https://doi.org/10.1590/1678-4499.2017406

SOIL AND PLANT NUTRITION - Article

Performance evaluation of different soil water retention functions for modeling of water flow under transient condition

Fatemeh Zakizadeh Abkenar[1], Ali Rasoulzadeh[2]*, Ali Asghari[3]

1.University of Mohaghegh Ardabili - Faculty of Agriculture and Natural Resources - Soil Science Department - Ardabil - Islamic Republic of Iran.
2.University of Mohaghegh Ardabili - Faculty of Agriculture and Natural Resources - Water Engineering Department - Ardabil - Islamic Republic of Iran.
3.University of Mohaghegh Ardabili - Agronomy and Plant Breeding - Ardabil - Islamic Republic of Iran..

ABSTRACT: Description and prediction of water flow through unsaturated soils is necessary to understand their hydraulic properties, including soil water retention curve (SWRC). Many models have been developed for estimation of SWRC and many researchers compared water retention curve derived from these models with the measured values. In this paper, in addition to comparing measured and derived SWRC, a functional evaluation of SWRC for modeling of soil water movement was carried out using van Genuchten, Brooks-Corey, Campbell and Hutson-Cass models in three sites including Loamy sand, Loam and Clay loam soils. Therefore, the functional behavior of SWRC was quantitatively compared by applying mentioned SWRC to numerical code (HydroGeoSphere) to simulate soil profile drainage under steady-state and transient conditions. The agreement between simulated and measured free drainages values was evaluated using statistical criteria including mean absolute error (*MAE*), modified index of agreement (*d'*), modified coefficient efficiency (*E'*), and t-test. The results demonstrated that the van Genuchten model was slightly better than the other models for estimation of SWRC (*MAE* 0.014 – 0.016, *E'* 0.80 – 0.87 and *d'* 0.90 – 0.93) while according to t-test, it was found that the measured and estimated SWRC using various models did not differ significantly. Therefore, it is expected that the simulated free drainage using mentioned SWRC models did not differ significantly with observed values. But the results demonstrated that the simulated free drainage using Brooks-Corey model for Loamy sand soil and van Genuchten and Brooks-Corey models for Loam soil differed significantly ($p \leq 0.05$) with measured values.

Key words: HydroGeoSphere, soil hydraulic properties, soil water flow simulation, soil characteristic curve.

*Corresponding author: rasoulzadeh@uma.ac.ir

Received: Nov. 23, 2017 – Accepted: Mar. 26, 2018

INTRODUCTION

Soil water retention curve (SWRC) is one of the important soil hydraulic properties in the simulation of water flow in vadose zone. Measurement of the SWRC is time consuming and many attempts have been made to extend pedotransfer functions that describe the relationship between SWRC and ease to measure soil properties (Assouline et al. 1998; Campbell and Shiozawa 1994[4]; Rajkai et al. 2004; Williams et al. 1992). Many empirical models for the SWRC estimation are presented, and each of them has strengths and weaknesses.

The van Genuchten (1980) model for the SWRC and Mualem (1976) model for the unsaturated hydraulic conductivity ($K(\theta)$) are popular and widely used for simulation of water flow, which are stated as follows (Eqs. 1 and 2):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^{n})^{m}} \quad (1)$$

$$K(\theta) = K_s \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right)^{0.5} \left[1 - \left(1 - \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right)^{1/m} \right)^{m} \right]^{2} \quad (2)$$

where h represents the pressure head (cm-water); $\theta(h)$ is the soil water content (cm³·cm⁻³) at the h pressure head; K_s is saturated hydraulic conductivity; and θ_s and θ_r denote saturated and residual soil water contents (cm³·cm⁻³), respectively. The symbols α, n and m are shape parameters and m is assumed to be $m = 1 - 1/n$. Note that n parameter affects the steepness of the S-shaped of SWRC (Wösten et al. 1995).

Brooks and Corey (1964) proposed other models for the SWRC and $K(\theta)$, given by Eqs. 3 and 4:

$$\theta(h) = \begin{cases} \theta_r + (\theta_s - \theta_r) \times |\alpha h|^{-\lambda} & h > 1/\alpha \\ \theta_s & h \le 1/\alpha \end{cases} \quad (3)$$

$$K(\theta) = K_s \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right)^{2/\lambda + 4} \quad (4)$$

where θ_r and θ_s are the residual and saturated water contents (cm³·cm⁻³), respectively; α is the inverse of the air entry value (cm⁻¹); and λ is a pore-size distribution parameter. For notational convenience, h and α are considered positive values for unsaturated soils (i.e., h denotes suction). The Brooks-Corey model has been shown to create moderately accurate results for many coarse-textured soils branded with large λ values and in high suction but results have normally been less accurate for fine-textured with small λ values (van Genuchten et al. 2000; Gimenz et al. 2001).

Campbell (1974) have used the same power law model offered by Brooks and Corey (1964) to state SWRC as a function of the air entry pressure head h_e and factor b, which depends on soil texture (Eq. 5):

$$\theta(h) = \theta_s \times \left(\frac{h}{h_e} \right)^{\left(-\frac{1}{b}\right)} \quad (5)$$

where h and h_e are the soil water and air entry pressure head, respectively; $\theta(h)$ is the soil water content (cm³·cm⁻³) at the h pressure head; θ_s and b are the saturated water content and empirical parameter, respectively. The $K(\theta)$ model is considered as follows (Eq. 6):

$$K(\theta) = K_s \left(\frac{\theta}{\theta_s} \right)^{2b+3} \quad (6)$$

with all the parameters defined previously.

