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Evaluating models for predicting hydraulic characteristics of layered soils

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Abstract

Soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity (K-coefficient) are critical hydraulic properties governing soil water activity on layered soils. Sustainable soil water conservation would not be possible without accurate knowledge of these hydraulic properties. Infield rainwater harvesting (IRWH) is one conservation technique adopted to improve the soil water regime of a number of clay soils found in the semi arid areas of Free State province of South Africa. Given that SWCC is much easier to measure, most soil water studies rely on SWCC information to predict in-situ K-coefficients. This work validated this practice on the Tukulu, Sepane and Swartland layered soil profiles. The measured SWCC was first described using Brooks and Corey (1964), van Genuchten (1980) and Kasugi (1996) parametric models. The conductivity functions of these models were then required to fit in-situ based K-coefficients derived from instantaneous profile method (IPM). The same K-coefficient was also fitted by HYDRUS 1-D using optimised SWCC parameters. Although all parametric models fitted the measured SWCC fairly well their corresponding conductivity functions could not do the same when fitting the in-situ based K-coefficients. Overestimates of more than 2 orders of magnitude especially at low soil water content (SWC) were observed. This phenomenon was pronounced among the upper horizons that overlaid a clayey horizon. However, optimized α and n parameters using HYDRUS 1-D showed remarkable agreement between fitted and in-situ K-coefficient with root sum of squares error (RMSE) recording values not exceeding unity. During this exercise the Brooks and Corey was replaced by modified van Genuchten model (Vogel and Cislerova, 1988) since it failed to produce unique inverse solutions. The models performance appeared to be soil specific with van Genuchten-Mualem (1980) performing fairly well on the Orthic and neucutanic horizons while its modified form fitted very well the prismatic and pedo-cutanic horizons. The lognormal distribution model of Kasugi (1996) showed an extraordinary good fit among the Swartland profile horizons especially the saprolite rock layer. It was therefore concluded that in-situ K-coefficient estimates from SWCC

parameters could be acceptable if only rough estimates were required. Optimization of parameters for in-situ conditions especially for HYDRUS 1-D carried much prospects in characterising the hydraulic properties of most of the layered soils earmarked for IRWH in the province.

1 Introduction

Characterising soil hydraulic properties of layered profiles has become more attractive because of the increased availability in computer based models. These models rely on parameterization of the soil water characteristic curve (SWCC) and unsaturated soil hydraulic conductivity (K-coefficient) that serve as inputs in soil water flow and solute transport simulations. The flexibility of this models to describe hydraulic functions for any given flow domain through parameter optimization implies that most of the inefficiencies from traditional methods could be avoided.

Successes of parameter based models have been based on integrating indirect and inverse techniques. Hopmans et al. (2002) defined inverse modelling as a general mathematical method to determine unknown causes on the basis of observation of their effects. Since SWCC is the much easier function of soil water content (SWC) to measure, early models used the Burdine theory (Millington-Quirk, 1961) based on SWCC to predict the K-coefficient. The convenience of predicting the K-coefficient either as a function of SWC (Θ) or suction (h) from SWCC was carried over to subsequent parameters based models with greater accuracies (Brooks and Corey, 1964; Mualem, 1976). Under controlled laboratory conditions it later proved that SWCC and K-coefficient could be simultaneously determined from transient outflow experiments (Gardener, 1956) by inverse modelling (Valiantzas and Kerkides, 1990). Recent models including among others the van Genuchten-Mualem (1980), modified van Genuchten and the Kosugi (1996) have been reported to be more efficient under different conditions (Kosugi et al., 2002). To improve parameters estimation of various soils the pedo-transfer functions were developed that use soil physical properties such as

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 301–336, 2012

Predicting hydraulic characteristics of layered soils

S. S. W. Mavimbela and L. D. van Rensburg

pore-size distribution and bulk density as well as the shape of the SWCC to predict the K-coefficient (Schaap et al., 2001; Hopmans et al., 2002). Although the application of the pedo-transfer functions could be limited to specific soil or horizons (Zavattaro and Grignani, 2001) their rough estimates could facilitate the simulation of water flow and solute transport in the absence of reliable data (Simunek et al., 2008).

Challenges of inverse modelling including parameter uniqueness, selecting of transient flow variables and spatial variations of the porous media have been fairly addressed (Zachman et al., 1982; Kool and Parker, 1988; Russo et al., 1991; Kosugi and Hopmans, 1998; William and Ahuja, 2003; Simunek et al., 2008; Hunt and Ewing, 2009). Dane and Hruska (1983) was also among the first to demonstrate that with the correct objective function and parametric model it was possible to improve inverse solutions from in-situ conditions from the instantaneous profile method (IPM) transient experiment. Essential ingredient of transferring the $\Theta - h$ relationship from the SWCC to in-situ conditions was that the selected model should fit the measured data fairly well for the SWC range in question (van Genuchten, 1980; Kosugi et al., 2002). This was confirmed by Russo (1988) and Chen et al. (1999) who tested various models, respectively for one-step outflow optimization and multistep outflow experimental data and found that only a few fitted the measured data very well. Among the highly rated was the van Genuchten (1980) model and its ability to improve stability of inverse solution was supported by other studies (Russo, 1991; Mallants et al., 1996; Chen et al., 1999; Simunek et al., 2008). However, excellent results from other models have been reported (Pachepsky et al., 1996; Tomasella and Hodnett, 1997; Kosugi et al., 2002; Kawamoto et al., 2006; Lamara and Derriche, 2008).

Critical to in-situ conditions is taking into account the spatiality of the flow boundary conditions and horizons differentiation especially in layered profiles. To address the sensitivity of the optimised parameters to lower boundary conditions and size of input data, Kool et al. (1987) and Kool and Parker (1988) showed that coupling of the optimization procedure with simultaneous measurements of pressure heads and SWC improves model's predictions. Increased number of measurements was also found to

HESSD
9, 301–336, 2012

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

be able to account for spatial variations and to improve effect of scaling soil heterogeneity (Abbasi et al., 2003; Sharma et al., 2011). Models predictions have been shown to be more sensitive to the number of optimised parameters than the optimization procedure (Zijlstra and Dane, 1996; Abbasi et al., 2003; Brunone et al., 2003; Simunek et al., 2008).

To address the erratic soil water regime among the cultivated layered soils in the Free State province of South Africa, the in-field rainwater harvesting (IRWH) technique (Hensley et al., 2000) has been developed. This technique is geared to convert surface runoff losses into deep infiltration and soil water storage. However, the success of this initiative and the sustainability there off could not be possible without appropriate knowledge of the soil hydraulic properties. Layered soils earmarked for IRWH developed constitutes of about 10 % of the provincial landscape (Hensley et al., 2006). Common in this group of soils includes the Tukulu, Sepane and Swartland soil forms (Soil Classification Working Group, 1991). Integrating laboratory and field based analysis of soil hydraulic properties would be key to this exercise. It is therefore within the initiative of this study to attain the following objectives; firstly, to characterise the SWCC of the respective horizons of the three soil profiles and secondly, to validate the conductivity functions based on the SWCC parameters for the estimation of in-situ K-coefficient; Thirdly, to estimate in-situ K-coefficient from optimised SWCC based parameters.

2 Material and methods

2.1 Experimental site and location

Three soil types cultivated at the Parady's Experimental Farm (29°13′25″ S, 26°12′08″ E, altitude 1417 m) of University of the Free State were selected. These included Tukulu (Tu), Sepane (Se) and Swartland (Sw). (Soil Classification Working

HESSD
9, 301–336, 2012

Group, 1991). The SWCC and K-coefficient were determined under laboratory and in-situ conditions, respectively.

