Hydraulic Properties of Rocky Soils in a Semi-Arid Savanna on the Edwards Plateau, TX

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Abstract: Hydraulic properties of rocky soils, especially the water retention curve (WRC), play an important role in assessing regional hydrology in terrain such as the karstic Edwards Plateau, TX, USA, where rock occupies a significant fraction of the soil volume. However, estimation of hydraulic parameters is a challenge because rocky soil makes it difficult to measure the parameters directly. The objective of this study was to observe the effect of volume fraction of rock on hydraulic properties and to estimate the unsaturated hydraulic properties for rocky soil using the evaporation method. We examined the validity of the van Genuchten (VG) and the Durner models to express unsaturated hydraulic properties for clay loam containing rock fragments. Hydraulic model parameters of the VG and the Durner models were inversely optimized over a wide range of pressure heads. The evaporation measurements showed that small volume fractions of rock can increase evaporation from soils by slowing upward movement of water, thereby maintaining capillary connectivity to the surface for a longer period of time. Two simulation models, VG and Durner, were compared with the data from evaporation experiments. Results showed that the Durner model was more appropriate than the VG model for describing water retention and hydraulic conductivity of rocky soils.

Key Words: Evaporation method, Hydraulic properties, Rocky soils, Water retention curve

1. Introduction

Hydraulic properties of rocky soils, especially the water retention curve (WRC), play an important role in assessing regional hydrology in karst ecosystems. Karst areas are located widely across the U.S., and soils on karst are generally shallow and rock occupies a significant fraction of the soil volume (Schwinning, 2013). Tokumoto *et al*. (2012) showed that rock reduces volumetric water content (θ). This supports the idea that volume fraction of rock needs to be included in defining WRC for rocky soils.

The van Genuchten model (VG) (van Genuchten, 1980) is widely used to estimate WRC, which is adapted for S-shaped retention curves characteristic of relatively fine-textured soils. Durner (1994) proposed a modified VG model to predict more accurately WRC, especially in low ranges of pressure head (h). The VG and the Durner models have a pore connectivity parameter, l, which can represent the tortuosity factor for better estimating unsaturated hydraulic conductivity based on the statistical pore-size distribution model of Mualem (1976).

The evaporation method involving monitoring pressure head and water content during the process of evaporation from soil samples has been commonly used to estimate both WRC and unsaturated hydraulic conductivity. Wind (1968) estimated WRC from average θ and h readings at several depths in a soil column, and determined hydraulic conductivity from measured h profiles and changes in θ distribution. With the evaporation method, unsaturated hydraulic conductivities can be particularly determined for h ranging from approximately -50 cm to -700 cm (Šimůnek *et al*., 1998). These authors evaluated optimum conditions for predicting hydraulic parameters for the VG model using the evaporation method. Studies have assessed the significance of the hydraulic model selection, depending on soil types. Sakai and Toride (2007) compared the VG and the Durner models, and suggested that the Durner model can express unsaturated hydraulic conductivity at h lower than -700 cm with appropriate model parameters. Their results highlighted the importance of proper estimation of l. Mualem (1976) assumed l = 0.5 based on empirical studies. However l may be different in rocky soils because tortuosity increases with rock content.

The objective of this study was to observe the effect of volume fraction of rock on hydraulic properties and to estimate the unsaturated hydraulic properties for rocky soil using the evaporation method. We examined the validity of the VG and the Durner models to express unsaturated hydraulic properties for clay loam containing rock fragments. Using the experimental data, hydraulic model parameters of the VG and the Durner models were inversely optimized over a wide range of h. We also investigated the relationship between l and rock volume fraction. The effect of rock fragments on unsaturated hydraulic properties was evaluated by comparison

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of measured and predicted h and θ.

2. Theory

2.1. Water flow model for rocky soils

The water content of rock, and flow of water between soil and rock are assumed to be negligible. Bulk volumetric water content includes the impact of rock, and is estimated as:

$$\theta = (1 - R_V)\theta_{soil} \qquad (1)$$

Where R_V is the volumetric fraction of rock (cm^3 cm^{-3}), and θ_{soil} is volumetric water content of the soil (cm^3 cm^{-3}). The prediction of water flow requires functions for the water retention curve and hydraulic conductivity so that accurate determination of proper hydraulic functions and estimation of the function parameters for rocky soils are important. In this paper, we used the evaporation method (Šimůnek *et al*., 1998) to examine the van Genuchten (1980) and the Durner (1994) models for obtaining the water retention curve and hydraulic conductivity.