Campbell model is not able to predict SWRC below the air entry point. For this reason, Hutson and Cass (1987) modified Campbell model and obtained soil water retention curve in two parts (the exponential and hyperbolic) based on Campbell model. Hutson-Cass models are expressed as follows (Eq. 7):

$$\theta(h) = \begin{cases} \theta_s \left(\frac{h}{h_e} \right)^{-1/b} & \theta < \theta_i \\ \theta_s - \dfrac{\theta_s h^2 \left(1 - \frac{\theta_i}{\theta_s} \right)}{h_e^2 \left(\frac{\theta_i}{\theta_s} \right)^{-2b}} & \theta \ge \theta_i \end{cases} \quad (7)$$

where θ_i refers to water contents at curvature of parabolic curve and obtained from the Eq. 8 and the parameters →

[4]Campbell, G. S. and Shiozawa, S. (1994). Prediction of hydraulic properties of soils using particle-size distribution and bulk density data. Proceedings of the International Workshop on Indirect Methods for Estmating the Hydraulic Properties of Unsaturated Soils; Riverside, USA.

defined before:

$$\theta_i = \frac{2b\theta_s}{(1+2b)} \quad (8)$$

Accuracy of these models was evaluated by their correlation between estimated and measured SWRC. Among mentioned models, van Genuchten and Brooks-Corey are the most popular because of more strength points and better adaptation with measured SWRC, but their results are compared with measurement of one branch of SWRC (mostly drying branch). It is necessary to note that due to the complicated essence of liquid-phase form in an unsaturated porous medium, the relation between water pressure and water content is not unique and presents hysteresis effects. Many researchers investigate accuracy of soil water retention curves estimation via the SWRC models. Ross et al. (1991) and Nimmo (1991) expressed that the van Genuchten model has good performance in middle and high range of saturation but often there was poor result in low moisture. Manyame et al. (2007) compared operation of three van Genuchten and Campbell and Vauclin models (basing indirect methods) in sandy soils of Niger. Their results showed that the estimation of Campbell model is more accurate than van Genuchten model for the soil samples with higher content of sand. Rasoulzadeh and Ghoorabjiri (2011; 2014) used Van Genuchten and Brooks-Corey's soil water models along with HydroGeoSphere, which is based on Richards' equation, to simulate water flow in the forest floors. They implemented the reverse model to get the parameters of SWRC. The good compatibility between measured and simulated free drainage for all treatments in the validation period shows that the Van Genuchten and Brooks-Corey's models efficiently characterize the water flow in the forest floor.

All of these investigations have evaluated the estimation of these models with one branch of SWRC, while the main application of SWRC is modeling water movement in soil. Due to uniqueness of SWRC, there is complexity to evaluate accuracy of the SWRC models. In this study, the accuracy of four SWRC models (Campbell, Brooks-Corey, van Genuchten and Hutson-Cass) to estimate the water retention curve has been studied. In addition, the function of these models to simulate the water movement in soil by employing them as input data in a numerical code (HydroGeoSphere) was evaluated.

MATERIALS AND METHODS

Study area and Experimental device

Guilan province (study area) is located in northwest of Iran with average annual temperature of 15.3 °C, precipitation of 1853 mm. Three sites in the study area were taken into account for soil sampling with different textural classes including Loamy sand, Loam and Clay loam, denoted sites A, B and C, respectively (Fig. 1). Undisturbed soil samples were supplied from 0 – 30 cm depth using three iron cylinders as micro-lysimeter. The inside diameter of micro-lysimeter was 25 cm with 40 cm height (Fig. 2).

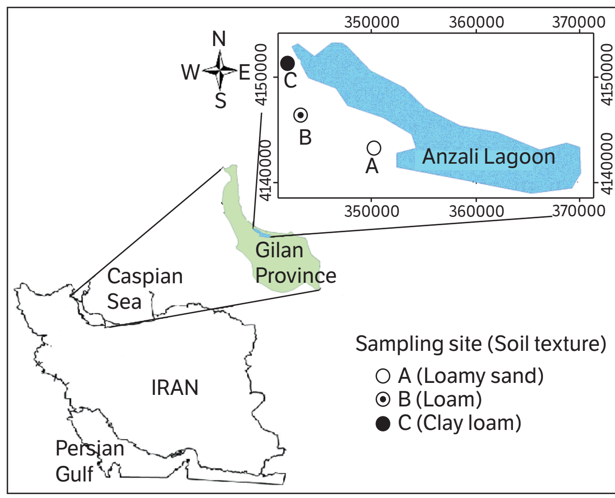

Figure 1. Location map of the study area.

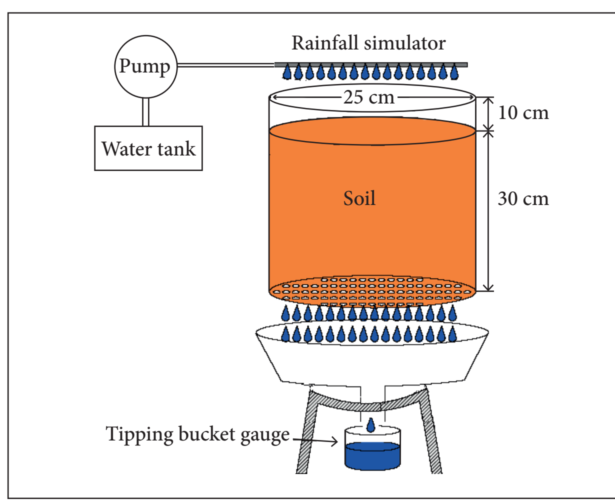

Figure 2. Schematic of the micro-lysimeter.

Artificial rainfall was applied on the surface of the micro-lysimeter and free drainage from the end of micro-lysimeter was measured. Rainfall intensity was well-ordered by a pump connected to a raindrop maker to create water drops. Free drainage from the bottom of the micro-lysimeter was gathered and measured using an electronic balance. First, a constant intensity rain was contacted to reach to steady condition as a constant discharge rate from bottom of micro-lysimeter was established so as to accurately define the initial condition required for the numerical simulation of water movement. After reaching the state steady experiment, transient condition was carried out. In transient condition, the random rainfall experiment was conducted and the transient discharge rate from bottom of micro-lysimeter was continuously monitored.

