Turkish Journal of Agriculture - Food Science and Technology, 11(4): 625-633, 2023
DOI: https://doi.org/10.24925/turjaf.v11i4.625-633.5279

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Cross-Correlation of Soil Moisture and Stone Content and Their Spatial Pattern Across the Different Slope Aspects and Soil Depth

Hailu Kendie Addis[1,a,*], Baye Ayalew[2,b], Muuz Gebretsadik[3,c], Atikilt Abera[2,d],
Legese Abebaw Getu[2,e], Amsalu K. Addis[4,f]

[1]*Soil and Water Management Directorate, Amhara Regional Agricultural Research Institute, Bahir Dar, Ethiopia*
[2]*Soil and Water Management Directorate, Gondar Agricultural Research Center, Gondar, Ethiopia*
[3]*College of Agriculture and Environmental Science of Adigrat University, Adigrat, Ethiopia*
[4]*School of Economics and Management, Fuzhou University, Fuzhou, China*
[*]*Corresponding author*

ARTICLE INFO

Research Article

Received : 18-05-2022
Accepted : 30-03-2023

Keywords:
Ethiopian Highlands
North facing slope
Stone content
Topsoil moisture
Watershed

ABSTRACT

The analysis of the spatial interrelationship between soil properties and slope aspect is vital for understanding the range of influence on soil depth, moisture, and stone content distribution. This study aimed to investigate the spatial interrelationship of topsoil moisture and stone content in different slope aspects and soil depth. The 53.7 km^2 watershed was divided into a 500m by 500m grid using ArcGIS and 230 soil samples were collected. In each sampling point, the soil was taken at three soil depth classes (0–25cm, 25–60cm, and 60–100cm) using a cylindrical auger, then soil samples were tested to determine the percentage of topsoil moisture, and stone content. The spatial interrelationship between aspect, soil depth, topsoil moisture, and stone content was analyzed using the R and GS+ software. The study had shown non-significant effects of aspect on topsoil moisture, stone content, and soil depth. However, topsoil moisture tends to be higher on the north-facing slope, while stone content tends to be higher on the southeast-facing slope. The analysis of Local Moran's I revealed that topsoil moisture, stone content, and soil depth were significantly autocorrelated. The cross-semivariogram analysis of soil depth with topsoil stone content depicted a negative spatial correlation. The experimental cross-semivariogram of soil depth versus topsoil moisture was positively fitted to the exponential function, whereas soil depth with topsoil stone content was best fitted to the Gaussian model. Overall, soil depth is the more influential factor than the slope aspect regarding topsoil moisture depletion and stone content distribution in the study watershed.

[a] *hailukendie@gmail.com* *https://orcid.org/0000-0003-0265-0261*
[b] *ayalew.baye@yahoo.com* *https://orcid.org/0000-0001-7565-9238*
[c] *muuzgebre7@gmail.com* *https://orcid.org/0000-0002-3393-4841*
[d] *atikilt.3@gmail.com* *https://orcid.org/0000-0002-0074-7783*
[e] *legeseabebaw08@gmail.com* *https://orcid.org/0000-0002-7300-6249*
[f] *amy.kid370@gmail.com* *https://orcid.org/0000-0002-6661-7201*

Introduction

Soil plays a vital role in the hydrological process, which can store rainwater temporarily and allow it to drain gradually (Zhu et al., 2014). Knowledge of soil moisture dynamics provides valuable information on the hydrological cycle (Legates et al., 2011), such dynamics typically exhibited high spatial and temporal variability over multiple scales (Zhu et al., 2014). Spatial scales reach from quite a small square meter to the watershed and further occurring at large scales, while temporal scales extent from seconds to centuries and longer (Addis and Andreas, 2015). The spatial patterns and temporal variation of soil moisture are influenced by several environmental factors, such as rainfall, topography (Qiu et al., 2001; Brocca et al., 2010; Kim, 2012; Feng et al., 2013), solar radiation (Brocca et al., 2010), wind (Gates, 2012; Moeslund et al., 2013; Alexandridis et al., 2016), soil texture (Baroni et al., 2013; Zhang and Shao, 2015), sampling scale (Feng et al., 2013), soil depth (Tromp-van Meerveld and McDonnell, 2006; Geroy et al., 2011), groundwater (Rosenbaum et al., 2012; Ries et al., 2015), time (Famiglietti et al., 2008) and vegetation cover (Zribi et al., 2010; Lu et al., 2011; Venkatesh et al., 2011; Wang et al., 2012; Baroni et al., 2013), and the impacts of the different environmental parameters are complex since the factors could interact with each other (Qiu et al., 2001; Guo et al., 2002; Famiglietti et al., 2008; Zhu et al., 2014). Spatial patterns and temporal variability of soil moisture in a watershed affect infiltration, runoff, soil erosion, evapotranspiration, solute transport, and ecosystem dynamics (Qiu et al., 2001; Yang et al., 2012; Yang et al., 2014; Zhu et al., 2014).

Knowledge of soil moisture variability is also essential for hydrological modeling and watershed management (Latron et al., 2008; Brocca et al., 2012), climate models (Hauser et al., 2017), and nutrient availability (Rodriguez-Iturbe, 2000; Wernerehl and Givnish, 2015). Several studies have been conducted on soil moisture to document the mechanisms driving moisture variability and precisely characterize its association with environmental parameters (Tromp-van Meerveld and McDonnell, 2006; Moeslund et al., 2013; Yang et al., 2014; McMillan et al., 2015). Recently, more studies have also focused on the impacts of slope direction (aspect) on the spatial distribution of soil moisture (Geroy et al., 2011).

The slope aspect is the important topographic factor in the Ethiopian Highlands, due to high radiation and the prevailing wind direction, as well as due to its effect on the soil temperature. Several scholars have been documented that available water content is greater in soils on the north-facing slope than in soils on the south-facing slope (Hanna et al., 1982; Bretherton et al., 2010). Similarly, the north-facing slope displaying high infiltration rates, while the south-facing slope had low infiltration rates in the northern hemisphere (Cerdà, 1997). Typically, north-facing slopes have less sunlight and, in turn, have higher moisture levels and greater vegetation establishment (Kutiel et al., 1998; Gallardo-Cruz et al., 2009), while slopes with south-facing slopes are dominated by bare soil with stone patches (Kutiel et al., 1998). According to Gong et al. (2008), north-facing slopes have higher productivity and species diversity compared to south-facing slopes.

