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Multi-scale correlations between soil hydraulic properties and associated factors along a Brazilian watershed transect

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ABSTRACT

Soil hydraulic properties are important to the understanding and modeling of hydrological processes at the watershed scale. These properties are presumed to be correlated with associated topographic attributes and other soil factors operating at different intensities and scales. Using multivariate empirical mode decomposition (MEMD), this study examined the multi-scale correlations among two soil hydraulic properties and two topographic attributes and three soil factors along a transect in the Pelotas River Watershed (PRW) situated in Southern Brazil. Soil water content at field capacity (θ_{FC}) and saturated hydraulic conductivity (K_S) were determined for 100 soil samples taken at 250-m intervals along a 25-km transect that cut through the PRW. The five selected factors were elevation (*Ele*), slope (*Slo*), sand content (*Sand*), bulk density (*Bd*), and soil organic carbon (*SOC*). The topographic attributes were derived from a digital elevation model, while those related to soils were determined for the collected samples. The multivariate data series of the two soil hydraulic properties and five associated factors were decomposed into six intrinsic mode functions (IMFs). For θ_{FC}, 52.4% of the total variance was separated at IMF1 (scale of 728 m) and IMF2 (1,113 m), while for ln K_S, 35.9% of the variance was separated at IMF1 (728 m) and IMF6 (scale of 11,877 m). It was found that scale-specific relationships between soil hydraulic properties and the associated factors varied with scale. The associated factors exerted influence on the soil hydraulic properties at their own dominant scale(s). The θ_{FC} and ln K_S values at each IMF (specific scale) and residue were predicted from the scale-specific associated factors at the same IMF or residue. The total of all the predicted IMFs including the residue was then used to predict the θ_{FC} and ln K_S at the measurement scale. *Sand* had the greatest relative importance to the measurement-scale θ_{FC} prediction model, while topographic properties were clearly the dominant explanatory factors for the overall ln K_S prediction. The overall ln K_S predictions using the MEMD outperformed those based on the original data.

1. Introduction

Soil hydraulic properties are factors that are key to understanding the different processes of the hydrological cycle. Therefore, they are of great importance to supporting water resources management decision making at the watershed scale. These properties are also critical parameters in hydrologic models (Wang et al., 2012). Nevertheless, there is usually a great deal of practical difficulty and expense involved in obtaining information about the spatial distributions of soil hydraulic properties within a watershed that can used in various hydrologic models. Due to such difficulties, along with the fundamental need to acquire soil information, several studies have used soil maps at the soil class level to provide inputs for hydrologic models (Andrade et al., 2013; Pinto et al., 2013; Beskow et al., 2016).

Furthermore, great progress has been made within the past 20 years that has substantially improved or developed new methods by which soil hydraulic properties could be determined, either directly or indirectly. These methods are necessary in order to more accurately quantify the retention and transport of water and chemicals in soils using hydrologic models. Soil hydraulic parameters, such as the soil water content at field capacity (θ_{FC}) and the saturated hydraulic conductivity (K_S), are typically spatially and temporally variable. However, as noted above, the acquisition of sufficient and reliable data of these parameters through in situ measurements is labor-intensive (Herbst et al., 2006). As an alternative, an indirect but reasonably accurate estimation of these properties might be made from widely available or more easy-to-obtain

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data of other variables by using pedotransfer functions (PTFs) (Wang et al., 2012).

A variety of PTFs has been developed to estimate soil hydraulic properties using data of other easy-to-obtain variables, including intrinsic soil properties and extrinsic factors. Bouma (1989) introduced the term pedotransfer function for a model that used basic soil properties (i.e., soil texture, soil bulk density, and soil organic matter) as inputs and gave hydraulic parameters as outputs. Since then, other explanatory variables have been considered as inputs in order to improve the prediction accuracy of the PTFs and to facilitate their potential future development (Leij et al., 2004). For example, Wang et al. (2012) developed a new PTF for estimating K_S, θ_{FC} and saturated soil water content based on 252 datasets of basic soil properties and elevation. Their results indicated that the inclusion of a topographic attribute, such as elevation, significantly improved the predictive capability of a PTF used to determine $\log_{10} K_S$ in the vadose zone. Similarly, Romano and Palladino (2002) found that taking landscape features into account, improved water retention predictions. However, from these developed PTFs, it was evident that the relationships between soil hydraulic properties and the factors affecting them were highly variable among various measurement scales (Niedda, 2004). Furthermore, Parasuraman et al. (2006) indicated that the poor performance of PDF in predicting hydraulic properties within a field might be due to only considering the effects of soil texture at the measurement scale; accuracy might be improved by considering the effects of soil texture at different scales. Some easy-to-obtain variables that were dominant at one scale might not have a significant effect at another scale, which gave rise to chaotic and nonlinear distributions of soil hydraulic properties, and to the low accuracies of the statistically derived PTFs used to estimate them (She et al., 2015). Therefore, there is a need to investigate whether relationships between soil hydraulic properties and easy-to-obtain properties are scale dependent and if predictions of such properties can be improved through a scale-by-scale analysis.