Numerical model description

HydroGeoSphere code is applied to the modified form of Richards' equation to simulate water flow in a variably-saturated porous media (Eq. 9) (Therrien et al. 2008):

$$-\nabla.(W_m\, q) + \sum \Gamma_{ex} \pm Q = W_m \frac{\partial}{\partial t}(\theta_s\, S_w) \qquad (9)$$

where W_m stands for the volumetric fraction of the total porosity occupied by the porous media. This parameter is dimensionless and always equal to 1.0 except when a second porous continuum is considered for a simulation. The q ($L \cdot T^{-1}$) is calculated by Eq. 10:

$$q = -K.k_r \nabla(\psi + z) \qquad (10)$$

where $k_r = k_r(S_w)$ shows the relative permeability of the medium (dimensionless) regarding the degree of water saturation S_w (dimensionless); ψ and z are the matric and elevation head (L), respectively; θ_s is the saturated water content ($L^3 \cdot L^{-3}$); K is the hydraulic conductivity tensor ($L \cdot T^{-1}$); and Q ($L^3 \cdot L^{-3} \cdot T^{-1}$) is the fluid exchange with the outside of the simulation domain. The amount of Q is considered positive for a source and negative for a sink of the porous medium system. The S_w is related to the θ as $S_w = \theta/\theta_s$. In Eq. 9, Γ_{ex} is the volumetric fluid exchange rate ($L^3 \cdot L^{-3} \cdot T^{-1}$) between the subsurface domain and all other types of domains supported by the model such as wells, tile drains, discrete fractures and dual continuum.

HydroGeoSphere solves the pressure-head based modified form of Richards' equation (Eq. 9) for variably-saturated flow in up to three dimensions using a Galerkin finite element approach.

Model discretization and Boundary condition

The GRID BUILDER (McLaren 2004) was used to generate finite element grid as shown in Fig. 3. Grid independency was carried out and the grid size in the vertical direction was yielded 1.5 cm.

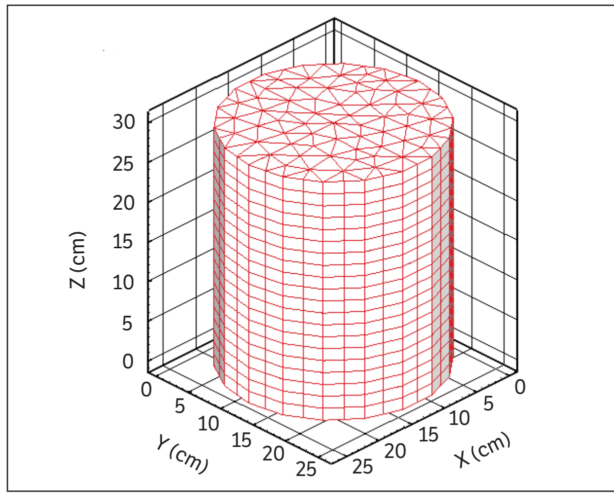

Figure 3. Numerical model mesh.

The upper boundary of each experimental model (micro-lysimeter) is characterized by specified rainfall fluxes during experiments. The lower boundary is set to free drainage. For the sides of each model no-flow boundary condition is considered. Initial values for water content as well as matric suction head were unknown. To solve this, first the HydroGeoSphere was run for a very long time to reach to pseudo steady as simulated free drainage indicated good consistent with observed value. The matric suction head yielded from pseudo steady condition was applied as the initial value for unsteady simulation.

Laboratory measurements

Disturbed and undisturbed soil samples to determine the soil properties were collected at three sites in the study area (Fig. 1). Soil properties of each site were obtained through a number of experiments in the laboratory including soil particle size distribution, bulk density, soil particle density and organic carbon. Stainless steel cylinders with volume of 100 cm^3 were used to sample the undisturbed →

soil for measuring water retention curve lower than 1000 cm-water as well as bulk density. The undisturbed soil samples were transported carefully to avoid disturbance. The bulk density, particle size distribution and soil particle density were obtained using the oven dried, hydrometer and pycnometer methods, respectively. To obtain the SWRC of each soil sampling in low suctions (less than 100 cm-water), hanging column apparatus and in high suctions (more than 100 cm-water), ceramic pressure plate extractors were used (Dane and Topp 2002).

To estimate the parameters of SWRC models, the measured values of water retention curve were fitted to these models using WATREC software (Rasoulzadeh 2010). In other words, to convert SWRC data (θ versus h) to the SWRC models, the experimental water retention data were fitted to the van Genuchten (Eq. 1) and Brooks-Corey (Eq. 3) as well as Campbell (Eq. 5) and Hutson-Cass (Eq. 7) equations.

The fundamental variable of solution for partial differential flow Eq. 9 is SWRC models. The van Genuchten and Brooks-Corey models were defined in HydroGeoSphere as SWRC models. Campbell and Hutson-Cass parameter's equations after obtaining by WATREC software were applied in HydroGeoSphere as unsaturated tables.

Saturated hydraulic conductivity of sites B and C were measured in the laboratory by falling head permeability method. The undisturbed soil samples of these sites were the saturated with calcium chloride 0.01 molar. Then saturated hydraulic conductivity was calculated by measuring the duration of water drain from the soil samples. The constant head permeability is used to determine the saturated hydraulic conductivity of site A. In this method, let water move within the soil sample at a uniform pressure (the height of the water in the pressure pipes is uniform). The saturated hydraulic conductivity was calculated by measuring the volume of water displaced over the soil sample at a given time interval (Dane and Topp 2002).

Statistical criteria

Performance of Brooks-Corey, van Genuchten, Campbell and Hutson-Cass models were evaluated by three statistical criteria: mean absolute error (*MAE*, Eq. 11), modified coefficient efficiency (*E'*, Eq. 12) and modified index of agreement (*d'*, Eq. 13):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|O_i - S_i\right| \tag{11}$$

$$E' = 1.0 - \left(\frac{\sum_{i=1}^{n}\left|O_i - S_i\right|}{\sum_{i=1}^{n}\left|O_i - O'\right|}\right) \tag{12}$$

$$d' = 1.0 - \left(\frac{\sum_{i=1}^{n}\left|O_i - S_i\right|}{\sum_{i=1}^{n}\left(\left|S_i - O'\right| + \left|O_i - O'\right|\right)}\right) \tag{13}$$

where O_i and S_i are the observed and simulated free drainage values at different time, respectively; *O'* is the mean observed value; and *n* is the number of paired observed-simulated values. *MAE* describes the difference between the free drainage simulations and observations. The *MAE* equal to zero indicates perfect fit between the observed and estimated data. The value of *E'* varies from $-\infty$ to 1.0, with higher values indicating better agreement with the observations. The value of *d'* ranges from 0.0 to 1.0, where *d'* equal to 1.0 shows the best fit and lower than 1.0 values represent less accurate consistent between the estimation and observations (Legates and McCabe Jr. 1999). Also t-test was carried out to compare simulated and measured values using SPSS software.

