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Extended Analysis Of Unsaturated Hydraulic Functions Using The RETC Code

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Abstract

Ten descriptive models; two describe the water content as a function of matric potential [$\theta(\Psi)$], four describe unsaturated hydraulic conductivity as a function of water content [$k(\theta)$], and four describe unsaturated hydraulic conductivity as a function of matric potential [$k(\Psi)$]; were used by the RETC optimizing program to analyze seven-observed different data sets for predicting or estimating unsaturated hydraulic characteristics. The seven data sets are: 1) all laboratory measured $\theta-\Psi$ data, 2) all laboratory measured $\theta-\Psi$ data with one $k-\theta$ matching data point, 3) all laboratory measured $\theta-\Psi$ data with one $k-\Psi$ matching data point, 4) all laboratory measured $\theta-\Psi$ data with all $k-\theta$ data, 5) all laboratory measured $\theta-\Psi$ data with all $k-\Psi$ data, 6) one $\theta-\Psi$ matching data point with all $k-\theta$ data point and, 7) one $\theta-\Psi$ matching data point with all $k-\Psi$ data; where θ, Ψ, *and* k indicate volumetric water content, applied suction or pressure head, and k is field determined instantaneous-unsaturated hydraulic conductivity. Highly significant correlation values, $R^2 > 0.99$, were obtained from fitting of van Genuchten and Brooks and Corey models to laboratory measured $\theta(\Psi)$ relationship. Predicted $k(\theta)$, and $k(\Psi)$ functions from soil water retention compared very well with observed data with linear correlation exceeded 0.800 and regression coefficient approached unity on 1:1 line. When one $k(\theta)$, or $k(\Psi)$ matching point was used in the analysis besides $\theta(\Psi)$ data, the $k(\theta)$, and $k(\Psi)$ functions were more precisely predicted. The linear correlation between matched and observed $k(\theta)$, and $k(\Psi)$ functions exceeded 0.959 with a regression coefficient of 1.0158 on 1:1 line. Estimated $k(\theta)$, and $k(\Psi)$ functions obtained from analyzing both the retention and conductivity data matched the observed values with correlation coefficient of 0.937 and a regression coefficient of 0.9888. Predicted $\theta(\Psi)$ relationships obtained form analyzing observed $k(\theta)$ besides one $\theta(\Psi)$ matching point underestimated observed data especially near saturation suggesting the susceptibility of the prediction to high water content values. Predicted $\theta(\Psi)$ values obtained from analyzing the $k(\Psi)$ besides one $\theta(\Psi)$ matching point compared precisely with observed $\theta(\Psi)$ values. When all predicted $\theta(\Psi)$ data were plotted against measured $\theta(\Psi)$ data on 1:1 line, it produced correlation coefficient value of 0.846 and a regressing coefficient value of 0.9308.

الخلاصة

استخدمت عشرة نماذج وصفية؛ نموذجان يصفان المحتوى المائي θ كدالة الى الجهد المائي Ψ ، اربعة نماذج تصف الأيصالية المائية، k، كدالة الى الى المحتوى المائي θ , و اربعة نماذج تصف الأيصالية المائية، k، كدالة الى الجهد المائي Ψ ؛ من قبل البرنامج التوافقي RETC لتحليل سبعة تشكيلات لبيانات مقاسة للتنبأ او لتقدير الخصائص الايصالية غير المشبعة. تشمل التشكيلات ألسبعة ما يلي: 1)بيانات المحتوى المائي والجهد المائي التي تم تحديدها في المختبر, 2)بيانات المحتوى المائي والجهد المائي اضافة الى نقطة $k-\theta$ واحدة كنقطة مطابقة، 3) بيانات المحتوى المائي والجهد المائي اضافة الى نقطة $k-\Psi$ واحدة كنقطة مطابقة, 4)بيانات المحتوى المائي والجهد المائي اضافة الى بيانات $k-\theta$ ، 5))بيانات المحتوى المائي والجهد المائي اضافة الى بيانات $k-\Psi$, 6)نقطه بيانات $\theta-\Psi$ كنقطة مطابقة اضافة الى بيانات $k-\theta$, 7) نقطه بيانات $\theta-\Psi$ كنقطة مطابقة اضافة الى بيانات $k-\Psi$. تم الحصول على قيم ارتباط عالية (>0.99)من مطابقة انموذجي van Genuchten و Brooks and Corey الى بيانات منحنى الوصف الرطوبي. حصل حسن المطابقة للايصالية ألمائية غير المشبعة بين القيم المقاسة والمتنبأ عنها من بيانات منحنى الوصف الرطوبي بمعامل ارتباط زاد عن 0.800 ومعامل انحدار يقترب من وحدة واحده على خط 1:1. عندما استخدمت نقطة بيانات واحدة $k-\theta$ أو $k-\Psi$ كنقطة مطابقة اضافة الى بيانات منحنى الوصف الرطوبي فأن $k(\theta)$ و $k(\Psi)$ المتنبأ عنها كانت اكثر دقة بمعامل ارتباط 0.956 ومعامل انحدار 1.0158 على خط 1:1. اما قيم $k(\theta)$ و $k(\Psi)$ المقدرة الناتجة من تحليل بيانات المحتوى المائي والجهد المائي اضافة الى بيانات $k(\theta)$ أو $k(\Psi)$ فقد

اعطت معامل ارتباط 0.937 ومعامل انحدار 0.9888. كانت قيم $\theta(\Psi)$ المتبأ عنها من بيانات $k(\theta)$ اضافة الى نقطة مطابقة من $\theta(\Psi)$ اقل من البيانات المقاسة خاصة قرب الاشباع, مما يعكس حساسية القيم المتنبأ عنها الى القيم العالية من المحتوى المائي .في حين قورنت القيم المتنبأ عنها جيداً مع القيم المقاسة عند استخدام $k(\Psi)$ اضافة الى نقطة $\theta(\Psi)$ مطابقة واحدة. أعطت العلاقة أالناتجة عن رسم جميع بيانات $\theta(\Psi)$ المتنبأ عنها مع بيانات $\theta(\Psi)$ المقاسة على خط 1:1 معامل ارتباط 0.846 ومعامل انحدار 0.9308.

