Ponte della Pietra (PPI), Ingegneria (ING) and Colorso (COL). The region is characterized by a Mediterranean semi-humid climate (Pandey and Ramasastri, 2001), with precipitation occurring mostly in the autumn–spring

period. Considering the period 1951–1999, the mean annual rainfall for the first two sites was 823 mm and 936 mm for the third one. The maximum mean monthly rainfall occurs in November (101 mm for the first two sites and 130 mm for the third one) and the minimum is in July (40 mm for all sites). In summer, the mean of the minimum and maximum temperature is 16.9 °C and 26.7 °C, respectively, while in winter is 3.2 °C and 9.7 °C, respectively (period 1951–1999).

The near-surface (15 cm) volumetric soil moisture content was sampled by a portable unit using a two wire connector-type time domain reflectometry (TDR) probe of the Soilmoisture Equipment Corporation TRASE® TDR. The equipment has a quoted error of $\pm 2\%$ vol/vol or less. Table 2 summarizes the main characteristics of each study site with a synthetic description of the soil moisture samplings. Fig. 2 shows the framework of the sites with the location of the measurement points.

The first site, PPI, is located inside an experimental field for soil moisture and runoff monitoring settled up by the Department of Civil and Environmental Engineering of Perugia University. The land use is a nearly homogeneous grassland with an erratic presence of tap-roots. The soil consists of three horizons. The topsoil, until a depth of 1.5 m, is composed by a light brown silty clay with a significant presence of organic matter. Under this layer, until a depth of 3.5 m, a yellowy silty clay is present, and, more in depth, a bluish clay. The surface soil cracks during dry periods. In the area a TDR system for continuous soil moisture monitoring at seven locations and three depths was set up along with a system for the determination of surface and subsurface runoff. Four rain gauges, a meteorological station and an evapormeter are also present in the field. The near surface soil moisture measurements were carried out with a portable TDR unit in a flat plot of $\sim 400 \text{ m}^2$ ($45 \text{ m} \times 9 \text{ m}$) on a regular grid of $3 \text{ m} \times 3 \text{ m}$ and repeated 14 times in a period of two months from August to September, 2002. In October 2002, further three series of measurements over a smaller plot of 9 m^2 ($3 \text{ m} \times 3 \text{ m}$) with a finer resolution ($0.3 \text{ m} \times 0.3 \text{ m}$) were performed. A total of 930 TDR measurements were collected in PPI site.

The second site, ING, is localized near the Engineering Faculty of Perugia University. The mean slope of the plot is 7% (maximum 25%). The land use is a non-homogeneous grassland and the soil is mainly sandy-clay loam with a significant presence of shingle. The near surface soil moisture measurements were carried out in an area of $\sim 5000 \text{ m}^2$ ($100 \text{ m} \times 50 \text{ m}$) on an irregular grid with a resolution of about 10 m. The measurements were repeated 14 times in a period of four months from February to May, 2004. A total of 700 TDR measurements were collected in ING site.

Table 2 Description of study sites and soil moisture samplings

Name	Soil type	Land use	Dimension (m × m)	Measurement period	Spacing (m)	NS	NSP
Ponte della Pietra (PPI)	Silty-clay	Grass	45 × 9	13/08/02–24/09/02	3.0	14	45
			3 × 3	02/10/02–04/10/02	0.3	3	100
Ingegneria (ING)	Silty-sand	Grass	100 × 50	13/02/04–31/05/04	~10.0	14	50
Colorso (COL)	Sandy-loam	Grass	110 × 80	29/10/02–11/01/06	10.0	7	108
			20 × 20	21/04/05	2.0	1	121

NS, samplings number; NSP, number of sampling points.

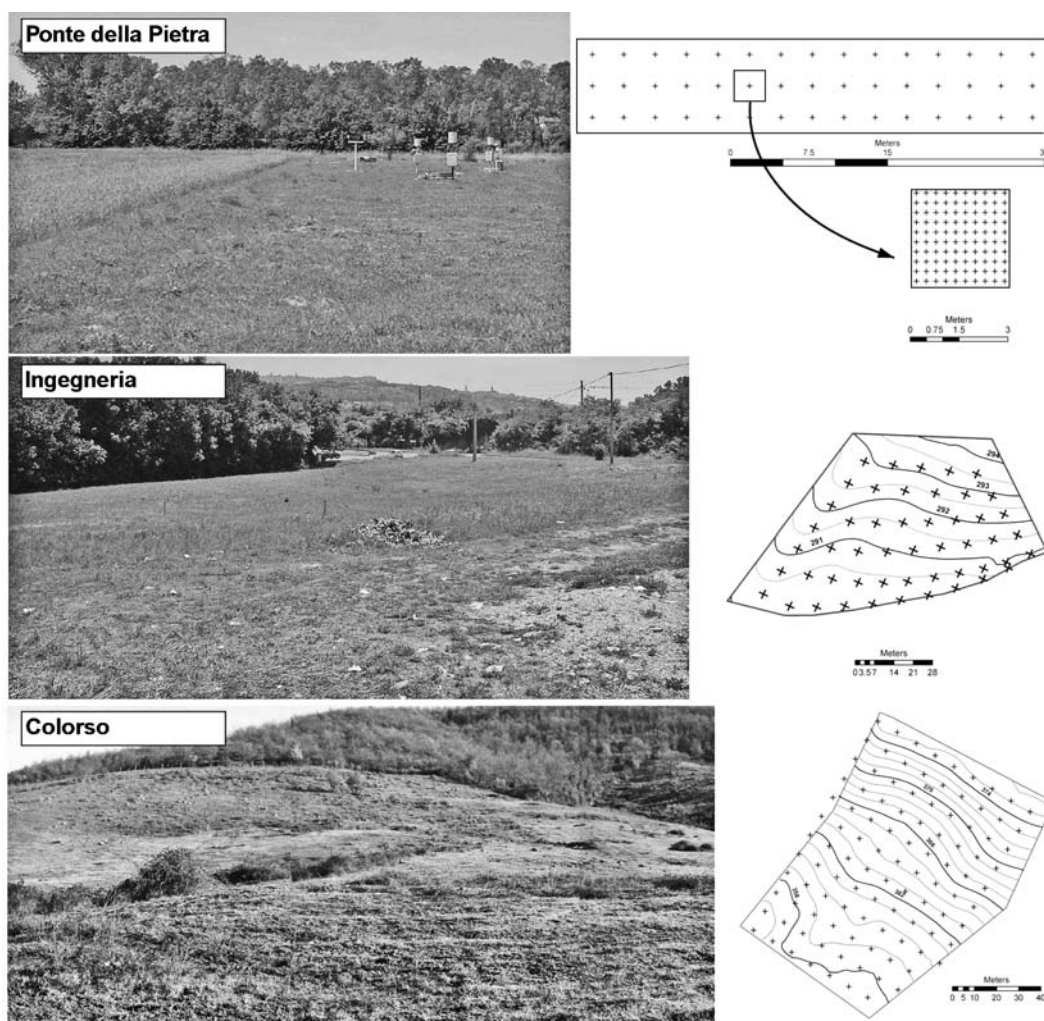


Figure 2 Photographs of study sites with schematic representation of soil moisture sampling points (+) and topographic contours with labelled elevation (in m a.s.l.).

