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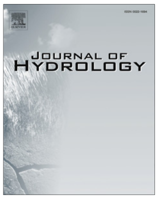

Vertical variations of soil hydraulic properties within two soil profiles and its relevance for soil water simulations

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SUMMARY

Numerical simulations of soil water dynamics can be valuable tools for the assessment of different soil and land management practices. For accurate simulations, the soil hydraulic properties (SHP), i.e. the hydraulic conductivity and water retention function have to be properly known. They can be either estimated from physical soil properties by pedotransfer functions (PTF) or measured. In most studies, soil profiles are analyzed and sampled with respect to their pedogenic horizons. While considerable effort has been put on *horizontal* spatial SHP variations, *vertical* changes within soil profiles have not been analyzed in detail. Therefore, the objectives of this study were (i) the SHP measurement along vertical transects within two soil profiles, (ii) to evaluate their spatial variation and correlation with physical soil properties, and (iii) to assess the impact of the SHP determination method and its spatial discretization on simulated soil water balance components. Two soils, an agriculturally used silty-loam Chernozem and a forested sandy Cambisol were sampled in 0.05 m increments along vertical transects. The parameters of a dual porosity model were derived using the evaporation method and scaling was applied to derive representative mean SHP parameters and scaling factors as a measure of spatial variability. State-space models described spatial variations of the scaling factors by physical soil properties. Simulations with HYDRUS 1D delivered the soil water balance for different climatic conditions with the SHP being estimated from horizon-wise PTFs, or discretized either sample-wise, according to the pedogenic horizons, or as hydrologically relevant units (hydropedological approach). Considerable SHP variations were found for both soil profiles. In the Chernozem, variations of the hydraulic conductivity were largest within the ploughed Ap-horizon and could be attributed to variations in soil structure (macropores). In the subsoil, soil water retention showed a gradual decrease within each horizon. The observed water retention variations could be described by state-space models that comprised the contents of clay and total carbon, whereas variations of the hydraulic conductivity were described by clay content and total porosity. The hydraulic conductivity in the Cambisol was slightly undulating throughout the profile. Here, water retention was largest in the upper part of the profile and considerably decreased within the lower part of the Bhs-horizon. Simulated soil water balance components differed distinctly between the SHP discretizations. Compared to observed soil water contents, the simulations where the SHP were given by small-scale layers or hydropedological units performed best for both experimental sites. The different SHP discretizations mainly affected the estimated drainage losses and the simulated crop transpiration under medium to dry climatic conditions. The study confirmed the importance of an adequate spatial SHP discretization. The results indicate that SHP estimations by PTFs or the standard horizon-mean sampling strategy might fail to parameterize soil water simulations, especially in structured soils. The presented hydropedological approach showed a way to receive good simulation results by reducing the SHP observation density.

1. Introduction

Numerical simulations of soil water dynamics can be valuable tools for the assessment of different soil and land management practices (Roger-Estrade et al., 2009). However for accurate

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Abbreviations: AICc, corrected Akaike Information Criterion; ARE, average relative error; HPL, hydropedological layer; OC, organic carbon; PH, pedogenic horizon; PTF, pedotransfer function; RMSE, root mean square error; SHP, soil hydraulic properties; SSL, small-scale layers; TC, total carbon.

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simulations, the soil hydraulic properties (SHP) – i.e. the hydraulic conductivity $K(h)$ and water retention functions $\theta(h)$ – have to be properly known. These parameters can be either derived from physical soil properties using pedotransfer functions (PTF) or from direct or inverse measurements (Dane and Topp, 2002). PTFs allow a cheap and fast SHP estimation for soils with an unimodal pore-size distribution such as sandy soils. However, their applicability for structured soils that contain macropores and other preferential flow paths might be limited (Vereecken et al., 2010). As direct measurement techniques are time-consuming and laborious, inverse methods such as multistep-outflow or evaporation experiments have become useful methods for the efficient and precise SHP determination of structured soils (Hopmans et al., 2002).

A major challenge in the proper SHP description is the considerable variation across spatial and temporal scales. For instance, there is extensive empirical evidence that SHP are subject to *temporal* changes (Daraghmeh et al., 2008; Schwen et al., 2011a,b). It was shown that especially the structure of soil top layers is subject to changes during time, caused by wetting / drying cycles, biological activity, and agricultural operations (Leij et al., 2002; Mubarak et al., 2009). Other studies have assessed the *spatial* variability of SHP, mainly with a focus on the comparison of different soil management practices and its implications on surface soil properties (Alletto and Coquet, 2009; Messing and Jarvis, 1993; Ndiaye et al., 2007; Sauer et al., 1990; Strudley et al., 2008). Recently, new technologies such as ground-penetrating radar or electromagnetic induction have been applied to cover variations at larger spatial scales up to the field-scale (e.g., Jonard et al., 2013; Wang et al., 2013).

