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Predicting available water of soil from particle-size distribution and bulk density in an oasis–desert transect in northwestern China

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SUMMARY

A detailed understanding of soil hydraulic properties, particularly the available water content of soil, (AW, $cm^3\ cm^{-3}$), is required for optimal water management. Direct measurement of soil hydraulic properties is impractical for large scale application, but routinely available soil particle-size distribution (PSD) and bulk density can be used as proxies to develop various prediction functions. In this study, we compared the performance of the Arya and Paris (AP) model, Mohammadi and Vanclooster (MV) model, Arya and Heitman (AH) model, and Rosetta program in predicting the soil water characteristic curve (SWCC) at 34 points with experimental SWCC data in an oasis–desert transect (20 × 5 km) in the middle reaches of the Heihe River basin, northwestern China. The idea of the three models emerges from the similarity of the shapes of the PSD and SWCC. The AP model, MV model, and Rosetta program performed better in predicting the SWCC than the AH model. The AW determined from the SWCCs predicted by the MV model agreed better with the experimental values than those derived from the AP model and Rosetta program. The fine-textured soils were characterized by higher AW values, while the sandy soils had lower AW values. The MV model has the advantages of having robust physical basis, being independent of database-related parameters, and involving subclasses of texture data. These features make it promising in predicting soil water retention at regional scales, serving for the application of hydrological models and the optimization of soil water management.

1. Introduction

Reasonable management of the soil water content status is crucial for plant growth and crop production in arid and semi-arid regions (Lawes et al., 2009; Hosseini et al., 2016). The soil available water, AW ($cm^3\ cm^{-3}$), is the amount of water released between in situ field capacity and the permanent wilting point. To determine AW, the pressure-based values of field capacity and wilting point are usually derived from the soil water characteristic curve (SWCC). This property measures the capability of soil to retain water, and reflects the effects of textural composition, mineralogy, soil structure, organic matter content and management practices (Arya et al., 2008). A quantitative and precise estimation of the SWCC is required in many hydrological models and is essential for a wide range of applications, such as soil and water conservation, irrigation scheduling, solute transport, and plant stress and growth (Ramos et al., 2014).

Direct measurement of the SWCC are always preferred in a small area, but laboratory procedures to determine it are time-consuming and costly, measuring it for large-scale regions at a fine spatial resolution is impractical (Gijsman et al., 2003). Indirect estimation of the SWCC from routinely available soil properties is simply one of the most feasible alternatives (Soet and Stricker, 2003; Ramos et al., 2014; Arya and Heitman, 2015). Particle-size distribution (PSD) is a basic property of mineral soils and can be measured easily and quickly. Using PSD, alone or in combination with bulk density and soil organic matter content, as surrogate data is attractive to predict selected points on the SWCC or the entire SWCC (Arya et al., 1999; Skaggs et al., 2001; Ramos et al., 2014; Jensen et al., 2015).

Current indirect methods for the SWCC estimation are classified into empirical, semi-physical, and conceptual methods (Schaap et al., 2004; Arya and Heitman, 2015). Following an empirical approach, a considerable number of pedotransfer functions (PTFs)

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have been developed (Nemes et al., 2006; Bayat et al., 2013; Ghanbarian et al., 2015). Overviews of the current status of PTF approaches have been given by Wösten et al. (2001) and Gijsman et al. (2003). Pachepsky et al. (2015) comprehensively summarized the trends in PTF development and in input and output data, and methods to build PTFs. Various PTFs are usually given in the form of either a tabulation (Schaap and Leij, 1998; Soet and Stricker, 2003; Al Majou et al., 2008) or continuous functions (Wösten et al., 1999; Nemes and Rawls, 2006; Bayat et al., 2013; Haghverdi et al., 2015) to predict either a single point on the SWCC (Skaggs et al., 2001; Ramos et al., 2014) or parameters for the entire SWCC (Schaap et al., 2001). For example, the PTFs in the Rosetta program allow the estimation of parameters of van Genuchten equation for describing SWCC (van Genuchten, 1980) using limited (textural classes only) to more extended (texture, bulk density, and one or two water retention points) input data (Schaap et al., 2001). The reliability of PTFs can be hindered by the mismatch in measurements of data for developing the functions. The utility of PTFs may be limited to the environmental conditions the original data were collected and can be compromised by the mismatch in measurement times (Pachepsky et al., 2015). The application of regional PTFs has to be adapted to the particular situation under consideration (Wösten et al., 2001; Gijsman et al., 2003; Botula et al., 2012; Antinoro et al., 2014).

