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Estimation of effective hydraulic parameters in heterogeneous soils at field scale

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ABSTRACT

Determination of soil hydraulic parameters at field scale is of great importance for modeling soil water dynamics and for agricultural water management practice. The parameter regionalization has been a hot topic for many decades in soil science and hydropedology. Based on the statistical description and spatial structure of the soil physical and hydraulic properties measured via soil sampling in the field, three inverse modeling approaches had been proposed to obtain the effective hydraulic parameters. The validity and effectiveness of the three approaches had been discussed by designing four simulation scenarios (a 'fine scale solution' plus the three upscaling approaches). For each inverse modeling, the soil water distribution along the profiles and their dynamics during seven growing seasons (from the year of 2000 to 2006) in the study area had been simulated through the combined use of HYDRUS-1D and PEST. Results demonstrated that the effective soil hydraulic parameters derived from all the three approaches were comparable and fairly close to the 'fine scale solution'. Although, statistics of the hydraulic parameters indicated that the median of K_s of first soil layer, as compared to that of other layers, was most closest to the effective K_s values that were obtained through the three upscaling approaches; while the median of θ_s values for the top three layers was close to the effective θ_s values in scenario 2 and scenario 3, but fairly smaller than that in scenario 4. The soil water dynamics were not sensitive to the residual soil water content (θ_r), even though the θ_r showed quite different distribution pattern from that of K_s and θ_s. In conclusion, the practice of combining the PEST with the HYDRUS-1D provided an effective and reasonable method to inversely determine the effective hydraulic parameters of the equivalent soil profile in the field.

1. Introduction

Soil hydraulic properties are by far the most important land surface parameters to govern the partitioning of soil water fluxes at a range of spatial scales (Mohanty, 2013). A very good knowledge of the 'within-field' spatial variability of soil properties and water distribution and its temporal dynamics is of prime importance to estimate field areal soil water productivity (Jhorar et al., 2002). However, an obstacle to the practical application of soil hydraulic properties at the field, catchment, or regional scale is the difficulty of quantifying the "effective" soil hydraulic functions (Feddes et al., 1993; Ahuja et al., 2010). It is intensified by the fact that soil water movement is mainly controlled by the soil properties which are characterized by a small measurement support. Therefore, accurate estimate of the soil hydraulic parameters at the application scale of interest is critically important to the models simulating flow and transport through the vadose zone (Vrugt et al., 2008).

A number of field and laboratory measurement techniques have been developed (Klute and Dirksen, 1986) and research has continued with the objective of improving the measurement of hydraulic parameters and analytical techniques (Kosugi, 1996; Vachaud and Dane, 2002). However, for practical consideration, general experimental procedures are time consuming, costly; in addition, most of these procedures have focused on relatively small soil cores or support area (Arya and Heitman, 2010). Unfortunately, many contributions to the soil science and hydrology literature have demonstrated an inability of these laboratory-scale measurements on small soil cores to accurately characterize flow and transport processes at larger spatial scales. Thus, it necessitates the development of alternative methods to derive the soil hydraulic properties at the application scale of model. As a result, indirect methods to obtain soil hydraulic parameters have gained popularity (Schaap and Leij, 2000; Priesack and Durner, 2006; Rucker, 2010).

Geologic formations are heterogeneous at various length scales. Such a critical length scale marks the transition towards hydraulic non-equilibrium where water content and water potential are not directly coupled anymore by a static retention characteristic. At this point the application of Richards' equation starts to be doubtable (Vogel et al., 2010; Szymkiewicz et al., 2012). An alternative approach is to

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predict the mean flow and transport behavior at the field scale by defining an equivalent homogeneous medium with upscaled (effective or macroscopic) flow and transport properties (Yeh, 1998). However, to represent a heterogeneous medium by its homogeneous equivalent, one needs to estimate the effective flow and transport properties that represent this equivalent homogeneous medium.

There are different approaches for scaling of soil hydraulic properties and soil water processes in heterogeneous porous media (Vereecken et al., 2007). The strengths and limitations of those methods have been previously discussed (Sadeghi et al., 2014). Among many of those approaches, inverse modeling provided a useful tool to estimate the effective parameters of an equivalent soil column at different spatial scales. In Chrysikopoulos (1995), effective parameters for flow in saturated porous media were obtained by considering both periodic and stationary porous medium properties. The results showed that the effective hydraulic conductivity is equal to its volume average plus a term expressing the effect of the locally variable hydraulic conductivity. Hughson and Yeh (2000) presented an inverse model using a successive linear estimator approach for estimating unsaturated hydraulic parameters during transient, three-dimensional, variably saturated flow. Khaleel et al. (2002) used stochastic theory-based analytical formulas and numerical Monte Carlo simulations to obtain upscaled (effective) flow and transport properties to represent a heterogeneous unsaturated medium. More recently, Erdal et al. (2012) investigated the reliability of inverse modeling for finding the effective hydraulic parameters in three different heterogeneity structures (random, periodic and layered). In Sadeghi et al. (2014), a new solution for prediction of the effective unsaturated hydraulic conductivity of layered soils was presented and evaluated. Shafiei et al. (2014) demonstrated that simulation uncertainty in soil moisture at field scale is relative small and a good model performance was obtained. The typically used effective parameters were assumed that the equivalent hydraulic properties still follow the same form of hydraulic property functions as the local ones did, but have the parameters in the hydraulic property functions replaced by the so-called effective parameters so that the hydraulic parameters can be used in heterogeneous soil and large-scale applications (Desbarats, 1998; Zhu and Mohanty, 2003; Zhu, 2008). However, additional work is needed to determine effective hydraulic parameters across spatial scales, develop subsurface soil property databases, and implement the approach on spatially correlated pixels (Corwin et al., 2006). Numerical simulation models, which were capable to validate the effective hydraulic parameters of the equivalent homogeneous medium, can be used to screen a promising upscaling practice that warrants future field studies among various upscaling practices. Therefore, in this study, three inverse modeling approaches were proposed to obtain effective hydraulic parameters of equivalent soil columns from field sampling data. The objective of this study was to explore the validity of these three inverse modeling approaches. Thus, field sampling and numerical experiments were designed to simulate the water movement dynamics at field scale.

