Topsoil moisture mapping using geostatistical techniques under different Mediterranean climatic conditions

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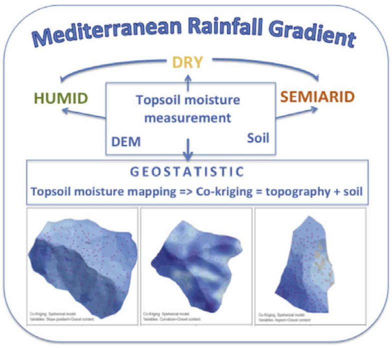
HIGHLIGHTS

- This study deals with topsoil moisture mapping in rangelands under different Mediterranean climatic conditions.
- Topsoil moisture is highly variable in space in the studied environments and controlled by topography and soil properties.
- Field survey and geostatistical techniques were combined for accurately mapping topsoil moisture.
- Topsoil moisture was mapped through kriging and co-kriging techniques considering topography and soil properties.

GRAPHICAL ABSTRACT



Keywords:
Rainfall gradient
Topsoil moisture
Topography
Ordinary kriging
Co-kriging
Mediterranean

ABSTRACT

Soil mapping has been considered as an important factor in the widening of Soil Science and giving response to many different environmental questions. Geostatistical techniques, through kriging and co-kriging techniques, have made possible to improve the understanding of eco-geomorphologic variables, e.g., soil moisture. This study is focused on mapping of topsoil moisture using geostatistical techniques under different Mediterranean climatic conditions (humid, dry and semiarid) in three small watersheds and considering topography and soil properties as key factors. A Digital Elevation Model (DEM) with a resolution of 1 × 1 m was derived from a topographical survey as well as soils were sampled to analyzed soil properties controlling topsoil moisture, which was measured during 4-years. Afterwards, some topography attributes were derived from the DEM, the soil properties analyzed in laboratory, and the topsoil moisture was modeled for the entire watersheds applying three geostatistical techniques: i) ordinary kriging; ii) co-kriging considering as co-variate topography attributes; and iii) co-kriging ta considering as co-variates topography attributes and gravel content. The results indicated topsoil moisture was more accurately mapped in the dry and semiarid watersheds when co-kriging procedure was performed. The study is a contribution to improve the efficiency and accuracy of studies about the Mediterranean eco-geomorphologic system and soil hydrology in field conditions.

1. Introduction

In the Mediterranean region, rainfall gradients can be found in mountainous areas (Imeson and Lavee, 1998; Lavee et al., 1998; Ruiz-Sinoga et al., 2010a,b,c, 2011a,b, 2015). The hydrological and erosive response within the eco-geomorphologic system including climate, vegetation, soil and water as well as human activity are highly dependent on the annual rainfall (Lavee et al., 1998). This occurs due to those elements are modified with the rainfall variability which introduces changes in the abiotic and biotic factors but dependent on the scale approach: for instance, at catchment scale, both land use and vegetation patterns highly control soil erosion, whilst soil structure and spatial organization influence at patch scale (Cammeraat, 2004; Imeson and Lavee, 1998). Various studies have highlighted topsoil moisture as a key variable in the description of many hydrological and climatological processes (Pachepsky et al., 2003; Vereecken et al., 2007). In particular, regulation of matter and energy flow between the soil and the lower layer of the atmosphere is controlled by soil moisture, and is characterized by high spatial and temporal variability at finer scales (Bell et al., 1980; Brocca et al., 2007; Hupet and Vanclooster, 2005; Lin et al., 2006; Ruiz-Sinoga et al., 2011b; Schume et al., 2003). Likewise, its variations have substantial influence on nutrient losses and availability (Schmidt et al., 2011). Soil moisture is variable in space and time and, thus, the knowledge of their variability across spatio-temporal scales is important to the understanding of land surface processes, highly dependent on topography (Beven and Kirkby, 1979; Florinsky et al., 2002; Qiu et al., 2001; Western et al., 1999), soil properties, vegetation and climate (Koster and the GLACE Team, 2004; Bolten et al., 2010; Lin, 2011; Ruiz-Sinoga et al., 2010b).

Brevik et al. (2016) stated soil mapping have been important drivers in the advancement of our knowledge of soil since the beginnings of the scientific study of soils, indicating as well that, although many advances have been made since 19th century, there are still many unanswered questions and additional needs in soil mapping. Nevertheless, accordingly these authors, the geospatial revolution introduced tools and technologies such as geographic positioning systems (GPS), geographic information systems (GIS), remote sensing, GIS-linked proximal sensing, and spatial statistics. The techniques mentioned, greatly improve the ability to collect, analyze, and predict spatial information related to soils (McBratney et al., 2003; Scull et al., 2003; Lagacherie, 2008).

From recent decades, geostatistical techniques have been applied for soil modelling and mapping, which become an extremely useful tool in Soil Science (Sauer et al., 2006). Geostatistical techniques, e.g. kriging, let calculate the spatial autocorrelation between sample points and quantify uncertainty (Goovaerts, 1999). The prediction accuracy of these techniques may be improved applying spatial association via covariates (Odeh et al., 1995; Adhikari et al., 2013; Holleran et al., 2015). Also, it exits the so-called hybrid interpolation techniques which combine two conceptually different approaches to modelling and mapping spatial variability as the interpolation relying solely on point observations of the target variable with the interpolation based on regression of the target variable on spatially exhaustive auxiliary information (Hengl et al., 2007). One of these hybrid interpolation techniques, not very frequent used, is known as regression-kriging (Hengl et al., 2004), which first uses regression on auxiliary information and then uses simple kriging with known mean to interpolate the residuals from the regression model. This allows the use of arbitrarily-complex regression methods, including generalized linear models (Hengl et al., 2007). Another geostatistical technique is the cokriging, useful when there is availability of auxiliary information what is important to optimize sampling schemes (Minasny and McBratney, 2006; Shaner et al., 2008) and to serve as ancillary variable in the local prediction of a soil property (Vašát et al., 2010). Thus, cokriging can be applied whether there are two or more spatially interdependent variables, which incorporates those interdependent variables into spatial interpolation in order to obtain high prediction accuracy with limited sample data (Wang et al., 2013). Nonetheless, according to Brevik et al. (2016), spatial interpolation methods are by nature limited to the area between samples and often require a sampling density that is not practical for mapping large areas as well as the construction of stable semivariograms (the main tool on which geostatistics is based) requires considerable amount of geo-referenced data (Davidson and Csillag, 2003). All these geostatistical techniques have been applied to characterize the spatial distribution of soil moisture content and its variability (Vieira et al., 2008). During the last decades, great efforts were undertaken to detect spatio-temporal variability of soil moisture content by using geostatistics (Wang et al., 2001; Brocca et al., 2007; Schneider et al., 2011; Baroni et al., 2013; Korres et al., 2015; Yang et al., 2016).

In accordance with the previous statements, the hypothesis is the following: under contrasted Mediterranean climatic conditions, soil moisture is spatially dependent on i) rainfall supply, ii) topography and other iii) soil properties in watershed with no changes in geology and land use. The objectives are: i) characterizing the spatial variability of soil moisture in three watersheds located under different conditions of rainfalls; ii) mapping soil moisture through geostatistical techniques; and iii) selecting topography attributes and soil properties to improve the mapping of soil moisture. Accordingly, this investigation may provide an improvement of the soil sampling and mapping efficacy in Mediterranean eco-geomorphological environments.

2. Study area and field sites

This study was based on the climatic gradient approach which let compare sites with similar topography, geology and land use conditions but differing in climate (Imeson and Lavee, 1998). The study area covered a Mediterranean mountainous region and corresponds to three field sites located in South of Spain, Gaucín, Almogía and Gérgal watersheds as indicate in the Fig. 1. The rainfall gradient in the study area was defined by the analysis of a rainfall database (1960–2006) that included a total of 395 pluviometric stations distributed from the Straits of Gibraltar to Almería along the Bética Mountains (Ruiz-Sinoga et al., 2015). A rainfall gradient map was derived using cokriging through a model of linear coregionalization with two direct variograms and one cross variogram with two variables: annual rainfall and elevation. Afterwards, the three watersheds were selected according to the criteria of differences in rainfall regime and similarities in topography, parent material and land use, using aerial photography and fieldwork.