Many methods have been applied in order to study the multi-scale correlations between the spatial pattern of soil properties and the factors affecting them by means of Pearson linear correlation analysis and geostatistical analysis. Although the advantages of these methods were obvious, they assumed stationarity or linearity in the mean and/or variance of the data over the spatial extent of sampling (Biswas et al., 2013). However, in nature the effects of different processes as represented by different frequency components are not cumulative and do not follow the principle of superposition, thus indicating that the system is non-stationary and nonlinear. Wavelet analysis can be used in cases where non-stationarity exists. For example, Si and Zeleke (2005) succeeded in identifying scale specific factors that affected soil saturated hydraulic properties in a hummocky landscape using wavelet coherency. In addition, a relatively new multi-scale analysis method, i.e., the empirical mode decomposition (EMD), which was developed by Huang et al. (1998), and its extension algorithm, the Multivariate Empirical Mode Decomposition (MEMD) (Rehman and Mandic, 2010) are now available. Recently, this method has been applied in order to characterize the scale-dependent spatial relationships between environmental factors and soil properties of non-stationary and nonlinear systems (Biswas and Si, 2011). For example, Hu and Si (2013) used MEMD to separate the overall spatial patterns of soil water and environmental factors (i.e., elevation, and sand, silt, clay, and organic carbon contents) into different intrinsic mode functions (IMFs) and a residue representing different scales. She et al. (2014) investigated the scale- and season- specific depth persistence of 0–1.0 m soil water content distributions in a complicated landscape ecosystem by combining MEMD with Spearman's rank correlation analysis. In that study, three or four IMFs representing “common” scales were separated out for the soil water contents in ten soil layers. Using Spearman's rank correlation analysis for each of the different IMFs of the soil water contents in the ten soil layers, She et al. (2014) concluded that the depth persistence of soil water content varied with scale and that it was strongest at the dominant IMF scales. The results of these previous studies highlighted the potential of using MEMD to clarify multi-scale correlations between soil hydraulic properties and environmental factors.

A number of studies (e.g., Si and Zeleke, 2005; She et al., 2015) suggested that topographic attributes, such as elevation (*Ele*) and slope (*Slo*), and other soil properties related to texture (e.g., sand content (*Sand*)) and soil structure (e.g., bulk density (*Bd*) and soil organic carbon (*SOC*)), are expected to affect the spatial variation of soil hydraulic parameters. Some of the factors associated with soil hydraulic variables may also be affected by each other. At the catchment scale, where adequate measurement of basic soil properties may not even be feasible, the question of whether topographical attributes alone could be used to replace or augment basic soil properties as the predictors in PTFs has been raised (Leij et al., 2004). Topographic attributes are widely available or can be readily calculated with the advent of the Geographical Information System (GIS) by means of digital elevation models (DEMs) and digital terrain analysis techniques. Furthermore, if soil hydraulic properties can be accurately estimated using easy-to-measure topographic attributes, considerable labor can be saved. However, some preliminary unpublished research by the authors suggested that topographic attributes must be used in combination with other parameters, such as easy-to-measure soil properties. A good understanding of the relationships between soil hydraulic parameters and these variables is essential in both soil–water process studies and environmental management. To date, there appear to be no published studies on the use of the MEMD method applied to field capacity scale-related spatial distributions and only one to those of K_S (She et al., 2015). Therefore, the purpose of this study was to investigate the multi-scale spatial relationships between two soil hydraulic properties (θ_{FC} and K_S) and topographic attributes along a 25-km transect established in the Pelotas River Watershed (PRW), which is situated in Southern Brazil. The specific objectives were: (1) to investigate the spatial distribution of θ_{FC} and K_S along a transect (with various basic soil properties) that cut through the PRW; and (2) to reveal the multi-scale correlations between the soil hydraulic parameters and two topographic attributes (slope and elevation) and three easy-to-measure soil properties (soil bulk density, soil organic carbon content, and sand content) based on MEMD analysis. Furthermore, a comparison was made between the distributions of K_S in this study and in that of She et al. (2015), which were conducted in different areas of the world in order to demonstrate the effects of site conditions on the scale-specific relationships.

2. Materials and methods

2.1. Study site description

The study was carried out in the Pelotas River Watershed, which is located in Southern Rio Grande do Sul (RS) State, Brazil (Fig. 1). The portion of the PRW considered in this study was the drainage area upstream from the outlet named “Ponte Cordeiro de Farias”, which covered an area of about 370 km^2 with an elevation range between 35 and 494.8 m. According to the Köppen climate classification, the climate of the region is the Cfa type (Kuinchtner and Buriol, 2001), which indicates a wet subtropical climate having a mean temperature >22 °C during the hottest month of the year. Data collected by the Pelotas agro-meteorological station in the municipality of Capão do Leão-RS was considered to be representative of the study watershed. The climatological normal dataset for 1971 to 2000 indicated that the mean annual temperature, the mean annual rainfall and the mean annual potential evapotranspiration were 17.8 °C, 1366.9 mm and 1103.1 mm, respectively. The main types of soils in the watershed were classified as Hapludalf + Udorthent (79.8%), Hapludalf + Hapludult (6.3%), Udorthent (8.4%), and Paleudult (5.5%) according to the US Soil Taxonomy (Soil Survey Staff, 2010). The parent material was granite.