2. Materials and methods

2.1. Study site description

The field experiments were conducted at the Xuebai Experimental Station (103°03′ E, 38°54′ N, 1324 m a.s.l.) of Minqin Agricultural Extension Center of Gansu province, north-west China from July to August in 2005 (Fig. 1). The experimental site was located in Minqin oasis, which is surrounded by Badanjilin desert at north and west sides and Tengger desert at east. It is a large and plain area and far from the highland or hills. The soil type is classified as the anthropogenic alluvial soil, and loamy fine sand and silt loams are the predominant textures for the surface soil (Minqin Water Conservancy Bureau, 1996). The climate is classified as a typical continental temperate semi-arid climate with mean annual precipitation of 110 mm, which largely comes during the summer and fall months. The annual potential evaporation is about 2600 mm. The spring wheat (*Triticum aestivum* L.) was planted in the experimental plot.

2.2. Soil sampling and data collection

Totally three groups of sampling were conducted within the 120 m × 120 m experimental plot (Fig. 1). The first group consisted of 30 (5-row × 6-line) sampling sites which separated by an interval of 20 m. At each site, soil samples have been collected at eight layers (0–20 cm, 20–40 cm, and so on, down to 160 cm). The second group consisted of 169 (13-row × 13-line) sampling sites which separated by an interval of 10 m. At each site, soil samples have been collected at two layers (0–10 cm and 10–20 cm). These samples were used to investigate the spatial structure of soil properties in the experimental plot. All these two groups of soil samples were collected by means of auger and then the soil particle size distribution had been measured using processed air-dry soil. Field measured soil texture data (Fig. 2) were used to derive the effective parameters of all 30 so-called homogeneous '*simulation units*'. For the third soil sampling group, seven soil profiles of 200 cm in depth had been dug to detect the soil layer and to measure soil bulk density of each layer. The determined soil layer was shown in Fig. 3.

In addition, 338 (2 × 169) undisturbed soil samples were taken at the 169 sampling sites by using core method. Firstly, a flat sampling

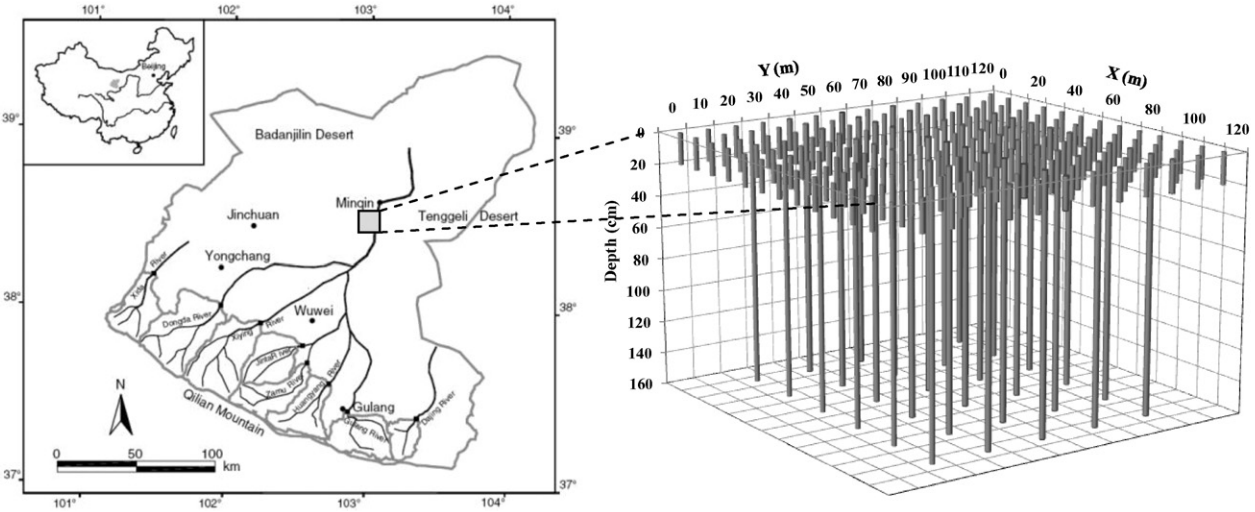

Fig. 1. The location and depth for soil sampling in an experimental plot located in the Shiyang river basin (shaded in the inset map of China).