The main characteristics of the three watersheds were selected as experimental field sites are presented in the Table 1. These experimental sites were selected because of their similarity in topography, parent material and land use, what permits a suitable comparison of results: steep slope gradient (SG), metamorphic lithology and land use of rangeland. Gaucín watershed is the most humid field site (humid Mediterranean climate) where vegetation cover is high (>80%; evergreen oaks and scrubland) and enhances infiltration processes. The driest field site is Gérgal watershed whose climatic conditions correspond to semiarid Mediterranean, characterized by evident signs of water erosion, with very shallow soil, a high number of rock fragments on soil surface and rock outcrops. Almogía watershed is the field site located in intermediate climatic conditions (dry-Mediterranean climate) characterized by evergreen oaks and dense scrubland; bare soil areas are not abundant but can be characterized by rock fragment covers major than 50%. From Gaucín to Gérgal watersheds, we observed a reduction in the quality, fertility and resistance to degradation according to the soil properties of each study area, taking into account properties such as texture, organic matter (OM), aggregate stability and cation exchange capacity. More details from the field sites can be found in Ruiz-Sinoga and Romero-Diaz (2010), Ruiz-Sinoga et al. (2010b, 2011a,b, 2012).

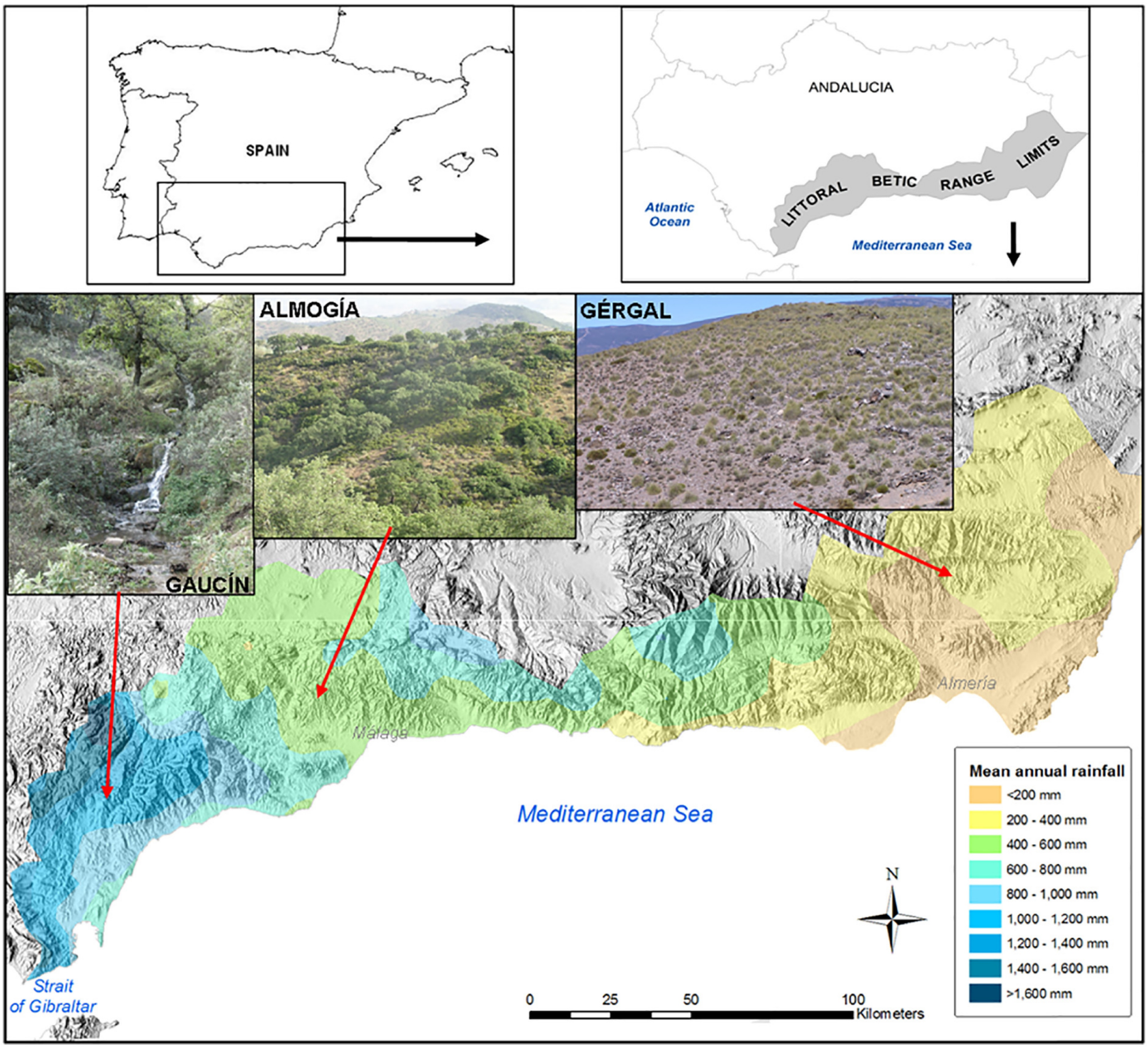


Fig. 1. Rainfall gradient in South of Spain and location of field sites.

3. Methodology

3.1. Field survey and soil sampling and analysis

A detailed topographical survey was performed in order to obtain the Digital Elevation Model (DEM) from the three watersheds. The DEM was of 1 × 1 m of spatial resolution (Fig. 2). Afterwards, a total of 404 points were randomly distributed within the watersheds to measure soil moisture in field conditions as follows: 170, 114 and 120 in Gaucín, Almogía and Gérgal watersheds, respectively. The topsoil moisture was measured between 0 and 10 cm of depth every two week during 44 months, from Feb-2007 to Sep-2010. Moisture was measured using a TDR-Tektronix 1502C cable tester with a probe inserted vertically into the soil. In total, 88 visits were made to each watershed.

In order to characterize soil properties that influence in soil moisture, a number of samples were taken according to the sampling surface area of the watersheds, using a ratio of 1 soil sample per 1000 m^{-2}; in total, 270, 180 and 210 in Gaucín, Almogía and Gérgal watersheds, respectively. All of them were taken in similar eco-geomorphologic conditions than those of the soil moisture sampling points but not in the same one. Besides, other soil samples were randomly taken in the three watersheds in order to give consistency to the cokriging techniques later described. Two samples were taken at each sampling point: one was a disturbed soil sample and the other was undisturbed, using a cylinder of 100 cm^3. The soil properties considered were the following: gravel content, texture, soil organic carbon (SOC), bulk density, porosity, permeability and aggregate stability. Texture was assessed by sieving using the method of Robinson (1922). SOC was analyzed using the AFNOR method of carbon measurement (AFNOR, Association Française de Normalisation, 1987). Porosity was determined using a pycnometer as well as water holding capacity with a sand-box and Richard's membrane. Finally, the aggregates stability was measured by means of wet sieving (Kemper and Rosenau, 1986). Other soil properties were also analyzed to characterize soils with the following methods: soil acidity (pH) was measured in a deionized water suspension of the soil (2.5:1) using a Crisol GLP 21 pH meter; soil salinity (EC) in a deionized water suspension of the soil (5:1) using a Crisol Micro CM 2200 conductivity meter (ISRIC, 2002); and cationic exchangeable capacity (CEC) was determined by saturating the exchange sites with an index cation (NH_4^+) using 1 N NH_4OAc at pH 8.2 (Bower et al., 1952).

3.2. Statistical and spatial analysis

3.2.1. Statistical analysis

The statistical analysis was performed in order to evaluate the difference in soil moisture and topography attributes between the three

Table 1
Eco-geomorphologic features from the three field sites. Abbreviations: VC, vegetation cover; BD, bulk density; ASF, aggregate stability fraction; SOC, soil organic carbon content; OM; organic matter content; EC, electrical conductivity; CEC, cationic exchangeable capacity; Ksat, saturated hydraulic conductivity.

Field site	Gaucín	Almogía	Gérgal
Climate	Humid - Mediterranean	Semiarid Mediterranean	Semiarid - Mediterranean
R (mm $year^{-1}$)	1100	550	240
T (°C)	14.9	15.6	13.9
Area (ha)	10.9	7.8	8.2
Altitude (m)	625–729	526–588	1090–1165
Parent material	Phyllites	Phyllites	Schists
VC (%)	90	75	35
Vegetal species	*Quercus suber, Quercus faginea, Quercus ilex, Cistus salvifolius, Erica arborea, Cistus albidus, Phlomis purpurea, Pistacia lentiscus, Calicotome villosa.*	*Quercus suber, Cistus monspeliensis, Cistus albidus, Phlomis purpurea, Lavandula stoechas, Helichrysum stoechas, Genista umbellata.*	*Stipa tenacissima, Thymus mastichina, Retama sphaerocarpa.*
Gravel (%)	52.6	63.0	57.6
Sand (%)	30.5	44.3	59.0
Silt (%)	46.9	35.2	28.1
Clay (%)	22.7	20.4	12.9
Texture	Loam	Loam	Sandy loam
BD (g cm^{-3})	1.08	1.13	1.44
ASF (%)	86.6	77.9	50.5
OM (%)	11.3	5.9	1.6
SOC (kg ha^{-1})	35,037.7	17,643.7	6392.9
EC (mS cm^{-1})	0.45	0.85	0.60
CEC	(meq 100 g^{-1})	33.0	20.5
8.9			
Ksat (cm h^{-1})	9.8	15.0	6.5

watersheds. Descriptive statistical tests, as mean, standard deviation and maximum and minimum values were calculated. The normality and homogeneity of variance were assessed by means of the Kolmogorov-Smirnov and Levene's test, respectively. Differences between variables were tested using analysis of variance (one-way ANOVA). The significance level of differences within variables was determined using the post hoc text of Tukey test; when variables were not parametric, the Games-Howell test was used. In all the analyses the selected significance limit was $p < 0.05$. The correlation between soil moisture and topography was carried out with the Pearson coefficient of correlation. Significant differences were observed at a $p < 0.05$. All these analyses were performed using SPSS software (version 21) for Windows (IBM Corp.).