Most earlier studies (Qiu et al., 2001; Guo et al., 2002; Zhu et al., 2014) have considered more than one environmental factor affecting soil moisture content, but few researches have studied the effect of slope aspect and soil depth following the dry period of a season at a watershed scale. Therefore, the objectives of this study were (i) to assess the effect of slope aspect on the distribution of topsoil moisture, stone content as well as soil depth; and (ii) to investigate the spatial pattern and dependence of soil depth, topsoil moisture and stone content following the dry period of a season.

Materials and methods

Description of the Study Site

The study was carried out in the Gumara-Maksegnit mountainous agricultural watershed (12° 24’ N, 37° 33’ E) located in the northwest Amhara region, Ethiopia (Figure 1). This hilly agricultural basin, which covers an area of 53.7 km^2, is one of the most heavily eroded parts of the Ethiopian highlands. The soils of the study watershed are dominated by Cambisol and Leptosol in the upper and central parts of the watershed and Vertisol in the lower part near the outlet. Elevation data were derived from a 30m resolution Shuttle Radar Topography Mission (SRTM) based on that that covers the entire study watershed (Figure 1). The slope aspect was calculated using the ‘Aspect’ tool (default settings) in the Spatial Analyst module of ArcGIS. The land-use types of the study watershed are mainly agricultural land (63.5%) followed by forest (24.3%) and grazing land (12.2%) and the canopy composition of the forest land of the study watershed is dominated by species such as *Acacia abyssinica*, *Olea africana*, *Ficus sur*, *Dodonaea vissosa*, *Entada abyssinica*, *Carissa spinarum*, and *Ephorbia abyssibica.*

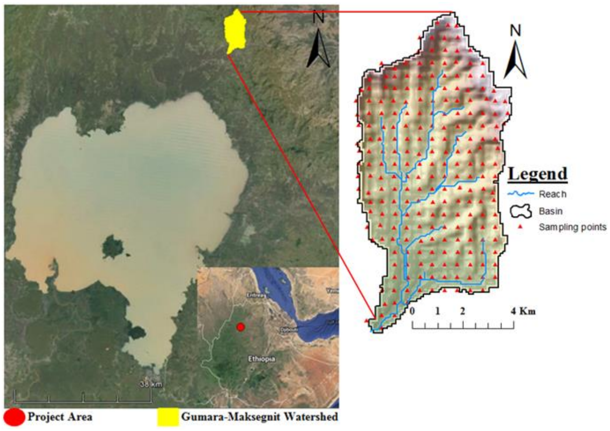

Figure 1. The digital elevation model used in this study is superimposed on the watershed, and the 230 soil sampling sites under study are shown as triangles.

Data Collection

The sampling sites were selected with the use of a regularized sampling interval, one sample within a 500 by 500 m square grid section of the watershed and a total of 230 soil sampling points distributed across the different slope aspects were collected. Furthermore, based on the depth of the soil, the measurement and recording of soil moisture and stone content were taken in three soil depth classes namely: 0–25 cm (a total of 230 samples), 25–60 cm (a total of 96 samples) and 60–100 cm (a total of 59 samples), then each sample is provided a specific name and placed and sealed in a bag to retain moisture. For this study, the depth of the soil means the depth of a soil profile from the top to the parent material or bedrock or to the layer of obstacles or barriers (such as rock, gravel, or cement) for the roots of the surface plants. Soil samples in the study watershed were collected after the dry period of the season for three weeks in April and there was no precipitation during the sampling period. The amount of soil sample, around 2 kg, was collected with the best available tool (bucket auger), to ensure that the sample would be sufficient to complete all necessary laboratory analysis.

Soil Moisture and Stone Content Analysis

According to Dobriyal et al. (2012), due to the destructive nature of the gravimetric method, composite soil samples were collected within a from 1 m radius of the sampling point at three depth classes. Each soil sample had a mass of approximately 2 kg and the collected soil samples were placed in a tightly shaped plastic bag and weighed before and after oven-drying for 24 hours at 105°C and calculated using the following formula:

$$((\text{original mass of soil sample} - \text{the mass of dry soil})/(\text{mass of the dry soil})) \times 100 \qquad (1)$$

So, the gravimetric soil moisture was calculated for each observed sample in the watershed. Meanwhile, the percentage of stone content of the soil was calculated through the following formula:

$$(\text{Weight of stones in the original soil sample}/\text{original mass of the soil sample}) \times 100 \qquad (2)$$

Statistical analysis

The basic classical statistical features, which includes mean values, standard deviation (SD), standard error of the mean (SEM), and coefficient of variation (CV) were analyzed and reported for each observed soil variables. One-way analysis of variance (ANOVA) was used to evaluate the influence of slope aspect as well as soil depth on soil moisture and stone content. A pairwise comparison was made using the Tukey honestly significant difference (HSD) method to determine statistical significance ($P<0.05$) in the R statistical software (Team RC, 2022).

Local Moran's I Spatial Autocorrelation

The Moran's I scatter plot provides a tool for visual exploration of spatial autocorrelation (Anselin and Francis, 1996). According to Anselin (2002), describes Moran's I as the spatial lag of the variable on the vertical axis and the standardized variable on the horizontal axis, the spatial lag refers to a separation distance between neighboring observations. The variables were standardized to facilitate the elucidation and labeling of the type of spatial autocorrelation (spatial association or spatial randomness). Spatial randomness means values measured at a location do not depend on values measured at neighboring locations. When the relationship between the geographically nearby values of a parameter tends to be similar on a map: high values tend to be located near high values, medium values near medium values, and low values near low values then there is spatial autocorrelation (Anselin et al., 2010). Many statistical methods do not use raw data but standardized versions of the datasets. Similarly, the Moran's I scatter plot displays standardized variables, not the raw data. Standardization is denoted by a (Z), for z-score, after the variable name. Z-score produces values with zero mean and a variance of 1. The Z-score equation is described as follows:

$$Z=\frac{x_{i,t}-\bar{x}}{s_{x,t}} \qquad (3)$$

Where $x_{i,t}$ is the value of the variable x observed at location i at time t, $\bar{x}$ is the mean of the variable x and $s_{x,t}$ is the standard deviation of the variable x at time t.