RESULTS AND DISCUSSION

Comparision of the SWRC models to simulate the soil water retention curves

Physical properties of soil samples from studied sites are presented in Table 1. The parameters of the SWRC models obtained by fitting to measured data of water retention curve (Laboratory measurements section) for the three studied sites are shown in Table 2. Figure 4 illustrates the results of estimated SWRCs using these models in comparison with the measured SWRC. As can be seen in Fig. 4, Campbell and Hutson-Cass models in low value of matric suction (less than 100 cm-water) and Brooks-Corey and van Genuchten models in high value of matric suction could not mimic measured SWRC for sites A and B. In other words, Campbell and Hutson-Cass models tend to underestimate matric suction for volume wetness more than 0.3 and 0.4 $cm^3 \cdot cm^{-3}$ for sites A and B, respectively, while Brooks-Corey and van Genuchten models tend to overestimate matric suction for lower wetness. At these sites, the SWRCs modeled using the van Genuchten and Brooks-Corey models show a sharp increase in matric suction with little decrease in volume →

Table 1. Physical properties of the three selected sites.

Site	Soil texture	Sand (%)	Silt (%)	Clay (%)	Bulk density ($g \cdot cm^{-3}$)	Particle density ($g \cdot cm^{-3}$)	Organic carbon (%)	Saturated hydraulic conductivity ($cm.min^{-1}$)
A	Loamy sand	86.81	9.12	4.07	1.34	2.69	1.03	0.86
B	Loam	32.98	48.99	18.03	1.10	2.46	3.15	0.60
C	Clay loam	29.90	41.05	29.05	1.17	2.50	2.22	0.09

Table 2. Parameters of various SWRC models for the three sites.

SWRC model	Parameters	Site A (Loamy sand)	Site B (Loam)	Site C (Clay loam)
van Genuchten	θ_r ($cm^3 \cdot cm^{-3}$)	0.102	0.211	0.061
	θ_s ($cm^3 \cdot cm^{-3}$)	0.511	0.560	0.541
	θ (cm^{-1})	0.054	0.065	0.243
	n	1.931	1.615	1.159
Brooks-Corey	θ_r ($cm^3 \cdot cm^{-3}$)	0.091	0.202	0.011
	θ_s ($cm^3 \cdot cm^{-3}$)	0.502	0.550	0.531
	θ (cm^{-1})	0.084	0.097	0.310
	λ	0.652	0.470	0.131
Campbell and Hutson-Cass	θ_s ($cm^3 \cdot cm^{-3}$)	0.557	0.552	0.540
	h_e (cm)	3.676	2.830	3.932
	b	3.563	7.752	7.721

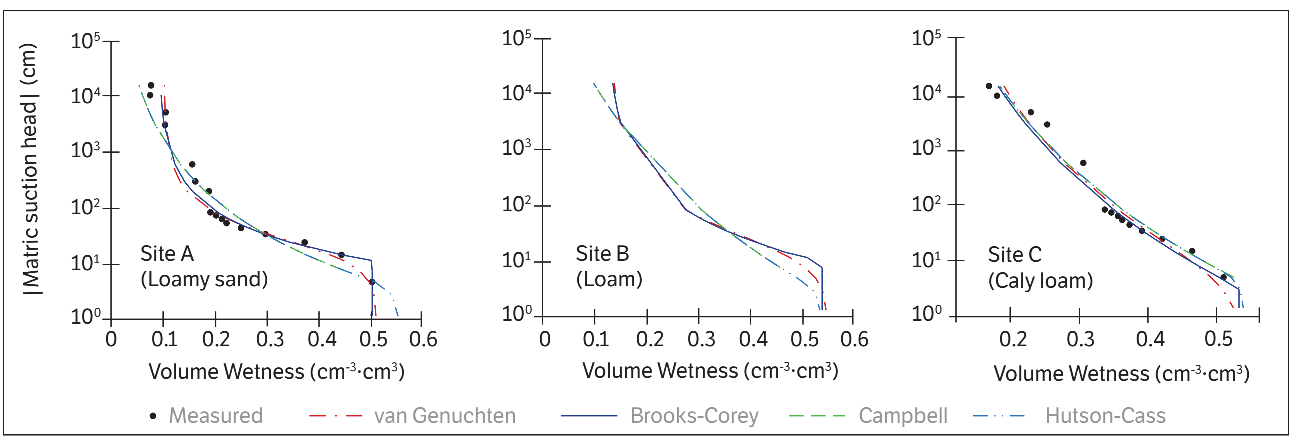

Figure 4. Estimation of soil water retention curves by van Genuchten, Brooks-Corey, Campbell and Hutson-cass models compared with measured values at three sites.

wetness in lower value of soil moisture. This result is in line with the findings of Manyame et al. (2007), who have stated that SWRCs modeled by the van Genuchten model have fast matric suction increase in low amounts of moisture for light texture soils. All SWRC models performed well for site C (Clay loam soil). At this site, the van Genuchten model tends to somewhat underestimate matric suction head for volume wetness more than 0.4 $cm^3 \cdot cm^{-3}$. The four models had slightly differences in simulation of SWRCs. They all represent the low water holding capacity on this site.

To quantify performance of the different models in SWRC estimation, statistical criteria (*MAE*, *E'* and *d'*) were calculated and are shown in Table 3. At site A with Loamy sand soil, van Genuchten and Brooks-Corey models with slight difference in *MAE* (0.014 versus 0.016), *E'* (0.871 versus 0.868) and *d'* (0.935 versus 0.922), could mimic SWRC better than Campbell (with *MAE*, *E'* and *d'* 0.029, 0.732 and 0.867, respectively) and Hutson-Cass (with *MAE*, *E'* and *d'* 0.028, 0.747 and 0.873, respectively) models. Also, van Genuchten with *MAE* 0.016, *E'* 0.810 and *d'* 0.908 and

Brooks-Corey with *MAE* 0.016, *E'* 0.808 and *d'* 0.902 with almost similar statistical results could estimate SWRC better than the other models at site B (Loam soil). For Clay loam soil (site C), all models showed similar estimation of SWRC.