3.3. Mapping of topography attributes

Some topography attributes including contour lines, slope gradient, aspect, flow length, drainage area as well as slope curvature were determined from the watershed DEMs using the 3D-Analyst tools of ArcGIS 10.3 (ESRI, Redlands, CA). Flow length and drainage area refer to the upstream distance along a flow path for each cell and the catchment size upwards a certain cell and the water division, respectively. Slope curvature refers to the curvature observed within the pixel: negative and positive values indicate convexity and concavity, respectively. These topographic variables were selected because of their influence in the soil hydrology, specifically, in the soil moisture. Afterwards, the Topographic Wetness Index (TWI) was also mapped; this index models the overland flow surface and subsurface dynamic based on the control which the topography exerts in both of them and thus in the spatial distribution of soil moisture. This was performed using the drainage area and slope gradient maps following the Eq. (1) (Sorensen et al., 2005):

$$TWI = \ln\left(\frac{af}{\tan\beta}\right) \quad (1)$$

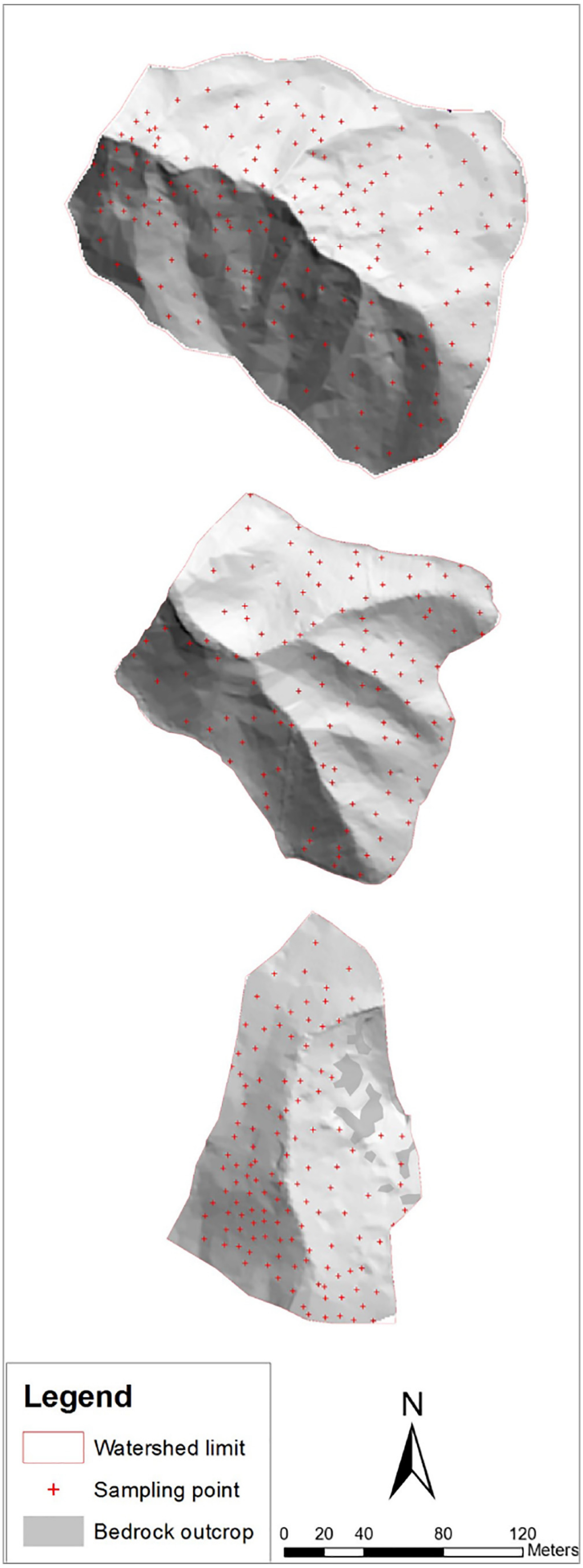


Fig. 2. Shaded-Digital Elevation Model (DEM) and spatial distribution of soil sampling points in the watersheds. Top, middle and bottom maps correspond to Gaucín, Almogía and Gérgal watersheds, respectively.

where: ln, napeirian logarithm; af, drainage area; $\tan\beta$, directional slope gradient. This algorithm partially expresses the relative volume and flow movement from one pixel to another: the major drainage area and lower slope gradient, the higher infiltration and saturation of soils.

3.4. Geostatistical analysis

The spatial auto-correlation of topsoil moisture was assessed in each watershed through geostatistical analyses, via the semivariogram, which measures the average dissimilarity of data as a function of distance (Goovaerts, 1999) as illustrated in Eq. (2):

$$\gamma(h) = \frac{1}{2N(h)} \Sigma_i \Sigma_{i+h} [Z(i) - z(i+h)]^2 \tag{2}$$

where γ is the semivariance for N data pairs separated by a distance lag h; and z the variable under consideration at positions i and i + h. Values were calculated for each possible pair of observation points and the mean values of the semivariance were displayed for chosen distance intervals to produce the experimental semivariogram (Chica-Olmo, 1987).

The variables were transformed in case of heteroscedasticity to approximate normality and to stabilize variance (Goovaerts, 1999; Olea, 2006; Reimann and Filzmoser, 2000). Anisotropy (effect of direction in the intensity of spatial dependence) was not taken into account, as this analysis required a higher number of samples for the construction of stable variograms in each direction. When number of samples is limited an omnidirectional (isotropic) characterization of spatial dependence is more recommendable (Davidson and Csillag, 2003). Thus, spatial correlation was assessed omnidirectionally due to there were no sufficient sampling points in the three watersheds to consider the analysis directionally. The standardization was achieved by dividing the semivariance data by the sample variance what allowed a fair comparison among field sites (Pozdnyakova et al., 2005). The half of the maximum sampling distance in each field site was considered as the lag distance in all semivariograms, being including >50 pairs per each lag distance class interval in the calculations. A logarithmic transformation of data was applied when the normal QQ plot showed that the data were not normally distributed, since the points in the plot did not form a straight line.

Once semivariograms were constructed, theoretical variogram models were fitted to the data. This was done by selecting and fitting the spherical model because the lowest residual sum of squares and highest R^2 were obtained in all cases (e.g., Cambardella et al., 1994; Davidson and Csillag, 2003; Gallardo and Paramá, 2007; Wei et al., 2008). The spherical model is defined in Eq. (3) (Liu et al., 2004; Pozdnyakova et al., 2005):

$$\gamma(h) = \begin{cases} Co + C\left[1.5\left(\frac{h}{a}\right) - 0.5\left(\frac{h}{a}\right)^3\right] & 0<h\leq a \\ = \{Co + C & h>a \end{cases} \tag{3}$$

where: γ, semivariance; h, distance; Co, nugget; Co + C, sill; and a, range. These parameters were used to describe and compare spatial structures of soil moisture in each watershed.

Ordinary kriging and two co-kriging approaches were used to interpolate topsoil moisture at unsampled locations. Ordinary kriging is a widely used interpolation technique that estimates the values at unsampled locations by a weighted averaging of nearby samples. The correlations among neighboring values were modeled as a function of the distance between the samples across the watersheds, defined by a variogram. Thus, ordinary kriging relies on a variogram representing the variance of the linear increments of a variable under the assumption of intrinsic stationary, and variogram models are then used to assign weights to neighboring points for the kriging function (Webster and Oliver, 2007).