The third site, COL, is located inside a small experimental catchment of area 12.9 km^2 set up for studying the rain-fall-runoff relationship. The plot has an extension of $\sim 9000 \text{ m}^2$ ($110 \text{ m} \times 80 \text{ m}$), and a mean slope of 12% (maximum 70%). The area is vegetated mostly with natural grasses (permanent pasture) and it is used for grazing of beef cattle. On the basis of textural analysis, the soil was classified as loamy sand until a depth of 0.3 m, and silt loam until a depth of 1.5 m (*Typic Haplustept*). A TDR system has been operating since 2002 for continuous soil moisture monitoring at six locations and three depths along with one rain gauge. The near-surface soil moisture measurements were carried out on a regular grid and were repeated 6 times from April 2005 to January 2006. Another more intensive campaign of measurement over irregular grid was performed on 29 October, 2002; in order to compare the results with the other grids, the data was resampled with a resolution of $\sim 10 \text{ m}$. Moreover, a campaign in a portion of the area of extension of 400 m^2 ($20 \text{ m} \times 20 \text{ m}$), on a regular grid of $2 \text{ m} \times 2 \text{ m}$, was carried out to better investigate the soil moisture spatial behavior for short distances. A total of 877 TDR measurements were collected in COL site.

Results and discussion

In the following, the analysis of the results obtained for the soil moisture data collected at the three study sites is grouped in accordance with the three different methodologies employed.

Statistical analysis

The main statistical characteristics of the field data set are reported in Table 3. As the number of the samplings in the sites of PPI and ING is greater, the results obtained for them are reported and discussed to a greater extent. In particular, Fig. 3 shows the daily rainfall pattern and the box plots of the soil moisture measurements. As can be seen, the mean moisture content responds predictably to rainfall, with a fast increase after a storm event and a slow decrease in the periods without rainfall.

Table 3 shows that PPI site experienced a higher soil moisture content in respect to the other two sites, even if the measurements were carried out in different periods (see Table 2). This behavior was confirmed through some

Table 3 Near surface soil moisture statistics for the data set collected at the three study sites (D plot dimension in m × m, CV coefficient of variation)

Study site	Date	Mean (%)	SD (%)	CV	Range (%)	25° p. (%)	75° p. (%)	Kurt.	Skew.	χ^2
Ponte della Pietra(PPI)										
D = 45 × 9	13/08/2002	34.9	2.45	0.07	29.1–39.2	33.5	36.5	2.73	−0.48	2.5*
	13/08/2002	34.7	1.98	0.06	29.3–37.7	33.7	36.0	3.45	−0.92	10.3*
	19/08/2002	26.9	2.53	0.09	20.6–32.6	25.6	28.3	3.39	0.15	7.8*
	22/08/2002	28.6	3.08	0.11	21.6–36.6	27.1	29.6	3.84	0.3	9.6*
	29/08/2002	36.6	1.61	0.04	30.6–38.6	35.8	37.9	5.48	−1.32	8.9*
	03/09/2002	32.9	2.34	0.07	28.7–37.9	31.1	34.9	2.10	−0.16	6.0*
	04/09/2002	33.6	2.62	0.08	28.5–37.6	31.8	35.6	2.06	−0.38	3.5*
	05/09/2002	38.7	1.20	0.03	35.2–41.4	38.3	39.2	4.66	−0.62	6.7*
	09/09/2002	36.0	1.68	0.05	30.3–38.5	35.0	37.1	4.19	−0.72	6.7*
	10/09/2002	35.5	1.92	0.05	30.8–38.9	34.3	36.9	2.55	−0.34	1.0*
	11/09/2002	35.5	1.61	0.05	30.0–38.4	34.9	36.7	4.95	−1.16	12.4**
	13/09/2002	32.9	2.26	0.07	29.3–36.4	30.9	34.8	1.71	−0.17	10.3*
	20/09/2002	28.4	1.94	0.07	24.0–34.8	27.4	29.3	5.43	0.75	9.2*
	24/09/2002	39.6	1.50	0.04	36.5–43.1	38.7	40.3	2.86	0.52	17.4 ^a
D = 3 × 3	02/10/2002	34.3	1.56	0.05	30.1–37.0	33.6	35.3	3.18	−0.66	12.0**
	03/10/2002	33.1	1.71	0.05	29.6–36.4	32.0	34.3	2.36	−0.22	1.9*
	04/10/2002	33.1	1.73	0.05	29.2–37.2	32.4	34.3	2.81	−0.3	4.8*
Ingegneria(ING)										
D = 100 × 50	13/02/2004	28.2	3.56	0.13	19.5–35.0	26.0	30.0	2.82	−0.34	13.4**
	20/02/2004	37.6	3.82	0.10	29.3–47.6	35.1	39.3	3.18	0.23	7.0*
	02/03/2004	35.2	5.81	0.17	26.2–53.0	30.8	37.9	3.87	0.88	12.1**
	05/03/2004	30.7	3.96	0.13	21.0–38.5	28.1	33.8	2.88	−0.11	13.0**
	12/03/2004	34.1	3.78	0.11	27.4–40.7	30.5	37.3	1.75	−0.26	14.3**
	17/03/2004	28.8	4.49	0.16	15.8–38.5	27.2	31.0	3.64	−0.53	10.8*
	26/03/2004	30.7	3.63	0.12	22.4–38.5	28.5	32.7	3.07	−0.02	7.0*
	02/04/2004	30.1	3.45	0.11	21.5–37.3	28.2	32.7	2.90	−0.16	7.6*
	07/04/2004	27.8	4.95	0.18	15.2–36.1	26.6	30.6	3.22	−0.85	22.0 ^a
	22/04/2004	31.7	6.25	0.20	22.2–51.5	27.5	34.1	5.08	1.42	25.5 ^a
	27/04/2004	29.3	4.60	0.16	19.2–41.6	26.9	32.6	3.00	0.36	12.4**
	10/05/2004	33.7	5.34	0.16	23.0–46.3	29.1	36.1	3.00	0.33	6.3*
	20/05/2004	23.3	3.98	0.17	15.8–32.4	20.5	26.2	2.60	0.23	3.8*
	31/05/2004	21.8	5.40	0.25	15.1–36.9	17.8	24.0	3.24	1.04	22.6 ^a
Colorso(COL) D = 110 × 80	29/10/2002	29.8	2.08	0.08	21.2–36.7	28.9	30.9	4.21	−0.03	22.5 ^a
	21/04/2005	38.2	5.02	0.13	27.2–52.5	35.5	39.9	3.31	0.56	23.0 ^a
	28/04/2005	34.5	5.39	0.16	26.1–48.9	30.5	37.7	3.03	0.93	22.5 ^a
	05/05/2005	24.8	7.13	0.29	13.3–46.6	19.6	29.9	2.84	0.69	13.8**
	27/09/2005	28.1	3.18	0.11	17.0–36.7	26.9	29.5	5.17	−0.48	20.0 ^a
	02/12/2005	39.7	4.72	0.12	27.8–54.2	37.2	43.3	3.14	0.29	24.0 ^a
	11/01/2006	38.7	5.35	0.14	29.0–55.7	35.1	41.1	3.27	0.61	13.9**
D = 20 × 20	21/04/2005	34.1	2.56	0.07	27.2–38.7	32.5	36.13	2.40	−0.1	7.5*

*,** normal with 5% and 1% significance level, respectively.

