EFFECT OF SOIL HYDRAULIC PROPERTIES ON THE RELATIONSHIP BETWEEN SOIL MOISTURE VARIABILITY AND ITS MEAN VALUE

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RESUMEN. La caracterización de la humedad del suelo y su variabilidad son determinantes en proyectos ambientales. En este trabajo se analiza la relación entre la variabilidad espacial de la humedad del suelo y su valor medio para suelos sin cubierta. Se realizaron simulaciones de flujo de agua en suelo analizando distintos patrones climáticos y con variaciones de sus propiedades hidráulicas. Observamos que la sección de la curva que relaciona la humedad media con su variabilidad se determina por la interacción entre las propiedades del suelo y las características del clima. El valor medio que corresponde a la máxima variabilidad en la humedad del suelo viene determinada por las propiedades hidráulicas del suelo y la presencia o ausencia de vegetación. Los resultados muestran que al ajustar linealmente la relación entre humedad media y variabilidad, la pendiente de esa recta está directamente relacionada con un parámetro de la curva característica del suelo. En investigaciones futuras se debería analizar la influencia de otros factores como la variabilidad espacial de la lluvia o la correlación espacial de varios parámetros del suelo.

ABSTRACT. Knowledge of soil moisture and its variability is needed for many environmental applications. We analyzed dependencies of soil moisture variability on average soil moisture contents in bare soils using ensembles of non-stationary water flow simulations by varying soil hydraulic properties under different climatic conditions. We focused on the dry end of the soil moisture range and found that the magnitude of soil moisture variability was controlled by the interplay of soil hydraulic properties and climate. The average moisture at which the maximum variability occurred depended on soil hydraulic properties and vegetation. A positive linear relationship was observed between mean soil moisture and its standard deviation and was controlled by a soil moisture characteristic parameter. The influence of other controls needs to be studied further to see if such relationship persists and could be used for the inference of soil hydraulic properties from the spatiotemporal variation in soil moisture.

1.- Introduction

Understanding soil water content variability is critical for improving the performance of hydrologic and atmospheric models and for up- and down-scaling remotely sensed soil moisture (Vereecken et al., 2008). Surface soil moisture variability has been shown to depend on mean soil moisture content and that has been demonstrated at different scales (Famiglietti et al., 1999, 2008; Martinez-Fernández and Ceballos, 2003; Teuling and Troch, 2005; Choi et al., 2007; Vereecken et al., 2007; Mittelbach and Seneviratne, 2012; Rosenbaum et al., 2012). This variability is affected by several factors such vegetation (Teuling and Troch, 2005), climate (Teuling et al., 2007), soil hydraulic properties (Vereecken et al., 2007), topography (Grayson et al., 1997) and antecedent soil moisture (Ivanov et al., 2010). The dependency between the mean soil moisture (<θ>) and its variability (σ_θ) has been described to increase (Famiglietti et al., 1999; Martinez-Fernández and Ceballos, 2003), or to decrease (Famiglietti et al., 1999; Brocca et al., 2007) and both to increase and decrease with increasing mean moisture. The body of literature that addressed this topic for more than a decade (from Famiglietti et al., 1998; to Rosenbaum et al., 2012), generally shows that the graph of this relationship is typically convex (Teuling and Troch, 2005; Choi et al., 2007; Rosenbaum et al., 2012). Regression models for σ_θ have been proposed, including an exponential model (Famiglietti et al., 2008), a third-order polynomial (Rosenbaum et al., 2012) and a linear equation for the dry-end (Teuling et al., 2007).

Soil properties, and more specifically soil hydraulic properties-related parameters, often had the largest influence on the variability of soil moisture (Choi et al., 2007). The dependence of the standard deviation of soil moisture σ_θ on average soil moisture as affected by soil hydraulic properties was previously studied by Vereecken et al. (2007) using an analytical solution of a stochastic steady state flow model. They used the moisture retention characteristic parameters, the saturated hydraulic conductivity and their spatial statistics to determine the σ_θ relationship and its main characteristics. They found that the mean water content at which the standard deviation became maximal depended on the shape parameters of the moisture retention characteristic. Here we examine the σ_θ in the non-stationary flow model framework under several types of climatic conditions. We also show that the linearization of the pre-peak relationship σ_θ may be useful to evaluate soil moisture retention parameters of bare soils at different scales.