The distribution is shown in four quadrants to indicate negative and positive spatial autocorrelation. The slope of the regression line (Moran's I) shows the degree of spatial association between the observed attributes at nearby locations. The expected value of Moran's I is similar but not equivalent to the correlation coefficient which ranges from -1 to 1, where +1 depicts strong positive, –1 strong negative spatial autocorrelation and 0 depicts random spatial ordering. GeoDa (Anselin et al., 2010) and GS+ software packages (Robertson, 2000) were employed for this study. Moran's I for the local indicator is given by the following equation;

$$I=\frac{n(x_i-\bar{x})\sum_{j=1}^{n}w_{ij}(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2} \qquad (4)$$

Where n is a number of observations, x_i and x_j are the values of the variable x observed at location *i* and *j*, $\bar{x}$ is the mean of the variable x, and w_{ij}, an element of spatial weight matrix w, is the spatial weight between the locations of *i* and *j*.

Cross Semivariogram

Cross semivariogram expresses the spatial association between two properties or attributes when measured at progressively greater separation distance across the landscape. Cross- semivariogram was intended to explore and determine spatial interrelations using co-regionalized models between selected soil attributes. Cross-semivariograms identify variables that are leading indicators of other variables or how much and how far one variable is predicted to change in relation to the other variable. Spatial dependence between two variables Z1 and Z2 can be expressed by the cross semivariogram

$$\gamma_{12}(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}[Z_1(x_i+h)-Z_1(x_i)][Z_2(x_j+h)-Z_2(x_j)] \qquad (5)$$

The cross semivariogram is subject to the same hypothesis as the semivariogram and can be fit to the same model equations (Ceddia et al., 2009). The main difference is that the cross semivariogram can be negative if one variable changes in the opposite direction to the other (Goovaerts, 1999).

Results and Discussions

Effects of Aspect on Topsoil Moisture

The distribution of topsoil moisture and stone content, as well as the depth of soil under the different slope aspects, were shown in Table 1. The availability of the soil for the plant is determined by the moisture content of the soil (Rodriguez-Iturbe, 2000; Wernerehl and Givnish, 2015), which is also the most important factors that affect runoff (Yang et al., 2014) and soil erosion (Yang et al., 2012). The measured soil variables were classified according to the slope aspects. To provide insight into the topsoil moisture, topsoil stone content, and soil depth for the different slope aspects, a selection of descriptive statistics summary was used. The average topsoil moisture percentage across the different slope aspects varies between 4.75±0.77% and 14.72±5.62%. According to Brandt et al. (2017), the resulting topsoil moisture contents of the study watershed during the sampling period ranges from extreme stress (wilting point) to good (Table 1). Compared to the other slope aspects, the topsoil moisture content tends to be higher on the north-facing slope, which agreed with the study conducted by Bretherton et al. (2010). The result indicated that the highest average topsoil moisture content at different slope aspects was found, in descending order, for north, northwest, northeast, south, southwest, west, east, and southeast facing slope. The coefficient of variation (CV), standard deviation (SD), and basic statistical parameters of topsoil moisture content on different slope aspects showed that observed soil variables had relatively large variance (Table 1). According to the soil variability guidelines provided by Wilding (1985), the soil property shows low variability when CV is < 0.15, moderately variable when the CV is between 0.15 and 0.35, and the most variable when the CV is > 0.35. According to Wilding (1985), the CV values of topsoil moisture contents across the different slope aspects were generally considered as highly variable (CV ranges from 0.36 to 1.14).

The resulting topsoil moisture distribution seems not significantly dependent on the slope aspect (Table 2), which contradicts the study conducted by Geroy et al. (2011), where the slope aspect affects particularly the soil moisture distribution. The non-significant topsoil moisture distribution on the different slope aspects might be because of the measurement was carried out following the dry period of the season. Similarly, Tromp-van Meerveld and McDonnell (2006) and Famiglietti et al. (2008) documented that time of the year had an effect on the soil moisture distribution. However, it was evident that the slope aspect had an influence on the numerical values of the topsoil moisture percentage, and this could probably due to variation in hydrological processes, land use, land management coupled with the different hillslope processes in the watershed. Generally, a larger number of sample sizes and an intensive temporal measurement would have resulted in a better understanding of the soil moisture and its behavior through time, as reported by Qiu et al. (2001).

Meanwhile, the descriptive statistical summary of the measured soil depth for various slope aspects is presented in Table 1. The mean soil depth varies from 19.8±1.5 cm to 53.44±5.86 cm. Regarding the slope aspect, the depth of the soil exhibited moderate to high variation, as indicated by the values of coefficient of variation (0.17 in the southeast to 0.78 in the west) (Wilding, 1985). This variability could be related to the heterogeneity of land use patterns (Addis et al., 2016), overlaid with severe but variable erosion occurrence within the watershed (Addis et al., 2015). The soil depth measured on the north-facing slope seems higher than on the other slope aspect (Table 1). However, there is no statistically significant difference between the mean values of soil depth measured across the different slope aspects (Table 2). The highest soil depth values were found in ascending order in the different slope aspects for southeast, south, east, southwest, northeast, west, northwest and north (Table 1).

Distribution of Topsoil Stone Content on Different Slope Aspect

The descriptive statistical summary of measured topsoil stone content indicates a mean value that ranges from 14.04±1.73% to 24.56±3.54% (Table 1). The variation of topsoil stone content observed across the different slope aspects is not significant (Table 2). However, focusing on only the numerical values, the highest topsoil stone content was obtained on the southeast facing slope, with the mean value equals to 24.56%. Meanwhile, the lowest topsoil stone content was obtained on the northeast facing slope, with a mean value equal to 14.04% (Table 1). One of the main factors, which might be responsible for the reduction of stone content at the northeast facing slope might be due to the soil and water conservation structures in the location, which reduced the removal of fine soil particles (Addis et al., 2015), leading to least stone content distribution. Meanwhile, the higher topsoil stone content on the southeast facing slope could probably be due to long-term cultivation practices coupled with rainfall-driven erosion. Generally, the topsoil stone content across the slope aspects was moderate to highly variable with CV ranges from 0.32 to 0.92 (Table 1). The resulting distribution of the topsoil stone content is not significantly dependent on the slope aspect (Table 2). The non-significant topsoil stone content across the different slope aspects might be because of the variation in geological processes, topographic conditions, land management practices and rainfall-driven erosion processes in the study watershed (Addis et al., 2016).