An alternative to kriging is co-kriging, a specific method of analysis that includes auxiliary information incorporated into the estimation at un-sampled locations using the spatial correlation of the primary and secondary variables (Goovaerts, 1999). In the case of co-kriging, this approach relies on a cross-variogram and was fitted using the linear model of co-regionalization that fits a single spatial structure to both direct and cross-variogram by optimizing the partial sills and the nugget by least squares (Rossiter, 2012). In order to ensure a valid linear model of co-regionalization, any negative eigenvalues were set to zero and the eigenvectors were recomputed to ensure positive semi-definite matrices of the partial sills and the nugget (Pebesma, 2004). Deutsch and Journel (1998) indicated co-kriging methods are used to take advantage of the covariance between two or more regionalized variables that are related, and are appropriate when the main attribute of interest is sparse, but related secondary information is abundant. Accordingly, as Domenech et al. (2017) pointed out, cokriging needs two previous processes to improve prediction accuracy: i) a selection of the most important variables of auxiliary information characterized by high interdependence with the variable to predict (in our case, topsoil moisture); ii) selection of a model-based sampling scheme that allows quantifying of the spatial dependence and provide good area coverage for reliable prediction (Simbahan and Dobermann, 2006).

The common co-kriging methods are multivariate extensions of the kriging system of equations, and use two or more additional attributes. Co-kriging methods were attractive in our study because they allow for the effective incorporation of point-measured covariates if both feature space- and spatial-correlations can be verified. This geostatistical technique has been widely applied to map different soil properties (Yates and Warrick, 1987; Pei et al., 2010; Landrum et al., 2015).

Subsequently, topsoil moisture was modeled considering three geostatistical approaches: i) ordinary kriging was applied to obtain the prediction maps of topsoil moisture in the three watershed; ii) partially heterotopic co-kriging using one auxiliary variable (topography attribute) significantly correlated with the predicted variable (topsoil moisture); and iii) partially heterotopic co-kriging using two auxiliary variables (topography attribute and soil property).

The ratio between nugget and sill was calculated to characterize the spatial dependencies of soil moisture: a ratio < 25 shows a strong dependence, 25–75 a moderate dependence, and >75% a weak dependence (Cambardella et al., 1994). The range was also assessed in all the geostatisical techniques. The spatial model evaluation criteria were performed with the leave-one-out cross validation method, which estimates the sampling point from the surrounding samples. From the errors between observed and predicted values the Root-Mean-Squared Error (RE) was calculated; the most accurate model is that closer to 0. Also, using REE, the relative improvement (RI) of co-kriging over ordinary kriging was determined with the Eq. (4) in order to compare the accuracy of co-kriging models:

$$RI = \frac{RE(K) - RE(cK)}{RE(K)} \times 100 \tag{4}$$

where RE(K) and RE(cK) correspond to RE values of the ordinary Kriging and cokriging methods, respectively, obtained with the leave-one-out cross validation procedure.

The kriging and co-kriging techniques were performed using the Geostatistical Analyst Package of ArcGIS version 10.3 (ESRI, Redlands, CA).

4. Results

4.1. Topsoil moisture

The general statistic of topsoil moisture measurements from the watersheds during the study period is shown in Table 2. The watershed locations within the rainfall gradient were clearly observed through this

Table 2
General statistic of soil moisture data in Gaucín, Almogía and Gérgal watersheds. Abbreviations: SD, standard deviation; VC, variation coefficient; wet, soil moisture mean value of wet season; dry, soil moisture mean value of dry season. Different letters represent significant differences at a $p < 0.05$.

	Field sites			ANOVA
	Gaucín	Almogía	Gérgal	
Mean (%)	16.5[a]	11.3[b]	7.8[c]	p = 0.00
Median (%)	15.9	10.1	6.1	
SD (%)	10.4	7.0	5.8	
VC	0.62	0.62	73.4	
Max. (%)	60.1	59.6	44.4	p > 0.05
Min. (%)	1.0	1.0	1.0	p > 0.05
Wet (%)	20.2[a]	13.0[b]	9.0[c]	p = 0.00
Dry (%)	4.4	4.5	3.7	p > 0.05
Annual rainfall (mm year^{-1})	1010.0	550.0	240.0	

data, either considering the whole period or the wet season period as well. The higher the annual rainfall, the major topsoil moisture measured into the first 10 cm depth of soils. The one-way ANOVA indicated that there were significant differences between soil moisture from the three watersheds. These differences were corroborated by the Tukey's test ($p < 0.05$) in the case of the mean and wet season values (Gaucín: p = 0.000; Almogía: p = 0.000; Gérgal: p = 0.000). However, no differences were observed in the case of the dry season. This dry season was corresponded to 3, 4 and 5 months with no rainfalls in Gaucín, Almogía and Gérgal watersheds, respectively. Anyway, the topsoil moisture measured during this period usually was similar in all of them given the lack of rainfalls under the Mediterranean climatic conditions from the study area.

4.2. Soil properties

The soil properties are presented in Table 3. Soil properties from the field sites were in correspondence with the eco-geomorphologic conditions observed. Gaucín watershed, with major annual rainfall and higher vegetation cover, were characterized with soils of more organic carbon, aggregate stability fractions, water holding capacity, among others. Oppositely, soils from Gérgal watershed showed typical features from semiarid environments (scarcity in rainfalls and low vegetation cover): very high rock fragment content, shallow soils (<10 cm), low content of clays and organic carbon, and very unstable aggregates. In the case of Almogía watershed, its eco-geomorphologic condition rendered in soils characterized by transitional values regarding the analyzed properties. Thus, the Gaucín to Gérgal, it could be observed a reduction in the quality, fertility and resistance to soil degradation. Nevertheless, all of the watersheds were affected by grazing of low pressure implying a lesser vegetation cover than expected for the original conditions what enhanced water erosion processes and forms: bare soil areas with crusts and embedded rock fragments into the soil surface, in the case of Gaucín and Almogía, and shallow soils covered by very high rock fragment cover, in Gérgal.

Table 3
General statistic of soil properties in Gaucín, Almogía and Gérgal field sites. Abbreviations: SD, standard deviation; EC, electrical conductivity. Number of samples: Gaucín, 170; Almogía, 114; Gérgal, 120. Different letters represent significant differences at a $p < 0.05$.

	Gaucín		Almogía		Gérgal		ANOVA
	Mean	SD±	Mean	SD±	Mean	SD±	
Field capacity (%)	33.6[a]	5.5	25.6[b]	3.9	20.9[c]	4.4	p = 0.00
Wilting point (%)	13.7[a]	3.03	9.6[b]	2.5	5.1[c]	1.2	p = 0.00
Gravel content (%)	51.9[a]	10.9	54.0[bc]	10.1	62.0[a]	10.7	p = 0.00
Clay content (%)	23.8[a]	4.1	21.1[b]	3.8	15.8[c]	6.4	p = 0.00
Sand content (%)	32.1[b]	8.9	41.3[b]	3.5	45.3[a]	3.2	p = 0.00
pH	6.7[c]	0.28	6.8[b]	0.18	7.6[a]	0.30	p = 0.00
EC (mS cm^{-1})	0.83[ab]	0.40	1.3[a]	0.37	0.69[b]	0.29	p = 0.00
CEC (meq 100 g^{-1})	32.8[a]	9.1	24.9[ab]	9.5	10.4[a]	2.8	p = 0.00
SOC (%)	5.3[a]	2.0	3.6[b]	2.3	1.01[c]	0.69	p = 0.00
Aggregate stability (%)	75.7[a]	6.7	64.7[b]	10.3	56.8[c]	11.4	p = 0.00
Porosity (%)	50.1[ab]	9.7	45.6[ac]	8.3	46.3[c]	6.4	p = 0.03

4.3. Topography attributes

The general statistic of topography attributes that were obtained from the 1 × 1 m-resolution DEM in the three watersheds is compiled in Table 4 and the mapping of these topography attributes is shown in Fig. 3. Although these field sites differed in altitude, the rest of attribute ranged in similar order of magnitudes. The mean slope gradient decreased from the wettest to the driest field site regarding the mean values. Regarding the hillslope aspect, Gaucín and Almogía watersheds were characterized by two main north and southfacing exposures, whilst the southfacing exposure was the dominant in Gérgal watershed.

The slope curvature was mainly negative in all the watersheds. Respect to the flow length from the sampling point upward the watershed boundary, the lower values were found in Almogía watershed where the hillslope length was shorter as well as the distance to the outlet than in Gaucín and Gérgal. The contributed area to each soil sampling point shows a similar declining trend from Gaucín to Gérgal watersheds and joined the decrease in the annual rainfalls implied less potential amount of water converted into runoff flowing to the sampling point or the watershed outlet.

