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# Controls of soil hydraulic characteristics on modeling groundwater recharge under different climatic conditions

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SUMMARY

To meet the challenge of estimating spatially varying groundwater recharge (*GR*), increasing attention has been given to the use of vadose zone models (VZMs). However, the application of this approach is usually constrained by the lack of field soil hydraulic characteristics (SHCs) required by VZMs. To tackle this issue, SHCs based on the van Genuchten or Brooks–Corey model are generally estimated by pedotransfer functions or taken from texture based class averages. With the increasing use of this method, it is important to elucidate the controls of SHCs on computing *GR* mostly due to the high nonlinearity of the models. In this study, it is hypothesized that the nonlinear controls of SHCs on computing *GR* would vary with climatic conditions. To test this hypothesis, a widely used VZM along with two SHCs datasets for sand and loamy sand is used to compute *GR* at four sites in the continental Unites States with a significant gradient of precipitation (*P*). The simulation results show that the distribution patterns of mean annual *GR* ratios ($\overline{GR}/\overline{P}$, where $\overline{GR}$ and $\overline{P}$ are mean annual *GR* and *P*, respectively) vary considerably across the sites, largely depending on soil texture and climatic conditions at each site. It is found that $\overline{GR}/\overline{P}$ is mainly controlled by the shape factor *n* in the van Genuchten model and the nonlinear effect of *n* on $\overline{GR}/\overline{P}$ varies with climatic conditions. Specifically, for both soil textures, the variability in $\overline{GR}/\overline{P}$ is smallest at the Andrews Forest with the highest $\overline{P}$ (191.3 cm/year) and $\overline{GR}/\overline{P}$ is least sensitive to *n*; whereas, the variability in $\overline{GR}/\overline{P}$ at the Konza Prairie ($\overline{P}$ = 84.2 cm/year) is the largest and $\overline{GR}/\overline{P}$ is most sensitive to *n*. With further decreasing $\overline{P}$, the nonlinear effect of *n* weakens at the Barta Brothers ($\overline{P}$ = 57.3 cm/year) and Sevilleta ($\overline{P}$ = 20.3 cm/year), leading to smaller $\overline{GR}/\overline{P}$ variability at those two sites than at the Konza Prairie. The results also reveal that $\overline{GR}/\overline{P}$ in finer soils with smaller *n* values decreases more rapidly with decreasing $\overline{P}$.



## 1. Introduction

Groundwater recharge (*GR*) is an important process in terrestrial hydrological cycles. Knowledge of *GR* and its spatial distribution is critical for closing groundwater balance equations and for assessing sustainable use of groundwater resources (Scanlon et al., 2006). However, the complex dependence of recharge processes on various affecting factors (e.g., soil, climate, topography, landscape position, and vegetation) precludes accurate estimates of *GR* as it may vary substantially across landscapes (Scanlon et al., 2002; Kim and Jackson, 2012). Although a range of physical, chemical, and isotopic techniques have been developed over the past several decades to estimate *GR* (Lerner et al., 1990; Allison et al., 1994; Scanlon et al., 2002), increasing attention has been given to the use of process-based vadose zone models (VZMs) for estimating spatially varying *GR* due to the cost and time efficiency of the method (Keese et al., 2005; Small, 2005; Wang et al., 2009a; Le Coz et al., 2013; Ibrahim et al., 2014).

Application of VZMs for calculating *GR* requires soil hydraulic characteristics (SHCs), which are usually unavailable for needed spatial resolutions. To overcome this problem, a general practice is to apply SHCs estimated from pedotransfer functions (PTF) to obtain *GR* at large spatial scales (Keese et al., 2005; Small, 2005; Faust et al., 2006; Wang et al., 2009a). Pedotransfer functions are used to convert easily obtainable or readily available soil properties to SHCs (Schaap et al., 2001; Wösten et al., 2001). For instance, Small (2005) analyzed the climatic controls on *GR* in the Southwestern US using a 1-D VZM with mean SHCs, and revealed that the occurrence of *GR* was significantly affected by rainfall characteristics. Also based on a 1-D VZM, Keese et al. (2005) evaluated the spatial distribution of *GR* in Texas by employing the Rosetta

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program (Schaap et al., 2001) to estimate SHCs. The authors found that *GR* was higher in sandy soils under bare surface conditions, and could be reduced by factors of 2–11 for finer-textured soils and by factors of 2–30 under vegetated conditions. Moreover, PTF-estimated SHCs have been recently used for simulating various land surface processes (Gutmann and Small, 2007; Decharme et al., 2011; Wood et al., 2011).

Despite the advantages of utilizing PTF-estimated SHCs, the reliability of such approaches might be problematic due to the uncertainties in the SHCs estimates (Schaap and Leij, 1998; Schaap et al., 2001), the nonlinear nature of subsurface flow systems (Wang et al., 2009a), and soil heterogeneity (Hohenbrink and Lischeid, 2014). Faust et al. (2006) calculated catchment-scale *GR* and showed that computed *GR* might vary by an order of magnitude depending on the choice of PTFs. By applying a VZM, Wang et al. (2009a) calculated *GR* in a semiarid region based on three SHCs datasets, and showed that the use of mean SHCs for obtaining representative *GR* values had caveats and generalizations to other climatic regimes were not apparent. In particular, future *GR* projections require a thorough understanding of the SHCs uncertainty impacts on *GR* calculations under different climatic conditions (Green et al., 2011; Taylor et al., 2013).