Table 1. Overview of the descriptive statistics of the selected physical soil variables classified based on slope aspects

Soil variables	Aspect in degree‡	No	Min	Max	Range	Mean	SD†	SEM†	CV†
Moisture (%)	E (67.5–112.5)	24	0.47	13.46	12.99	5.27	3.81	0.78	0.72
	N (337.5–360) and (0–22.5)	7	4.45	42.12	37.67	14.72	13.76	5.62	0.93
	NE (22.5–67.5)	40	0.62	53.53	52.91	8.52	9.71	1.53	1.14
	NW (292.5–337.5)	15	2.32	33.64	31.32	9.35	7.73	2.00	0.83
	S (157.5–202.5)	52	0.69	46.35	45.66	8.37	7.90	1.10	0.94
	SE (112.5–157.5)	6	1.81	6.31	4.5	4.75	1.72	0.77	0.36
	SW (202.5–247.5)	36	0.86	26.97	26.11	8.14	6.74	1.12	0.83
	W (247.7–292.5)	50	1.05	49.60	48.55	8.03	8.87	1.25	1.10
Stone content (%)	E (67.5–112.5)	24	0.00	73.75	73.75	19.51	17.43	3.56	0.89
	N (337.5–360) and (0–22.5)	7	0.00	31.88	31.88	16.26	10.77	4.40	0.66
	NE (22.5–67.5)	40	0.00	45.90	45.90	14.04	10.92	1.73	0.78
	NW (292.5–337.5)	15	0.00	36.93	36.93	17.04	12.52	3.23	0.73
	S (157.5–202.5)	52	0.00	61.90	61.90	18.93	12.15	1.69	0.64
	SE (112.5–157.5)	6	15.33	36.93	21.6	24.56	7.92	3.54	0.32
	SW (202.5–247.5)	36	0.00	59.52	59.52	16.78	15.46	2.58	0.92
	W (247.7–292.5)	50	0.00	50.99	50.99	16.49	13.19	1.87	0.80
Soil depth (cm)	E (67.5–112.5)	24	8.00	101.00	93.00	39.46	29.29	5.98	0.74
	N (337.5–360) and (0–22.5)	7	9.00	101.00	92.00	53.44	35.17	5.86	0.66
	NE (22.5–67.5)	40	12.00	101.00	89.00	46.25	32.31	5.11	0.70
	NW (292.5–337.5)	15	10.00	101.00	91.00	51.07	37.22	9.61	0.73
	S (157.5–202.5)	52	10.00	101.00	91.00	37.58	28.64	3.97	0.76
	SE (112.5–157.5)	6	16	25	9	19.8	3.35	1.5	0.17
	SW (202.5–247.5)	36	10.00	101.00	91.00	43.50	32.55	13.29	0.75
	W (247.7–292.5)	50	10.00	101.00	91.00	47.20	36.81	5.21	0.78

No: No. sample; Notes. †SD – standard deviation; SEM (mean) – standard error of mean; CV – coefficient of variation; ‡E – East; N – North; NE – Northeast; NW – Northwest; S – South; SE – Southeast; SW – Southwest; W – West.

Table 2. Effects of slope aspect and soil depth on mean values of selected soil properties

Variable	Slope aspect								Soil depth (cm)		
	E	N	NE	NW	S	SE	SW	W	0–25 cm	25–60 cm	60–100 cm
Soil moisture (%)	5.27^{A}	14.72^{A}	8.52^{A}	9.35^{A}	8.37^{A}	4.75^{A}	8.14^{A}	8.03^{A}	8.11^{B}	14.88^{A}	16.50^{A}
Stone content (%)	19.51^{A}	16.26^{A}	14.05^{A}	17.04^{A}	18.93^{A}	24.56^{A}	16.78^{A}	16.49^{A}	17.19^{A}	9.61^{B}	5.00^{B}
Soil depth (cm)	39.46^{A}	53.44^{A}	46.25^{A}	51.07^{A}	37.58^{A}	19.8^{A}	43.5^{A}	47.2^{A}			

Different letters in the same row represent a significant difference ($P<0.05$).

Table 3. Overview of the descriptive statistical summary of soil moisture and stone content classified based on soil depth

Variables	Soil depth (cm)	No. sample	Min	Max	Range	Mean	SD	SEM	CV
Soil moisture (%)	0–25 cm	230	0.47	53.53	53.06	8.11	8.12	0.54	1.00
	25–60 cm	96	0.60	62.19	61.59	14.88	8.79	0.90	0.59
	60–100 cm	59	2.14	26.86	24.72	16.50	5.56	0.74	0.34
Stone content (%)	0–25 cm	230	0.00	73.75	73.75	17.19	13.29	0.88	0.77
	25–60 cm	96	0.00	55.07	55.07	9.61	13.04	1.33	1.36
	60–100 cm	59	0.00	40.74	40.74	5.00	9.10	1.21	1.82

Impact of Soil Depth on Topsoil Moisture and Stone Content

The basic descriptive statistics for soil moisture and stone content measured in the three soil depth classes are given in Table 3. Soil depth linked to soil capacity to hold moisture in the occurrence or absence of rainwater regulates crop production (Christopher et al., 2008). The mean values of the physical properties of the soil measured in different soil depth classes ranged from 8.11% to 16.5% for soil moisture and 5.0% to 17.19% for stone content (Table 3). The variability of soil moisture and stone content observed at different soil depth classes within the study watershed was classified as medium to highly variable for topsoil moisture and highly variable for stone content (Table 3). Pearson's correlation coefficients (*r*) of soil depth with topsoil moisture (with the *r* values of 0.57) and soil depth with topsoil stone content (with *r* values of -0.63) were significantly correlated. The basis of the negative relationship between soil depth and topsoil stone content is direct, which indicts higher soil depth values are associated with smaller topsoil stone content. Topsoil moisture content is positively correlated with soil depth and thus it is directly affected by soil depth. Similarly, Tromp-van Meerveld and McDonnell (2006) and Geroy et al. (2011) documented that the spatial variability of soil moisture is influenced by soil depth. However, there is no clear indication that soil moisture and stone content are correlated with each other in the three soil depth classes. Soil moisture data observed at different soil depth classes indicated that there is a significant difference in the mean soil moisture observed at 0-25 cm with 25-60 cm and 60-100 cm determined by ANOVA (Table 2). Comparison of the soil moisture content for the soil depth classes suggests that overall soil moisture content on 25–60 cm and 60–100 cm soil depth classes were significantly higher than the topsoil (0–25 cm) moisture content (Table 2). With increasing soil depth, mean soil moisture increases significantly for the two layers (from 0-25 cm to 25-60 cm and from 0-25 cm to 60-100 cm), which is consistent with the previous finding (Qiu et al., 2001). However, the CV of soil moisture is decreased with increasing depth (Table 3), which contradicts with the study conducted by Qiu et al. (2001) and Baskan et al. (2013). The ANOVA performed also suggests that the topsoil stone content at the 0-25 cm soil depth is significantly changed compared to the soil depth classes of the soil of 25-60 cm and 60-100 cm (Table 2). According to Kassaye et al. (2018), the actual and potential soil erosion in the study watershed covers a huge area, which contributes to the low overall soil moisture and low soil depth.