^a non normal.

erratic measurements (not reported in this study) performed contemporaneously in PPI and ING sites, and can be ascribed to the soil type which in the former area presents an elevated value of clay content. For PPI site the coefficient of variation was found very low, ranging between 0.03 and 0.11, and lower than that of the other two sites, which present an average value of about 0.06 (ING) and 0.15 (COL). Moreover, it was similar for the sam-

plings in the small plot carried out in the period 2–4 October, 2002. On the contrary, for COL site the coefficient of variation was half-reduced for the sampling carried out in the small plot on April 21, 2005. Moreover, we point out that the value of the coefficient of variation for this last sampling is similar to those of PPI site characterized by the same areal dimension (~400 m²). Finally, a close inspection of Table 3 reveals that: (a) for all sites the

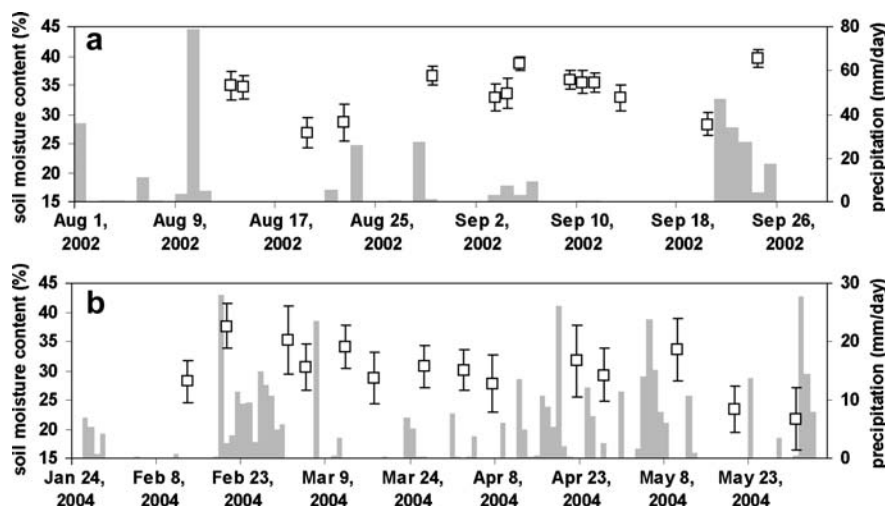


Figure 3 Time series of precipitation (grey bar) and near-surface soil moisture samplings (box plot with error bars corresponding to $\pm$ SD) for the sites of: (a) PPI; (b) ING.

range of the field-mean moisture content is nearly 5 times greater than the range of the standard deviation; (b) some of the samplings at PPI site shows a standard deviation comparable with the quoted error of the TDR equipment.

The statistical characteristics were investigated in relation to the field-mean moisture content, $\bar{\theta}$, in order to test if the θ variability is linked to the wetness conditions. Specifically, Fig. 4a highlights a general decreasing trend of variance with increasing mean moisture content, more regular for PPI site. This behaviour makes the measurement error

relatively more important for wetter conditions and is consistent with the previous works carried out in humid and semi-humid climates (see Fig. 1b). However, as pointed by Jacobs et al. (2004), the relationship between soil moisture variability and $\bar{\theta}$ becomes more evident when standard deviation is scaled by $\bar{\theta}$.

For the above reason the relationship between the coefficient of variation and the mean soil moisture was deeply investigated in order to have indications on the number of point measurements required to estimate a reliable mean value or on the accuracy of soil moisture remote sensing

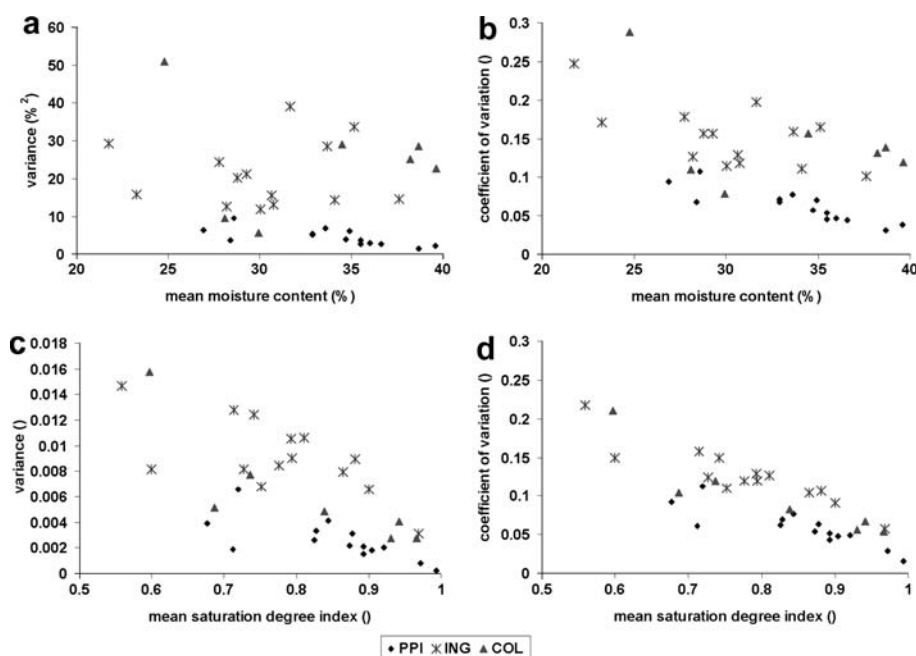


Figure 4 Correlation between statistical parameters for the investigated sites: (a) variance versus mean moisture content, (b) coefficient of variation versus mean moisture content, (c) variance versus mean saturation degree index, Eq. (1), and (d) coefficient of variation versus mean saturation degree index, Eq. (1).