2.2 Theory

Several parametric models are used to describe the measured SWCC using shape (α) and (n) pore size distribution parameters. Among the common parametric models include the Brooks and Corey (1964), van Genuchten (1980) and Kasugi (1996). These models constitute of expression that aid in transferring the measured SWCC into a θ-h relationship applicable to any field conditions. Development of these models was informed by the general retention Eq. (1) widely accepted to represent the pore distribution of a many of soils.

$$S_e = \frac{\theta_S - \theta_R}{1 + (\alpha h)^n} \tag{1}$$

$$S_e = \frac{\theta - \theta_R}{\theta_S - \theta_R} \tag{2}$$

where S_e is effective saturation, θ_S and θ_R are the respective saturated and residual values of the volumetric water content, θ (mm mm^{-1}), h is the matric suction (mm), while α and n are the shape and pore size distribution parameters, respectively.

Brooks and Corey (1964) reduced the expression Eq. (1) into the following general equation

$$S_e = |\alpha h|^{-n} \tag{3}$$

where α is this case is the inverse of air entry value and the rest as defined previously. This expression allows a zero slope to be imposed on SWCC as h equals air entry value. S_e equals to unity when $h \geq -1/\alpha$. This principle gives to the SWCC a zero slope at relatively higher suctions since measuring SWCC above 85 % of saturation

HESSD
9, 301–336, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

was considered impractical general disconnection of the gas phase (Brooks and Corey, 1999). Conductivity function corresponding to this expression is written as

$$K = K_S\, S_e^{\frac{2}{n}+1+2} \tag{4}$$

where, l is the pore-connectivity parameter assumed to be 2. Similarly this expression allows K-coefficient to approach K_S at or near air entry suctions.

Van Genuchten (1980) retention model assumes the following expression

$$\theta(h) = \theta_R + \frac{\theta_S - \theta_R}{\{1 + |\alpha h|^n\}^m}, \tag{5}$$

where the condition $m = 1 - 1/n$ should be satisfied. According to the mathematical structure of this model $\theta(h)$ equals θ_S when at zero or positive suctions. The square root relationship of $\theta(h)$ to the n and m parameters gives the SWCC a typical symmetrical shape with zero slope approached both towards θ_S and θ_R. The conductivity function referred to as the van Genuchten-Mualem (1980) is given as

$$(h) = K_S\, S_e^{l} \left\{1 - \left\{1 - S_e^{\frac{1}{m}}\right\}^m\right\}^2, \tag{6}$$

where the parameters are as defined before with n maintained above unity value. This model has undergone several revisions with the recent modification by Schaap and van Genuchten (2005). However, one revision implemented in many computer models is the modification by Vogel and Cislerova (1988). The modified version assumes the same structure the expression except that θ_S and θ_R are replaced by fictitious parameters given as θ_m and θ_a, respectively with θ_m slightly greater than θ_S and θ_a slightly smaller than θ_R. This was done to force the SWCC to be constant between θ_S and some small negative suction value. Its corresponding conductivity's expressions are more complex and well detailed by Schaap and van Genuchten (2005). The introduction of some small capillary height just next to saturation allows the K-coefficient to be more stable than the original version that exhibited a steep slope at suctions very

HESSD
9, 301–336, 2012

close to saturation with air entry value kept around −2 cm. This modification has made it to be highly recommended for clay textured soils (Schaap and van Genuchten, 2005; Simunek et al., 2008).

Another parametric model of different form is that of Kasugi (1996) that assumes a lognormal distribution for the retention and conductivity functions. The retention expressions for $S_e(h)$

$$S_e = \frac{\theta - \theta_R}{\theta_S - \theta_R} = \frac{1}{2} \operatorname{erfc}\left\{\frac{\ln (h/\alpha)}{\sqrt{2}\, n}\right\} \tag{7}$$

$$K = K_S\, S_e^l \left[\frac{1}{2} \operatorname{erfc}\left\{\frac{\ln (h/\alpha)}{\sqrt{2}\, n} + \frac{n}{\sqrt{2}}\right\}\right]^2, \tag{8}$$

where symbol α instead of h_0 and n instead of σ as used in original Kasugi (1996) are adopted for uniformity reasons by some computer optimization programmes such as RECT and HYDRUS 1-D.

2.3 Experimental set up and measurements

2.3.1 Soil profile classification

Pedological classification of the three soils was carried out on excavated soil profile pits to a depth of 1 m. Three soil pits were opened on each representative site. Diagnostic horizons were described according to the physical, chemical and biological features used by the SCWG (1991).

2.3.2 Soil particle distribution and bulk density

Undisturbed soil core samples from representative profile horizons were taken for the determination of bulk density and soil textural analysis. Sampling cores had an inner diameter of 103 mm and a height of 77 mm. Each core was mounted on a hydraulic jack that was manually operated to extract samples at the respective horizons depths. Particle size distribution was established using the pipette procedures proposed by the Non Affiliated Soil Analysis Work Committee (1990). For the determination of gravimetric soil water content soil samples were oven dried at 105 °C for a period of 24 h.

2.3.3 Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_S) for the individual profile layers of the three soil types was measured using double ring infiltrometers as described by Scotter et al. (1982). Soil profile pits were excavated in a stepwise manner to allow the fitting of both rings with diameters of 400 and 600 mm to a depth of 20 mm. The falling head of 10 mm depth was used to determine K_S with every fall recorded by means of timer and a calibrated floater. After a steady state was recorded for three consecutive times and the K_S constant value (mm h^{-1}) was then computed using Jury et al., (1991) formula given as

$$K_S = \frac{L}{t_1} \ln \frac{b_0 + L}{b_1 + L}, \quad (9)$$

where L is the depth of the soil layer in question (mm), b_0 is the initial depth of total head above the soil column, b_1 is the depth the falling head is not allowed to fall below (mm), t_1 is the time taken for b_0 to fall to b_1 (in hours).

2.3.4 Internal drainage experiment

The instantaneous profile method (IPM) (Hillel et al., 1972; Marion et al., 1994) was used to determine soil water flux and unsaturated hydraulic conductivity from the draining profiles. Monoliths of 4 m × 4 m surface area with 1 m depth from the Tukulu and Sepane were prepared in triplicates. From the Swartland monoliths were of 1.2 m × 1.2 m with a depth of 0.5 m. To minimise spatial variations monoliths were

HESSD
9, 301–336, 2012

semi-detached but difficulty in excavating the Swartland soil resulted in solitary monoliths at spacing of 30 m interval. Neutron access tubes to a depth of 1.1 m were installed on the central area of each monolith section from the Tukulu and Sepane while DFM probes were installed to a depth 0.6 m. Side walls were isolated with polythene plastics with ridges around sides and a slurry prepared to seal the sides from the surface. Monoliths were pre-ponded for three executive days and then covered to keep weather elements from interfering with the trial. Measurements were taken at centre block of each profile horizon daily for a period of 50 days. Changes in water storage between time intervals were computed into drainage flux (q_{Dr}) which was then described using the Darcy's Law given as

$$q_{Dr} = -K(\theta)\left\{\frac{dh}{dZ} + 1\right\} \quad (10)$$

where $K(\theta)$ is unsaturated hydraulic conductivity (mm h^{-1}), dh is the change in matric suction (mm) between the neighbouring horizons, Z (mm) being the thickness of the horizon layer in question.

2.3.5 Measurements of the soil water characteristics curve

Determination of the SWCC for the three soil profile horizons was carried out by a laboratory desorption experiment. Undisturbed soil samples in triplicates were first de-aired with a vacuum chamber pump set at −70 kPa for 48 h under room temperature. Then de-aired water was introduced to saturate samples by capillarity for a 24 h period. Samples were then desorbed through a series of pressure head including a 0–10 kPa, 10–100 kPa and 100–1500 kPa. The first phase of desorption involved hanging-column method described by Dirksen (1999). At every step, interval samples were weighted before and after equilibration. At suctions of 100 to 1500 kPa samples were disturbed and packed in 20 000 mm^3 PVC tubes at the measured bulk densities. Measured soil water content (θ) at every suction (h) level was plotted to produce the θ-h relationship that depicted the SWCC.

HESSD
9, 301–336, 2012

S. S. W. Mavimbela and L. D. van Rensburg

Mathematical description of soil water characteristic curve

Parametric models use hydraulic parameters to describe the SWCC. A parameter optimization computer program RECT (van Genuchten et al., 1991) is included some of these models including the Brooks and Corey (1964), van Genutchen (1980) and Kasugi (1996). A summary of physical characteristics from the three soil profiles used as inputs into these models are summarized in Table 1. Parameters related to pore-size distribution (n) and shape (α) of the SWCC was initially fitted using the Rosetta pedo-transfer (Schaap et al., 2001) and then optimised for the respective models.