Local Moran's I

The spatial autocorrelation of the observed topsoil moisture content (0-25 cm), topsoil stone content (0-25 cm), and soil depth were illustrated using Moran's I scatterplots (Figure 2). In Figure 2a-c the Moran's I scatterplots of (a) topsoil moisture content, (b) topsoil stone content and (c) soil depth is presented. The correlogram for topsoil moisture content exhibited significantly positive autocorrelation (p = 0.001) within 4108 m with Moran's I value of 0.38, and then did not show an autocorrelation and negative correlation with increasing lag distances (Figure 2a). The Moran's I scatterplot (correlogram) showed that the topsoil stone content (Figure 2b) was significantly positively autocorrelated (p = 0.001) up to 3081 m with Moran's I value of 0.30, and a negative correlation at the lag distance between 3081 m and 10270 m, then positively autocorrelated with increasing lag distances. The correlogram of soil depth showed that there was significantly positively autocorrelated (p = 0.001) within 4108 m with a Moran's I value of 0.56, and a negative correlation at the lag distance between 4108 m and 11297 m, then positively autocorrelated with the increasing lag distances (Figure 2c).

Cross Semivariogram

Considering the relationships of topsoil moisture and topsoil stone content with soil depth, one might expect that the spatial pattern and magnitude of observed topsoil moisture and stone content should be strongly related to a soil depth of the watershed as a soil depth indicates the soil genesis process, which eventually affects water holding capacity and soil fertility status of the soil. GS+ software was used to obtain the cross-semivariogram model of each of the observed soil physical attributes and the Gaussian model and exponential function were best fitted to the experimental values of the measured physical soil attributes (Figure 3).

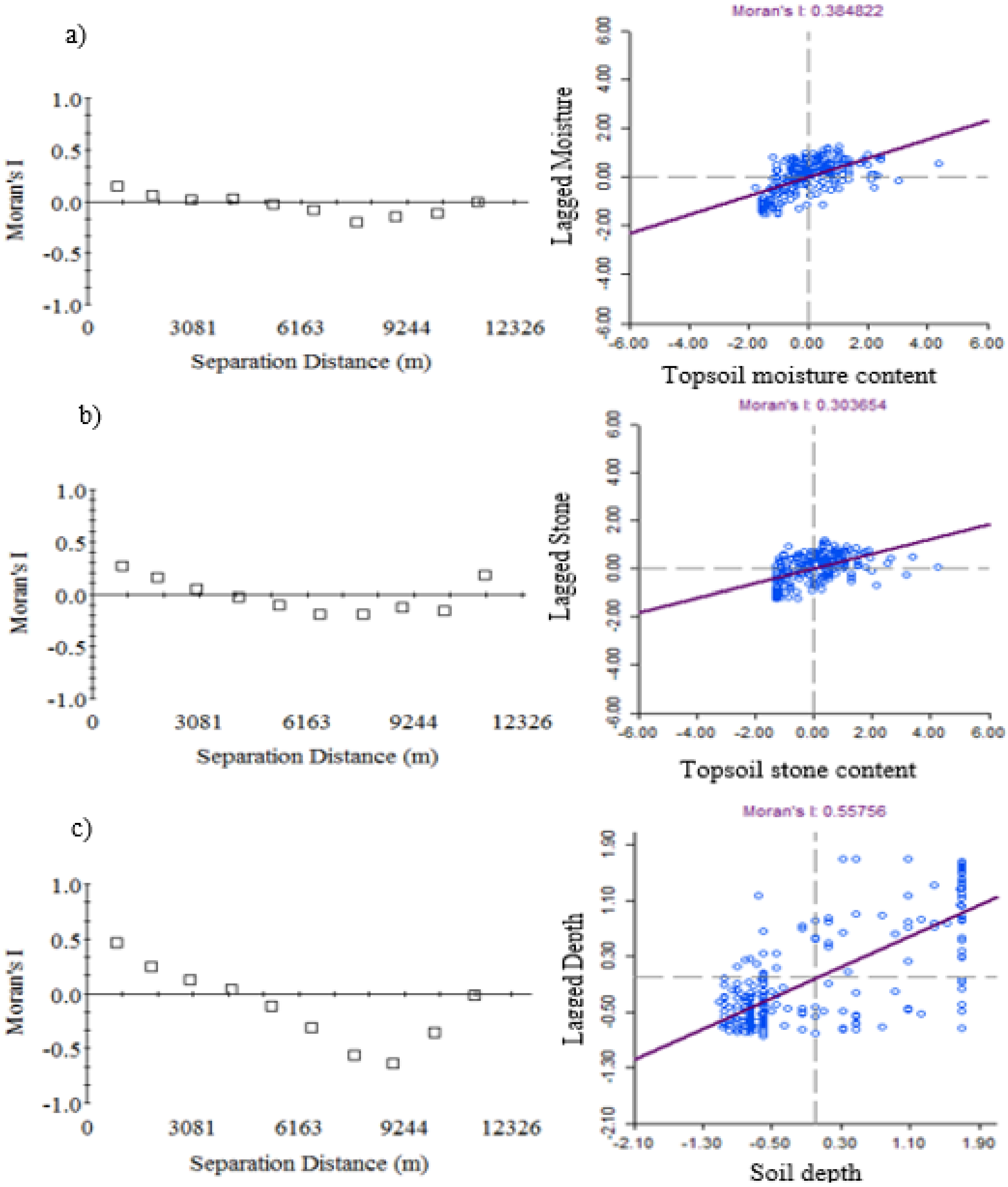

Figure 2. Spatial autocorrelation, Moran's I scatterplots with trend line of soil physical properties, (a) topsoil moisture content, (b) topsoil stone content, (c) soil depth