Introduction

Movement and accumulation of pollutants in the vadose zone environment are soil water content dependent and can be estimated or predicted with different parametric models(Abbasi *et al.,* 2003). The reliability of a model to predicting depends on the extent or the ability of the model to characterize the hydraulic properties under variably saturated soil conditions (Ramos & Goncalves, 2006). When Field scale measurements of soil water content and pressure head as a function of time on covered field plot are available, the obtained precise determination of unsaturated conductivity can serve as assessment criterion for evaluating the reliability of predicting or estimating of a model(Jacques *et al.,* 2002). The data input criterion is another significant approach for utilizing all possible combination of available data to be used in the analysis. Sisson and van Genuchten (Sisson *et al.,* 1991) used the program UNGRA to analyze five data sets for parameter estimation including $\theta - \Psi$, $k - \theta$, $k' - \theta$, $k - \theta - \psi$, and $k' - \theta - \Psi$ where θ is the volume-based water content, Ψ is the pressure head, k is unsaturated hydraulic conductivity, and k' is the slope, $dk/d\theta$, of a fitted $k(\theta)$ function.

The RETC (Van Genuchten *et al.,* 1991) is a simple one dimensional solute transport - window or DOS based program for analyzing and (or) predicting the $\theta(\Psi)$, $k(\theta)$, $k(\Psi)$, $D(\theta)$ and $dk/d\theta$ data where D is soil water diffusivity. In this study the program also was used to fit analytical functions simultaneously to observed water retention and hydraulic conductivity data.

This program utilizes the Brooks and Corey model(Brooks & Corey, 1964) and van Genuchten model (VanGenuchten, 1980) for describing soil-water retention relationship and theoretical pore size distribution model of Burdine (Burdine, 1953) and Mualem (Mualem, 1976). Accurate estimation of unsaturated hydraulic properties is essential for applied purposes including water and solute transport in unsaturated soil(Russo, 1988). The required hydraulic properties are the water retention curve, hydraulic conductivity as a function of water content or soil water pressure head. Popular field methods for the unsaturated hydraulic conductivity include the instantaneous profile(Vachaud & Dane, 2002), and the internal drainage and zero-flux plane methods(Arya, 2002). Laboratory methods for the unsaturated hydraulic conductivity include the long-column method (Bruce & Klute, 1956) and the crust method (Bouma *et al.,* 1983), as well as transient procedures that simplify the Richards equation, such as the horizontal infiltration method(Bruce & Klute, 1956; Corey, 2002), the hot-air method(Arya, 2002), and the evaporation method (Wendroth *et al.,* 1993; Scanlon, 2005). Evaporation methods also allow simultaneous measurement of both the water retention function and the hydraulic conductivity.

RETC allows the description of the hydraulic properties of the soil with analytical expressions which simplifies the characterization, allows rapid comparison of hydraulic properties of different soils, and allow interpolating and extrapolating of hydraulic properties(Brooks & Corey, 1964; Van Genuchten, 1980; Russo, 1988).

The flexibility of the RETC code to analyzing different data sets improves program ability to predict or estimate unsaturated hydraulic characteristics from different data sets. Thus the input data sets may include laboratory measured $\theta(\Psi)$ relationship for predicting the $k(\theta)$, $k(\Psi)$ and D(θ), all $\theta(\Psi)$ plus one $k(\theta)$ or $k(\Psi)$ data point, to scale (predict) $k(\theta)$, and $k(\Psi)$, all $\theta(\Psi)$ and $k(\theta)$ (or) $k(\Psi)$ data to estimate $\theta(\Psi)$, and $k(\theta)$, and $k(\Psi)$, and all $k(\theta)$ or $k(\Psi)$ data and one $\theta(\Psi)$ data point to scale (predict) the $\theta(\Psi)$ relationship.

The objectives of this study is to extend the predictability of the RETC by analyzing different combinations of available field and laboratory measured and calculated unsaturated hydraulic data sets and to evaluate two retention models and eight different pore-size conductivity models associated with the program. A general but basic objective is to compare predicted and estimated unsaturated hydraulic data values with the laboratory or field determined data.

Models for Retention and Hydraulic Functions

Two functional relationships between soil water content and soil water retention were assumed for hydraulic parameter analysis. The first function is the van Genuchten model (18) which will be referred to as the VG model:

$$\theta(\Psi) = \theta_r + \frac{\theta_s - \theta_r}{(1+(\alpha\Psi)^n)^m} \qquad (\theta_r \le \theta \le \theta_s) \qquad 1$$

where $\theta(\Psi)$ is the volumetric water content as a function of pressure head (Ψ), α is an empirical parameter(L^{-1}) whose inverse is referred to as the air entry value or bubbling pressure, n, and m are empirical parameters, and the subscript s, and r represent parametric-saturated and residual water contents . The second function is the Brooks and Corey model (5) which will be referred to as BC model:

$$\theta(\Psi) = \theta_r + \frac{\theta_s - \theta_r}{(\alpha\Psi)^\lambda} \qquad (\theta_r \le \theta \le \theta_s) \qquad 2$$

where λ is a pore size distribution parameter which affects the slope of the fitted water retention curve**.**

Unsaturated hydraulic conductivity may be obtained from easily measured water retention curve by combining equation 1 with the pore-size distribution model of Mualem (10) , the VGM model. The RETC code utilizes VG model to predict unsaturated hydraulic conductivity as a function of both volumetric water content, $k(\theta)$, and pressure head, $k(\Psi)$, as follows:

$$k(\theta) = k_s(\frac{\theta-\theta_r}{\theta_s-\theta_r})^l\{1-[1-(\frac{\theta-\theta_r}{\theta_s-\theta_r})^{1/m}]^m\}^2 \qquad (m = 1-1/n) \qquad 3$$

$$k(\Psi) = \frac{k_s\{1-(\alpha\Psi)^{mn}[1+(\alpha\Psi)^n)^{-m}\}^2}{[1+(\alpha\Psi)^n]^{m/2}} \qquad (m = 1-1/n) \qquad 4$$

where k_s is the saturated hydraulic conductivity, l is pore-connectivity parameter, $\frac{\theta-\theta_r}{\theta_s-\theta_r}$ is the effective saturation and will be referred to as S for simplicity, i.e.;

$$S = \frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad (0 \le S \le 1) \qquad 5$$