Regarding TWI, the general statistic shows similar values for the three field sites as it can be seen in Table 4. The mean TWI was equal major in Gaucín, as well as the maximum and minimum. The TWI maps from the three field sites are represented in Fig. 4. Thalwegs concentrated the major values of TWI in the three watersheds, but also areas in hillslopes prone to concentrate water flows were highlighted. After calculating the Levene's test which indicated significant homoscedasticity ($p < 0.05$), the one-way ANOVA indicated there were no significant differences regarding the TWI between the field sites (in all cases, $p > 0.05$) Subsequently, all of them were not too much different in the mean values of the TWI, but the spatial patterns of TWI showed relevant

Table 4
General statistics of topography attributes from the pixels where the soil sampling points are located within the DEM from Gaucín, Almogía and Gérgal field sites. Abbreviations: SD, standard deviation; TWI, topographic wetness index.

Attribute		Field sites		
		Gaucín	Almogía	Gérgal
Altitude (m)	Mean	687.6	547.3	1094.0
	SD	31.8	12.9	12.0
	Max	758.4	568.0	1127.2
	Min	626.2	516.4	1073.5
Slope (%)	Mean	26.2	18.8	15.6
	SD	5.8	5.6	4.5
	Max	38.9	31.6	31.5
	Min	3.0	0.0	0.0
Aspect (°)	Mean	206.8	187.3	166.5
	SD	117.7	112.5	66.5
	Max	359.1	355.2	278.5
	Min	0.06	Flat	Flat
Curvature	Mean	−0.86	−1.51	-0.95
	SD	8.68	8.62	5.6
	Max	28.8	28.3	15.2
	Min	−37.1	−41.1	−37.0
Flow length (m)	Mean	40.0	27.4	37.1
	SD	57.8	35.2	32.6
	Max	418.8	282.5	218.1
	Min	0	0	0
Contributed area (m^2)	Mean	394.6	183.6	122.6
	SD	2745.6	1190.9	787.9
	Max	26,656	11,789.1	8268.2
	Min	0	0	0
TWI	Mean	4.62	4.16	3.93
	SD	1.44	1.62	1.80
	Max	14.03	15.14	15.53
	Min	−0.61	−1.34	-0.09

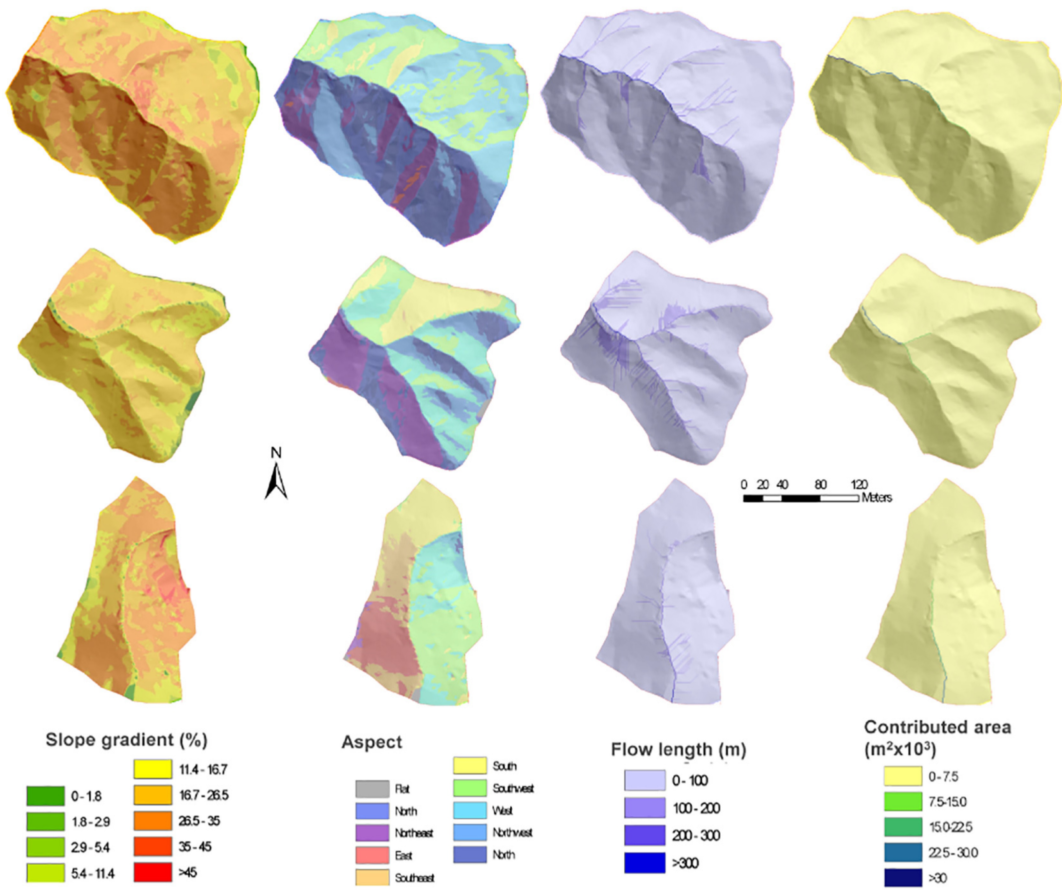


Fig. 3. Spatial distribution of slope gradient, aspect, flow length and contributed area in Gaucín (top), Almogía (middle) and Gérgal watersheds (bottom).

differences: especially, in Gaucín watershed, with the highest slope gradients, flows concentrate rapidly in hillslopes before reaching the main channel.

4.4. Relationships of topsoil moisture with topography and soil properties

The results of Pearson's correlation coefficient are showed in Table 5. Considering the whole database of soil moisture measured in the field sites, it is remarkable that two topographic attributes notably influenced in the soil moisture values. Soil moisture was inversely correlated with the altitude. Also, very significant correlations were obtained when slope gradient were related to soil moisture. Unless the mean soil moisture in dry seasons, the soil moisture was positively correlated to the slope gradient. However, if only the soil moisture database from each field site were considered, the correlation coefficients differed between them. In general, Gaucín field site obtained less significant correlation coefficients. The major coefficients were those obtained with the slope gradient and altitude. The sampling points characterized by wider ranges of soil moisture values were those located at a higher altitude, far from the bottom of hillslopes and thalwegs. Conversely, during the dry seasons, the highest soil moisture values were registered at low altitude in both mentioned topographic locations.

In the case of Almogía field site, the number of statistically significant correlations were higher than in the other field sites. In any case, Almogía field site was the field site where the TWI was better correlated to the measured soil moisture. TWI is a parameter especially dependent on slope gradient. Flow length and drainage area were positively correlated to the major values of standard deviation. Finally, the soil moisture was also negatively correlated to the slope curvature indicating that convex slope sections usually registered the lower soil moisture values.

In Gérgal field site, the topography attributes influencing in soil moisture were less important. Only altitude and aspect obtained statistically significant correlations ($p < 0.05$). Altitude was negatively correlated to mean and maximum soil moisture values indicating that those

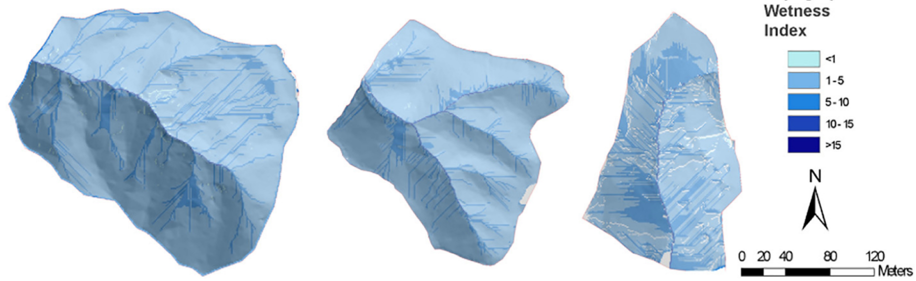


Fig. 4. Spatial distribution of Topographic Wetness Index in Gaucín (left), Almogía (center) and Gérgal (right) watersheds.

Table 5
Pearson's correlation coefficient between soil moisture data and topography attributes in the sampling point. Abbreviates: SM_m, mean soil moisture; SM_{md}, median soil moisture; SM_{sd}, standard deviation; SM_{max}, maximum value; SM_{rain}, mean soil moisture in the rainy season; SM_{dry}, mean soil moisture in the dry season; correlations statistical significant at $p < 0.05^*$ and $p < 0.01^{**}$.