Studying the relationship of soil depth with moisture content is crucial as a soil depth affects available water capacity since it can limit the volume of soil available for root growth (Kirkham, 2005). The isotropic cross-semivariogram of soil depth with topsoil moisture content showed a positive correlation up to a lag distance of 9244 m with $r^2 = 0.82$ (Figure 3a). This result indicated that over the range of the cross-semivariogram, depth and moisture content exhibited the same spatial dependence; hence, the spatial relationship was obtained at pairs of sample sites separated by distances no greater than the range. Meanwhile, the isotropic cross-semivariograms of soil depth with topsoil stone content showed a negative correlation up to a range of 12325 m, and the coefficient of determination (r^2) equals 0.96, indicating a strong negative spatial interdependence between soil depth and topsoil stone content (Figure 3b). The cross-semivariogram of soil depth with topsoil moisture content was best fitted with the exponential function while soil depth with topsoil stone content was best fitted with the Gaussian model. On the contrary, the isotropic cross-semivariogram constructed for the moisture content of the topsoil versus topsoil stone content was not correlated ($r^2 = 0.08$).

Overall, the resulting isotropic cross-semivariograms showed that a significant spatial relationship existed between soil depth with topsoil moisture and stone content observed at the same location, and the resulting r^2 show that models fit the experimental cross-semivariogram data very well while the nugget effect was smaller (for soil depth with topsoil stone content, the relative nugget effect equal 0.2) to moderately spatially dependent (for soil depth with topsoil moisture content, the relative nugget effect equal 0.48). As an illustration, the cross semivariograms of the measured pairs of physical soil attributes, such as soil depth with topsoil moisture and topsoil stone content, are displayed in Figure 3.

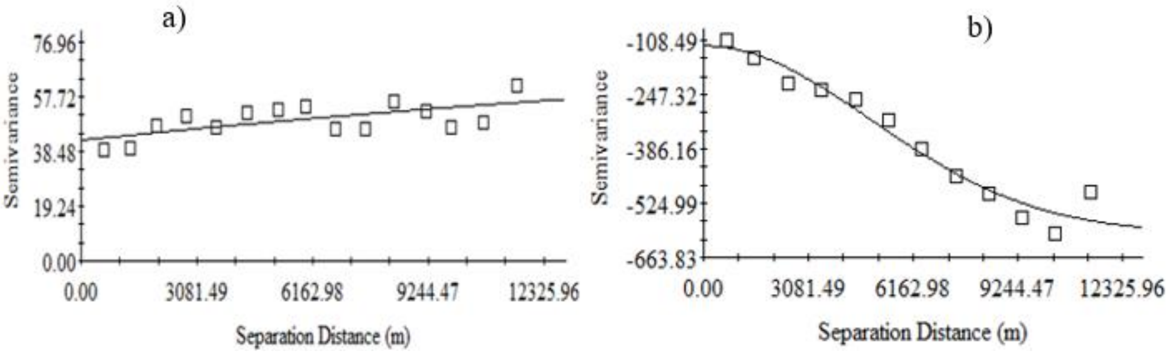

Figure 3. Cross-semivariograms of the attributes measured in the study watershed (a) soil depth versus topsoil moisture content using the exponential function, (b) soil depth versus topsoil stone content using the Gaussian model

Conclusions

This work aims to investigate the potential influence of slope aspect and soil depth on soil moisture and stone content and shows the importance of soil depth in any further analysis to be developed in soil and environmental modeling in the study watershed or nearby areas with similar characteristics. Classical statistics indicated that soil moisture increased with increasing soil depth and the amount of variation (CV) in soil moisture decreased with increasing depth. Regarding the interrelationship, there was a significant positive correlation between soil depth and soil moisture, while a significant negative correlation was detected between stone content and soil depth. This linkage implies that soil moisture distribution in the study watershed is sensitive to soil depth and thus represents an important factor in the regional as well as the global water cycle. However, the slope aspect had no significant effect on the spatial distribution of topsoil moisture, topsoil stone content as well as soil depth.

Meanwhile, the Moran’s I scatterplot of topsoil moisture, stone content and soil depth had significantly positively autocorrelated, which means the dependence of the values of topsoil moisture, stone content and soil depth on the values of the same variable recorded at neighboring locations in the study watershed. The composition of the parental material, soil erosion and sedimentation may be responsible for the strong spatial dependence of topsoil moisture, stone content and soil depth. The experimental cross-semivariograms of soil depth with topsoil stone content displayed a negative correlation up to a range of 12325 m with the coefficient of determination (r^2) equals to 0.96, while depth with topsoil moisture content was positively correlated up to a lag distance of 9244 m with (r^2) equals to 0.82.

Generally, the study showed the potential of soil depth over slope aspect for controlling the distribution of soil moisture and stone content, which in turn regulates the microclimate, soil formation, parent material and hydrological and geological processes in the Ethiopian Highlands of the study watershed; nevertheless, further studies are required to fully understand the interactive relationships of several environmental factors.

Acknowledgments

The authors would like to recognize the contribution of Gondar agricultural research center for providing logistical support. We would like to thank the International Center of Agriculture Research in the Dry Areas (ICARDA), BOKU University of Natural Resources and Life Sciences, Vienna, Amhara Regional Agricultural Research Institute (ARARI), and Austrian Development Agency (ADA) for their technical and financial support.

References

Addis HK, Andreas K. 2015. Predicting the spatial distribution of soil erodibility factor using USLE nomograph in an agricultural watershed, Ethiopia. *Int. Soil Water Conserv Res* 3(4): 282–290. Doi: https://doi.org/10.1016/j.iswcr.2015.11.002

Addis HK, Klik A, Strohmeier S. 2015. Spatial variability of selected soil attributes under agricultural land use system in a mountainous watershed, Ethiopia. *Int J Geosci* l(6): 605–613. Doi: http://dx.doi.org/10.4236/ijg.2015.66047

Addis HK, Strohmeier S, Ziadat F, Melaku ND, Klik A. 2016. Modeling streamflow and sediment using SWAT in Ethiopian Highlands. 9, 51-66. *Int J Agri. Biol Eng* 9(5): 51–66. Doi: http://dx.doi.org/10.3965/j.ijabe.20160905.2483

Alexandridis TK, Cherif I, Bilas G, Almeida WG, Hartanto IM, Van Andel SJ, Araujo A. 2016. Spatial and temporal distribution of soil moisture at the catchment scale using remotely-sensed energy fluxes. *Water* 8(32): 1–16. Doi: https://doi.org/10.3390/w8010032

Anselin L. 2002. Exploring spatial data with DynESDA2 CSISS and spatial analysis laboratory University of Illinois, Urbana-Champaign 12

Anselin L, Syabri I, Kho Y. 2010. GeoDa: an introduction to spatial data analysis. *Geogr Anal* 38(1): 5–22. Doi: https://doi.org/10.1111/j.0016-7363.2005.00671.x

Anselin LJT, Francis L. 1996. The Moran scatterplot as an ESDA tool to assess local instability in spatial association. Spatial analytical perspectives on GIS.