2.- Methods

2.1. Simulations setup

We used the HYDRUS code (Simunek et al., 2005) to simulate water flow by solving the Richard equation numerically. Time-dependent atmospheric boundary conditions were imposed at the soil surface and a constant head boundary condition was imposed at the bottom of a 3-m long profile. The Initial condition was obtained from a spin up model run of 1 year. Simulations were performed in a1-D soil profile with homogeneous properties. The profile was deep enough to make the soil moisture of the top 1 m layer insensitive to the bottom boundary condition. We used different climatic conditions to run our simulations. For that, we generated different time series of rainfall and evaporation with the CLIGEN weather generator (Nicks et al., 1995) for the humid subtropical and continental and the cold and hot semiarid climates. Seven soil texture classes were used in the analysis (Table 1). For a particular soil and climate we ran an ensemble of models defined with variable saturated hydraulic conductivity (K_s), following the commonly encountered lognormal distribution (Jury, 1985). The value of the spatial variability of ln K_s ($\sigma_{\ln Ks}$) used in most of the simulations was 0.8 as it lies inside the range observed for most of the soils (Cosby et al., 1984). Values of $\sigma_{\ln Ks}$ between 0.2 and 1 were also used to illustrate the effect of increasing $\sigma_{\ln Ks}$ on σ_θ for a soil with the hydraulic properties of the loamy soils and the cold semiarid weather. We included evapotranspiration by simulating root water uptake from a well established grass (100% soil surface coverage) with a root system extending to a depth of 0.5 m.

Table 1. Soil hydraulic properties used in simulations

	θ_s (m^3 m^{-3})	θ_r (m^3 m^{-3})	α (cm^{-1})	n	m	ln K_s (cm day^{-1})
Loamy sand	0.41	0.06	0.12	2.3	0.6	5.7
Sandy loam	0.41	0.06	0.06	1.9	0.5	5.0
Sandy clay loam	0.39	0.10	0.06	1.5	0.3	3.2
Loam	0.43	0.08	0.03	1.6	0.4	2.8
Silt loam	0.45	0.07	0.02	1.4	0.3	3.7
Clay loam	0.41	0.10	0.02	1.3	0.2	2.6
Silty clay loam	0.43	0.09	0.01	1.2	0.2	2.5

2.2. Data analysis.

One-year data of simulated soil moistures at the 5 cm depth were used for the analysis as this is widely used depth in many of the remote sensing works for validation of soil moisture products. To illustrate the influence of a different σlnKs and to compare the effect of soil hydraulic properties and climate we limited our analysis of the σ_θ to its dry part. Although film flow might become important in the dry range we assume that it would not affect the general tendency in that part. The cutoff $<\theta>$ that defined the dry part or "pre-peak" of σ_θ was obtained by trimming the data with $<\theta>$ larger than the peak $<\theta>$. A linear regression was applied to the resulting data in order to get the slope of the dry part of σ_θ, similarly to Teuling et al. (2007).

3.- Results and discussion

The typical convex shape of σ_θ could be observed by running a non-stationary flow model with an ensemble of spatially variable K_s in the fine-textured soils (Fig. 1). A clear peak could not be seen with the LS and SL textures as previously reported for the steady-state flow case (Vereecken et al., 2007). The soil textures with a high percentage of sand show a linear increase of σ_θ with increasing $<\theta>$ where no peak could be determined similarly to the field observations of Martinez-Fernández and Ceballos (2003). Soil texture was responsible for the differences between peak σ_θ and the corresponding $<\theta>$ values (Table 2) with values ranging between 0.022 and 0.034.