The semi-physical models provide conceptual insights into the physical relationship between soil particle size and pore size. These models are developed based on the close similarity between the shapes of PSD and pore size distribution (Arya and Paris, 1981; Arya et al., 1999; Hayashi et al., 2006; Hwang and Choi, 2006). A significant contribution, the AP model, was made by Arya and Paris (1981). In this semi-physical approach, pore radii were determined by scaling the pore lengths of cubic close-packed assemblages with spherical particles to those of the natural structure. Researchers thereafter have suggested that the SWCC prediction by the AP model would improve if the scaling parameter (α) were formulated as a varying rather than a constant value over soil particle ranges and textural classes (Basile and D'Urso, 1997; Arya et al., 1999; Vaz et al., 2005). The AP model has been progressively modified and used to predict SWCC. Arya et al. (1999) expressed the α values by logistic growth and linear fitting equations, which improved the SWCC estimation for 23 soils from the UNSODA hydraulic properties database (Leij et al., 1996). Antinoro et al. (2014) found that SWCCs of 140 Sicilian soils predicted by the AP model with α values formulated by the logistic growth equation were more biased than using α values given by the linear equation with regression coefficients directly from Arya et al. (1999). Therefore, the empirical parameters in the semi-physical models need to be determined in individual studies (Arya and Heitman, 2015; Jensen et al., 2015).

Attempts have been made to develop conceptual methods for reducing dependence on experimental data. Mohammadi and Vanclooster (2011) introduced a packing-state coefficient into the calculation of pressure heads for individual particle ranges in natural structure soil. The SWCCs predicted by this model (the MV model) approximated to the experimental SWCCs across 80 soils from the UNSODA hydraulic properties database (Mohammadi and Vanclooster, 2011). Arya and Heitman (2015) proposed a conceptual model (the AH model) involving only soil PSD and bulk density for predicting the SWCC. The predicted SWCCs showed reasonable to excellent agreement with experimental SWCCs in 75% of 41 soils from the UNSODA hydraulic properties database (Arya and Heitman, 2015). The performance of the conceptual procedures is generally robust and independent of soil type, allowing improvement of the SWCC prediction at regional or watershed scales.

The performance of semi-physical models could be affected by the database used for calibration and validation (Mohammadi and Vanclooster, 2011). The conceptual models have robust physical basis, but the reduced sensitivity to measured data might generate some deviations due to the simplified pore geometric concepts of the models, and the uncertainty and errors of measurements. Few studies comparing the semi-physical and conceptual models in SWCC prediction have been reported (Mohammadi and Vanclooster, 2011; Arya and Heitman, 2015). It is necessary to assess the applicability of these models in studies at regional or watershed scales in arid and semi-arid regions where the soil water content status is vital for plant growth. In the middle reaches of the Heihe River in northwestern China, various land use types intersperse with one another. Soils have a layered structure with obvious heterogeneity in both the horizontal and vertical directions (Li and Shao, 2013). It has been reported that land use, soil texture and structure have substantial effects on water retention (Hayashi et al., 2006; Wu et al., 2011; Haghverdi et al., 2015). Accurate prediction of soil water retention is essential for optimizing irrigation schedules, draining to alleviate salinization, and calculating ecological water requirement in this region.

The objectives of this study were: (1) to compare the performance of the AP, MV, and AH models, and Rosetta program in predicting the SWCC of various soil types, (2) to choose the most appropriate model for estimating AW in an oasis–desert transect in the middle reaches of the Heihe River basin.

2. Model description

2.1. Model theory

The idea of the three models (the AP model, MV model and AH model) emerges from the similarity between the shapes of the PSD and SWCC. The cumulative PSD is divided into m ($m \geqslant 20$) fractions, with solid mass and mean particle radius, w_i (g g^{-1}) and R_i (cm), respectively, for the ith fraction ($i = 1, 2, \cdots, m$). Solid particles in each fraction are assembled to form a hypothetical, cubic close-packed structure consisting of uniform-sized spherical particles with bulk density (ρ_b, g cm^{-3}) and particle density (ρ_s, 2.65 g cm^{-3}) equaling those measured on the natural structure sample.

The void ratio, e (dimensionless), is determined by:

$$e = (\rho_s - \rho_b)/\rho_b \quad (1)$$

Starting with the first fraction, calculated pore volumes are progressively summed and considered filled with water. The summation of filled pore volumes is divided by the bulk volume to obtain the volumetric water content, θ_i (cm^3 cm^{-3}), which is given by (Arya and Paris, 1981):

$$\theta_i = \theta_s \sum_{j=1}^{j=i} W_j, \quad i = 1, 2, \cdots, m \quad (2)$$

where θ_s is the measured saturated water content (cm^3 cm^{-3}).

Pressure heads, h_i (cm water), corresponding to pore radii are computed based on different hypotheses and explanations of the structure of each assemblage in these models. Brief introduction of the calculation of the three models are given sequentially in this study. Readers are referred to Arya et al. (1999), Mohammadi and Vanclooster (2011), and Arya and Heitman (2015) for detailed instructions on the AP, MV, and AH models, respectively.

2.2. Arya and Paris model

In this model, the pore volume formed by the assemblage with spherical particles in each fraction is approximated as a uniform-sized cylindrical capillary tube. The pore radius (r_i, cm) is related to R_i, and is calculated by (Arya and Paris, 1981):