In overall, the van Genuchten model appeared to be slightly better for estimation of soil water retention curve at the three studied sites. Brooks-Corey had close performances to van Genuchten in this study.

The van Genuchten model is a popular model for SWRC estimation, this model is able to estimate S-shaped of SWRC and predicting retention curve in the suction below air entry point, while the Campbell model could not estimate SWRC below air entry head, but this model did not offer very impressive superiority compared with the other models (Fig. 4 and Table 3).

Table 3. Statistical criteria for comparing estimated SWRC by models with measured values.

Site	SWRC model	MAE	E'	d'
Optimum		0	1	1
Site A (Loamy sand)	van Genuchten	0.014	0.871	0.935
	Brooks-Corey	0.016	0.868	0.922
	Campbell	0.029	0.732	0.867
	Hutson-Cass	0.028	0.747	0.873
Site B (Loam)	van Genuchten	0.016	0.810	0.908
	Brooks-Corey	0.016	0.808	0.902
	Campbell	0.023	0.724	0.868
	Hutson-Cass	0.021	0.868	0.878
Site C (Clay loam)	van Genuchten	0.016	0.802	0.903
	Brooks-Corey	0.014	0.828	0.916
	Campbell	0.020	0.758	0.888
	Hutson-Cass	0.017	0.790	0.901

Compartion of the SWRC models to simulate soil free drainage

To simulate soil free drainage, parameters of four empirical SWRC models (Brooks-Corey, van Genuchten, Campbell and Hutson-Cass) along with measured saturated hydraulic conductivity (K_s) were used as input in HydroGeoSphere code. Note that K_s was a fixed amount for each soil and only SWRC models were changed. So SWRC models play a major role in simulation of soil free drainage. The ability of the various SWRC models along with HydroGeoSphere code for simulaion of the water flow (free drainage) in the soil is shown in Figs. 5 to 7. According to Fig. 5, all models provided approximately similar performance in simulation of soil free drainage, but Campbell and Hutson-Cass models could mimic free drainage fluctuations slightly better than the other models especially in maximum and minimum points for site A (Loamy sand soil). None of the models gave suitable performance in the beginning of the free drainage simulation. As mentioned in section 2.3, due to lack of information about the initial value of the matric pressure head along the lysimeter, first pseudo steady condition in HydroGeoSphere was implemented until estimated free drainage be similar with observed. After that, the obtained values of matric pressure head by model are employed as the initial condition for unsteady phase simulations. Taking this issue into account, the disagreement between the predicted and measured discharge rate at the beginning

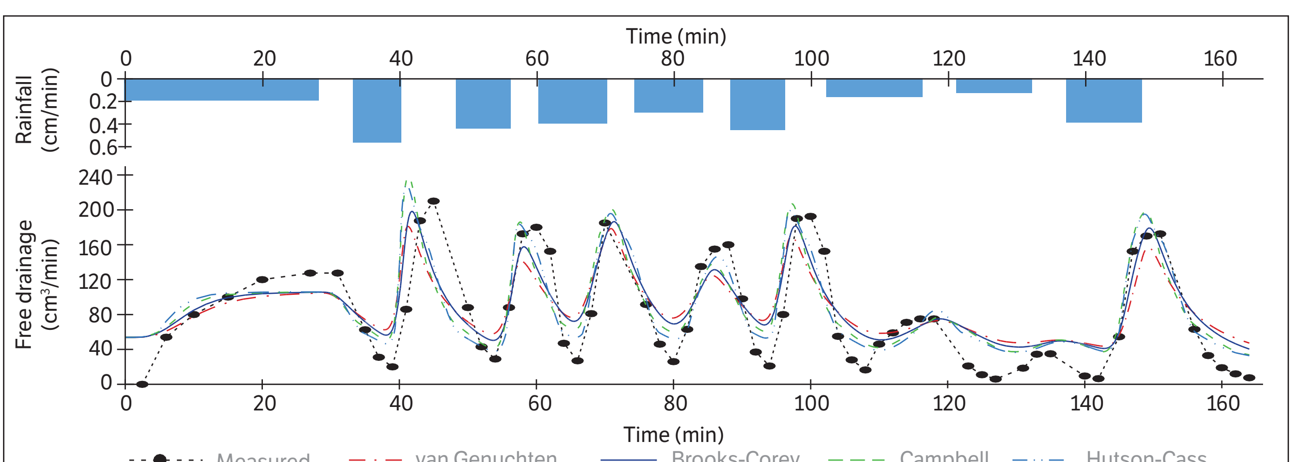

Figure 5. Rainfall intensity and observed and simulated free drainage by HydroGeoSphere using van Genuchten, Brooks-Corey, Campbell and Hutson-Cass models in site A (Loamy sand soil).

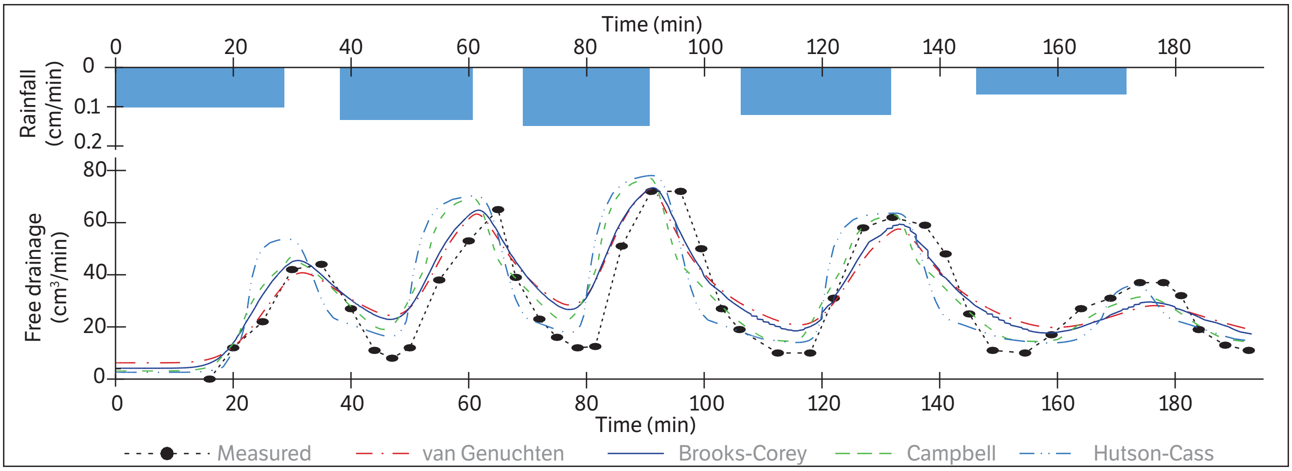

Figure 6. Rainfall intensity and observed and simulated free drainage by HydroGeoSphere using van Genuchten, Brooks-Corey, Campbell and Hutson-Cass models in site B (Loam soil).