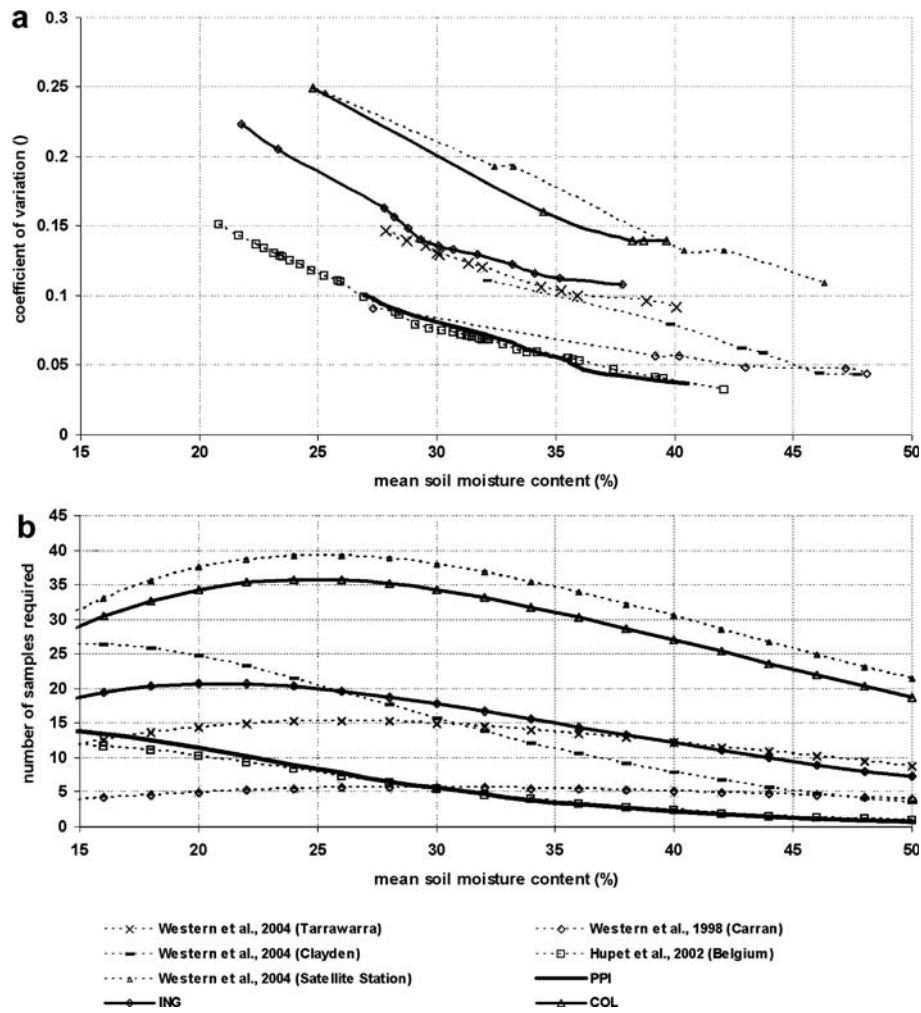


Figure 5 (a) Smoothed relationship between mean moisture content and coefficient of variation for the experimental campaigns carried out in this study and in other previous studies. (b) Number of independent soil moisture samples required to capture the field mean moisture content with a 95% confidence interval and an error of $\pm 2\%$, for the same experimental campaigns of (a).

for regions of Central Italy. Specifically, a decrease in the relative variability, measured by the coefficient of variation, with increasing mean moisture content was observed for all the three study sites (Fig. 4b). Also in this case a more robust relationship was observed for PPI site. These results are in conformity of other experimental campaigns reported in the literature (see Fig. 5a) and carried out in different regions (Australia, New Zealand and Belgium). The three different patterns showed in Fig. 5a seem to be related mainly to the site mean slope, as the soil type is not greatly different. The relationship between $\bar{\theta}$ and the coefficient of variation can be represented by an exponential law, $CV(\bar{\theta}) = A \exp[-B(\bar{\theta})]$ (Bell et al., 1980; Owe et al., 1982; Jacobs et al., 2004) which allows to quantify the number of required samples in relation to the mean moisture content and to the confidence interval. In fact, for a significant level α (i.e. with $1 - \alpha$ confidence interval) the error, e , will not exceed a specific volumetric soil moisture content with a sample size of $n = \left(\frac{z_{\alpha/2} \sigma(\bar{\theta})}{e} \right)^2$, with $\sigma(\bar{\theta}) = CV(\bar{\theta}) \cdot \bar{\theta}$ and $z_{\alpha/2}$ is the standard normal variable with exceedance probability $\alpha/2$. Fig. 5b shows the number of independent sam-

ples required to obtain a value of the field mean moisture content within an error less than $\pm 2\%$, at a 95% confidence interval, for the sites reported in Fig. 5a. Analogously with the other investigations, results show that for our study sites the highest measurements number is required under almost dry conditions. A strong analogy can be inferred between PPI site and the site investigated by Hupet and Vanclooster (2002) having a negligible relief and between COL site and Satellite Station characterized, from the other hand, by a significant topography. To assess accurately the field mean soil moisture more resources are needed for COL site with a number of measurements ranging from 25 to 35. For the other two sites the maximum measurements number was found less than 20, corresponding to a field mean soil moisture content of 15% and 20% for PPI and ING site, respectively. Moreover, for all sites the number of measurements effectively collected was much higher, making the field mean moisture content data set very accurate.

Another important issue of the statistical analysis is the knowledge of the probability distribution of soil moisture content, which allows to assess its variability within remote

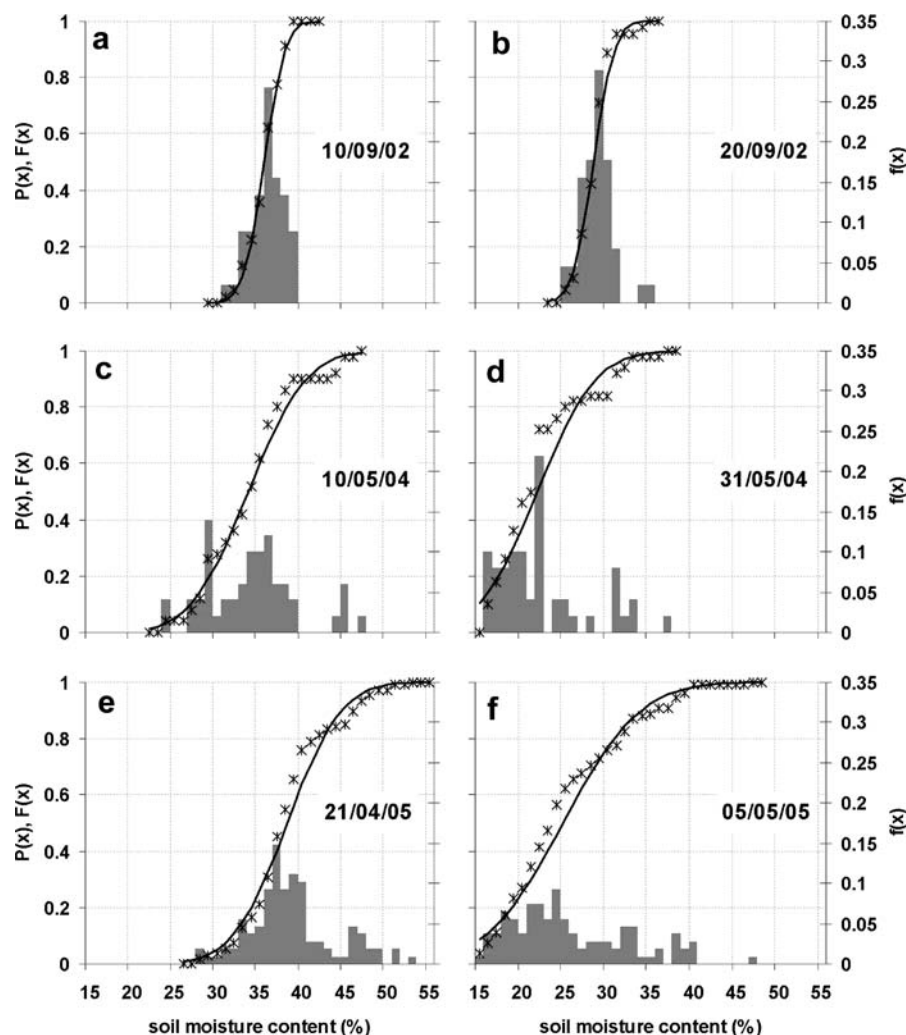


Figure 6 Relative frequency distribution, $f(x)$, (histogram) and cumulative frequency, $F(x)$, against theoretical normal probability function, $P(x)$, for samplings during a dry-down sequence: (a,b) PPI site; (c,d) ING site; (e,f) COL site.