Baroni G, Ortuani B, Facchi A, Gandolfi C. 2013. The role of vegetation and soil properties on the spatio-temporal variability of the surface soil moisture in a maize-cropped field. *J Hydrol* 489: 148–159. Doi: https://doi.org/10.1016/j.jhydrol.2013.03.007

Baskan O, Kosker Y, Erpul G. 2013. Spatial and temporal variation of moisture content in the soil profiles of two different agricultural fields of semi-arid region. *Environ Monit Assess* 185(12): 10441–10458. Doi: https://doi.org/10.1007/s10661-013- 3343-8

Brandt MJ, Johnson KM, Elphinston AJ, Ratnayaka DD. 2017. Chapter 3 - Hydrology and Surface Supplies. In: Brandt MJ, Johnson KM, Elphinston AJ, Ratnayaka DD (eds) Twort's Water Supply (Seventh Edition). Butterworth-Heinemann, Boston, pp 65-116. Doi: https://doi.org/10.1016/B978-0-08-100025-0.00003-X

Bretherton M, Scotter D, Horne D, Hedley M. 2010. Towards an improved understanding of the soil water balance of sloping land under pasture. *N Z J Agric Res* 53(2): 175–185. Doi: https://doi.org/10.1080/00288233.2010.482957

Brocca L, Melone F, Moramarco T, Morbidelli R. 2010. Spatial-temporal variability of soil moisture and its estimation across scales. *Water Resour Res* 46: 1–14. Doi: https://doi.org/10.1029/2009WR008016

Brocca L, Tullo T, Melone F, Moramarco T, Morbidelli R. 2012. Catchment scale soil moisture spatial–temporal variability. *J Hydrol* 422–423: 63–75. Doi: https://doi.org/10.1016 /j.jhydrol.2011.12.039

Ceddia MB, Vieira SR, Villela ALO, Mota LdS, Anjos LHCd, Carvalho DFd. 2009. Topography and spatial variability of soil physical properties. *Sci Agric* 66(3): 338–352. Doi: http://dx.doi.org/10.1590/S0103-90162009000300009

Cerdà AJJH. 1997. Seasonal changes of the infiltration rates in a Mediterranean scrubland on limestone. *J Hydrol* 198(1–4): 209–225. Doi: https://doi.org/10.1016/S0022-1694(96)032 95-7

Christopher J, Manschadi A, Hammer G, Borrell A. 2008. Developmental and physiological traits associated with high yield and stay-green phenotype in wheat. *Aust J Agric Res* 59(4): 354–364. Doi: https://doi.org/10.1071/AR07193

Dobriyal P, Qureshi A, Badola R, Hussain SA. 2012. A review of the methods available for estimating soil moisture and its implications for water resource management. *J Hydrol* 458–459: 110–117. Doi: https://doi.org/10.1016/j.jhydrol. 2012.06.021

Famiglietti JS, Ryu D, Berg AA, Rodell M, Jackson TJ. 2008. Field observations of soil moisture variability across scales. *Water Resour Res* 44(1): 1–16. Doi: https://doi.org/10.1029/2006WR005804

Feng Q, Zhao W, Qiu Y, Zhao M, Zhong L. 2013. Spatial heterogeneity of soil moisture and the scale variability of its influencing factors: A case study in the loess plateau of China. *Water* 5(3): 1226–1242. Doi: https://doi.org/10.3390 /w5031226

Gallardo-Cruz JA, Pérez-García EA, Meave JA. 2009. β-Diversity and vegetation structure as influenced by slope aspect and altitude in a seasonally dry tropical landscape. *Landsc Ecol* 24(4): 473–482. Doi: https://doi.org/1 0.1007/s10980-009-9332-1

Gates DM (2012) Biophysical ecology. Courier Corporation.

Geroy I, Gribb M, Marshall HP, Chandler D, Benner SG, McNamara JP. 2011. Aspect influences on soil water retention and storage. *Hydrol Process* 25(25): 3836–3842. Doi: https://doi.org/10.1002/hyp.8281

Gong X, Brueck H, Giese K, Zhang L, Sattelmacher B, Lin S. 2008. Slope aspect has effects on productivity and species composition of hilly grassland in the Xilin River Basin, Inner Mongolia, China. *J Arid Environ* 72(4): 483–493. Doi: https://doi.org/10.1016/j.jaridenv.2007.07.001

Goovaerts P. 1999. Geostatistics in soil science: state-of-the-art and perspectives. *Geoderma* 89(1–2) 1–45. Doi: https://doi.org/10.1016/S0016-7061(98)00078-0

Guo D, Mou P, Jones RH, Mitchell RJ. 2002. Temporal changes in spatial patterns of soil moisture followingafter disturbance: an experimental approach. *J Ecol* 90(2): 338–347. Doi: https://doi.org/10.1046/j.1365-2745.2001.00667.x

Hanna A, Harlan P, Lewis DJAJ. 1982. Soil available water as influenced by landscape position and aspect 1. *Agron J* 74(6): 999–1004. Doi: https://doi.org/10.2134/agronj1982.0002196 2007400060016x

Hauser M, Orth R, Seneviratne SIJGMD. 2017. Investigating soil moisture–climate interactions with prescribed soil moisture experiments: an assessment with the Community Earth System Model (version 1.2). *Geosci Model Dev* 10(4): 1665–1677. Doi: https://doi.org/10.5194/gmd-10-1665-2017

Kassaye G, Addis HK, Teklay A. 2018. Assessment of Spatial Soil Erosion Susceptibility Based on the CORINE Model in the Gumara-Maksegnit Watershed, Ethiopia. *J Nat Resour Dev* 8: 38–45. Doi: https://doi.org/10.5027/jnrd.v8i0.05

Kim S. 2012. Characterization of annual soil moisture response pattern on a hillslope in Bongsunsa Watershed, South Korea. *J Hydrol* 448: 100–111. Doi: https://doi.org/10. 1016/j.jhydrol.2012.04.030

Kirkham MB. 2005. Field Capacity, Wilting Point, Available Water, and the Nonlimiting Water Range, in *principles of soil and plant water relations*, *2nd* ed. California, *Elsevier Academic Press*, Chap. *8*, sec. *598*, pp. *101–110*.