In this study, we hypothesize that the controls of SHCs on *GR* calculations are dependent on climatic conditions. To illustrate our hypothesis, Fig. 1 shows a group of soil water retention curves based on the van Genuchten model (van Genuchten, 1980), which were derived from the UNSODA soil database for loamy sand (Nemes et al., 2001). It can be seen from Fig. 1 that near the wet end of the retention curves (e.g., −10 cm), the variations in the curves are smaller than in the intermediate range (e.g., −100 cm), which might lead to less impacts of SHCs uncertainties on modeling *GR* under very wet conditions. Similarly, the uncertainty impacts of SHCs on modeling *GR* would be also smaller under very dry conditions as demonstrated by the dry end of the retention curves (e.g., −1000 cm) in Fig. 1. Thus, one can expect that the controls of SHCs on *GR* calculations would be climate-dependent.

To test our hypothesis without the need to generate synthetic hydrometeorological data (e.g., Small, 2005), four research sites located in the continental United States with a significant precipitation (*P*) gradient were selected to analyze the controls of SHCs on modeling *GR* under different climatic conditions. To be consistent with previous modeling studies (Small, 2005; Wang et al., 2009a), two SHCs datasets for sand and loamy sand were chosen to represent the variability in SHCs. Daily hydrometeorological data from each site were used to drive a 1-D VZM for computing *GR*. In addition, both bare surface and vegetated conditions were considered to examine the effect of vegetation on *GR* distributions. For the vegetated condition, remotely sensed data and literature values of physiological parameters were adopted. Finally, the controls of SHCs on *GR* distributions were analyzed using histograms as well as a sensitivity analysis of *GR* to different van Genuchten parameters.

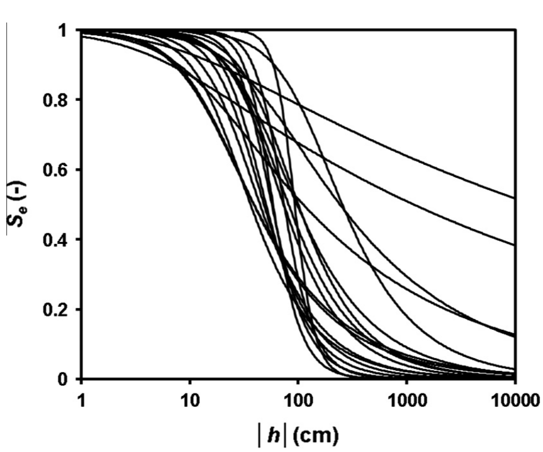


**Fig. 1.** Relationships between effective saturation degree ($S_e$) and water pressure head ($h$) for loamy sand derived from the UNSODA soil database (Nemes et al., 2001).

## 2. Methods and materials

### 2.1. Flow model

A widely used 1-D VZM, Hydrus-1D (Šimunek et al., 2005) was chosen in this study due to the accuracy of its numerical algorithm (Zlotnik et al., 2007). The Hydrus-1D model can simulate 1-D vertical soil moisture flow in porous media by solving the Richards equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}[K(h)(\frac{\partial h}{\partial x}) - K(h)] - S(h) \quad (1)$$

where $\theta$ [L$^3$/L$^3$] is volumetric moisture content, $t$ [T] is time, $x$ [L] is spatial coordinate (positive downward), $h$ [L] is pressure head, $K$ [L/T] is hydraulic conductivity, and $S$ [1/T] is root water uptake.

The van Genuchten model (Mualem, 1976; van Genuchten, 1980) was used to describe the constitutive relations among $\theta$, $h$, and $K$:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m}, & h < 0 \\ \theta_s & h \geqslant 0 \end{cases} \quad (2)$$

$$K(h) = K_S \times S_e^l \times \left[1 - (1 - S_e^{1/m})^m\right]^2 \quad (3)$$

where $\theta_r$ [L$^3$/L$^3$] is residual moisture content, $\theta_s$ [L$^3$/L$^3$] is saturated moisture content, $K_S$ [L/T] is saturated hydraulic conductivity, $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ is effective saturation degree, and $\alpha$, $n$, and $l$ are shape factors: $\alpha$ [1/L] is inversely related to air entry pressure, $n$ [–] is a measure of pore size distribution, and $l$ [–] is a lumped parameter accounting for pore tortuosity and connectivity, and $m = 1 - 1/n$.

A standard atmospheric upper boundary condition was adopted in this study (Neuman et al., 1974), which can switch from a prescribed flux to a prescribed head boundary condition when limiting pressure heads are exceeded. Surface runoff (without ponding) was allowed to occur when $P$ exceeded soil infiltration capacity (e.g., $K_S$) or soil was saturated. The other option in the Hydrus-1D model with ponding (e.g., the maximum ponding depth = 0.5 cm) was also evaluated. It was shown that the inclusion of ponding did not affect the conclusions made in this study, and therefore the results are not analyzed here. At the lower boundary, a unit hydraulic gradient condition was applied (Keese et al., 2005; Small, 2005; Wang et al., 2009a). Accordingly, *GR* is defined here as the amount of water leaving the lower boundary. The length of simulated soil columns was 5 m with 501 nodes evenly distributed between the surface and bottom. Numerical experiments showed that additional spatial nodes did not improve the model performance.

In this study, *GR* was computed for both vegetated and bare surface conditions to examine the impact of vegetation on the *GR* distributions. For the bare surface condition, potential evapotranspiration ($ET_p$) was set to be equal to potential soil evaporation ($E_p$). For the vegetated condition, $ET_p$ was partitioned between potential transpiration ($T_p$) and $E_p$ based on Beer's law (Ritchie, 1972):

$$E_p(t) = ET_p(t) \times e^{-k \times \mathrm{LAI}(t)} \quad (4)$$

$$T_p(t) = ET_p(t) - E_p(t) \quad (5)$$