sensing footprints or within homogeneous catchment elements in distributed rainfall-runoff modelling. On the basis of previous analysis reported in the scientific literature, the near-surface moisture content was supposed to follow a normal probability distribution. Specifically, considering the χ^2 test and a significance level of 5%, 14 of 17 samplings of PPI site (16 of 17 at 1%), 6 of 14 samplings (11 of 14 at 1%) for ING site and 1 of 8 samplings (3 of 8 at 1%) for COL site follow the normal distribution. From these results, can be inferred that only the data sampled at PPI site, characterized by a flat terrain, can be considered normally distributed and the soil moisture spatial pattern random. For the other sites the distributions appearing normal are not linked to the wetness conditions. Moreover, considering the sampling of April 21, 2005 carried out at the COL site, the distribution has low probability to be normal for the larger area and high probability being normal for the small plot, revealing a spatial pattern at the larger extent.

In order to test if the soil moisture variability is linked to a particular condition of the soil (drying or wetting), the frequency distributions of the samplings carried out during an interstorm period were considered. Fig. 6 shows the normal

probability function, the relative frequency distribution as well as the cumulative frequency for two successive samplings during a dry-down sequence for the three study sites, whereas Fig. 7 shows the corresponding near surface soil moisture map. According to Famiglietti et al. (1999), the distribution of θ was found to evolve from negatively skewed under wet conditions to positively skewed under dry conditions for PPI site, with an high probability to be normal. For COL site an increase of the skewness was also observed even if only one dry-down sequence was available. Specifically, the skewness was positive for all the three samplings carried out during the interstorm period April–May 2005 (see Table 3), and through the χ^2 statistic test the hypothesis of a normal distribution can not be assumed. Finally, for ING site a general behavior was not observed.

The above results might be influenced by a spatial deterministic trend. In fact, Grayson et al. (1997) argued that soil moisture pattern is expected to be highly organized with a significance influence of topography under wet conditions, whereas in dry conditions the pattern is more patchy and vegetation, soil properties and micro-relief are most important. To remove a possible trend, the moisture content ob-

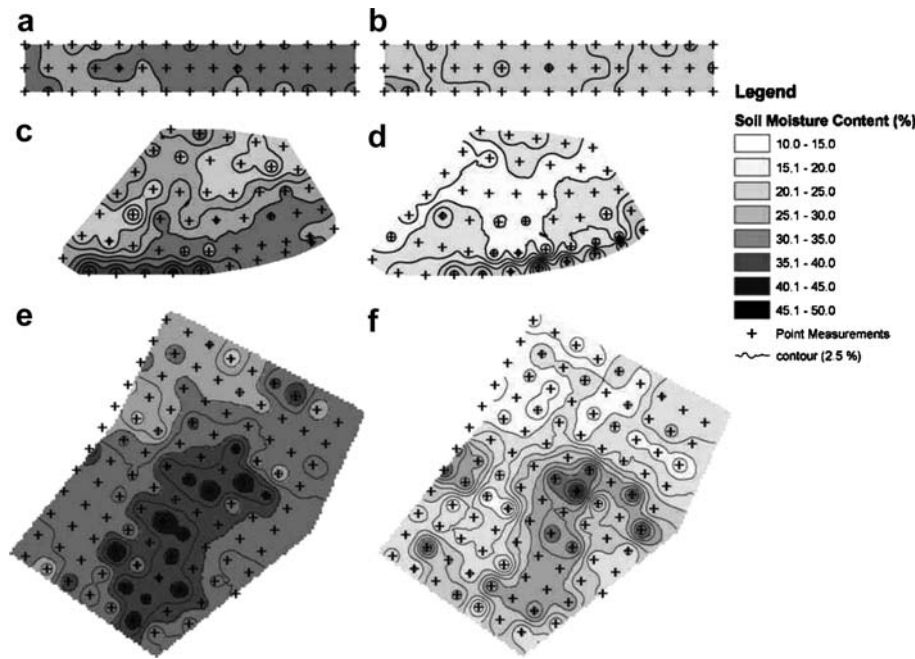


Figure 7 Near-surface soil moisture maps for the samplings in Fig. 6.

served at time j at position i , θ_{ij} , was scaled by the maximum value, $\theta_i^{\max}$, observed at the same location, as follows:

$$\hat{\theta}_{ij} = \theta_{ij} / \theta_i^{\max} \quad \text{for } i = 1, \dots, \text{NSP } j = 1, \dots, \text{NS} \quad (1)$$

where:

$$\theta_i^{\max} = \max(\theta_{ij})_{j=1, \dots, \text{NS}} \quad \text{for } i = 1, \dots, \text{NSP} \quad (2)$$

with NSP the number of measurement points for each sampling and NS the number of samplings for each location. Obviously, in this case the samplings carried out in the small plot of PPI and COL sites were not considered. The new variable, $\hat{\theta}_{ij}$ can be assumed as an index of the saturation degree even if it should be related to soil properties rather than the observed maximum water content. We note that for each study site, $\theta_i^{\max}$ was observed for the same sampling for almost all the measurement locations. Through the χ^2 test for normality with a 5% significance level, it can be assumed that 12 of 14 samplings collected at PPI site, 11 of 14 samplings collected at ING site and 5 of 7 samplings collected at COL site follow the normal distribution. Therefore, using the saturation degree index, the number of samplings for which a normal distribution can be assumed increases for ING and COL sites characterized by a gentle slope orography. Comparing Fig. 4b and d highlights that $\hat{\theta}_{ij}$ for ING and COL sites is characterized by a more robust decreasing trend than that between the mean moisture content value and the coefficient of variation whereas the pattern keeps unchanged for PPI site. The same happens for the relationship mean value-variance (see Fig. 4a and c). Moreover, both the coefficient and the variance become comparable for all sites. This analysis reveals that removing the influence of local variability, which can be supposed to be mainly linked to topography, ING and COL sites behave in a random manner such as the case of the flat site of PPI.