When Brooks and Corey model is combined with Mualem model (BCM) then equations 3 and 4 will be given by:

$$k(\theta) = K_s (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{l+2+2/\lambda} \quad 6$$

$$k(\Psi) = \frac{k_s}{(\alpha\Psi)^{\lambda(l+2)+2}} \quad 7$$

As well, when van Genuchten model is combined with Burdine pore–size distribution model (VGB) then equations 3 and 4 will be given by:

$$k(\theta) = k_s (\frac{\theta - \theta_r}{\theta_s - \theta_r})^l \{1 - [1 - (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{1/m}]^m\} \quad (m = 1 - 2/n) \quad 8$$

$$k(\Psi) = \frac{k_s \{1 - (\alpha\Psi)^{n-2}[1 + (\alpha\Psi)^n)^{-m}\}}{[1 + (\alpha\Psi)^n]^{2m}} \quad (m = 1 - 2/n) \quad 9$$

Also when the Brooks and Corey model is combined with Burdine pore-size distribution model (BCB) then equations 3 and 4 will be given by:

$$k(\theta) = k_s (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{l+1+2/\lambda} \quad 10$$

$$k(\Psi) = \frac{k_s}{(\alpha\Psi)^{\lambda(l+1)+2}} \quad 11$$

Inspecting of above mentioned hydraulic functions reveals that they contains seven unknown parameters (l, θ_r, θ_s, α, n, λ, k_s) when assuming that the value of the parameter m is restricted to $m = 1 - 1/n$ for the VGM, based models and $m = 1 - 2/n$ for the VGB based models. RETC code may be used to fit one, several, or all parameters simultaneously to observed data.

Derivation of the final formula of equations 3, 4, 6, 7, 8, 9, 10, and 11 from equations 1, and 2 in conjunction with the pore size conductivity models of Mualem (Mualem 1976) and Burdine (Burdine, 1953) are given in details in van Genuchten and Nielsen (Van Genuchten & Nielsen, 1985).

Materials and Methods

The data sets were obtained from an in situ infiltration-drainage study in which a minimum depth of infiltration water was allowed to pond on the surface of an 8m $\times$ 8m field plot for enough time to establish equilibrium between soil water content and soil water potential. The soil was silt clay loam, located at the experimental field of the College of agriculture , 20 km west of Baghdad, and classified as a typic torrifluvent. The plot was covered to prevent evaporation from the soil surface. Drainage was initiated directly after the cessation of infiltration. Soil water content as a function of time was measured gravimetrically at 14 depths (10 cm increments) during 90 days of drainage while soil water pressure head was inferred from laboratory determined soil water-retention relationship for the whole pressure head range between 0 and 1500 KPa. Unsaturated hydraulic conductivity was calculated from the time rate of change in soil water content and inferred soil water pressure head during drainage according to the instantaneous profile theory (Arya *et al.*, 1975; Vachaud & Dane, 2002).

Field and laboratory measured data sets

Seven different combinations of data sets were used in the hydraulic parameter optimization process for fitting, estimating or predicting soil water-retention relationship and , unsaturated hydraulic conductivity as a function of water content and pressure head. The following data sets were used for analysis:

1. data set 1 is the laboratory measured $\theta(\Psi)$ data only for fitting the $\theta(\Psi)$ functions and predicting $k(\theta)$ and $k(\Psi)$ relationships.
2. data set 2 is the laboratory measured $\theta(\Psi)$ data together with one measured $k(\theta)$ data point to predict $k(\theta)$ relationship.
3. data set 3 is the laboratory measured $\theta(\Psi)$ data together with one measured $k(\Psi)$ data point to predict $k(\Psi)$ relationships.
4. data set 4 is the laboratory measured $\theta(\Psi)$ data together with all $k(\theta)$ data to estimate $\theta(\Psi)$, $k(\theta)$ and $k(\Psi)$ relationships.
5. data set 5 is the laboratory measured $\theta(\Psi)$ data together with all $k(\Psi)$ data to estimate $\theta(\Psi)$, $k(\theta)$ and $k(\Psi)$ relationships.
6. data set 6 is one laboratory measured $\theta(\Psi)$ data points together with all $k(\theta)$ data to predict $\theta(\Psi)$ and estimate the $k(\theta)$ and $k(\Psi)$ relationships.
7. data set 7 is one laboratory measured $\theta(\Psi)$ data points together with all $k(\Psi)$ data to predict $\theta(\Psi)$ and estimate $k(\theta)$ and $k(\Psi)$ relationships.

The RETC does nonlinear least-squares fitting for equations 1, 2, 3, 4, 6, 7, 8, 9, 10, and 11 into different data sets for parameter estimation. In this study curve fitting refers to analyzing measured data alone for parameter estimation such as fitting equations 1 or 2 to laboratory measured $\theta(\Psi)$ relationship, in the same time the fitted parameters can be used to predict other functions as the case when parameters of equation 1 are used to create the predictive curves for equations 3 or 4.

An estimating curve results from simultaneous fitting of both the retention and conductivity models to observed water retention and hydraulic conductivity data, consequently the same fitted parameters will be used to give an estimating curves for both the retention and hydraulic conductivity functions. For example, estimating curves were obtained from simultaneous fitting of equations 1 and 3 and 8 to data set 4 or from fitting equations 1 and 4 and 9 to data set 5.

Results

Fitting of Retention and Hydraulic Models

Values of the hydraulic parameters(θ_r, θ_s α, n) obtained from fitting equations 1 and 2 to the laboratory measured soil water-retention relationship are given in the fitted equations shown on figure 1. Fitting of equations 1 and 2 resulted in high *R*-squared values; 0.999, 0.995; but sum of squares of deviations between measured and fitted values was lower for equation 1 than equation 2. The fitted curve of equations 2 matches observed data very well for the whole domain of observed data except at the wet end when the laboratory-observed θ at pressure head values of 0, and 10 cm of water (stand for measured water content values of 0.5324 and 0.5300 $cm^3.cm^{-3}$ respectively) were higher than the fitted value of the parameter θ_s ($0.5212 cm^3.cm^{-3}$) which indeed violates the boundary conditions of equations 2. The dotted line in figure 1 (BC model) suggest, at least, that a pressure head at 30 cm represent the air-entry value and a break in the fitted line has to be introduced at non-zero suction head which means that a straight line, represented by the arrow on the figure, with a zero slope may be extended from $\Psi = 30cm$ to complete saturation where $\Psi = 0$ and ($\theta = \theta_s$). Figure 1 also shows that the fitted curve of equation 1 matches the observed data very well for the whole domain of fitted θ where $0.1880 < measured\ \theta < 0.5336$ which satisfies the boundary conditions of equation 1. If we designate $\Psi(\theta_s) = \psi_s$ and that θ_s is less than θ_m, where θ_m represents total porosity, then ψ_s is the non-zero capillary height. According to equation of capillarity 10 mm capillary rise is approximately occurred in a pore radius of 1.5 mm which suggest applying a physical importance to ψ_s or consider ψ_s as a fitting parameter. Rawls et al. (12) mentioned that the value of ψ_s is somewhere between 10 and 1000 cm of water in the Brooks and Corey model.