Kutiel P, Lavee H, Ackermann O. 1998. Spatial distribution of soil surface coverage on north and south facing hillslopes along a Mediterranean to extreme arid climatic gradient. *Geomorphology* 23(2–4): 245–256. Doi: https://doi.org/10. 1016/S0169-555X(98)00007-5

Latron J, Soler M, Llorens P, Gallart FJHPAIJ. 2008. Spatial and temporal variability of the hydrological response in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). *Hydrol Process* 22(6): 775–787. Doi: https://doi.org/10.1002/hyp.6648

Legates DR, Mahmood R, Levia DF, DeLiberty TL, Quiring SM, Houser C, Nelson FE. 2011. Soil moisture: A central and unifying theme in physical geography. *Prog Phys Geogr* 35(1): 65–86. Doi: https://doi.org/10.1177/ 03091333 10386514

Lu N, Chen S, Wilske B, Sun G, Chen JJJPE. 2011. Evapotranspiration and soil water relationships in a range of disturbed and undisturbed ecosystems in the semi-arid Inner Mongolia, China. *J Plant Ecol* 4(1–2): 49–60. Doi: https://doi.org/10.1093/jpe/rtq035

McMillan H, Srinivasan M. 2015. Characteristics and controls of variability in soil moisture and groundwater in a headwater catchment. *Hydrol Earth Syst Sci* 19(4): 1767–1786. Doi: https://doi.org/10.5194/hess-19-1767-2015

Moeslund JE, Arge L, Bøcher PK, Dalgaard T, Ejrnæs R, Odgaard MV, Svenning JC. 2013. Topographically controlled soil moisture drives plant diversity patterns within grasslands. *Biodivers Conserv* 22(10): 2151–2166. Doi: https://doi.org/10.1007/s10531-013-0442-3

Qiu Y, Fu B, Wang J, Chen LJJAE. 2001. Spatial variability of soil moisture content and its relation to environmental indices in a semi-arid gully catchment of the Loess Plateau, China. *J Arid Environ* 49(4): 723–750. Doi: https://doi.org/10.1006/ jare.2001.0828

Ries F, Lange J, Schmidt S, Puhlmann H, Sauter MJH. 2015. Recharge estimation and soil moisture dynamics in a Mediterranean, semi-arid karst region. *Hydrol Earth Syst Sci* 19(3): 1439–1456. Doi: https://doi.org/10.5194/hess-19-1439-2015

Robertson G. 2000. GS+: Geostatistics for the environmental sciences. Gamma Design Software Plainwell

Rodriguez-Iturbe I. 2000. Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamies. *Water Resour Res* 36(1): 3–9. Doi: https://doi.org/10.1029/ 1999WR900210

Rosenbaum U, Bogena HR, Herbst M, Huisman J, Peterson T, Weuthen A, Western A, Vereecken H. 2012. Seasonal and event dynamics of spatial soil moisture patterns at the small catchment scale. *Water Resour Res* 48(10): 1–22. Doi: https://doi.org/10.1029/2011WR011518

Team RC. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Tromp-van Meerveld H, McDonnell J. 2006. On the interrelations between topography, soil depth, soil moisture, transpiration rates and species distribution at the hillslope scale. *Adv Water Resour* 29(2): 293–310. Doi: https://doi.org/10.1016/j.advwatres.2005.02.016

Venkatesh B, Lakshman N, Purandara B, Reddy V. 2011. Analysis of observed soil moisture patterns under different land covers in Western Ghats, India. *J Hydrol* 397(3-4): 281-294. Doi: https://doi.org/10.1016/j.jhydrol.2010.12.006

Wang S, Fu B, Gao G, Yao X, Zhou J. 2012. Soil moisture and evapotranspiration of different land cover types in the Loess Plateau, China. . *Hydrol Earth Syst Sci* 16(8): 2883–2892. Doi: https://doi.org/10.5194/hess-16-2883-2012

Wernerehl RW, Givnish TJ. 2015. Relative roles of soil moisture, nutrient supply, depth, and mechanical impedance in determining composition and structure of Wisconsin prairies. *PLoS One* 10(9): 1–20. Doi: https://doi.org/10.1371/journal.pone.0137963

Wilding L. 1985. Spatial variability: its documentation, accomodation and implication to soil surveys. In: Soil spatial variability, Las NV, 30 November-1 December 1984, pp. 166-194.

Yang L, Wei W, Chen L, Chen W, Wang J. 2014. Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China. *Catena* 115:123-133. Doi: https://doi.org/10.1016/j.catena.2013.12.005

Yang L, Wei W, Chen L, Jia F, Mo B. 2012. Spatial variation of shallow and deep soil moisture in the semi-arid loess hilly area, China. *Hydrol Earth Syst Sci* 16(9): 3199–3217. Doi: https://doi.org/10.5194/hess-16-3199-2012

Zhang P, Shao M. 2015. Spatio-temporal variability of surface soil water content and its influencing factors in a desert area, China. *Hydrolog Sci J* 60(1): 96–110. Doi: https://doi.org/10.1080/02626667.2013.875178

Zhu H, Shi Z, Fang N, Wu G, Guo Z, Zhang Y. 2014. Soil moisture response to environmental factors following precipitation events in a small catchment. *Catena* 120: 73–80. Doi: https://doi.org/10.1016/j.catena.2014.04.003

Zribi M, Paris AT, Duchemin B, Lili Z, Wagner W, Hasenauer S, Chehbouni A. 2010. Relationship between soil moisture and vegetation in the Kairouan plain region of Tunisia using low spatial resolution satellite data. *Water Resour Res* 46(6): 1–13. Doi: https://doi.org/10.1029/2009WR008196