In order to corroborate the results obtained for the areas investigated here, the analysis of the soil moisture probabil-

ity distribution was also done by using two further data set selected from the data base of the Tarrawarra (Western et al., 1998a) and Nerrigundah (Walker et al., 2001) catchments. Specifically, for the first catchment the data set consists of 13 samplings covering an area of 105,000 m² with the same measurement locations (NSP = 454) on a 20 m × 10 m grid. For the Nerrigundah catchment the data set consists of 12 samplings carried out during a one month intensive field campaign (August–September 1997) covering an area of 60,000 m² with the same measurement locations (NSP = 238) on a 20 m × 20 m grid. The data were collected by using of a two-wire connector-type time domain reflectometry (TDR) probe with a probe length of 30 cm and 15 cm for the Tarrawarra and the Nerrigundah catchment, respectively. The two catchments are characterized by an undulating terrain with a mean slope of 8% and 11% for the Tarrawarra and the Nerrigundah catchment, respectively. In particular, for the Tarrawarra catchment Western et al. (1999) noted that the topography explains up to 61% of the spatial variation of soil moisture during wet periods. For a 5% significance level the χ^2 test for normality was verified for only 1 of 13 samplings for Tarrawarra and 3 of 12 samplings for Nerrigundah. On the contrary, for the scaled moisture content, $\hat{\theta}_{ij}$, 10 of 13 and 11 of 12 samplings followed the normal distribution for the Tarrawarra and the Nerrigundah catchment, respectively.

Geostatistical analysis

To further explore the nature of soil moisture variability, a geostatistical analysis was executed based on the empirical correlogram and semivariogram. Interested readers should refer to textbooks such as Journel and Huijbregts (1978), Isaaks and Srivastava (1989), Goovaerts (1997) for a detailed presentation of the theory of random functions.

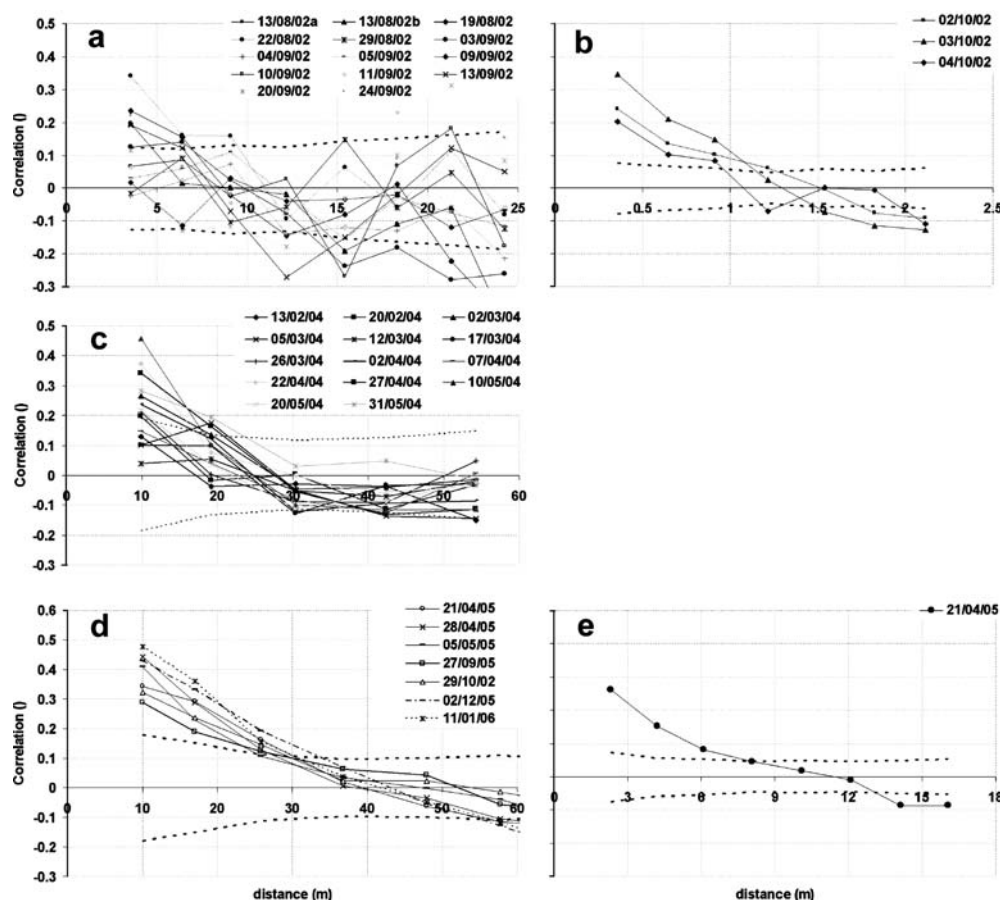


Figure 8 Correlograms of near-surface soil moisture data for: (a) PPI site, (b) small plot of PPI site, (c) ING site, (d) COL site, (e) small plot of COL site. The dashed lines indicate the approximate 95% confidence limits.

Fig. 8a reports the empirical correlograms for all the samplings collected in the larger plot of PPI site. As can be seen, there is a good deal of scatter revealing the absence of a significant correlation except 4 of the 14 samplings at the shortest lag bin of 3 m. Because these samplings refer to very different soil wetness conditions, it is reasonable to assume a random spatial pattern for soil moisture in flat areas of Central Italy as found by Hawley et al. (1983), Mohanty et al. (2000) and Hupet and Vanclooster (2002) for other countries. For the same site, the spatial structure was also investigated for the small grid ($3\text{ m} \times 3\text{ m}$) with a finer resolution. In this case, a significant correlation for distances less than 1.2 m was observed (see Fig. 8b), but these distances are not of interest for hydrological applications. For ING site the empirical correlograms reveal a weak correlation to a distance of nearly 20 m (Fig. 8c), with higher values for the sampling distance of 10 m. On the contrary, for COL site a significant correlation can be surmised for distances not exceeding 30 m and 9 m for the large plot (Fig. 8d) and the small plot (Fig. 8e), respectively. The comparison of the empirical correlograms obtained for the large and the small plot of PPI and COL sites pointed out the influence of both the areal extent and spacing in the determination of the geostatistical properties of a soil moisture sampling (Western et al., 1999; Petrone et al., 2004). In particular, the maximum distance with

a non negligible correlation was 40% and 30% of the small plot dimension and the large one, respectively. We note that the adopted spacing distance was about 10% of the plot dimension.