Since no observed hydraulic conductivity data were used in this fitting(data set1), values of the fitted parameters , shown on figure 1, will be used to predict unsaturated hydraulic conductivity either as a function of water content (equations 3 , 6 , 8 , and 10), or as a function of pressure head (equations 4, 7, 9, and 11) and hence this method will be referred to as the predictive method. Values of the parameter *l* was assumed to be 0.5 for Mualem-based conductivity models and 2 for Burdine-based conductivity models and value of k_s for the layer 0-10 cm was taken as the instantaneous hydraulic conductivity value at early drainage time, 1cm.day$^{-1,}$ as suggested by van Genuchten and Nielsen(19).

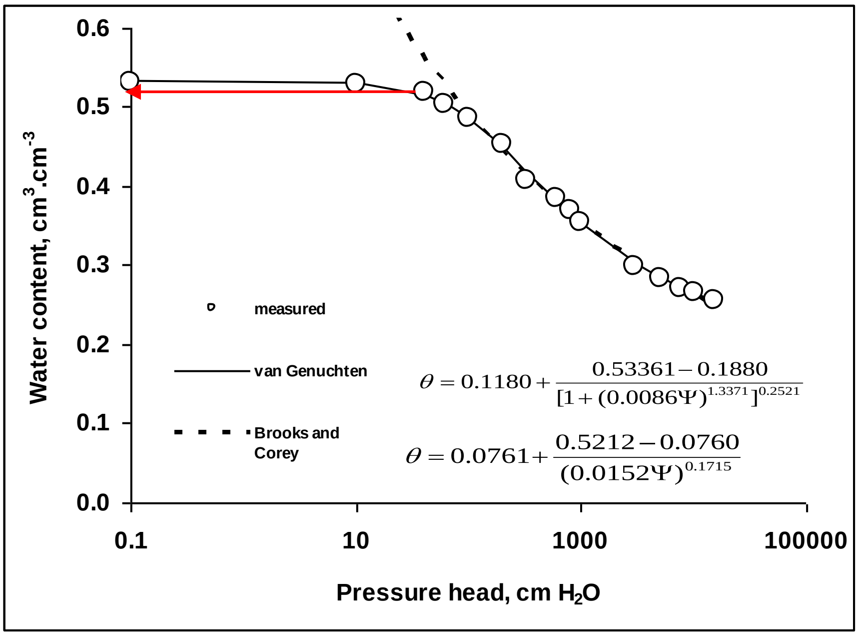


Figure 1. Measured (open circles) and fitted, solid and dotted lines, soil water retention relationships for silt clay loam textured- soil.

Figure 2 shows that the VGM predictive curve, equation 3, described the hydraulic conductivity data precisely over the whole range of the observed values while the VGB predicted values, equation 8, were lower than the observed values. When the RETC program was used to analyze the retention data, the VGM and VGB models produced different hydraulic parameters during the optimization process. The two predictive curves of BCM and BCB were identical and over estimated measured conductivity values since the same hydraulic parameter values were used to predicting conductivity using equations 6 and 10. The two curves overlapped over the whole range between saturated and residual water content indicating that the trend of the two equations were quite similar. Overall fitting of the four functions was quite acceptable with a linear correlation values exceeded 0.800 between observed and predicted conductivity values.

Same values of the parameters shown on figure 1 were used to predict hydraulic conductivity as a function of pressure potential using equations 4, 7, 9, and 11. It is clear from figure 3 that the four $k(\Psi)$ functions performed equally well in predicting the hydraulic conductivity at low pressure head values. The linear correlation between measured and predicted hydraulic conductivity values exceeded 0.960 suggesting the reliability of the four functions to delineating field unsaturated conductivity over the whole range of water retention data. At higher pressure head values the BCM and the BCB predictive curves performed better than the VGM and VGB predictive curves. Over all description of the hydraulic conductivity functions is quite acceptable.

The RETC code was used to estimate the hydraulic conductivity curves from data set 4 and data set 5 where all retention and conductivity data were included in the fitting process for parameters estimation. The four estimating curves of the $k(\theta)$

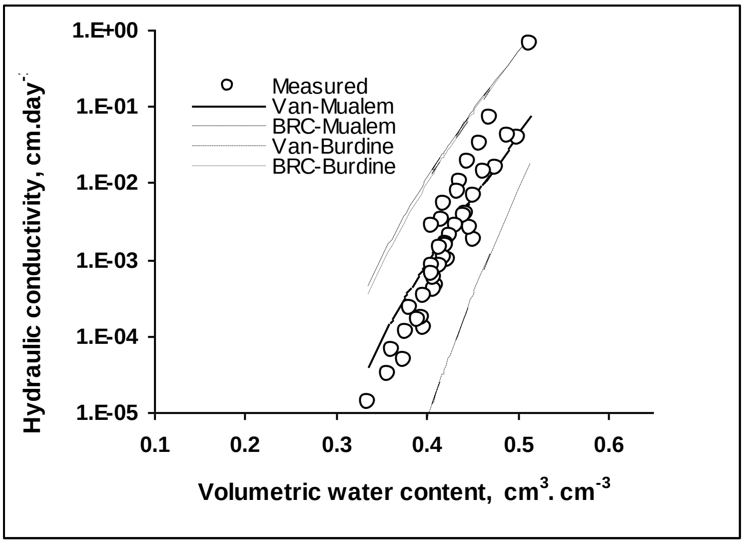


Figure 2. Soil water content and unsaturated hydraulic conductivity curves for silt clay loam textured-soil. Open circles indicate measured values and lines indicate different predictive curves based on indicated functions.

functions; equations 3, 6, 8, and 10; are shown on figure 4. This figure shows that the hydraulic conductivity of the Silt clay Loam was well described by the four functions even higher estimation was obtained from equations 3 and 8 as