Estimating unsaturated hydraulic properties for field based K-coefficient

Hydraulic parameters pertaining to the shape (α) and pore size distribution (n) of the SWCC were inversely optimised for the description of in-situ K-coefficient. The software HYDRUS 1-D (Simunek et al., 2008) was used for this optimization and also for the fitting of the in–situ K-coefficient at plot scale derived by the instantaneous profile method (IPM). This model numerically solves the Richard flow equation in one dimension using a Galerkin-type linear finite element scheme. A wide variety of parameter optimization problems could be handled through the minimization accomplished by the Levenberg-Marquardt nonlinear weighted least squares approach (Hopmans and Simunek, 1999; Lazarovitch et al., 2009; Wollschläger, et al., 2009; Kandelous and Simunek, 2010).

In this work the objective function contained pressure head from horizons centre block and K-coefficient determined by IPM as a function of soil water content (SWC). Preliminary tests on the parametric models showed that the Brooks and Corey (1964) required simultaneous optimisation of several parameters, an exercise that compromised the uniqueness of the inverse solution (Simunek et al., 2008). Therefore, only the van Genuchten-Mualem (1980), Modified van Genuchten and Kasugi (1996) models was selected for the optimization of the conductivity function. To enhance the convergence the l exponent parameter from the Mualem's (1976) equation was optimised

HESSD

9, 301–336, 2012

Predicting hydraulic characteristics of layered soils

S. S. W. Mavimbela and L. D. van Rensburg

as well. Initial conditions were set at saturated soil water content for the respective soil profile horizons. Observation points were fixed at centre block corresponding to field measurements. The constraint of respecting the model assumptions and the code requirements was followed in all data analysis.

2.4 Statistical analysis

Measured and optimised drainage and unsaturated hydraulic conductivity as well as the pertinent hydraulic parameters constituted the major findings. The coefficient of determination (R^2), root mean square error (RMSE) and the index of agreement or D-index as proposed by Willmot et al. (1985), were the statistical tools used to quantify the quality of fit and variability between measured and fitted data. A 1:1 line was used show the degree of scatter of the optimised model fit from the field based K-coefficient.

3 Results

3.1 Soil water characteristics curve

Figure 1 shows the measured and fitted soil water characteristics curves (SWCC) from the Tukulu, Sepane and Swartland profile horizon layer. The fitted hydraulic parameters from Brooks and Corey (1964), van Genuchten (1980), and Kasugi (1996) models are summarized in Table 2 with their corresponding statistical measure of fit.

Tukulu: measured and fitted SWCC were fairly similar in all horizons. The measured SWCC assumed the general segmoidale shape especially from the A and B horizons, while the C horizon resembled a nearly level but gentle slope. The A, B and C horizons had a θ-h relationship with saturated (θ_S) soil water content (SWC) to residual water content (θ_R) ranging from 0.34 to 0.13 mm mm^{-1}, 0.33 to 0.12 and 0.324 to 0.26 mm mm^{-1}, respectively. Corresponding saturated hydraulic conductivity (K_S) for this layers were 36.1, 40 and 1.9 mm h^{-1}. The Genuchten (1980) and Kasugi (1996)

HESSD
9, 301–336, 2012

approached saturated SWC (θ_S) at suctions of about 0.1 kPa with an air entry of around 3 kPa from the A and B horizons and 1.5 kPa from the C-horizon. On the other hand Brooks and Corey's model approached θ_S at about 5 kPa from the A and B horizons and 2 kPa from the C horizon. Fitting α parameter from Brooks and Corey for the A, B and C horizons was 0.0019, 0.0018 and 0.0073 with corresponding n values of 0.62. 0.47 and 0.27, respectively. From the van Genuchten model the A and B horizons shared the same α value of 0.001 while the C horizon had a value of 0.005. The n constant from this model was 1.77, 1.62 and 1.23 for the respective A, B and C horizons. The Kasugi's model had a lognormal α parameters of 2084, 3379 and 5146 for the respective A, B and C horizons with corresponding n values of 1.41, 1.59 and 3.31. The R^2 from the 1:1 linear relationship between the measured and predicted values ranged from 0.99 to 0.93 with lowest coefficient associated with the C horizon from Brooks and Corey model. Similarly, the D-index ranged from 0.999 to 0.981 with the lowest value depicting the least best fit from the C horizon. The RMSE from the A horizon ranged from 0.0115 to 0.005 with both van Genuchten and Kasugi models having the lowest values depicting a better fit. From the B and C horizon the RMSE ranged from 0.083 to 0.005 and 0.004 to 0.003, respectively with van Genuchten attaining a better fit in the former while Kasugi in the latter.

Sepane: a good fit between the measured and fitted SWCC was observed in all three horizons. The A, B and C horizons had a θ-h relationship with SWC of 0.34 to 0.1, 0.335 to 0.19 and 0.338 to 0.225 mm mm^{-1} with saturated conductivity (K_S) of 35, 10 and 1 mm h^{-1} from the respective A, B and C horizons. At near saturation the van Genuchten and Kasugi models approached θ_S at suctions between 0.1 to 0.01 kPa with an air entry value of around 1 kPa from the three horizons. Brooks and Corey model approached θ_S at around 1.1, 2.1 and 2.7 kPa from the A, B and C horizons, respectively. Fitting α parameters from the Brooks and Corey were 0.004 from the A horizons and 0.003 from the B and C horizons with corresponding n values of 0.31, 0.47 and 0.54 from the A, B and C horizons, respectively. The van Genuchten model the value for α parameter were 0.003 from the A horizons and B and 0.002 from C

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
9, 301–336, 2012

S. S. W. Mavimbela and L. D. van Rensburg

horizons with corresponding *n* values of 1.37, 1.59 and 1.69 for the A, B and C horizons. Residual squares were in the range of 0.999 to 0.985 and Brooks and Corey with the lowest coefficients. Similarly the D-index recorded lower agreement from the Brooks and Corey especially from the A horizon. The RMSE ranged from 0.0082 to 0.0054 and 0.053 to 0.0018 from the A and B horizons respectively with the van Genuchten model recording the lowest value in both cases indicating a better fit. From the C horizon the RMSE ranged from 0.0045 to 0.0013 with Kasugi attaining the better fit.

Swartland: Greater variability between measured and fitted SWCC were observed in this soil. The A horizon recorded a SWC ranging from 0.35 to 0.1 $mm\,mm^{-1}$ and B horizon with a range from 0.399 to 0.105 $mm\,mm^{-1}$. The C-horizon had a SWC ranging from 0.412 to 0.06 $mm\,mm^{-1}$. Saturated hydraulic conductivity (K_S) was 23.5 mm hour from the A horizon with 42.8 and 76.5 $mm\,h^{-1}$ from the respective B and C horizons. Brooks and Corey's model had α parameter that increased with depth ranging from 0.0025 to 0.0052. In a similar manner this parameter ranged from 0.0014 to 0.0041 from the van Genuchten model. From the Kasugi model α decreased with depth at a range of 3010 to 547.73. Corresponding n values in the A, B and C horizons ranged from 0.389 to 0.688 from the Brooks and Corey, 1.498 to 1.764 from the van Genuchten and 1.833 to 1.57, respectively. Models approached saturation at 0.1 to 0.01 kPa with the exception of Brooks and Corey that recorded 2.6, 2.1 and 1.9 kPa in the A, B and C horizons. The R^2 was in the range of 0.99 to 0.92 with Brooks and Corey recording the least from the A horizon. Similarly the D-index recorded lowest agreement from the Brooks and Corey especially from the A horizon. The RMSE ranged from 0.0104 to 0.0053 and 0.0095 to 0.004 from the respective A and B horizons with better fit obtained from Brooks and Corey in the former and Kasugi in the latter. From the C horizon the RMSE ranged from 0.062 to 0.0094 with a better fit attributed to Kasugi model.