The empirical semivariograms were estimated only for the samplings characterized by a significant correlation and, hence, for ING and COL sites. Moreover, as in almost all previous geostatistical analysis of soil moisture content, an exponential model with nugget was assumed for the theoretical semivariogram in order to characterize the geostatistical properties of each realization. Figs. 9a and b show the empirical and the theoretical semivariograms for the samplings on selected dates of ING site and all dates of COL site. As can be seen, the nugget is nearly zero for all the samplings. A close inspection of Fig. 9a reveals that the soil moisture content at ING site is characterized by a correlation length of 14 m for wet conditions (April 2, 2004 and April 27, 2004), whereas the correlation length decreases to 9 m under dry conditions (May 20, 2004 and May 31, 2004). A similar behaviour can be found (see Fig. 9b) for COL site; the semivariograms of the wet period (December–January) showed a correlation length of about 18 m against 14 m for the drier April–May period. Moreover, the sampling carried out after a long dry period (September 27, 2005) presents the lowest spatial continuity. This confirms the findings of Grayson et al. (1997) and Fitzjohn

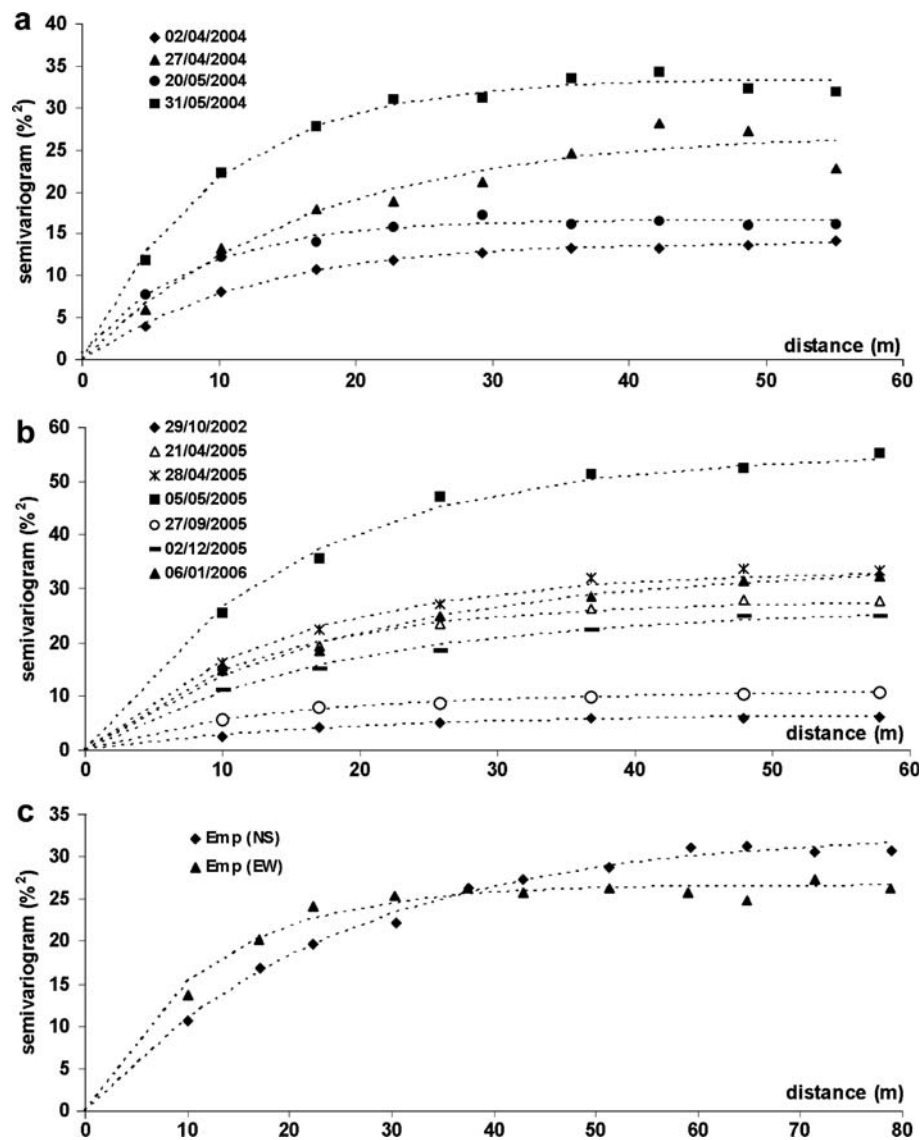


Figure 9 Comparison of empirical and theoretical semivariograms of near-surface soil moisture for: (a) ING site, (b) all samplings of COL site, and (c) specific directions of all samplings of COL site.

et al. (1998) that under wet conditions the soil moisture pattern has a spatial organization stronger than under dry conditions. Furthermore, the correlation length under wet conditions might be higher because the measurement error is expected to be spatially uncorrelated and, as just pointed out, it becomes relatively more important for these conditions. The correlation lengths estimated in this work are in agreement with those obtained by Loague (1992), Whittaker (1993), Nyberg (1996), Fitzjohn et al. (1998) and Williams et al. (2003) in areas of comparable dimension. Moreover, the obtained results suggest that the soil moisture pattern tends to be controlled by topography (Western et al., 1998c; Western et al., 2003), with correlation length increasing with the plot slope. To this end, Fig. 9c reports the directional semivariograms computed for COL site. In particular, for the North–South direction, representing the direction of principal drainage, the correlation length

(24 m) was found higher than that relative to the perpendicular direction (11 m).

Regression analysis

The previous analysis revealed different statistical and geostatistical properties of soil moisture in PPI site respect to those observed in ING and COL sites. Moreover, for the last two sites the soil moisture spatial pattern seems to be significantly influenced by the within-field variations of topographical attributes, considering that other factors in process control (i.e. soil texture, vegetation cover, precipitation and evapotranspiration) are not significant in the context of the small area investigated. To deepen this aspect, for each sampling a regression analysis (Famiglietti et al., 1998; Western et al., 1999) with the topographical attributes was conducted. At the purpose the selected