While considerable analysis effort has been put on the spatial variation of SHP in the *horizontal* direction, there is a lack of detailed analysis of *vertical* changes within soil profiles. Moreover, since vertical variations of physical soil properties have not been studied as a spatial process, there is no recommendation for a sampling strategy that accounts for hydrologically relevant profile sections. In most hydrological studies, soil profiles are analyzed pedogenetically, i.e. with respect to their pedogenic soil horizons (Dyck and Kachanoski, 2011): Typically, the pedogenic horizons (e.g. A-horizon) are identified and their hydraulic properties are either derived from physical soil properties using PTFs or from undisturbed samples taken in the middle of each horizon. However, this sampling strategy does not take into account changes of physical soil properties that are a result of gradually changing soil texture or inhomogeneities within horizons or pedons. The method also fails to quantify the complex spatial covariance between soil physical and hydraulic properties. As stated by Dyck and Kachanoski (2011), spatial patterns of soil physical and hydraulic properties are a result of sedimentary, hydrological, pedogenic, anthropogenic, and biological processes up to the time of observation. Understanding the vertical variance structure of SHP could help to understand the mechanisms of the interactions between the various processes responsible for spatial variability. It would also allow the assessment and optimization of sampling strategies that account for hydrologically relevant variations within a soil profile, and thus contributing to a more hydropedological understanding of soil profiles as stressed by Vogel et al. (2013). An optimal, site-specific sampling strategy could help to parameterize soil water simulations more precisely by means of simulated soil water balance components.

To faciliate the analysis of spatial SHP variations, the scaling approach of Miller and Miller (1956) has been widely applied in soil hydrological studies (Vereecken et al., 2007). This technique enables the description of SHP variations by a set of scale factors, relating the soil water retention and hydraulic conductivity data at each location to a representative mean. By this, the obtained scaling factors preserve the spatial variability of the individual measurements and can be used as a measure for the spatial or temporal variability of the analyzed sample series. Several methods have been developed to derive scaling factors and the corresponding representative mean parameters (Tillotson and Nielsen, 1984; Vereecken et al., 2007).

It is well known that the considerable spatial heterogeneity of physical soil properties can seriously hamper its analysis and correlation (Nielsen and Wendroth, 2003). As a consequence of this spatial variability, Pringle et al. (2007) stressed the need for developing site-specific PTFs. Gribb et al. (2009)showed that scaling PTFs using measured field soil water contents can improve model predictions substantially. As the authors used the soil water content distribution – which is a result of the hydraulic properties and dynamically changes over time – it would be highly desireable to derive correlations with physical soil properties that are independent from the soil hydraulic properties. When analyzing spatial heterogeneity in soils, adequate statistical methods need to be applied. Commonly, the analysis of soil-related data is carried out ignoring the fact that observations might be spatially or temporally dependent (Schwen et al., 2013). Since the existence of a spatial structure of heterogeneities has been demonstrated by Russo and Bresler (1981), however, several studies used the spatial covariance and cross-variance between measurements as decision and quality criteria (Nielsen, 1987; Cassel et al., 2000). Another method that is increasingly applied to describe spatial and temporal variations in agronomical and hydrological studies is state-space modeling (Nielsen and Wendroth, 2003). For instance, the spatial SHP variability along a transect was subject of a study by Wendroth et al. (2006). The authors analyzed spatial patterns of the hydraulic conductivity and parameters of a water retention model by a nested sampling approach combined with geoelectrical measurements and subsequent application of state-space models. Recently, Wendroth et al. (2011) and Schwen et al. (2013) demonstrated that state-space models can be also used to describe spatial variations of field-scale solute displacement depth as affected by land use, irrigation characteristics and underlying pedogenic properties. These studies – among others (e.g., Comegna et al., 2010; Poulsen et al., 2003; Timm et al., 2011; Vieira et al., 1981) – showed (i) that state-space models performed better when correlating variables of interest along spatial or temporal transects compared to classical regression methods and (ii) that state-space models can be used to reduce the number of required measurement points when predicting spatial fluctuations of hydrological soil processes.

Therefore, the objectives of this study were (i) to measure the SHPs in small spatial increments along vertical transects within two soil profiles under contrasting land use systems (agricultural and forest), (ii) to evaluate their spatial variation with respect to pedogenic horizons and correlation with physical soil properties by state-space models, and (iii) to assess the impact of the sampling design and spatial SHP discretization on simulated soil water balance components. Four different SHP parameterization and discretization methods were evaluated: In a first approach, mean SHP properties for the pedogenic horizons were estimated from physical soil properties by a PTF. Subsequently, the small-scale SHP determinations were either used as small-scale layers (*SSL*) or merged to representative mean parameters for the pedogenic horizons (*PH*) or a reduced number of hydrologically relevant units (hydropedological approach, *HPL*).

2. Material and methods

2.1. Experimental sites and sampling strategy

Two contrasting soil profiles were sampled and analyzed in this study. The sites were chosen since they represent typical land use