To calculate water flow in rocky soil numerically, we used Hydrus 1D, a simulation model for analysis of saturated-unsaturated water flow, developed by Šimůnek *et al.* (2005).

2.2. Water retention curve models

2.2.1. van Genuchten (VG) model

The van Genuchten (1980) model describes water content and hydraulic conductivity in unsaturated soil using the equations

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + \alpha h^n]^{-m} \qquad (2)$$

and

$$K(S_e) = K_s\, Se^l\, [1 - (1 - Se^{\frac{1}{m}})^m] \qquad (3)$$

Where S_e is the effective water content, K_s is the saturated hydraulic conductivity (cm d^{-1}), θ_r and θ_s are residual and saturated water contents (cm^3 cm^{-3}), respectively, n, m (=1-1/n) and α (cm^{-1}) are empirical parameters, and l is a pore connectivity parameter related to pore tortuosity. We assumed that θ_s and θ_r, calculated by Eq. (2), decreased as R_v increased. The VG model uses a predictive $K(S_e)$ model based on the statistical pore-size distribution model of Mualem (1976) in conjunction with Eq. (3) (Šimůnek *et al*., 1998). The pore connectivity, l in the hydraulic conductivity function, is considered as 0.5 for many soils (Mualem, 1976). However, l can vary and be used to optimize the other model parameters with the evaporation method (Sakai and Toride, 2007). For rocky soils, l could be affected by the volumetric fraction of rock and rock size.

2.2.2. Durner model

For conductivity estimation in heterogeneous pore systems, Durner (1994) modified the water retention curve of the VG model as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^{k} w_i [1 + (\alpha_i |h|^{n_i})]^{-m_i} \qquad (4)$$

Where w_i is a weighting factor for the water retention curves, subject to $0 < w_i < 1$ and $\Sigma\, w_i = 1$, and i, n_i and m_i are curve-shape parameters. The Durner model can define a water retention function for bimodal pore-size distributions ($i \leq 2$) in soils containing inter- and intra-aggregated pores. A hypothetical S_e water retention curve was used based on the Durner model in which the stepwise shape of the curve indicates intra-aggregate pores are depleted of water at high h and inter-aggregate pores at lower h (Sakai and Toride, 2007). Thus, S_e is expressed as the sum of intra-aggregate moisture (first curve) and inter-aggregate moisture (second curve). Although the Durner model is typically used for aggregated soils, we applied it to water retention curves for rocky soil. When the relative hydraulic conductivity is coupled to Eq. (4) by the predictive $K(S_e)$ model of Mualem (1976), it gives the unsaturated hydraulic conductivity for aggregated soils ($i \leq 2$) (Priesack and Durner, 2006) as

$$K(S_e) = K_s \left[\sum_{i=1}^{k} w_i [1 + (\alpha_i |h|^{n_i})]^{-m_i}\right]^l \times \frac{\left(\sum_{i=1}^{k} w_i \alpha_i \left[1 - (1 - S_{e_i}^{\frac{1}{m_i}})^{m_i}\right]\right)^2}{(\sum_{i=1}^{k} w_i \alpha_i)^2} \qquad (5)$$

3. Materials and Methods

3.1. Evaporation experiments

Soil sample was rumple gravelly clay loam (Clayey-skeletal, mixed, active, thermic Typic Argiustolls) with chert fragments above 1.0 m deep on the Edwards Plateau, TX (Tokumoto *et al*., 2012). The soil was screened by a 2 mm sieve. The particle density of the clay loam and the density of chert were 2.5 g cm^{-3} and 2.4 g cm^{-3}, respectively. The shape of chert fragments in this study was blocky, and the longest length was less than 7 cm. The average volumetric water content of chert (n = 72) was 0.01 cm^3 cm^{-3}. Additionally, spherical-shaped gravel (diameter < 1 cm and density = 2.6 g cm^{-3}) was used to compare with the effect of different rock sizes on hydraulic properties.