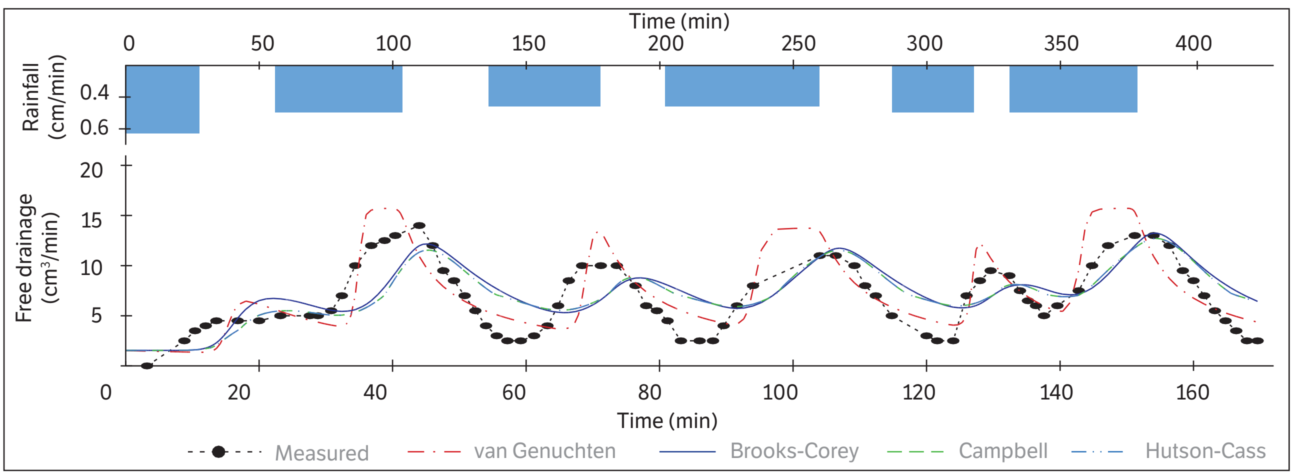

Figure 7. Rainfall intensity and observed and simulated free drainage by HydroGeoSphere using van Genuchten, Brooks-Corey, Campbell and Hutson-Cass models in site C (Clay loam soil).

of simulation indicated weak performance of model in the pseudo steady state condition.

Quantitative results of soil profile drainage simulation with three statistical criteria (*MAE*, *E'* and *d'*) for studied soil were calculated and presented in Table 4. Among four SWRC models, Hutson-Cass model with *MAE*, *E'* and *d'* 22.78, 0.55 and 0.75, respectively, had better simulation of free drainage than the other models for Loamy sand soil. Brooks-Corey and Campbell, with slight differences, are located in the next ranks, respectively, and van Genuchten with *MAE*, *E'* and *d'* of 32.51, 0.36 and 0.57, respectively, is in last rank. These results are in contrast with the results of SWRC simulations for site A, that van Genuchten was the best SWRC model in simulation of soil water retention curve.

Figure 6 illustrate the observed and estimated free drainage based on studied SWRC models, for site B (Loam soil). As one can be seen in Fig. 6, Hutson-Cass model and somewhat Campbell model tended to overestimate the maximum discharge point and the entire SWRC models tended to underestimate minimum discharge point. But in the simulation of the minimum points of discharge rate, Campbell and Hutson-Cass provided better predictions. It is visually difficult to compare the quality of the simulated free drainage using various SWRC models in Fig. 6. Therefore, statistical criteria were calculated to compare the quality of SWRC models (Table 4). According to Table 4, Brooks-Corey and Campbell models, with slightly differences in *MAE* (8.43 versus 8.67), *E'* (0.49 versus 0.47) and the same *d'* indicated better results. After these two models, van Genuchten and Hutson-Cass were in subsequent positions. Result of free drainage simulation in this soil like Loamy sand soil (site A) is in contrast →

with the result of SWRC simulation. The van Genuchten model performed better estimation of SWRC for Loam soil while this model wasn't better than the other models for simulation of free drainage.

At site C (Clay loam soil), the observed and simulated free drainage is presented in Fig. 7. In this site, none of the models could exhibit a good match with observed free drainage as well as the sites A and B. However, the van Genuchten model tended to overestimate free drainage in peak points, but it could mimic fluctuations in minimum point of free drainage better than the other models. According to Fig. 7, simulated free drainage using Campbell, Brooks-Corey and Hutson-Cass models indicated a lag time compared to observed free drainage in maximum and minimum points. The van Genuchten model with *MAE* 1.71, *E'* 0.38 and *d'* 0.68 showed the best performance of the free drainage simulation in Clay loam. Campbell and Hutson-Cass models showed same results and were placed after Brooks-Corey model (Table 4).

Table 4. Results of statistical criteria for simulation of free drainage by HydroGeoSphere using various SWRC models.

Site	SWRC model	*MAE*	*E'*	*d'*
Optimum		0	1	1
Site A (Loamy sand)	van Genuchten	32.51	0.36	0.57
	Brooks-Corey	27.41	0.46	0.66
	Campbell	27.44	0.46	0.69
	Hutson-Cass	22.78	0.55	0.75
Site B (Loam)	van Genuchten	9.15	0.44	0.66
	Brooks-Corey	8.43	0.49	0.70
	Campbell	8.67	0.47	0.70
	Hutson-Cass	10.38	0.37	0.68
Site C (Clay loam)	van Genuchten	1.71	0.38	0.68
	Brooks-Corey	2.36	0.15	0.51
	Campbell	2.21	0.20	0.53
	Hutson-Cass	2.21	0.20	0.53

Reviewing the Figs. 5 to 7, a point attracts attention. According to Figs. 5 to 7, the amount of measured free drainage was zero in the beginning of transient period while simulated free drainage showed discharge rate. In implementation of HydroGeoSphere model, first the model was run for steady state like experimental conditions and after reaching the steady state, estimated matric pressure head was applied as initial value for unsteady (transient) simulation in HydroGeoSphere. It seems that initial conditions derived from steady state stage didn't show good agreement with real condition for all sites.