HESSD
9, 301–336, 2012

S. S. W. Mavimbela and L. D. van Rensburg

3.2 Predicting *K*-coefficient from soil water characteristics curve

Figures 2 to 4 illustrates the variation between in-situ *K*-coefficient derived from instantaneous profile method (IPM) and estimated by conductivity based parametric models. Fitting parameters from measured SWCC including K_S were used to predict *K*-coefficient as a function of SWC. Statistical measure of fit from estimated *K*-coefficients are summarised in Table 3 for the Tukulu, Sepane and Swartland soil horizons.

Tukulu: deviation between in-situ and estimated *K*-coefficient could be observed especially at lower SWC. The in-situ *K*-coefficient in the A horizon ranged from 36.1 to 0.006 mm h^{-1}, for SWC range from 0.34 to 0.297 mm mm^{-1}. For the same SWC range the estimated *K*-coefficient ranged from 36.08 to 9.71, 36.1 to 3.36 and 36.1 to 2.18 mm h^{-1} from the Brooks and Corey (1964), van Genuchten-Mualem (1980), and Kasugi (1989) models. In the same order these models for the B horizon estimated *K*-coefficient within the range of 40 to 3.93, 40 to 14.13 and 40 to 2.73 mm h^{-1}, while the in-situ ranged from 40 to 0.0006 mm h^{-1}. In the C horizon the in-situ *K*-coefficient ranged from 1.9 to 0.0012 mm h^{-1} while estimates from Brooks and Corey (1964), van Genuchten-Mualem (1980), and Kasugi (1989) ranged from 1.9 to 0.0689, 1.9 to 0.003, and 1.9 to 0.00002 mm h^{-1}, respectively. The R^2 from the A and B ranged from 0.95 to 0.64 and 0.89 to 0.53 with the lowest values associated with Brooks and Corey. In the C horizon R^2 ranged from 0.99 to 0.78 with the lowest value.

Sepane: considerable variability between in-situ and estimated *K*-coefficient was observed especially at lower SWC. The IPM captured SWC ranging from 0.34 to 0.292, 0.335 to 0.313 and 0.338 to 0.323 mm mm^{-1} from the respective A, B and C horizons. Corresponding *K*-coefficient ranged from 35.19 to 0.0013, 10.2 to 0.0014 and 1 to 0.0006 mm h^{-1}. For the same SWC range the estimated *K*-coefficient from the A horizon were 35.19 to 3.95, 35.19 to 0.621, and 35.19 to 0.0953 mm h^{-1} from Brooks and Corey, van Genuchten-Mualem, and Kasugi models. Corresponding predictions from these models for the B and C horizons were 10.2 to 3.47 and 1 to 0.433, 10.2 to 0.81 and 1 to 0.101, and 10.2 to 0.413 and 1 to 0.112 mm h^{-1}, respectively. In-situ based

HESSD
9, 301–336, 2012

K-coefficients from the B horizon ranged from 10.2 to 0.0014 mm h^{-1}, while from the C horizon ranged from 0.0006 mm h^{-1}. The R^2 from the A, B and C horizons ranged from 0.96 to 0.85, 0.97 to 0.59 and 0.87 to 0.52, respectively, with Brooks and Corey scoring the lowest value in all three horizons. van Genuchten-Mualem model had a better fit from the A and C horizons shown by RMSE of 2.35 and 0.148 and D-index values of 0.97 and 0.88, respectively. The Kasugi model recorded a better fit in the B horizon with RMSE of 0.656 and D-index of 0.98.

Swartland: remarkable spatiality between in-situ and estimated K-coefficient was also observed. During the drainage period SWC ranged from 0.35 to 0.27, 0.35 to 0.28 and 0.42 to 0.23 mm mm^{-1} from the A, B and C horizons, respectively. Corresponding to these horizons was the in-situ K-coefficient ranging from 23.48 to 0.0002, 42.8 to 0.0028 and 76.5 to 0.002 mm h^{-1}. Estimated K-coefficient by Brooks and Corey, van Genuchten-Mualem, and Kasugi models from the A horizons were 23.48 to 1.4, 23.48, to 0.22 and 23.48 to 0.132, respective. From the B and C horizons these models in their respective order estimated K-coefficient within the range of 42 to 1.18 and 76.5 to 0.37, 42.8 to 4.63 and 76 to 1.42, and 42.8 to 0.52 and 76.5 to 0.13 mm h^{-1}. Estimates from Brooks and Corey had the lowest R^2 of 0.79, 0.59 and 0.93 from the respective A, B and C horizons. The Kasugi had a better fit in the A reflected by RMSE of 0.312 and D-index of 0.999. In the B-horizon van Genuchten-Mualem and Kasugi model shared similar RMSE and D-index values of 3.7 and 0.97, respectively. Kasugi also had a better fit in the C horizon with RMSE of 0.853 and D-index of 0.999.

3.3 Parameter optimisation for HYDRUS 1-D application

Table 4 shows the optimised α and n parameters for the fitting of the in-situ based K-coefficient using HYDRUS 1-D program. Statistical measure of goodness of fit from these optimised parameters corresponding to the fixed θ_S, θ_R and K_S values were also shown. Figure 5 illustrates how the fitted K-coefficient compared with the field based

HESSD
9, 301–336, 2012

K-coefficient on a 1:1 line from the Tukulu (a) Sepane (b) and (c) Swartland soils for the A (i) B (ii) and C (iii) horizons.

Tukulu: a general greater degree of accuracy could be observed from the fitting of the field based *K*-coefficient by optimised parameters using the inverse solution. The van Genuchten-Mualem and modified van Genuchten models shared the same optimised σ of 0.0015 and n of 2.511 to attain a better fit with a RMSE of 0.324 and D-index of 0.9996 in the A horizon. The Kasugi models had used the same optimised α value of 1000 and n value of 1 for all three horizons. A better fit was realised in the B horizon with a RMSE of 0.234 and a D-index of 0.9995. The modified van Genuchten model showed a better fit with α value of 0.0055 and n value of 1.656 for the C horizon. The RMSE from this soil ranged from 1.2 to 0.023 and D-index from 0.999 to 0.91. The crowding of the fitted data along the 1:1 line confirms this statistics not only at higher SWC but also for lower SWC with B and C horizons showing a good agreement for the entire curve.

Sepane: the most accurate fit were recorded from this soil. The R^2 and D-index from fitting models exceeded 0.99 from all the soil horizons. Fitted data clustered closely to the 1:1 line especially from the A and C horizons. The van Genuchten-Mualem model with α of 0.003 and n of 3.514 attained a better fit from the A-horizon with a RMSE of 0.2, followed by the modified form with RMSE of 0.202. The latter also showed a better fit in the B and C horizon alongside Kasugi model with a RMSE as low as 0.04 to 0.002, respectively.

Swartland: improved accuracy and better fit were limited to the upper horizons of this soil profile. The modified van Genuchten model attained better fit from the A horizons with RMSE of 0.02 while the Kasugi model attained better fit from the B and C horizons with RMSE of 0.12 and 2.8. All model had the poorest fit coming from the C horizon given that R^2 ranged from 0.90 to 0.80.

HESSD
9, 301–336, 2012

S. S. W. Mavimbela and L. D. van Rensburg

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3.4 Discussion

The goodness of fit from characterising SWCC to the estimating of in-situ K-coefficient was found to vary among models and soil types. Optimised parameters also exhibited the same trend even though consistency with in-situ K-coefficient showed remarkably improvement. Could these findings therefore, indicate that these hydraulic models were well developed to produce better fit than others or for specific soil types?