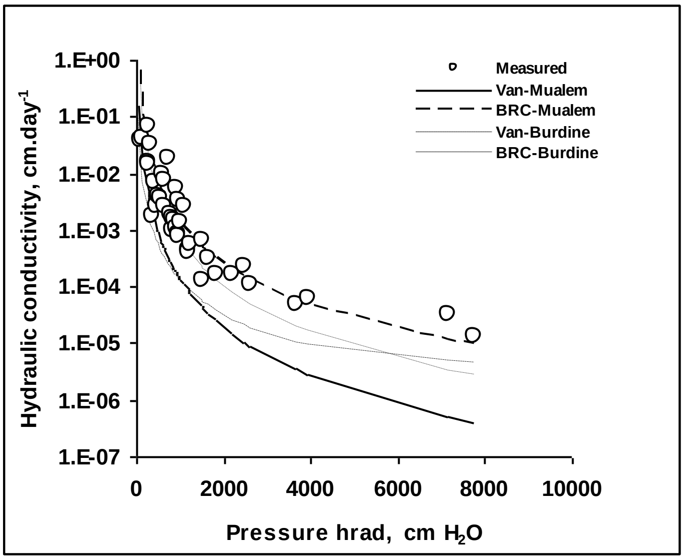


Figure 3. Pressure head and unsaturated hydraulic conductivity curves for silt clay loam textured soil. Open circles indicate measured values and lines indicate different predictive curves based on indicated functions.

evident from sum of squares of deviations between observed and estimated values (Table 1). The four estimating curves on figure 4 show that estimated values are accurate enough to replace observed values and the simultaneous fitting of the retention and conductivity data improved parameter estimation.

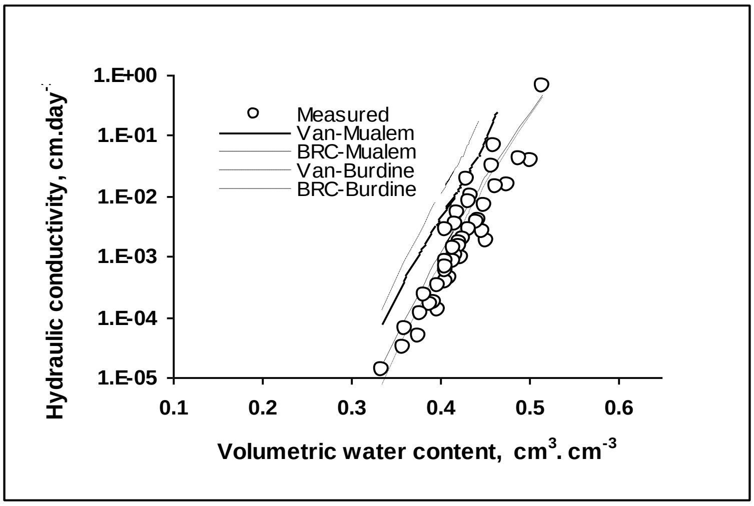


Figure 4. Soil water content and unsaturated hydraulic conductivity curves for silt clay loam textured-soil. Open circles indicate measured values and lines indicate different estimating curves based on indicated functions.

Estimated conductivity curves as a function of pressure head described observed values nicely especially at the low pressure head values, however; at high pressure head values the VGM and the VGB curves, equations 4 and 9, under estimated the observed $k(\Psi)$ (figure 5). Compared with VGM and VGB estimating curves the BCM and the BCB curves produced lower sum squares values between measured and estimated values over the whole range of measured data. Almost the same trend as in figure 3 was obtained in figure 5 for all estimating curves. An improved estimation could be obtained if the RETC program was allowed to optimize all seven parameters(θ_r, θ_s , α, m, n, l, *and* k_s) in equations 1 and 4 which increase curve fitting flexibility of the program as indicated by Abbasi et al. (1).

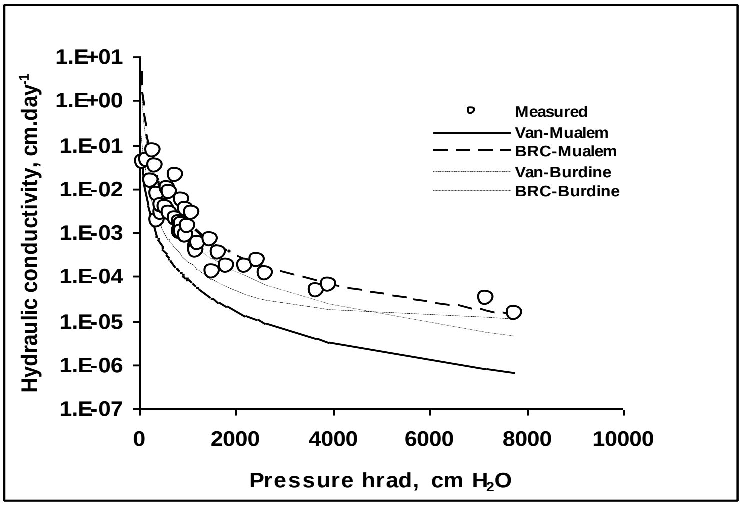


Figure 5. Pressre head and unsaturated hydraulic conductivity curves for for silt clay loam textured-soil. Open circles indicate measured values and lines indicate different estimating curves based on indicated functions.

Soil water-retention curve will be estimated from optimized parameters obtained from fitting of equations 3, 4, 6, 7, 8, 9, 10 and 11 to data set 4 and 5. Likewise prediction of the soil water-retention relationship will be obtained from parameter fitting of equations 3, 4, 6, 7, 8, 9, 10 and 11 to data set (6) and (7).

Values of the hydraulic parameters for estimating or predicting soil water retention relationship from different data sets are given in table 1. Estimation of the retention soil water content occurs when all observed $\theta(\Psi)$ and $k(\theta)$ or $k(\Psi)$ data were used in parameter estimation. The RETC in this case simultaneously fits the two function to observed data. Figure 6 shows that the VGM and the VGB models (equations 3 and 8) underestimated observed water content values at the wet end of soil water retention relationship otherwise a precise estimate was obtained from different equations over the whole range of observed values of the water retention relationship. When observed $k(\theta)$ or $k(\Psi)$ data were used besides observed $\theta(\Psi)$ data in parameter estimation, the fitted parameters imitated the inherent variability in the instantaneous hydraulic conductivity resulting in more precise estimate of the $k(\theta)$ and $k(\Psi)$. This case is reflected in figures 4 and 5 where precise estimate of $k(\theta)$ and $k(\Psi)$ values were obtained from the same parameters of figure 6.