Field site	Topography	SM_m	SM_{md}	SM_{sd}	SM_{max}	SM_{rain}	SM_{dry}
Whole database	Altitude	−0.52*	−0.52*	−0.42*	−0.51*	−0.50*	−0.38*
	Slope	0.48*	0.50*	0.42*	0.36*	0.48*	0.11
	Aspect	0.01	−0.01	0.02	0.02	0.01	−0.02
	Wetness	−0.08	−0.09	−0.07	−0.05	−0.08	0.05
	Length	0.06	0.06	0.05	0.06	0.05	0.09
	Accumulated	0.08	0.08	0.08	0.12	0.07	0.08
	Curve	−0.06	−0.05	−0.06	−0.11	−0.05	−0.10
Gaucín	Altitude	0.08	0.00	0.30*	0.22	0.11	−0.26**
	Slope	−0.37*	−0.10	−0.27**	−0.24**	−0.19	−0.13
	Aspect	−0.20	−0.25	−0.12	−0.07	−0.21	0.00
	Wetness	0.06	0.05	−0.01	0.00	0.04	0.17
	Length	−0.04	−0.01	−0.13	−0.06	−0.05	0.14
	Accumulated	0.04	0.04	0.02	0.09	0.03	0.11
	Curve	−0.06	−0.06	0.01	−0.02	−0.05	−0.12
Almogía	Altitude	0.00	0.05	−0.03	−0.01	0.00	0.07
	Slope	−0.08	−0.05	−0.16	−0.21	−0.09	0.06
	Aspect	−0.21	−0.17	−0.26**	−0.22	−0.22	−0.01
	Wetness	0.27**	0.27**	0.32*	0.33	0.28**	0.10
	Length	0.23	0.23	0.29**	0.31	0.24	0.08
	Accumulated	0.21	0.19	0.29**	0.30*	0.22	0.06
	Curve	−0.30*	−0.30*	−0.33*	−0.40*	−0.30*	−0.17
Gérgal	Altitude	−0.32*	−0.23	−0.38	−0.41*	−0.32	−0.23
	Slope	−0.17	−0.10	−0.24	−0.25	−0.18	−0.08
	Aspect	−0.36*	−0.38*	−0.21	−0.21	−0.36*	−0.34*
	Wetness	0.00	−0.01	0.02	0.02	0.00	0.01
	Length	0.07	0.06	0.04	0.05	0.07	0.09
	Accumulated	−0.15	−0.13	−0.14	−0.10	−0.16	−0.09
	Curve	−0.03	0.01	−0.08	−0.06	−0.04	0.01

sampling points located at the top of hillslopes usually registered the lower values in both variables. The other topography attribute, aspect, was negatively correlated as well: the lower values in soil moisture (mean, median, rainy and dry season) coincided with those sampling points mainly located in southfacing hillslopes.

The results obtained in the calculation of the Pearson's correlation coefficient between the topsoil moisture and the analyzed soil properties from the three watersheds are shown in Table 6. The major significant coefficient was registered in the case of gravel content in all of them. Also, other remarkable coefficients were obtained for the organic carbon and porosity, clay and sand content, and clay, organic carbon and porosity, in Gaucín, Almogía and Gérgal watersheds, respectively.

4.5. Topsoil moisture mapping

The spherical model was the most accurate to predict topsoil moisture in all cases (Table 7 and Fig. 5). The nugget effect was residual in all ordinary kriging cases and in one co-kriging procedure from Gérgal watershed, showing that the small-scale variance was minimal and the number of samples sufficient to assess the spatial variability of topsoil moisture. One sample per 1000 m^2 was representative to analyze the spatial variability of topsoil moisture in the three watersheds. The data transformations reduced the impact of the outliers on the nugget effect when it appeared. The spatial dependence was high in all cases.

Table 6
Pearson's correlation coefficient between topsoil moisture data and soil properties the watersheds. Correlations statistical significant at $p < 0.05^*$ and $p < 0.01^{**}$.

Watershed	Aggregate stability	Clay	Porosity	Organic carbon	Gravel content	Sand
GA	−0.08	0.25	0.28**	0.39*	−0.50*	−0.17
AL	0.02	0.42*	0.04	0.18	−0.59*	−0.29**
GE	0.02	0.32*	−0.36*	0.32*	−0.51*	−0.21

These results may indicate that topsoil moisture presents a specific spatial pattern. In general, spatial correlation was major in Almogía watershed whilst in Gaucín and Gérgal watersheds were similar among them. More precisely, the co-kriging techniques showed major spatial correlation than ordinary kriging, which rather indicated the autocorrelation of topsoil moisture. According to the Root-Mean-Square Error, the most accurate to estimate topsoil moisture in Gaucín watershed was the ordinary kriging, whilst the co-kriging considering both auxiliary variables of topography and gravel content was of major accuracy in Almogía and Gérgal watersheds.

The ordinary kriging mapped the spatial variability of the mean soil moisture in the first 10 cm of soil depth at the watersheds (Fig. 6). The resulting maps clearly showed the reduction in rainfall supply and, thus, in the topsoil moisture, with major values in Gaucín watershed and decreasing towards Gérgal watershed. Both field site with the major and lower annual rainfalls showed more spatial variability of topsoil moisture within the watershed boundary, whilst the Almogía field site did a more homogeneous distribution of soil moisture. Initially, here, the spatial variability in topsoil moisture regarding the aspect of hillslopes tended to be less than in Gaucín and Gérgal.

The maps obtained through this co-kriging technique using the best topographic attributes as auxiliary variable are included in the Fig. 6. Namely, slope gradient, curvature and aspect better estimated the spatial variability of soil moisture, though all of them did it differently in each field site; the soil moisture mapping was well-estimated for Gaucín, Almogía and Gérgal whether slope gradient, curvature and aspect were considered in the co-kriging procedure for each of them, respectively. Afterwards, in other co-kriging procedure was added to the previous variables the best-correlated soil property with topsoil moisture. Thus, this co-kriging considers slope gradient and gravel content, slope curvature and gravel content, and aspect and gravel content in Gaucín, Almogía and Gérgal field sites, respectively. Except in Gaucín watershed, the accuracy in mapping topsoil moisture was higher when co-kriging procedure was applied considering both co-variate topography attribute and gravel content.

Table 7
Semivariance models and their parameters for topsoil moisture in Gaucín, Almogía and Gérgal, watershed. Abbreviations: FS, field sites; K, ordinary kriging; cK1, heterotopic co-kriging 1; V, primary and/or secondary variable; TM, topsoil moisture; SI, slope gradient; G, gravel content; C, curvature; As, aspect; RE, Root-Mean-Squared Error; Omnid., omnidirectional; RI, relative improvement.

FS	Method	V	Direction	Model	Nugget	Sill	Nugg/sill ratio	Range (m)	RMSE	RI (%)
Gaucín	K	TM	Omnid.	Spherical	0.00	8.01	0.00	275.8	2.43	
	cK	TM + Sl	Omnid.	Spherical	7.15	10.9	1.55	294.8	2.50	−2.9
	cK						TM + Sl + G	Omnid.		
		Spherical	6.28	9.43	1.50		117.1	2.44	−0.4	
Almogía	K	TM	Omnid.	Spherical	0,00	3.52	0.00	109.8	2.34	
	cK	TM + C	Omnid.	Spherical	5.02	7.23	1.44	78.8	2.36	−0.9
	cK	TM + C + G	Omnid.	Spherical	3.88	5.98	1.54	64.5	1.86	20.9
Gérgal	K	TM	Omnid.	Spherical	0.00	7.74	0.00	268.4	1.81	
	cK	TM + As	Omnid.	Spherical	3.47	2.30	1.51	353.6	1.79	1.1
	cK						TM + As + G	Omnid.		
		Spherical	2.15	2.15	1.36		178.0	1.54	14.9	

5. Discussion

The soil properties from the three field sites were previously described in Ruiz-Sinoga and Martínez-Murillo (2009) and Ruiz-Sinoga et al. (2010a,b, 2011a,b, 2012). These authors found the key role played by biotic factors, especially the soil organic carbon content, which decreased from the most humid site to the driest one with the reduction in vegetation cover, with implications from the infiltration and water holding capacity of soils and, thus, in the soil moisture variability (Lavee et al., 1998). However, in those studies, the effect rock fragments on the soil surface and within the soil profile as well was reported as the most important factor in the soil hydrology of the studied watersheds (Ruiz-Sinoga et al., 2010c, 2011a,b). Accordingly, the location of the watersheds within the rainfall gradient showed the influence of rainfall supply in the topsoil moisture from the magnitude and temporal variability point of view, especially, during the wet seasons when the differences between them were more remarkable. In this sense, it has to be kept in mind that either soil moisture and water retention are both dependent on some abiotic and biotic factors, also influenced by the climate; namely: vegetation cover and land use, slope gradient and aspect, and soil properties (clay and organic carbon content, aggregate stability, among others) (Lavee et al., 1998).