Table 2. Average moisture content (m^3 m^{-3}) and standard deviation at the peak of the σ_θ (m^3 m^{-3}) and slope of the σ_θ dry-part of the modelled soils

	peak WC	peak std	slope LM
Loamy sand†	0.237	0.032	0.17
Sandy loam†	0.299	0.034	0.14
Sandy clay loam	0.337	0.023	0.07
Loam	0.361	0.030	0.09
Loam under vegetation	0.342	0.034	0.05
Silt loam	0.375	0.029	0.11
Clay loam	0.362	0.022	0.06
Silty clay loam	0.337	0.023	0.07

† The peak was not reached. Therefore the maximum σ_θ and its corresponding $<\theta>$ were used.

The effect of vegetation is illustrated for a loamy soil under cold semiarid climate. Root water uptake modified the characteristics of the σ_θ relationship (Figs. 1g and 1h). It halved the slope of the dry part, increased the maximum σ_θ, decreased slightly the $<\theta>$ at the σ_θ peak and had a larger range of mean moisture values with the highest σ_θ.

There was a clear difference between the average moisture content at the σ_θ peak calculated with the stationary approximation and Brooks-Corey parameters in Vereecken et al. (2007) and the non-stationary approximation with the van Genuchten parameters in our case (Table 2). We observed larger values of $<\theta>$ at the σ_θ peak than in the similar cases of Vereecken et al. (2007). One possible explanation is that the model of Brooks-Corey requires a clear air entry value and therefore determines the location of the σ_θ peak that may impose lower values. Values of $<\theta>$ at the σ_θ peak for a silty clay loam obtained in our simulations and in Vereecken et al. (2007) (0.34 and 0.20 m^3m^{-3}, respectively) are smaller than in Rosenbaum et al. (2012), 0.39 m^3m^{-3}, though our non-stationary case provided closer results. This difference with observed values can be explained by the effects of vegetation described before and the difference between the generalized moisture retention parameters used in the simulations and the actual values in the experimental site.