Fitting of SWCC was satisfactory from all the parametric models used. Of interest was the manner at which the traditional "*S*" shape of the SWCC was modified among the three soils from the models. Among the sandy textured orthic and neocutanic horizons this shape was well defined while from strongly textured prismacutanic and pedocunatic horizons it was diffused to a gentle almost a straight line. These findings were similar with those made by Wilson et al. (1997), Wildenchild et al. (2001), Chimungu (2009), and Fraenkel (2008) on sandy and clayey horizons. Narrow pore size distribution from the former could have triggered rapid drainage rates at near saturation due to the small air entry values associated with these soils (Kosugi et al., 2002). Consequently, the remaining SWC could have been subjected to very steep hydraulic gradients as suctions are increased giving the SWCC a symmetrical shape observed by van Genuchten (1980), Simunek et al. (2008) and Lamara and Derriche (2008). Given the diverse pore pathways in clayey horizons a strong matrix activity could have been triggered as suctions were increased resulting to an appreciable but slow release curve consistent with structured soils (Wildnchild et al., 2001; Zavattaro and Grignani, 2001). Nevertheless, the parametric models were consistent with the shape of the measured SWCC with the exception of Brooks and Corey especially at near air entry value. This was not a strange phenomenon since this model imposes a zero slope on the SWCC at near air entry point given the assumption that measuring saturations above 85 % was impractical, because of the general disconnection of the gas phase at this range of SWC (van Genuchten, 1980; Brooks and Corey, 1999).

HESSD
9, 301–336, 2012

Application of the conductivity functions based on SWCC parameters to estimate in-situ K-coefficient derived by the IPM produced very high inconsistencies. Agreements were only limited at and near the saturation domain. In-situ K-coefficient was generally overestimated by more than 2 to 3 orders of magnitude. This was well pronounced among the upper horizons of the Tukulu and Sepane. Overestimates from Swartland were less than 2 orders of magnitude especially at low SWC. Zavattaro and Grignani (2001) also observed that overestimation of K-coefficient was common among horizons overlying clay rich soils given the effect of abrupt transition on flow rates. Wildenchild et al. (2001) substantiated this by demonstrating that K-coefficient was dependent on flow rates. Given the absence of layering from soil columns used to measure SWCC it reasonable to consider that estimates of K-coefficient would be generally greater than those derived from IPM under in-situ environment.

Differences in suction range under which SWCC and in-situ coefficient were determined could be another source of inconsistency. This view was also supported by Zavattaro and Grignani (2001). The SWCC was determined using suction range of 0.1 to 1500 kPa while from the IPM ranged from 0.01 to about 1 kPa. The latter depicts structural pore domain while the former constitutes all the entire pore size distribution (Nhlabatsi, 2011). Therefore, desorption of pores the IPM was only represented by a small section on the SWCC. Although the parametric models were able to transfer the θ-h relationship from SWCC to of the field, the accuracy of this function was said to depend on how good these models fitted the SWCC (van Genuchten, 1980). This situation could be illustrating why inconsistencies from Brooks and Corey model were pronounced irrespective of soil type. Van Genuchten (1980) observed that if θ_R was inaccurately measured among the input parameters, given that it fall outside the IPM flow domain, inconsistencies when in-situ K-coefficient is estimates may arise. Under these circumstances the shape and pore-size distribution parameters representing θ-h relationship affecting the IPM based K-coefficient would need to be different from SWCC. This view was also shared by shared Zavattaro and Grignani (2001) who suggested that among others the shape (α) and pore size distribution (n) parameters of

HESSD
9, 301–336, 2012

S. S. W. Mavimbela and L. D. van Rensburg

SWCC should be optimised for in-situ applications. It was therefore not surprising that the use of SWCC based conductivity functions generally produced poor estimates of in situ K-coefficients especially at low SWC irrespective of soil type. Despite these inconsistencies some estimates from Brooks and Corey in the Tukulu C-horizon and Kasugi among the Swartland profiles were within acceptable range.

The view of optimising SWCC parameters for in-situ application was then validated using HYDRUS 1-D hydrological model. Inverse solution converged readily when α and n parameters were optimised allowing the rest of the parameters fixed under the constant SWC lower boundary condition for the Tukulu and Sepane while Swartland was allocated free drainage. The resulting suction distribution with depth from optimised parameters was shown in Fig. 6. Suctions ranged from 0 to −700, 0 to −550 and −150 to −650 mm in the the Tukulu, Sepane and Swartland soil profiles consisted with suctions corresponding to structural pore domain (Zavattaro and Grignani, 2001; Wang et al., 2003; Chimungu, 2009; Nhlabatsi, 2011). Evidence of differences in physical properties at interface could be seen by the change in regime in suction with depth. This could also be used to illustrate the extent of layering among the three soil profiles and the effect on hydraulic properties. A build up in positive suction at depth corresponding to the prismatic C-horizons of the Tukulu and Sepane 24 h of drainage indicates the restrictiveness of this horizon an observation that was also made by Chimungu (2009) and Fraenkel (2008) on the respective profiles. Interestingly, optimised α values appeared to increase with depth on profile with restrictive horizons while from free draining Swartland profile the opposite was observed. Failure to attain saturation from the Swartland after deep wetting was also indicative of the high permeability of this profile especially the underlying saprolite rock with average K_S of 76.5 mm h^{-1}.

Improvements in goodness of fit from optimised parameters were noticeable from the three soils irrespective of model used. However, level of agreement was variable among soils and horizon layers. van Genuchten- Mualem model produced consistency among the weakly structured horizons of the Tukulu and Sepane soil profiles. The modified van Genuchten model produced better fit on the clay rich horizons while

HESSD
9, 301–336, 2012

Kasugi model matched fairly well with K-coefficient from the Swartland soil. The use of lognormal distribution to describe pore size distribution among the Swartland layers could have given the Kasugi model a better urge over the van Genuchten expressions. Given the exponential mathematical background of the van Genuchten-Mualem model it is reasonable to associate its better fit on the orthic A and neocutanic B horizons since this soils has a well defined pore size distribution consistent with weakly developed sandy textured soils. However, due its exponential inheritance when n value approaches its lower limit of 1 then K-coefficient drops sharply at near saturation that could result to poor fit on clay soils with an appreciable drainage (Schaap and van Genuchten, 2006). The introduction of an extrapolated parameter that impose a non zero suction from saturation to some very small suctions could be attributed to the better fit of the modified van Genuchten model among the clay rich horizons (Schaap and van Genuchten, 2006; Simunek et al., 2009).

4 Conclusions

The question on to what extent could in-situ based K-coefficient be estimated from SWCC based parameters was evaluated. Firstly the SWCC were parameterised using the Brooks and Corey (1964), van Genuchten (1980) and Kasugi (1996). The three models fitted fairly well the retention functions from the soil profile horizons. Brooks and Corey model showed some deviation near or at the entry point given its assumption to impose a zero slope at this suction from saturation. Secondly, the conductivity based expressions that rely on SWCC parameters from these three models were used to fit the in-situ K-coefficient derived from IPM. Goodness of fit from all models showed remarkable overestimated of the in-situ K-coefficient by more than two orders of magnitude, especially at lower SWC. This finding gives the impression that SWCC parameters were not necessary appropriate to describe in-situ based K-coefficient but could be used when rough estimates are required particularly from layered soil. Thirdly, the SWCC based parameters were inversely optimised to serve as input to the

HESSD
9, 301–336, 2012

HYDRUS 1-D hydrological for the fitting of in-situ K-coefficient from a plot scale simulation. Agreement between fitted and in-situ K-coefficient improved by more than one order of magnitude from those obtained from SWCC parameters. The van Genuchten-Mualem (1980) appeared to be well posed for sandy textured soils while the modified van Genuchten model by Vogel and Cislerova (1988) was well posed for clay rich horizons. On the other hand the lognormal distribution model of Kasugi (1996) was able adapted for the Swartland soil profile layers. Over and above, the optimization procedure as well as the application of HYDRUS 1-D carries a lot of prospects in improving the knowledge on the hydraulic properties that characterise layered soils earmarked for IRWH.

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HESSD
9, 301–336, 2012

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S. S. W. Mavimbela and L. D. van Rensburg

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HESSD
9, 301–336, 2012

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Table 1. Summary of the physical characteristics of the three soil types.