The evaporation method was carried out with two different size columns: a 7.9-cm i.d. × 15-cm long cylindrical soil column for non-rocky soil, gravel, and small chert (longest length < 4 cm and thickness < 2 cm), and a 10-cm i.d. × 30-cm

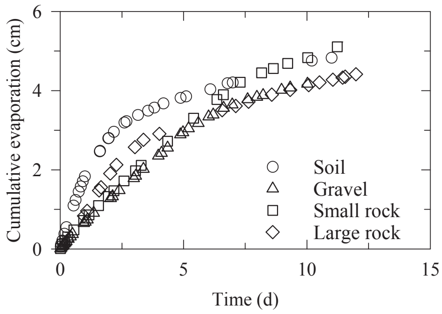

Fig. 1. Observed cumulative evaporation of soil + gravel (R_v = 0.20 cm^3 cm^{-3}), soil + small rock (R_v = 0.12 cm^3 cm^{-3}) and soil + large rock (R_v = 0.24 cm^3 cm^{-3}).

long soil column for large chert (longest length < 7 cm and thickness < 4 cm). Initially, the evaporation method used clay loam without chert. The air-dried soil sample was packed uniformly to a bulk density of 1.15 g cm^{-3} in the 15-cm soil column. The soil water pressure head was monitored with 5 mm diam. and 10 mm long tensiometers inserted horizontally at depths of 3, 8 and 13 cm in the smaller soil column. In the larger column, tensiometers were inserted horizontally at depths of 5 cm and 10 cm. The tensiometers were connected to pressure transducers, and soil samples were saturated using a mariotte bottle that provided water from the bottom of the column for 3 days. Saturated hydraulic conductivity K_s of the clay loam was measured with a constant hydraulic pressure head at the top of the soil column. Then, the bottom inlet was closed and the soil surface on the top of column was exposed to air to allow evaporation. A small fan circulated air over the soil surface. The soil column was placed on a digital scale, and the water loss was measured to calculate the average evaporation flux for a given time interval. After the experiment was completed, average volumetric water content in the entire soil column, θ_{ave} and bulk density, ρ_b were obtained gravimetrically.

4. Results and Discussion

4.1. Observed evaporation and pressure head

Figure 1 shows temporal changes in observed cumulative evaporation and pressure head of soil, gravel (R_v = 0.20 cm^3 cm^{-3}), small rock (R_v = 0.12 cm^3 cm^{-3}) and large rock (R_v = 0.24 cm^3 cm^{-3}). Initially, evaporation was highest for the soil alone and soil with gravel, but over time, cumulative evaporation with soil and small rocks reached values similar to the other two cases. Evaporation was lowest for soil with the larger rock. Saturated hydraulic conductivity was estimated at 20 cm d^{-1} for soil, 13 cm d^{-1} for gravel and 14 cm d^{-1} for soil with small rock. Gravel and small rock maintained a higher h than soil alone (not shown). These results suggest that gravel and small rocks slowed upward movement of water, thereby maintaining flow of liquid water to the surface for a longer period of time.

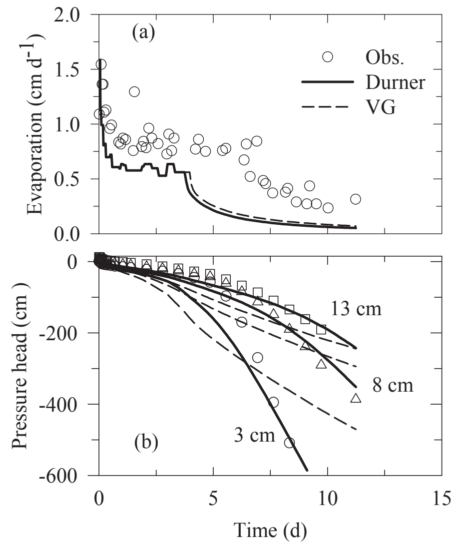

Fig. 2. Comparison of Durner and VG model simulation of evaporation (a) and pressure head (b) with measured values for soil + small rock (R_v = 0.12 cm^3 cm^{-3}).

4.2. Optimization with the Durner and VG models

We optimized the six unknown parameters defined by Eqs. (2) through (5): θ_r, θ_s, α_1, α_2, n_1, n_2, w_1, w_2, K_s, and l. Estimated l (≤ 0.03) was lower than 0.5, the value recommended by Mualem (1976). **Figure 2** compares measured and modeled evaporation and h for soil with volume fraction of small rock using the optimized Durner and VG model parameters.

Both models underestimated evaporation for small rock but the Durner model optimized h better than the VG model (Fig. 2**b**). As rock content increased, the Durner model performed well (**Fig. 3**). It may seem contradictory that the simulations of evaporation using with small rocks in the soil were not better (Fig. 2a), because simulated h was in good agreement with measured h (Fig. 2b). These results imply an uncertainty about the influence of rock size and R_v on unsaturated hydraulic conductivity $K(h)$. In unsaturated conditions, rocky soil with R_v (< 0.2 cm^3 cm^{-3}) maintained a stable evaporation flux longer than the non-rocky soil. However, simulations with the larger rocks (higher R_v) matched observations quite well (Fig. 3**b**). It is likely that higher rock volume disrupted capillary connections with the surface, creating regions of higher water content beneath the rocks.