Closely related to topsoil moisture variability, the topography emerges as another key factor through attributes as the slope gradient or aspect. The slope gradient implies either the location of potential areas of sink areas where soil moisture may be higher and soil becomes saturated when decreases or, oppositely, source areas when increases and thus topsoil moisture may be lower and runoff enhanced (Cammeraat, 2004). However, the maximum slope gradient easily exceeded 20% and flat areas were almost absent in all of them. Regarding the hillslope aspect, the major topsoil moisture values usually were found in northfacing hillslopes as expected where the water is storage in soil for longer periods what let the growth and maintenance of higher vegetation covers. This implies more organic matter supply to the soil, well-developed structure and higher water holding capacity in a feedback process leading to major volume of water into the soil (Pariente, 2004). Nevertheless, this major vegetation cover may also implicate more water uptake and topsoil moisture can be similar to that in southfacing hillslopes when rainfalls deceased during the summer period (Gabarrón-Galeote et al., 2013). Other influential topography

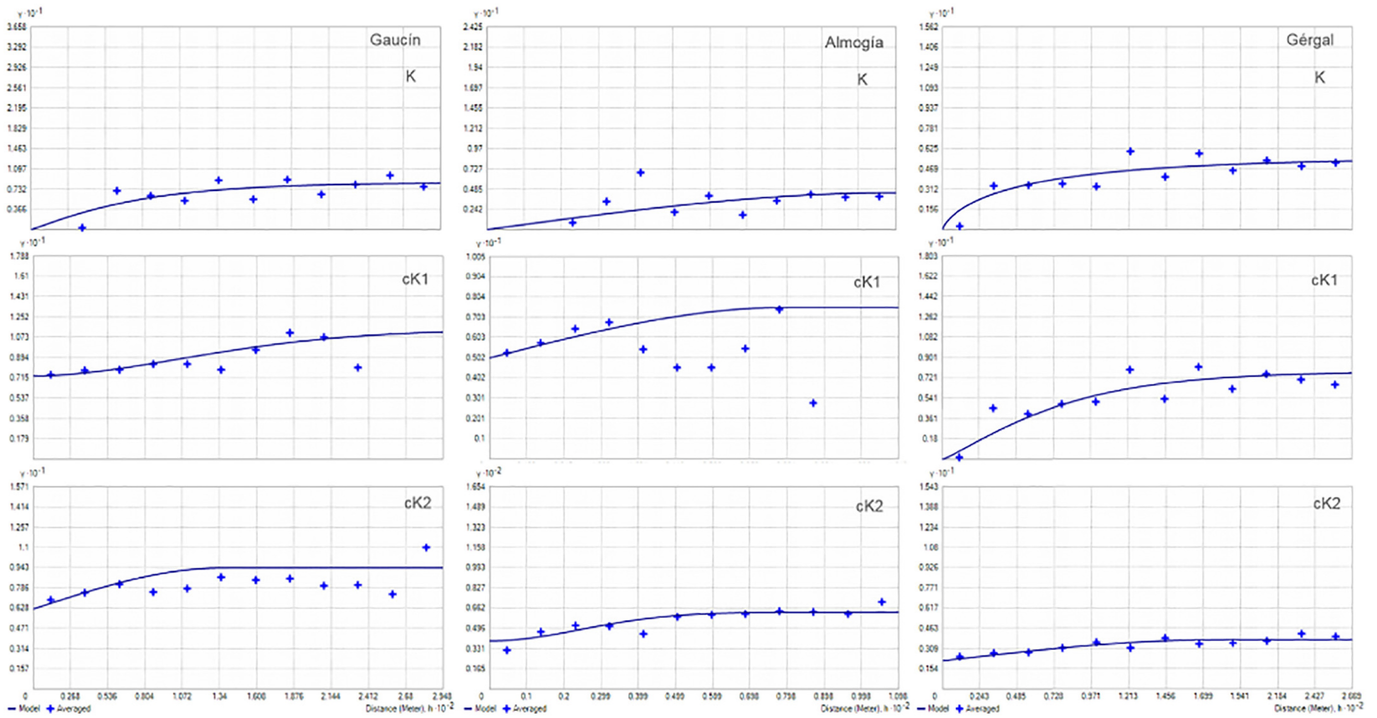


Fig. 5. Directional semivariograms calculated for kriging (using topsoil moisture), co-kriging 1 (using topsoil moisture and topography attribute as primary and auxiliary variable, respectively) and co-kriging 2 (using topsoil moisture as primary variable and both topography attribute and gravel content as auxiliary variables) in Gaucín (left), Almogía (center) and Gérgal watersheds (right).

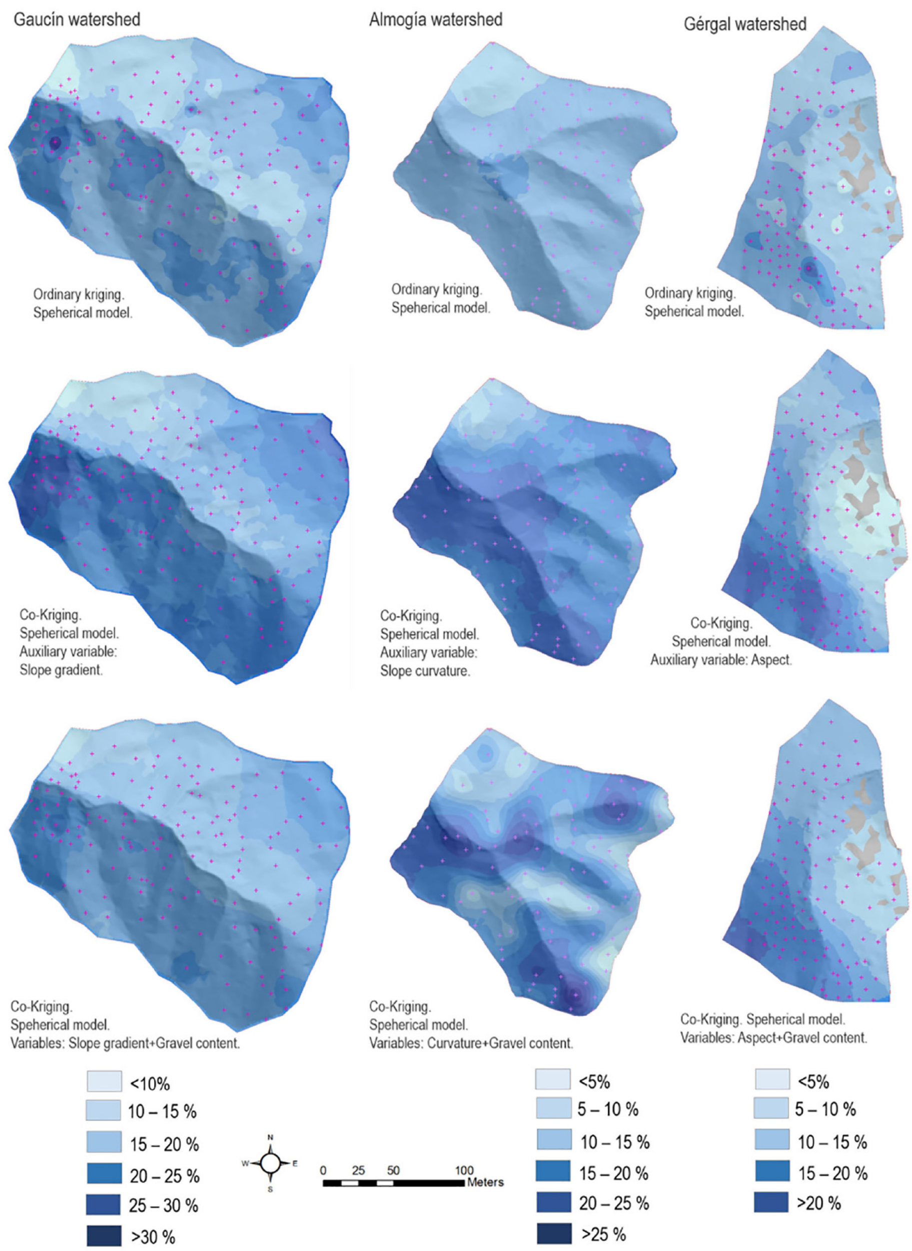


Fig. 6. Maps of mean soil moisture in the first 5 cm of depth at the three field sites (Gaucín, left; Almogía, center; Gérgal, right) obtained by means of ordinary kriging (left) and co-kriging techniques (considering as co-variate topography attributes, center; considering both co-variate topography attributes and soil property, right). The gradation in blue color only indicates where either the soil moisture is lower or higher. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

attribute in this study was the slope curvature, which influences in the divergences (negative values) and convergences (positive values) of surface flow and, thus, in the infiltration and runoff generation processes (Baartman et al., 2013). As the three field sites mainly showed negative slope curvature values, this had remarkable implications from the hydrological and erosive processes point of view, so that infiltration process may be more difficult whilst runoff was enhanced. However, this influence in the topsoil moisture was not similarly registered in the case of the Topographic Wetness Index because it did not significantly differ from one watershed to another. This was reasonable because the topography attributes defining the TWI (slope gradient and area) were not so different and allowed the comparison of the three watersheds according to the hypothesis and the climatic gradient approach considered in this study.