Soil physical properties									
Soil forms	Tukulu			Sepane			Swartland		
Master Horizons	A	B1	C	A	B1	C	A	B1	C
Coarse sand (%)	5.3	9.2	2.1	5.2	3.5	2.3	4.7	3.2	54.3
Medium sand (%)	9.3	8.8	3.8	10	4.1	2.3	7.6	5.3	4.6
Fine sand (%)	41.2	31	28.3	41.9	41	31	42	37.6	17.2
Very fine sand (%)	25.3	21	8.4	21.5	10.5	18	31.7	26.6	2.5
Coarse silt (%)	2.1	2	3	1	3	1	2	3	3
Fine silt (%)	4.6	2.5	6.5	1	3	1	1	2	3
Clay (%)	11.3	26.4	47.9	19	35	45	11.3	21.9	15
Bulk density ($kg\,m^{-3}$)	1670	1597	1602	1670	1790	1730	1670	1530	1450
Porosity (%)	34.0	33	32.4	34	33.5	33.8	35	39.9	41.6
K_S^* ($mm\,h^{-1}$)	36.1	40	9.6 (1.9)	35.2	18.1 (10.2)	1.9 (1)	23.5	42.8	76.5

K_S = Saturated hydraulic Conductivity, (*) optimised values considered in this paper.

HESSD
9, 301–336, 2012
Predicting hydraulic characteristics of layered soils
S. S. W. Mavimbela and L. D. van Rensburg

Table 2. Fitting models hydraulic parameters of the SWCC for the Tukulu, Sepane and Swartland soil.

Retention Models	Horizons	Q_s	Q_r	K_S	α	n	m	R^2	RMSE	D-index
Tukulu soil										
Brooks and Corey	A	0.34	0.13	36.10	0.0019	0.62	1.000	0.977	0.0112	0.9945
van Genutchen	A	0.34	0.13	36.10	0.0012	1.77	0.436	0.995	0.0054	0.9987
Kasugi	A	0.34	0.13	36.10	2084.0	1.41	0.359	0.995	0.0054	0.9987
Brooks and Corey	B	0.33	0.116	40.00	0.0018	0.47	1.000	0.991	0.0066	0.9979
van Genutchen	B	0.33	0.116	40.00	0.0009	1.62	0.381	0.990	0.0046	0.9990
Kasugi	B	0.33	0.116	40.00	3378.9	1.59	0.359	0.987	0.0083	0.9967
Brooks and Corey	C	0.32	0.26	1.90	0.0079	0.21	1.000	0.925	0.0043	0.9806
van Genutchen	C	0.32	0.26	1.90	0.0059	1.22	0.182	0.940	0.0038	0.9841
Kasugi	C	0.32	0.26	1.90	4770.7	3.38	0.359	0.964	0.0029	0.9905
Sepane soil										
Brooks and Corey	A	0.340	0.100	35.19	0.0044	0.31	1.000	0.985	0.0082	0.9963
van Genutchen	A	0.340	0.100	35.19	0.0027	1.37	0.270	0.994	0.0054	0.9983
Kasugi	A	0.340	0.100	35.19	2787.3	2.45	0.359	0.988	0.0063	0.9977
Brooks and Corey	B	0.335	0.190	10.20	0.0025	0.47	1.000	0.988	0.0053	0.9971
van Genutchen	B	0.335	0.190	10.20	0.0015	1.59	0.369	0.990	0.0018	0.9996
Kasugi	B	0.335	0.190	10.20	2343.6	1.73	0.359	0.997	0.0028	0.9992
Brooks and Corey	C	0.338	0.225	1.00	0.0025	0.54	1.000	0.987	0.0045	0.9968
van Genutchen	C	0.338	0.225	1.00	0.0014	1.69	0.408	0.998	0.0016	0.9996
Kasugi	C	0.338	0.225	1.00	1934.8	1.55	0.359	0.999	0.0013	0.9997
Swartland soil										
Brooks and Corey	A	0.350	0.100	23.48	0.0025	0.39	1.000	0.974	0.0053	0.9987
van Genutchen	A	0.350	0.100	23.48	0.0014	1.50	0.333	0.992	0.0055	0.9999
Kasugi	A	0.350	0.100	23.48	3010.0	1.84	0.359	0.990	0.0104	0.9996
Brooks and Corey	B	0.399	0.105	42.80	0.0141	0.26	1.000	0.995	0.0095	0.9996
van Genutchen	B	0.399	0.105	42.80	0.0088	1.30	0.231	0.999	0.0054	0.9999
Kasugi	B	0.399	0.105	42.80	1333.9	3.06	0.359	0.989	0.0040	0.9999
Brooks and Corey	C	0.416	0.061	76.50	0.0052	0.69	1.000	0.980	0.0094	0.9990
van Genutchen	C	0.416	0.061	76.50	0.0041	1.76	0.433	0.992	0.0100	0.9996
Kasugi	C	0.416	0.061	76.50	547.73	1.58	0.359	0.992	0.0162	0.9990

HESSD
9, 301–336, 2012

Predicting hydraulic characteristics of layered soils

S. S. W. Mavimbela and L. D. van Rensburg

Table 3. Statistical measure of fit for conductivity based parametric models on in-situ K-Coefficient from the Tukulu, Sepane and Swartland soil horizons.

Models	Horizons	Tukulu			Sepane			Swartland		
		R^2	RMSE	D-index	R^2	RMSE	D-index	R^2	RMSE	D-index
Brooks and Corey	A	0.64	11.467	0.577	0.85	5.337	0.881	0.79	4.558	0.812
van Genutchen-Mualem	A	0.90	4.046	0.928	0.96	2.35	0.974	0.99	0.381	0.998
Kasugi	A	0.95	2.763	0.966	0.94	2.78	0.965	0.99	0.312	0.999
Brooks and Corey	B	0.53	18.218	0.359	0.59	4.461	0.405	0.59	7.531	0.895
van Genutchen-Mualem	B	0.83	6.678	0.851	0.91	1.160	0.932	0.93	4.089	0.95
Kasugi	B	0.89	5.124	0.910	0.97	0.656	0.978	0.96	3.794	0.966
Brooks and Corey	C	0.99	0.105	0.990	0.52	0.532	0.235	0.93	7.471	0.948
van Genutchen-Mualem	C	0.82	0.357	0.852	0.87	0.148	0.884	0.99	1.229	0.999
Kasugi	C	0.78	0.377	0.824	0.83	0.175	0.839	0.99	1.580	0.998

HESSD
9, 301–336, 2012

S. S. W. Mavimbela and L. D. van Rensburg

Table 4. Optimised parameters for the fitting of in-situ K-coefficient from the Tukulu, Sepane and Swartland soil horizons using HYDRUS 1-D.

Conductivity models	Horizons	α	n	l	R^2	RMSE	D
Tukulu soil							
van Genutchen and Mualem	A	**0.0015**	**2.511**	**0.5**	0.9992	0.324	0.9996
Modified van Genuchten	A	**0.0015**	**2.511**	0.5	0.9992	0.324	0.9996
Kasugi	A	**1000**	**1.000**	0.5	0.9891	1.233	0.9937
van Genutchen and Mualem	B	**0.0019**	**2.000**	**0.5**	0.9999	0.324	0.9997
Modified van Genuchten	B	0.0039	2.000	0.5	0.9932	1.071	0.9888
Kasugi	B	**1000**	**1.000**	0.5	0.9997	0.234	0.9996
van Genutchen and Mualem	C	**0.0026**	1.500	**0.5**	0.9988	0.278	0.9046
Modified van Genuchten	C	**0.0055**	**1.646**	0.5	0.9993	0.023	0.9995
Kasugi	C	**1000**	**1.000**	0.5	0.9502	0.188	0.9638
Sepane soil							
van Genutchen and Mualem	A	**0.0030**	**3.514**	0.5	0.9997	0.200	0.9997
Modified van Genuchten	A	**0.0027**	**3.461**	0.5	0.9997	0.202	0.9998
Kasugi	A	**405.62**	**0.590**	8.9	0.9996	0.224	0.9998
van Genutchen and Mualem	B	**0.0007**	2.368	0.5	0.9989	0.164	0.9978
Modified van Genuchten	B	**0.0023**	**1.915**	0.5	0.9999	0.041	0.9998
Kasugi	B	**1113.70**	**1.228**	8.7	0.9998	0.050	0.9997
van Genutchen and Mualem	C	**0.0004**	1.500	0.5	0.9992	0.013	0.9992
Modified van Genuchten	C	**0.0005**	**1.751**	0.5	0.9999	0.002	0.9998
Kasugi	C	**683.42**	**1.015**	32.7	0.9999	0.002	0.9999
Swartland soil							
van Genutchen and Mualem	A	0.0017	1.85000	0.5	0.9998	0.025	0.9990
Modified van Genuchten	A	0.0018	1.97700	0.5	0.9998	0.025	0.9990
Kasugi	A	877.19	1.010	65.8	0.9999	5.092	0.7280
van Genutchen and Mualem	B	0.0028	2.4300	0.5	0.9998	0.155	0.9980
Modified van Genuchten	B	0.0028	2.4300	0.5	0.9998	0.155	0.9980
Kasugi	B	539.08	0.910	16.0	0.9999	0.119	
van Genutchen and Mualem	C	0.0019	1.760	0.5	0.8560	3.285	0.9890
Modified van Genuchten	C	0.0015	1.760	0.5	0.8560	3.285	0.9890
Kasugi	C	949.69	1.000	30.6	0.8900	2.877	0.9921