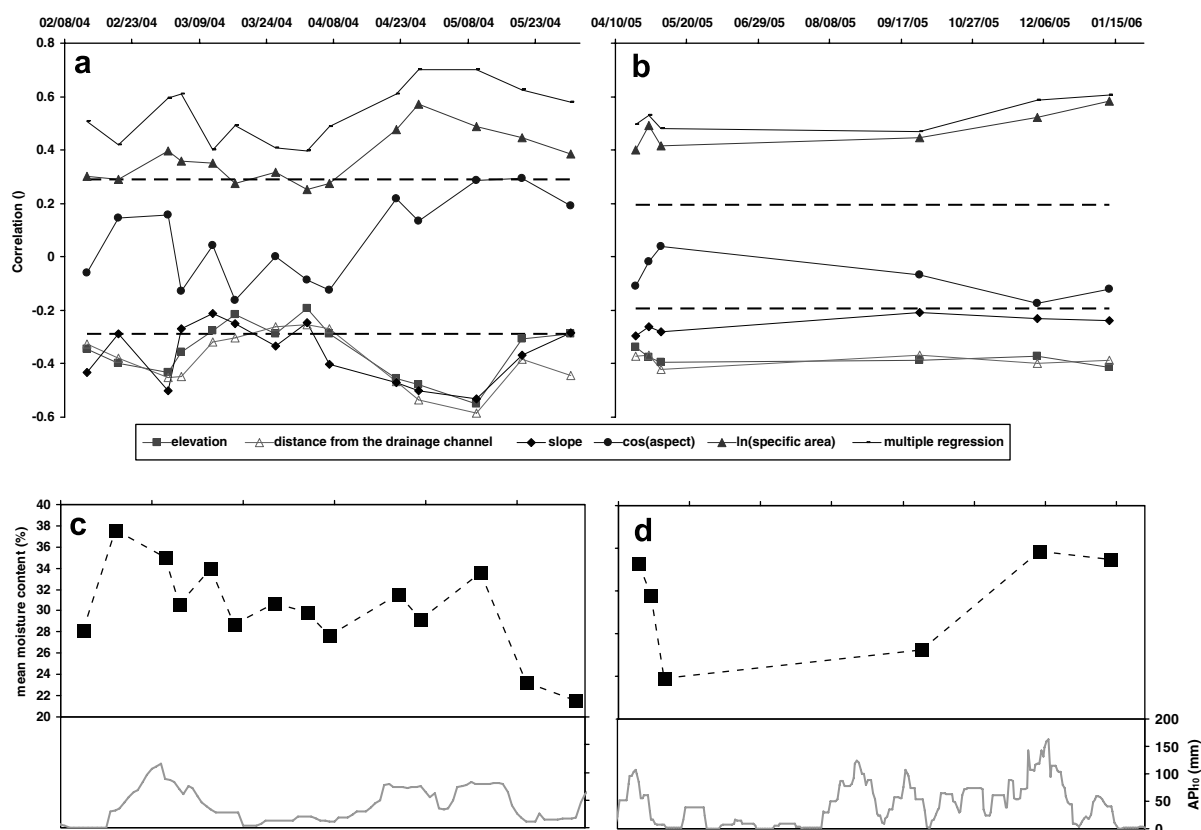


Figure 10 Correlation coefficient of soil moisture content with terrain indices for: (a) ING site, and (b) COL site. (the dashed lines indicate the approximate 95% confidence limits). Mean value of near-surface soil moisture for: (c) ING site, and (d) COL site. The cumulated precipitation over 10 antecedent days (API₁₀) is also shown.

terrain attributes were: elevation, slope, cos(aspect), mean curvature, tangent curvature, profile curvature, distance from stream bank, specific area computed through the algorithm of Quinn et al. (1991), and the topographic wetness index of Beven and Kirby (1979) widely used in hydrological modelling. In order to obtain accurate primary terrain attributes, they were first computed from a grid-based digital elevation model with a resolution of 2 m. Then the grid was resampled at a coarser resolution (5 m) equal to half of the sampling spacing, and exploited to estimate the topographic data corresponding to each point measurement. Fig. 10a and b show the correlation of soil moisture content with the significant topographic attributes for ING and COL site, respectively. These attributes are: logarithm of specific area, exhibiting a positive correlation; slope, distance from the stream bank, elevation, all exhibiting a negative correlation as found by Famiglietti et al. (1998) and Chaplot and Walter (2003); and cos(aspect), not exhibiting a specific behaviour. For ING site, Fig. 10a shows that the specific area attribute has an evident specular pattern respect to the other variables and higher values when the water volume in the soil is expected to be high, as suggested by the antecedent precipitation (Fig. 10c), and significant lateral redistribution (Western et al., 1999; Gómez-Plaza et al., 2001). However, the topographic attribute explains from 16% to 50% of the observed spatial variance defined as the correla-

tion square. As measurement errors can affect the calculated correlations, a correct coefficient of determination was computed assuming that the measurement error contributes to unexplained variance (Western et al., 1999). For the sampling of 2nd April, 2004 characterized by the lowest value of the observed spatial variance, 11.9 (% vol/vol)², the explained variance by topographic attributes was 1.94 (% vol/vol)². Considering the measurement error, the observed variance may reduce up to 7.9 (% vol/vol)² and hence the explained variance may increase up to 25%. Similar results were obtained by Western et al. (1999). For the other samplings the effect of the measurement error is smaller. For COL site, Fig. 10b shows that the specific area attribute is the best predictor and explains up to 36% of the spatial variation in soil moisture suggesting that lateral distribution plays a significant role also in this sloping plot. This can be also deduced by comparing the sampling of 21st April, 2005 with that of 11th January, 2006 having the same mean and variance of the near-surface soil moisture content. The specific area explains 16% and 36% of the total variance for the first and the second sampling, respectively. This means that topographic organization is greater during winter owing to extensive saturation control (Western et al., 1999). For both sites the topographic wetness index (not shown) did not furnish a substantial improvement, respect to the simple specific area, to explain the spatial

pattern of soil moisture content. This is in agreement with the findings of Famiglietti et al. (1998) and Western et al. (1999) for areas with significant relief. Moreover, improvements were not obtained by using a multiple regression with the primary topographical attributes, especially for COL site.

Conclusions

The near-surface soil moisture data set collected in different sites of Central Italy was investigated from a statistical and geostatistical point of view and in relation to topographical attributes. Specifically, for each approach the following insights can be drawn.

Statistical analysis

1. The coefficient of variation of the soil moisture samplings was found equal to ~ 0.1 much lower than that of the saturated hydraulic conductivity.
2. A general decreasing trend of variance with increasing mean moisture content was observed in accordance with the previous analysis carried out in humid and semi-humid climates making the measurement error relatively more important for wetter conditions.
3. An optimal measurements number ranging from 15 to 35 in the worse case was found for the study areas. The higher number was required for the site with more significant relief.
4. The probability distribution can be assumed normal only for soil moisture samplings collected in the flat study area.
5. Removing the local variability from the soil moisture spatial pattern, i.e. normalizing the samples with the maximum observed value of each site, the normal probability distribution can be assumed also for samplings collected in areas with non negligible topography.
6. A negative correlation between mean moisture content and skewness was observed only for the flat area.

Geostatistical analysis

1. For the flat area, where the spatial organization of soil moisture was found erratic, a correlation length cannot be identified.
2. For the areas with significant slope a connected structure was highlighted from the soil moisture spatial pattern, with correlation length of ~ 10 m for ING site and ~ 15 m for COL site.
3. An anisotropic structure with major correlation length along the drainage line was observed for COL site.

Regression analysis

The results of regression analysis confirm the importance of topography in the determination of soil moisture spatial pattern and hence of the lateral redistribution process, which has to be considered in the hydrological simulation. In particular:

1. The soil moisture spatial pattern was found correlated with the specific contributing area, the slope, the elevation and the distance from the drainage channel. The explained variance did not improve by using the wetness index.
2. The best correlation with the above mentioned topographical attributes was observed in the wetter conditions. Moreover, when the experimental plots are sufficiently wet to allow significant lateral contribution, the specific contributing area itself can account for almost all the variance explained by the topographic attributes.

Summarizing, for the three sites analyzed in this study the principal differences was found linked to their topographic characteristics. Whereas the flat site presents a random soil moisture spatial pattern, following the normal probability distribution, without a significant correlation length, the rolling sites present a soil moisture spatial distribution strongly linked to the topography with a correlation length ranging between 10 and 15 m.

The results and the data presented here can be useful to determine, as a function of the wetness conditions, the number of point measurements required to estimate the mean moisture content of a specific area in inland regions of the Mediterranean environment. Another important aspect concerns the remote sensing monitoring as regards the representation of the subgrid variability. Furthermore, these results can be addressed in the parameterization of soil moisture dynamics in hydrological and land surface problems.

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