Estimated water retention curves for the gravel, the small rocks, and the large rocks with the Durner model are shown in **Figure 4**. The measured retention curve for the non-rocky soil is also shown for comparison. To optimize the Durner model parameters, we assumed that the air entry value of the rocky soil would be similar to the value for the clay loam and

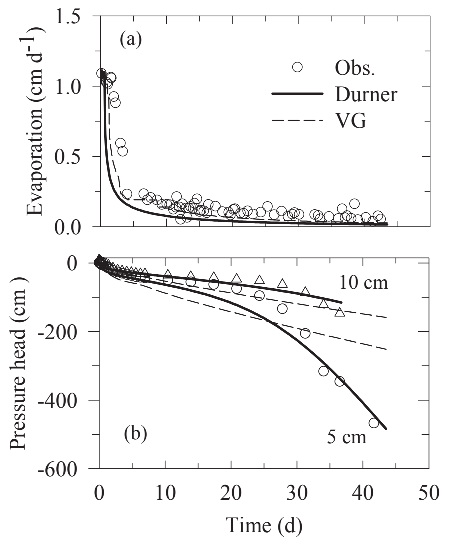

Fig. 3. Comparison of Durner and VG model simulation of evaporation (a) and pressure head (b) with measured values for soil + the large rocks (R_v = 0.24 cm^3 cm^{-3}).

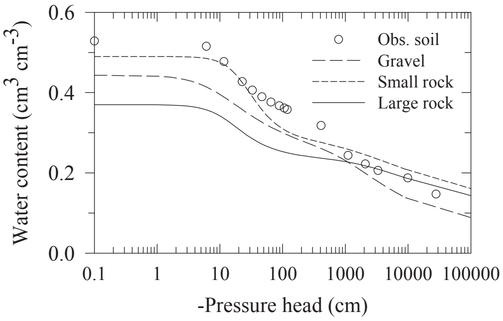

Fig. 4. Water retention curves for the gravel (R_v = 0.20 cm^3 cm^{-3}), the small rock (R_v = 0.12 cm^3 cm^{-3}) and the large rocks (R_v = 0.24 cm^3 cm^{-3}) using the Durner model.

the second curve would dominate the water retention curve for rocky soil. Our results showed that the difference between the optimized θ_s and the θ_s estimated by Eq. (1) were less than 0.03 cm^3 cm^{-3}. This suggests that the air entry values of the rocky soil were similar to the value for the clay loam. This differs from results of Fiés *et al*. (2002) that showed the air entry value of mixtures of soils and glass fragments (< 6 mm) increased with volume fraction of glass (> 30%) even though θ_s and θ_r decreased as glass volume increased.

This might have occurred because of increasing air gaps between glass fragments. However, if large air gaps do not exist, as was likely the case in our study, the impact of change in the air entry value due to larger air-filled porosity may be ignored. Evaluating whether the second curve can dominate a water retention curve for rocky soil is difficult, but the initial w_2 value (≥ 0.5) led to an increase in the flexibility of the Durner model in describing retention and hydraulic data across the range of h. For example, if initial w_2 value was lower than 0.4, it resulted in overestimated K_s (> 30 cm d^{-1}) and θ_s (> 0.50 cm^3 cm^{-3}). Thus, the initial w_2 value (≥ 0.5) was helpful to obtain reasonable water retention curves for rocky soil. These results confirmed our hypothesis that tortuosity increases with rock content, while most of earlier studies did not optimize the l (Sakai and Toride, 2007), which implied that hydraulic properties for rocky soil would be adjusted mainly by K_s. Our finding was that estimating $K(h)$ due to the parameter l, which represents the tortuosity factor, is the key for modeling hydraulic properties of rocky soil.

5. Conclusions

Two simulation models, the VG and Durner, were evaluated for estimating hydraulic properties of rocky soils. Estimated l (≤ 0.03), representing tortuosity was lower than 0.5, which improved simulation performance for both models. Results showed that the Durner model was more appropriate than the VG model for describing water retention and hydraulic conductivity of rocky soils across the wide range of pressure heads.

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