Table 1. Hydraulic parameters, Root Mean Square Errors(RMSE) and correlation coefficients(R^2) obtained from analyzing indicated data sets using the RETC program. Values of the parameters were used to calculate either the estimated or predicted curves according to the governing equations; 3, 4, 6, 7, 8, 9, 10 and 11.

model	van Genuchten-Mualem		Brooks and Corey-Mualem		van Genuchten-Burdine		Brooks and Corey-Burdine	
Governing equation	3	4	6	7	8	9	10	11
1. All $\theta(\Psi)$ and $k(\theta)$ or $k(\Psi)$ data								
θ_r	0.2089	0.0000	0.0000	0.0000	0.1815	0.0000	0.0000	0.0000
θ_s	0.4652	0.5204	0.5312	0.5077	0.4465	0.5157	0.5312	0.5172
α	0.0053	0.0091	0.0550	0.0176	0.0065	0.0108	0.0039	0.0184
n	1.2959	1.1497	0.0927	0.1137	2.2190	2.1455	0.0887	0.1230
k_s	0.1027	15.6496	0.4925	0.9635	0.0328	3.6259	0.4898	0.8282
$RMSE$	0.0102	0.0239	0.0238	0.0291	0.0439	0.0225	0.0246	0.0255
R^2	0.953	0.963	0.873	0.946	0.909	0.967	0.972	0.957
2. All $\theta(\Psi)$ and one $k(\theta)$ or $k(\Psi)$ matching data point								
θ_r	0.1384	0.2036	0.0316	0.1001	0.0000	0.1968	0.0933	0.1045
θ_s	0.5383	0.5324	0.5269	0.5269	0.5341	0.5256	0.5212	0.5269
α	0.0149	0.0078	0.0236	0.0183	0.0026	0.0102	0.0143	0.0182
n	1.2187	1.3804	0.1319	0.1804	2.1221	2.3356	0.1862	0.1835
k_s	1.9697	4.5363	0.1005	1.1865	1.5290	1.7508	0.0122	0.7349
$RMSE$	0.0056	0.0012	0.0052	0.0026	0.0058	0.0076	0.0025	0.0031
R^2	0.91	0.999	0.925	0.991	0.902	0.989	0.985	0.981
3. One $\theta(\Psi)$ matching data point and all $k(\theta)$ or $k(\Psi)$ data								
θ_r	0.1956	0.0000	0.0000	0.0000	0.0420	0.0000	0.0000	0.0000
θ_s	0.4447	0.4529	0.5312	0.4072	0.4256	0.4546	0.5194	0.4411
α	0.0042	0.0094	0.0550	0.0186	0.0047	0.0094	0.0924	0.0187
n	1.2980	1.1044	0.0927	0.0537	0.1312	2.1119	0.0860	0.0777
k_s	0.0314	25.2376	0.4925	0.6709	0.0149	3.0382	0.3278	0.6709
$RMSE$	0.0326	0.0204	0.0145	0.0257	0.0443	0.0198	0.0191	0.0223
R^2	0.917	0.967	0.977	0.961	0.854	0.968	0.974	0.962

At pressure head values below field capacity, estimated or predicted values obtained from fitting the different equation are sensitive to θ_s since small change in pressure head may cause big change in water content especially in well aggregated and course textured soils (Vogel *et al.*, 2001). Low converged values of the parameter θ_s , 0.4652 and 0.4465, obtained from fitting equations 3 and 8 to **all** $\theta(\Psi)$ and $k(\theta)$ data resulted in lowest $\theta(\Psi)$ relationship at the wet end and highest RMSE values. Highly significant correlation values were obtained between observed and estimated $\theta(\Psi)$ relationships on 1:1 line. It is worth mentioning that the slope of the regression line between observed and estimated values approached unity (0.9888) and the regression line (solid line) almost overlapped with the 1: l line (dotted line) as evident from figure 6 . When all $\theta(\Psi)$ data and only one $k(\theta)$ or

$k(\Psi)$ data point (data sets 2 and 3) were analyzed for parameter estimation, the resulting $\theta(\Psi)$ relationships are shown on figure 7. In this study, the weight of the matching observation was assigned to unity in the objective function as the weight of any observation in the input data which indeed produced a fitting parameters. Compared with data sets 4 and 5 , lower RMSE, and higher r^2 values of the fitted $\theta(\Psi)$ relationships were obtained (see Table 1). As suggested by Sisson and van Genuchten(Sisson & Van Genuchten, 1991), it is appropriate to match the calculated $\theta(\Psi)$, $k(\theta)$, and, $k(\Psi)$ curve at one observed $\theta(\Psi)$, $k(\theta)$, and $k(\Psi)$ data point to force the estimated curves to pass through the matching point for better fitting.

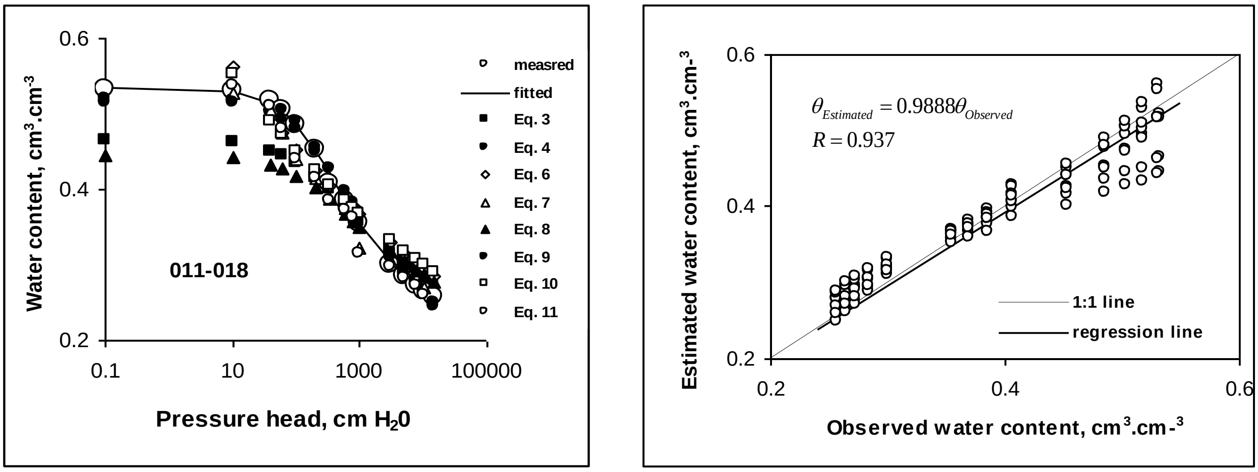


Figure 6. Fitted, solid line, and estimated (symbols) soil water retention functions based on data set 4 and 5 for silt clay loam textured-soil (left) and 1:1 line between observed and estimated soil water retention relationships (right).