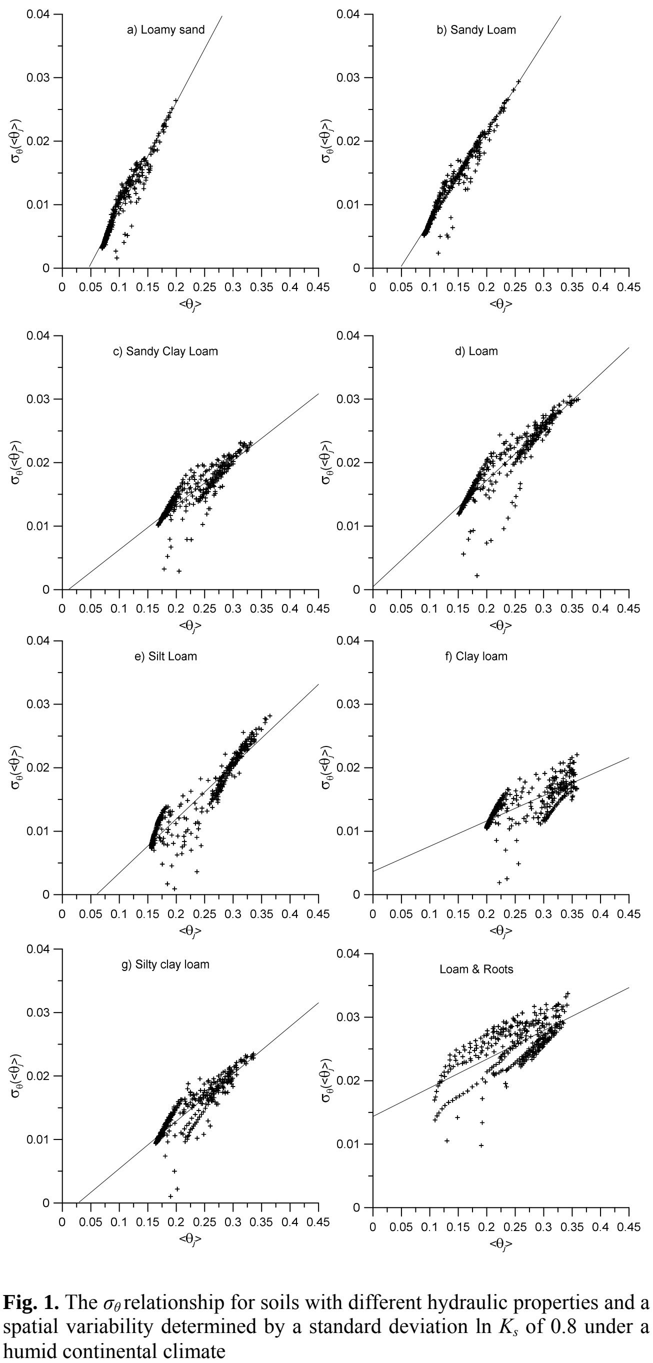

Fig. 1. The σ_θ relationship for soils with different hydraulic properties and a spatial variability determined by a standard deviation ln K_s of 0.8 under a humid continental climate

Slopes in linear regressions $<\theta>$ vs σ_θ depended on soil texture (Table 2). Larger slopes were found for the coarser soils. The lower slope in our model for the SL than in the field experiment of Martinez-Fernández and Ceballos (2003) with similar texture probably reflected the influence of vegetation and topography on the maximum σ_θ as generators of a larger variability of soil moisture. A strong relationship between the slope of the linearized pre-peak soil moisture variability and the "n" parameter of the van Genuchten moisture retention equation was observed (Fig. 2a). The relationship found between the soil moisture variability and the "n" parameter could be useful to infer large-scale water retention properties from soil moisture networks monitoring data. While that could only be done for weak perturbations of the standard deviation in Vereecken et al. (2007), this approach is more robust and has not such limitation. We fitted a linear regression to the points with soil moisture smaller than 25% of the LAGO data in Brocca et al. (2012, Fig. 4a) and obtained a slope of 0.15. Applying the regression shown in Fig. 2a we obtained an "n" value of 2.08. This value corresponds to n-values for soils having the LS texture. These soils represent the dominant textural class in the LAGO area. Deriving hydraulic parameters from the σ_θ using the presented approach opens perspectives for generating directly effective hydraulic properties from soil moisture content measurements that can be used in larger scale hydrological models; however it needs to be tested for systems affected by topography, soil layering or different kinds of vegetation among other controls.

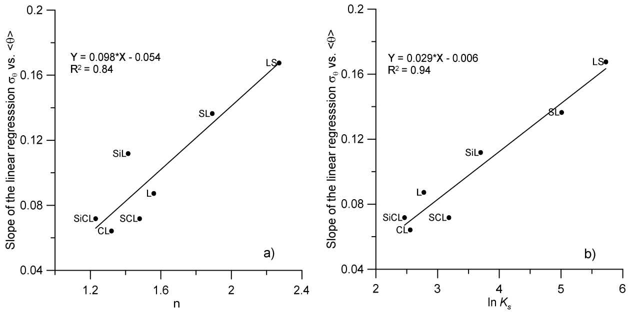

Fig. 2. Textural effect on the slope of the dry part of the σ_θ relationship: a) effect of ln Ks; b) effect of the "n" parameter in the van Genuchten's model for the soil moisture characteristic curve. Labels reflect the textural class (Table 1)

Different climates gave significantly different slopes at the 99% confidence level (Table 3). Average moisture at the peak σ_θ was practically insensitive to the differences in climate with a coefficient of variation between the cold semiarid and the humid weathers of 2 %. The effect of climate on the relationship between mean soil moisture and its variability was reported previously by Teuling et al. (2007) and was highly influenced by differences in the vegetation development. Rosenbaum et al. (2012) did not observe seasonal difference in σ_θ in the intermediate $<\theta>$ range within groundwater-distant upslope areas. The small, though statistically significant, difference that we observe may explain that they did not observe the seasonality. Maximum variability of soil moisture (ranging from 0.023 to 0.030) and the slope of the dry part of σ_θ (between 0.072 and 0.091) were more dependent on the climate. Nevertheless these ranges are smaller than those reported above for different textures (Table 2) and show the larger relevance of texture than climate on σ_θ. As previously observed with field data by Choi et al. (2007) soil hydraulic properties-related parameters had the largest influence in the variability of soil moisture followed by climate and topography.