T - test

The *MAE*, *E'* and *d'* values for comparing measured and estimated of SWRC as well as free drainage were presented in Tables 3 and 4, respectively. Comparing the *MAE*, *E'* and *d'* values in both tables, it is clear that the differences between estimated and measured SWRC and free drainage are often not striking. Therefore, besides the *MAE*, *E'* and *d'*, as well as visual interpretation for comparing the estimated and measured SWRC and free drainage, we also used paired t-test. T-values of paired t-test to comparison of estimated soil water retention curve (SWRC) and free drainage with the measurement are shown in Tables 5 and 6, respectively. It was found that measured and estimated SWRC using various models were not significantly different in all studied soils, implying that the same experimental water retention data were fitted to the different SWRC models. Estimated SWRCs using the models were not significantly different for site A (Loamy sand soil) and site B (Loam soil) while it differed significantly for site C (Clay loam soil). Note that estimated SWRCs using Campbell and Hutson-Cass models were not significantly different (Table 5).

Results of t-test show that in Loamy sand soil (site A), the simulated free drainage using only Brooks-Corey model differed significantly with the measured free drainage ($p \leq 0.05$), while simulated free drainage using the van Genuchten, Campbell and Hutson-Cass models did not differ significantly with measured free drainage. In Loam soil (site B), the simulated free drainage using the van Genuchten and Brooks-Corey models differed significantly ($p \leq 0.05$) and the other models did not differ significantly with measured free drainage. But in Clay loam soil (site C), simulated free drainage using the van Genuchten model was not significantly different with measurements, while applying the three other models showed significant difference with measured values. Furthermore, the t-test results indicated that simulated free drainages using various SWRC models did not differ with each other in Loamy sand and Loam (sites A and B) while in the Clay loam soil (site C), only simulated free drainage by van Genuchten model did not differ with others simulated free drainages (Table 6).

Table 5. T-value of paired t-test for comparing the measured and estimated SWRC by various models.

	Site A (Loamy sand)			
	Measured	**van Genuchten**	**Brooks-Corey**	**Campbell**
van Genuchten	0.27^{ns}			
Brooks-Corey	0.10^{ns}	0.46^{ns}		
Campbell	0.80^{ns}	0.60^{ns}	0.82^{ns}	
Hutson-Cass	0.03^{ns}	0.22^{ns}	0.09^{ns}	1.00^{ns}
	Site B (Loam)			
	Measured	**van Genuchten**	**Brooks-Corey**	**Campbell**
van Genuchten	0.72^{ns}			
Brooks-Corey	0.48^{ns}	1.35^{ns}		
Campbell	0.04^{ns}	0.57^{ns}	0.39^{ns}	
Hutson-Cass	0.30^{ns}	0.68^{ns}	0.37^{ns}	-
	Site C (Clay loam)			
	Measured	**van Genuchten**	**Brooks-Corey**	**Campbell**
van Genuchten	0.29^{ns}			
Brooks-Corey	1.02^{ns}	4.41^{**}		
Campbell	1.46^{ns}	2.47^{*}	7.37^{**}	
Hutson-Cass	1.54^{ns}	2.50^{*}	8.15^{**}	1.00^{ns}

ns = non-significant; * = significant ($p \leq 0.05$); and ** = significant difference ($p \leq 0.01$).

Table 6. T-value of paired t-test for comparing the measured and simulated free drainage by HydroGeoSphere using various SWRC models.

	Site A (Loamy sand)			
	Measured	**van Genuchten**	**Brooks-Corey**	**Campbell**
van Genuchten	1.68^{ns}			
Brooks-Corey	2.21^{*}	0.85^{ns}		
Campbell	1.88^{ns}	0.21^{ns}	0.26^{ns}	
Hutson-Cass	1.85^{ns}	0.30^{ns}	0.92^{ns}	1.13^{ns}
	Site B (Loam)			
	Measured	**van Genuchten**	**Brooks-Corey**	**Campbell**
van Genuchten	2.06^{*}			
Brooks-Corey	2.50^{*}	0.98^{ns}		
Campbell	1.46^{ns}	0.64^{ns}	1.14^{ns}	
Hutson-Cass	0.86^{ns}	0.80^{ns}	1.12^{ns}	0.74^{ns}
	Site C (Clay loam)			
	Measured	**van Genuchten**	**Brooks-Corey**	**Campbell**
van Genuchten	1.07^{ns}			
Brooks-Corey	2.73^{**}	1.67^{ns}		
Campbell	2.03^{*}	1.03^{ns}	5.66^{**}	
Hutson-Cass	2.03^{*}	1.03^{ns}	5.66^{**}	-

ns = non-significant; * = significant ($p \leq 0.05$); and ** = significant difference ($p \leq 0.01$).

CONCLUSION

In this study the performance of various SWRC models to estimate soil water retention curve was examined. In addition, we investigated the influence of these models directly on simulation of free drainage under transient condition using as input data in 3-Dimensional numerical code (HydroGeoSphere).

In spite of the superiority of van Genuchten and Brooks-Corey models for estimating SWRC which showed by three mentioned statistical criteria (*MAE*, *E'*, *d'*), t-test shows that the measured and estimated of SWRC using the studied models did not differ significantly for all sites, implying that the experimental water retention data were fitted the same to the different SWRC models.

Considering the fact that estimated SWRC by various models did not differ significantly with measured value, it was expected that the simulated free drainage by HydroGeoSphere code using these model as an input data did not differ significantly too, but it was found that the simulated free drainage using Brooks-Corey model for Loamy sand soil (site A) and van Genuchten and Brooks-Corey models for Loam soil (site B) differed significantly with measured values ($p \leq 0.05$). In Clay loam soil (site C), according to t-test, the SWRC estimated by van Genuchten model differs with SWRC estimated by Brooks-Corey ($p \leq 0.05$), Campbell ($p \leq 0.01$) and Hutson-Cass ($p \leq 0.01$) models, while the simulated free drainage by applying van Genuchten model did not differ with the simulated free drainage using Brooks-Corey, Campbell and Hutson-Cass models.