Figure 7 also shows that 1:1 line relationship between observed and estimated values of the $\theta(\Psi)$ functions resulted in a highly significant correlation and regression coefficient approached unity(1.0158).

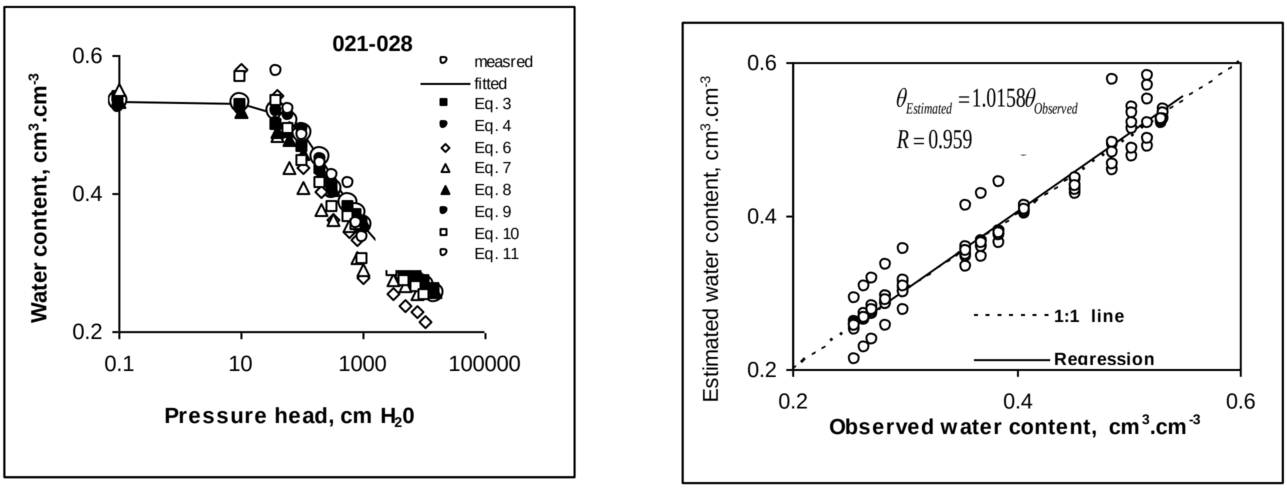
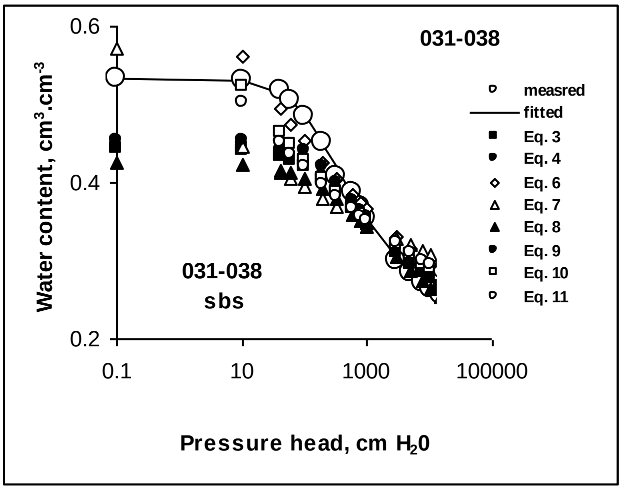


Figure 7. Fitted, solid line, and estimated (symbols) soil water retention functions based on data set 2 and 3 for silt clay loam textured-soil (left) and 1:1 line between observed and estimated soil water retention relationships (right).

When different equations were fitted to one observed $\theta(\Psi)$ data point and all $k(\theta)$ or $k(\Psi)$ the resulting parameters are given in Table 1. Values of the fitted parameters were used to predict the $\theta(\Psi)$ relationships since only one observed $\theta(\Psi)$ data point as a matching point was used in parameter estimation. This method may be referred to as the scaled-predictive method for the $\theta(\Psi)$ relationships. The predicted $\theta(\Psi)$ relationships are given in figure 8 (symbols). Lower water content values near saturation were obtained when equations 3, 4, 8, and 9 were used for parameters estimation, thus suggesting the sensitivity of the $\theta(\Psi)$ relationships near saturation. Better predicted $\theta(\Psi)$ relationships were obtained under the same equations when the relation between the variables n and m was not restricted. The restriction of the two parameters decrease the flexibility of the curve to fit observed values near saturation. Another alternative to improve the prediction of the $\theta(\Psi)$ at the wet end is to consider that θ_s has a physical meaning rather than fitted parameter and depend the observed value of θ_s at saturation as suggested by Schaap and van Genuchten ,(Schaap & Van Genuchten, 2006).

The regression line on figure 8 (solid line) occurs below 1:1 line indicating that the predicting equations underestimated the observed $\theta(\Psi)$ as evident from regression equation on the figure 8 where the regression coefficient value was 0.9308.



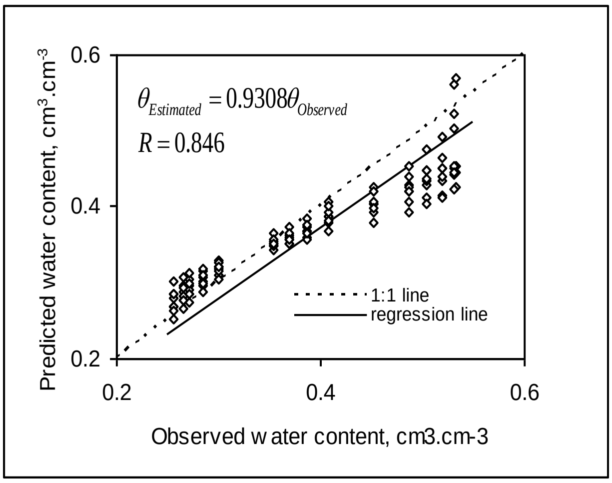


Figure 8. Fitted, solid line, and predicted (symbols) soil water retention functions based on data set 6 and 7 for silt clay loam textured-soil (left) and 1:1 line between observed and predicted soil water retention relationships (right).