Bold letters = optimised to improve objective function solution.

HESSD
9, 301–336, 2012

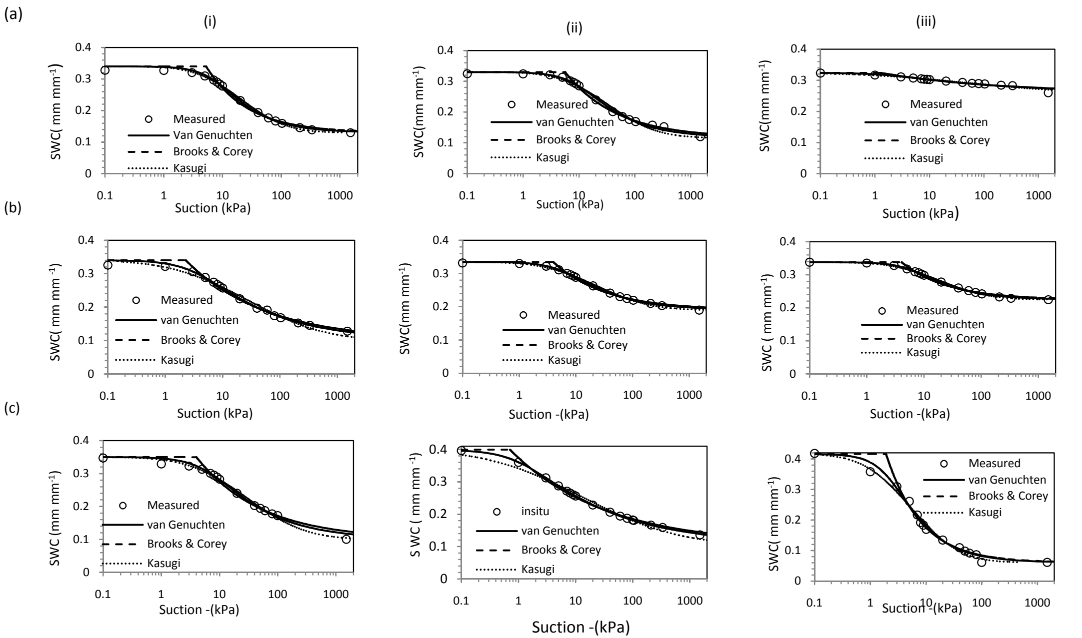

Fig. 1. Soil water characteristics curves from measured laboratory experiments and fitted using three pore size distribution models. $N = 3$ samples from A, B and C horizons of the Tukulu, Sepane and Swartland soil profiles. Desorption approach; undisturbed core samples from 0–100 kPa, disturbed samples from 100–1500 kPa.

HESSD
9, 301–336, 2012

Predicting hydraulic characteristics of layered soils

S. S. W. Mavimbela and L. D. van Rensburg

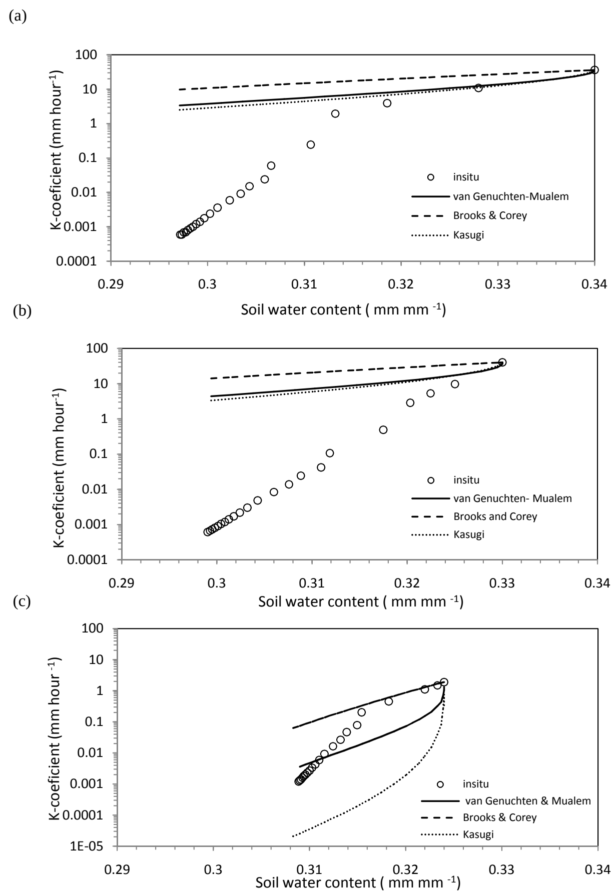

Fig. 2. Unsaturated hydraulic conductivity from two approaches of the Tukulu soil profile horizons are compared. Approaches; in-situ based instantaneous profile method versus retention based conductivity models including Brooks and Corey (1964), van Genuchten-Mualem (1980), and Kasugi (1996).

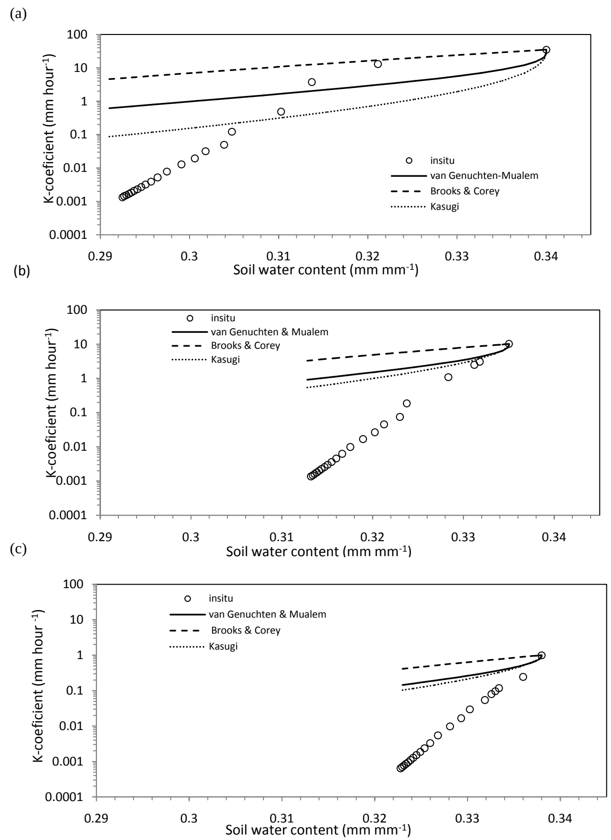

Fig. 3. Unsaturated hydraulic conductivity from two approaches of the Sepane soil profile horizons are compared. Approaches; in-situ based instantaneous profile method versus retention based conductivity models including Brooks and Corey (1964), van Genuchten-Mualem (1980), and Kasugi (1996).