The results of this study demonstrated that the SWRC models may be fitted well to the laboratory-measured SWRC but it is not able to simulate soil free drainage by applying these models in numerical codes such as HydroGeoSphere. It can be concluded that only the quality of the SWRC models in estimating soil water retention curve could not be a proper criteria for performance of these models in simulation of water flow in soil by numerical code. It may be justified by considering hysteresis phenomena and presumably weakness performance of unsaturated hydraulic conductivity models.

It is noticeable that water movement in soil usually occurs in high moisture content and, by looking at Fig. 4, it can be seen that in low matric suction head (high moisture content), there are differences between predicted soil water retention curves by various SWRC models. This can explain mismatching in simulations of free drainage.

Another founding of this study was that superiority of SWRC models for simulation of free drainage according to statistical criteria (*MAE*, *E'* and *d'*) is not in line with t-test in some cases. As based on *MAE*, *E'* and *d'*, the simulated free drainage using Brooks-Corey along with HydroGeoSphere code could mimic measured value better than van Genuchten model in site A (Table 4), while according to t-test, performance of van Genuchten model in simulation of free drainage along with HydroGeoSphere code was not significantly different with measured value, but applying the Brooks-Corey model showed significantly different ($p \leq 0.05$) with measured values in site A (Table 6). It should be noted that this conclusion is creditable for these soils and the criteria used in this particular study.

ACKNOWLEDGEMENTS

The authors would like to thank the University of Mohaghegh Ardabili for funding the study (Grant No. 51/325). The authors also are grateful to the Department of Earth Sciences, University of Waterloo, for access rights and permission to use the HydroGeoSphere code.

ORCID IDs

F. Z. Abkenar
https://orcid.org/0000-0001-9637-4610
A. Rasoulzadeh
https://orcid.org/0000-0001-7838-6773
A. Asghari
https://orcid.org/0000-0003-3072-5857

REFERENCES

Assouline, S., Tessier, D. and Bruand, A. (1998). A conceptual model of the soil water retention curve. Water Resources Research, 34, 223-231. https://doi.org/10.1029/97WR03039

Brooks, R. H. and Corey, A. T. (1964). Hydraulic properties of porous media. Hydrological paper, 3, 27.

Campbell, G. S. (1974). A simple method for determining unsaturated conductivity from moisture retention data. Soil Science, 117, 311-314.

Dane, J. H. and Topp, G. C. (2002). Methods of soil analysis: part 4, physical method. Madison: Soil Science Society of America.

Gimenz, D., Rawls, W. J., Pachepsky, Y. and Watt, J. P. C. (2001). Prediction of a pore distribution factor from soil textural and mechanical parameters. Soil Science, 166, 79-88.

Hutson, J. L. and Cass, A. (1987). A retentivity function for use in soil water simulation models. European Journal of Soil Science, 38, 105-113. https://doi.org/10.1111/j.1365-2389.1987.tb02128.x

Legates, D. R. and McCabe Jr., G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research, 35, 233-241. https://doi.org/10.1029/1998WR900018

Manyame, C., Morgan, C. L., Heilman, J. L., Fatondji, D., Gerad, B. and Payne, W. A. (2007). Modeling hydraulic properties of sandy soils of Niger using pedotransfer functions. Geoderma, 141, 407-415. https://doi.org/10.1016/j.geoderma.2007.07.006

McLaren, R. G. (2004). GRID BUILDER, a pre-processor for 2-D, triangular element, finite-element programs. Groundwater Simulation Group. Waterloo: University of Waterloo.

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research, 12, 513-522. https://doi.org/10.1029/WR012i003p00513

Nimmo, J. R. (1991). Comment on the treatment of a residual water content in a "A consistent set of parametric model for the two-phase flow of immiscible fluids in the subsurface by L. Luckner et al. Water Resources Research, 27, 661-662. https://doi.org/10.1029/91WR00165

Rajkai, K., Kabos, S. and van Genuchten, M. Th. (2004). Estimating the water retention curve from soil properties: comparison of linear, nonlinear and concomitant variable methods. Soil and Tillage Research, 79, 145-152. https://doi.org/10.1016/j.still.2004.07.003

Rasoulzadeh, A. (2010). Evaluation of water retention functions by developing a code for quantifying the hydraulic functions of unsaturated soils. Journal of Food, Agriculture & Environment, 8, 1180-1184.

Rasoulzadeh, A. and Ghoorabjiri, M. H. (2011). Estimation of hydraulic properties of forest floor using inverse method. International Agricultural Engineering Journal, 20, 146-152.

Rasoulzadeh, A. and Ghoorabjiri, M. H. (2014). Comparing hydraulic properties of different forest floors. Hydrological Processes, 28, 5122-5130. https://doi.org/10.1002/hyp.10006

Ross, P. J., Williams, J. and Bristow, K. L. (1991). Equations for extending water retention curves to dryness. Soil Science Society of America Journal, 55, 923-927. https://doi.org/10.2136/sssaj1991.03615995005500040004x

Therrien, R., McLaren, R. G. and Sudicky, E. A. (2008). HydroGeoSphere: a three-dimensional model describing fully-integrated subsurface and surface flow and solute transport. Waterloo: University of Waterloo.

van Genuchten, M. Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44, 892-898.

van Genuchten, M. Th., Simunek, J., Leij, F. J. and Sejna, M. (2000). The RETC code for quantifying the hydraulic functions of the unsaturated soils. USDA, ARS: US Salinity Laboratory.

Williams. R. D., Ahuja, L. R. and Naney, J. W. (1992). Comparisons of methods to estimate soil water characteristics from soil particle size distribution, bulk density and limited data. Soil Science, 153, 172-184.

Wösten, J. H. M., Finke, P. A. and Jansen, M. J. W. (1995). Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma, 66, 227-237. https://doi.org/10.1016/0016-7061(94)00079-P