We observed an increase in the slope of the σ_θ dependence proportional both to $\sigma_{\ln Ks}$ for the same soil texture, and to the mean ln K_s for different textures (Figs. 3a and 2b). This result is in disagreement with the observations of Famiglietti et al. (1998) and Vereecken et al. (2007) who found that variability in soil moisture is controlled strongly by porosity and hydraulic conductivity under wet conditions but not under drier conditions.

Table 3. Average moisture content ($m^3\ m^{-3}$) and standard deviation at the peak of the σ_θ ($m^3\ m^{-3}$) and slope of the σ_θ dry-part of a loamy soil subject to four different climates

Climate	peak WC	peak std	slope
Humid subtropical	0.349	0.030	0.072
Humid continental	0.357	0.030	0.088
Cold semiarid	0.363	0.023	0.084
Dry semiarid†	0.296	0.026	0.091

† The peak was not reached. Therefore the maximum σ_θ and its corresponding $<\theta>$ were used

Differences in $\sigma_{\ln Ks}$ had a minimum effect on the peak $<\theta>$. The average $<\theta>$ at the peak for the five levels of K_s variability was 0.362 with a coefficient of variation of only 0.5 %. An increase in the $\sigma_{\ln Ks}$ implied a proportional increase in the peak of σ_θ (Fig. 3b). Rosenbaum et al. (2012) observed that the differences between the 5 and 20 cm depths were more pronounced at intermediate moisture levels and especially for the peak of σ_θ. They attributed those differences to the strong effect of effective redistribution by vertical flow, lateral flow, and evapotranspiration in that range and also acknowledged to the commonly described effect of texture. Those differences could be also a reason of the strong dependence shown here of the peak of σ_θ on $\sigma_{\ln Ks}$ as a smaller variability and smaller values of ln K_s could be expected in the subsurface.

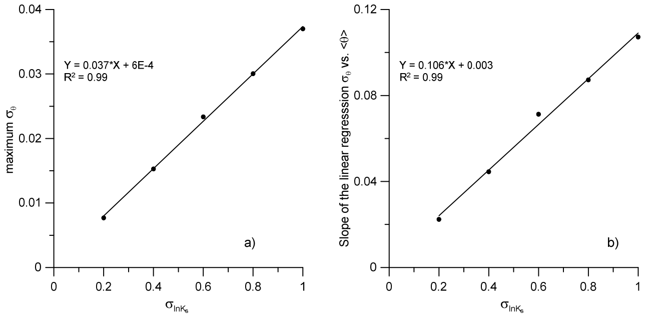

Fig. 3. Effect of the ln Ks spatial variability ($\sigma_{\ln Ks}$) in: a) the slope of the dry part of the soil variability and average moisture and b) the peak soil moisture spatial variability

Our results indicate that it may be beneficial to look for a relationship between the slope of the σ_θ and $\sigma_{\ln Ks}$ combined with the relation observed by Martinez et al. (2013) between the last and the temporal stability of soil moisture to infer up-scaled soil hydraulic properties. Also, topography might be included in the hydraulic parameter scaling algorithm as suggested by Jana and Mohanty (2012) to increase the scale of support and evaluate whether a better agreement with field experiments could be obtained.

4.- Conclusions

We analyzed the relationship between hydraulic parameters of the van Genuchten model, ln K_s and the σ_θ relationship. For bare soil conditions we were able to show the effect of $\sigma_{\ln Ks}$ on the slope of the σ_θ relationship in its dry end and on the maximum value of σ_θ. Vegetation flattened the σ_θ relationship and increased the maximum σ_θ. Soil hydraulic properties rather than climate controlled the value of soil water content at which the maximum variability was observed. Evaluating the strength of such relationships in natural systems, would be beneficial. The clear relationship between the n parameter of the soil moisture characteristic curve and the slope of the dry part of σ_θ found in this study may be of relevance for deriving soil hydraulic properties using soil moisture sensor networks and remotely sensed data as the data can be interpreted directly.

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