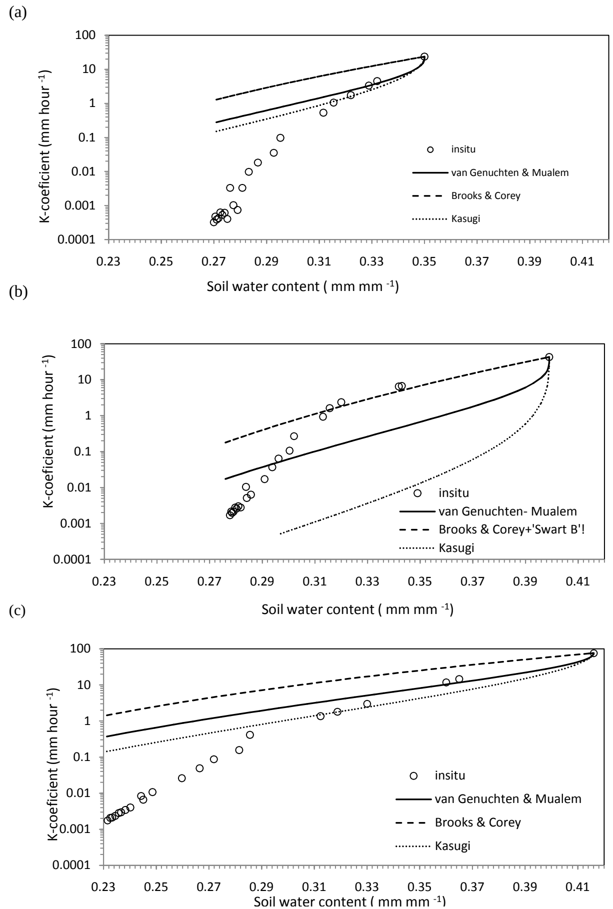

Fig. 4. Unsaturated hydraulic conductivity from two approaches of the Swartland soil profile horizons are compared. Approaches; in-situ based instantaneous profile method versus retention based conductivity models including Brooks and Corey (1964), van Genuchten-Mualem (1980), and Kasugi (1996).

HESSD

9, 301–336, 2012

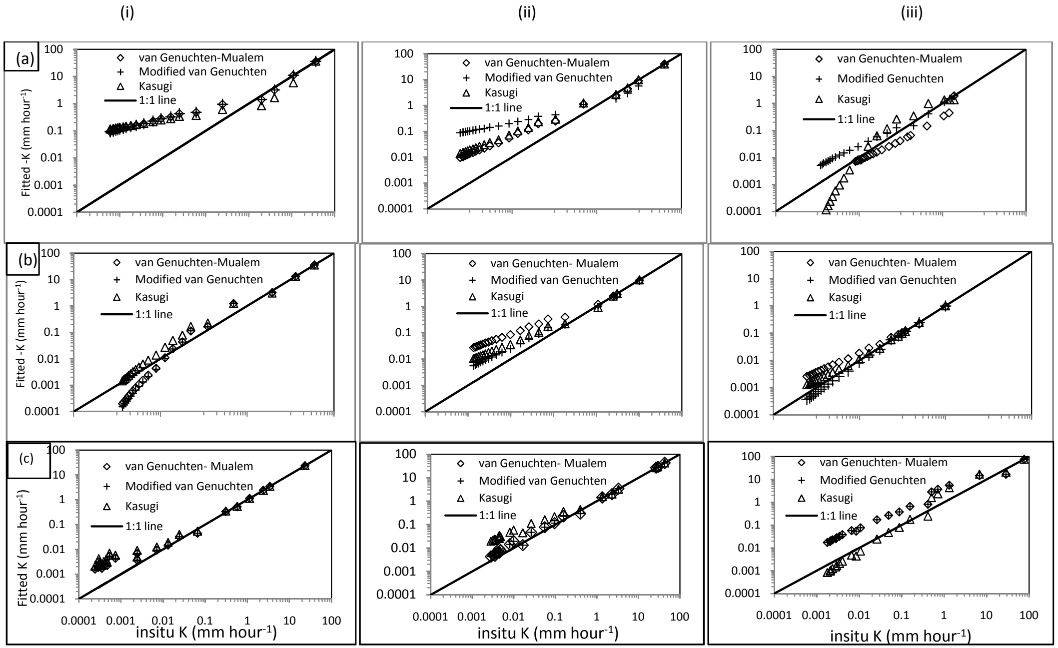

Fig. 5. Unsaturated hydraulic conductivity from in-situ and optimised retention parameters fitted using HYDRUS 1-D computer program for the Tukulu **(a)**, Sepane **(b)** and Swartland **(c)** soil profiles. The van-Genuchten-Mulaem (1980), Modified van Genuchten (Vogel and Cislerova, 1988) and Kasugi (1996) were used for analysis.

HESSD
9, 301–336, 2012

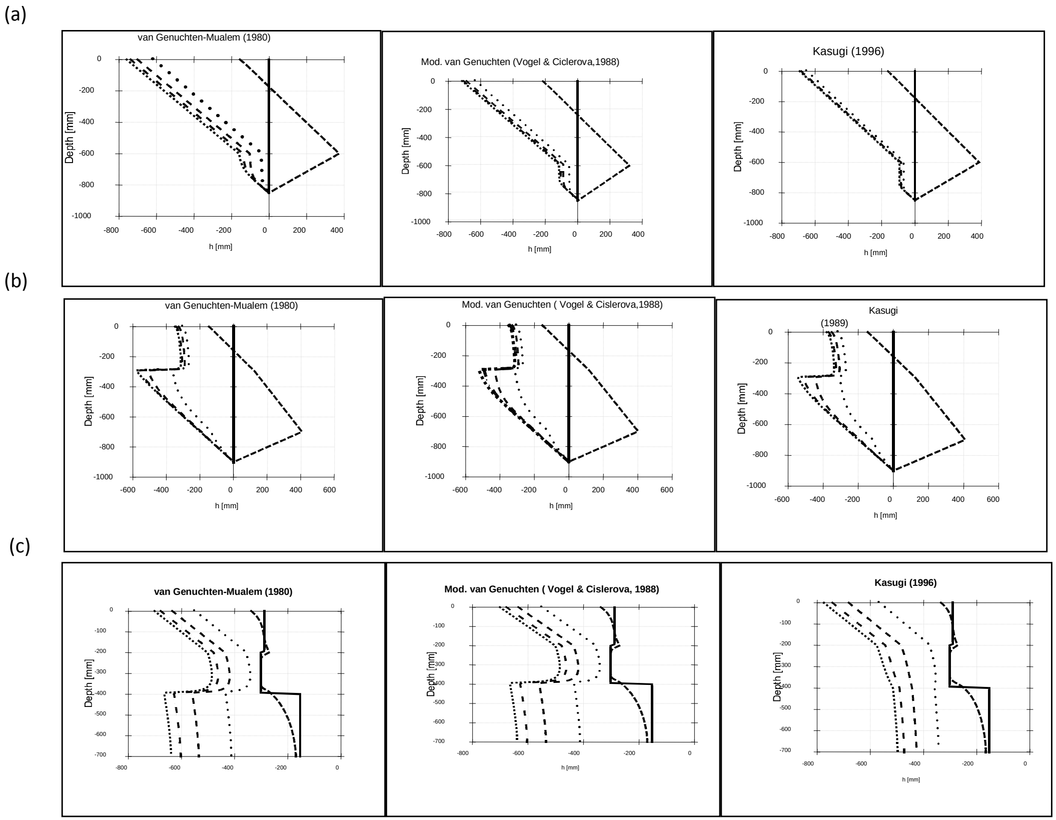

Fig. 6. Distribution of matric suction with depth from the Tukulu **(a)** Sepane **(b)** and Swartland **(c)** soil profiles. The van-Genuchten-Mulaem (1980), Modified van Genuchten (Vogel and Cislerova, 1988) and Kasugi (1996) hydraulic models were compared in each profile horizon.

HESSD

9, 301–336, 2012

Predicting hydraulic characteristics of layered soils

S. S. W. Mavimbela and L. D. van Rensburg