Conclusions

The result of this study indicated that the RETC program can be used to analyze different combinations of available unsaturated hydraulic data rather than a program for fitting laboratory measured water retention data to equation(1). Data analysis may be obtained from any of the 10 different equations and the resulting parameters can be used either for prediction and (or) estimation besides fitting for unsaturated characteristics. Extended analysis also permits one to interpolate or extrapolate experimental data when only a limited number of observed data are available such as the $\theta(\Psi)$ relation at low presser head values in the laboratory or field measured water content values.

The difference in fitted parameters from the seven different data sets used in this study may be reduced if more precise estimate for θ_s were obtained on undisturbed cores or by averaging many water content values sampled directly after initiating of drainage especially under the conditions of heavy textured soils. As well, an estimate of θ_r can be improved by averaging many water content values sampled at the end of the drainage cycle. More precise analysis at the wet end may be obtained if water content measurement were made for short time intervals immediately after initiating drainage.

Very precise measurements of the water content and unsaturated hydraulic conductivity function close to saturation are needed since small change in water content near saturation is accompanied with sharp change in unsaturated conductivity value. Small time step besides very sensitive equipments are required to measuring time rate of change in both water content and pressure potential during infiltration or flux studies for precise determination of unsaturated hydraulic conductivity at the wet end.

This study showed that the predicting equations of the hydraulic properties of unsaturated slit clay loam soil were very sensitive to changes in the soil water retention relationship near saturation.

References

Abbasi, F., Simunek, J.; Feyen, J.; van Genuchten, M.Th.; Shouse. P.J. 2003. Simultaneous inverse estimation of soil hydraulic and solute transport parameters from transient field experiments: Homogenous soil. Am. Soc. Agric. Eng. 46(4): 1085–1095.

Arya, L.M. 2002. Wind and Hot-Air Methods. p. 916–926. In J.H. Dane and G.C. Topp (ed.) Methods of Soil Analysis. Part 4. Physical Methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Arya, L.M., Farrel, D.A. and Blake. G.R. 1975. A field study of soil water depletion patterns in presence of growing soybean roots. I. Determination of hydraulic properties of the soil. Soil Sci. Soc. Am. J. 45:1023–103.

Bouma, J., Belmans, C. ; Dekker, L.W. and Jeurissen. W.J.M.1983. Assessing the suitability of soils with macropores for subsurface liquid waste disposal. J. Environ. Qual. 12:305–311.

Brooks, R.H., and A.T. Corey. 1964. Hydraulic properties of porous media. Hydrol. Pap. 3. Colorado State Univ., Fort Collins.

Bruce, K. K., and Klute. A. 1956. The measurement of soil-water diffusivity. Soil Sci. Soc. Am. Proc. 20:458-562.

Burdine, N. T. 1953. Relative permeability calculations from pore-size distribution data. Petrol. Trans., Am. Inst. Min. Eng. 198:71-77.

Corey, A.T. 2002. Long column. p. 899–903. In J.H. Dane and G.C. Topp (ed.) Methods of Soil Analysis. Part 4. Physical Methods. Book Ser. 5. SSSA, Madison, WI.

Jacques, D., Simunek, J.; Timmerman, A. and Feyen. J. 2002. Calibration of Richards' and Convection–Dispersion Equations to field–scale water flow and solute transport under rainfall conditions. J. Hydrology 259: 15–31.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12(3): 513–522.

Ramos, T.B., Gonçalves, M.C.; Martins, J. C.; van Genuchten, M. Th. and Pires. F.P. 2006. Estimation of soil hydraulic properties from numerical inversion of tension disk infiltrometer. Vadose Zone J. 5:684–696.

Rawls, W.J., Ahuja, L.R. and Brakensiek. D.J. 1992. Estimating Soil Hydraulic Properties from Soil Data. In: Mt. van Genuchten, F. J. Liej, and L. I. Lund Edition. Proc. Int. Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. Riverside, University of California; p-329-340.

Russo, D. 1988. Determining soil hydraulic properties by parameter estimation : On the selection of a model for hydraulic properties. Water Resour. Res. 24(3):453-459.

Scanlon, M.R. 2005. Evaluation of evapotranspirative covers for waste containment in arid and semiarid regions in the southwestern USA. Vadose Zone J 4:55-71.

Schaap, M.G., and van Genuchten. M.Th. 2006. A Modified Mulaem-van Genuchten. Formulation for improved description of the hydraulic conductivity near saturation. Vadose Zone J. 5:27-37.

Sisson, J.B., and M.Th van Genuchten. 1991. An improved analysis of gravity drainage experiments for estimating the unsaturated hydraulic properties. Water Resour. Res. 22(4):569-575.

Vachaud, G., and Dane. J.H. 2002. Instantaneous profile. p. 937–945. In J.H. Dane and G.C. Topp (ed.) Methods of Soil Analysis. Part 4. Physical Methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Van Genuchten, M.Th. 1980. A closed-form analytical equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44(5):892-898.

Van Genuchten, M.Th., and Nielsen. D.R. 1985. On describing and predicting the hydraulic properties of unsaturated soils. Ann. Geophys. 3(5):615-628.

van Genuchten, M.Th., Leij, F.J. and Yates. S.R.1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils. Report No. EPA/600/2–91/065. Ada, Okla.: U.S. Environmental Protection Agency, R. S. Kerr Environmental Research Laboratory.

Vogel T., van Genuchten, M. Th.; and M. Th.; Cislerova. M. 2001. Effect of the shape of the soil hydraulic functions near saturation on variably-saturated flow predictions. *Adv. Water Resour*. 24(2), 133-144.

Wendroth, D., Ehler., W. ;Hopmans, J. W.; Kage, H.; Halbertsma, J.; Wosten. J.H. M.1993. Reevaluation of evaporation method for determining hydraulic functions of unsaturated Soils. Soil Sci. Soc. M. J. 57:1436-1443.