According to considered co-variates, topsoil moisture was interpolated by ordinary kriging considering different procedures with auxiliary variables or not. Their application evidenced the location of each watershed within the rainfall gradient regarding the topsoil moisture as well as its spatial variability. The spatial dependency (autocorrelation) increased from the humid to the semiarid watershed when the ordinary kriging procedure was conducted; the spatial correlation between topsoil moisture, topography attribute and gravel content also followed the same trend when the cokriging was used in Almogía and Gérgal. It is generally accepted that a strong spatial dependency of soil properties, e.g. soil moisture, is controlled by intrinsic factors, like texture and mineralogy, whilst a weak dependence is attributed to extrinsic factors, topography or land use (Cambardella et al., 1994; Liu et al., 2004; Rüth and Lennartz, 2008; Liu et al., 2009). Thus, a lower spatial variability in the controlling variables of topsoil moisture, e.g. soil properties as clay and organic carbon, a lower spatial autocorrelation when rainfalls increased and the eco-geomorphologic system becomes more influential by biotic factors and less affected by degradation of soil quality.

Regarding the two attributes were remarkably influential: i) slope gradient (the lower slope gradient, the major topsoil moisture because infiltration is enhanced); and ii) slope gradient (the major slope, the lower soil moisture). However, some local differences were also observed. In Gaucín watershed, the above-mentioned topography attributes were not so influential in topsoil moisture than in the others considered in this study. This is a remarkable question given that Gaucín is the most humid site. Indeed, in this field site, Ruiz-Sinoga et al. (2010a,b) observed that soil surface conditions where controlled by biotic factors (herbaceous vegetation and moss) and other soil properties (organic matter and clay content) that implicated conditions prone to water infiltration and retention. In Almogía watershed, the transitional site, topsoil moisture was better correlated to TWI, a parameter especially dependent on the slope gradient: the major topsoil moisture values measured in field conditions coincided with those areas where the TWI predicts to locate them. Flow length and drainage area were positively correlated to the major values of standard deviation. This must be related to the fact that topsoil moisture was found greater more frequently in the bottom of hillslopes and flatter areas, but also both of them registered very low values of moisture during the dry season absence of rainfalls, similarly to what occurred in Gaucín field site. The lack of rainfalls in the dry season homogenizes the soil moisture in all sites, regardless the rainfall regime (Katra et al., 2007; Ruiz-Sinoga and Martínez-Murillo, 2009). Also, in Almogía, the negative correlation between topsoil moisture and the slope curvature clearly indicated that convex slope sections usually registered the lower topsoil moisture values due to the convex shape imply divergence in the flows and infiltration capacity as well as water content within the soil profile, may be lower than in concave sections where flows tend to converge (Baartman et al., 2013; Zaslavski and Sinai, 1981). Finally, in Gérgal watershed, the semiarid site, both aspect and altitude significantly influenced topsoil moisture negatively: the sunniest aspect, the lower topsoil moisture; and the lower altitude, the major topsoil moisture in both rainy and dry seasons as it was found in previous investigations in semiarid sites (Puigdefabregas, 2005; Ruiz-Sinoga et al., 2011a,b).

These better-correlated topography attributes were used jointly the soil moisture to map this variable by the ordinary co-kriging procedure in a first approach.

Regarding the nugget/sill ratios, the general decreasing trend from Gaucín to Gérgal indicated a loss of spatial dependence. Topsoil moisture highly varied in short distance at the three-field site. Nevertheless, the ordinary co-kriging improves the soil moisture mapping as it is subsequently explained: in Gaucín watershed, it highlighted better the major topsoil moisture in flatter areas as it was possible to observe either in the field surveys as well as in the soil moisture database, as well as the differences between the main north and southfacing exposures; in Almogía watershed, there was an improvement in the topsoil moisture mapping because the areas of the watershed with major soil moisture (sampling points located in the bottom of hillslopes characterized by a concave profile) were better mapped; and, finally, the effect of aspect in the soil moisture and observed in field surveys was well mapped in the driest site, Gérgal.

Several studies have addressed the factors that control the spatial and temporal dynamics of topsoil moisture: topography (e.g., slope, curvature, elevation, and exposure); climate (rainfall, temperature, and solar radiation); soil properties (e.g., clay content, albedo, and organic matter); and land use (Cantón et al., 2004; Hebrard et al., 2006; Imeson and Lavee, 1998; López-Vicente et al., 2015; Martinez et al., 2008; Qiu et al., 2001; Western et al., 1999; Wilson et al., 2005). We are aware of topsoil moisture is not exclusively controlled by rainfall supply and topography but land use and soil properties as well, and this must be taken in consideration in future investigations. Indeed, topography influences the accumulation, paths, convergences, divergences, etc., of water flows. Likewise, soil properties can be a factor affecting topsoil moisture as a resume of vegetation and land use cover because they are greatly interdependent. Thus, topography and soil properties can be jointly used to map topsoil moisture and obtain accurate results.

Accordingly, topsoil moisture was also mapped for each watershed by using co-kriging and considering one topography attribute and soil property: slope gradient and gravel content in Gaucín (humid); slope curvature and gravel content in Almogía (dry); and aspect and gravel content in Gérgal (semiarid), respectively. The reduction of the nugget/sill ratio from the rainiest to the driest indicated an increment in the spatial dependency of soil moisture as the rainfall supplies decreased. This is in accordance with previous studies dealing with the existence of fertility islands in semiarid and Mediterranean climatic conditions (Gabarrón-Galeote et al., 2013; Puigdefábregas et al., 1999; Schlesinger et al., 1990). The patchiness of vegetation cover in those environments implies a high spatial variation in soil properties and, thus, in the hydrological response, especially, in southfacing hillslopes where it is easily observed a patchy vegetation/soil pattern defining what it has been described as fertility islands (Puigdefábregas et al., 1999; Schlesinger et al., 1990). Conversely, this spatial dependency in the rainiest site was lower what implicate topsoil moisture was less spatially variable. This is in accordance with the hydrology response of soils from Mediterranean humid areas where infiltration and saturation mechanisms usually are the main hydrological processes (Lavee et al., 1998; Ruiz-Sinoga et al., 2010a,b,c). In this field site, the fitted spherical model represented accurately the topsoil moisture variability very similar to that obtained by the kriging procedure, though the limits of topsoil moisture regions followed more accurate the topography of watersheds and the presence of less stony soils. In the case of Almogía field site, under dry-Mediterranean conditions, this co-kriging strategy still mapped those more humid areas highly coinciding with the concave terrain, whilst the driest soils coincided with either the top hillslopes or southfacing exposure where more stony soils were observed in previous studies (Ruiz-Sinoga and Martínez-Murillo, 2009).

Regarding the lower results of the root mean square error in the driest site, Gérgal, it was pointed out the number of sampling points was enough to obtain accurate maps of topsoil moisture. This has important implications from the soil sampling strategy point of view in further investigations in order to gain more efficiency in field surveys. Kerry and Oliver (2007) indicated that the variables range might be considered a guide for choosing future sampling intervals. According to the authors, the sample interval should be less than half the variogram range. All ranges were higher than the sampling interval in this study, confirming that the sampling interval was appropriated to measure the spatial variability of the properties studied, especially, in Gérgal. In Gaucín and Almogía watershed, it should be reconsidered the number of samples because the errors were major. This could be related to the higher spatial variation of the eco-geomorphologic system: both of them are characterized by a vegetation/bare soil pattern more spatially variable than it was expected from their rainfall supplies due to the grazing activity.

6. Conclusions

Considering the hypothesis and objectives of this investigation, the conclusions are the following:

i) Under different Mediterranean climatic conditions, in watersheds with similar parent material and land use, topsoil moisture was highly dependent on the topography attributes as well as the soil properties, but not in a different magnitude.
ii) The topsoil moisture decreases from the most humid to the driest watershed following the declining trend in rainfalls as it was expected, but its spatial variability was lower in the semiarid watershed.
iii) The application of different geostatistical techniques mapped the topsoil moisture in the three watersheds. In general, co-kriging methods were accurate to map topsoil moisture, especially, in the dry and semiarid watersheds.
iv) The applied methodology has important implications in future investigations in order to improve the accuracy of sampling

strategies and the efficiency in field surveys and laboratory analysis to reduce research costs.

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