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Measurement of In-Situ Unsaturated Hydraulic Conductivity Using Inverse Approach

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ABSTRACT

The number of inverse approaches already been used for unsaturated hydraulic conductivity K_h estimation. Which are mostly based on the laboratory-scale experiments and not much compatible with in-situ conditions. In this study,an inverse approached was used for in-situ K_h estimation. The in-situ measured saturated hydraulic conductivity K_{fs} and soil water content data was used in RETC computer code for parametersoptimization. The optimized parametersα, n, and$l$, wereused in analytical models for K_h estimation and compared withthe observed K_h. During this study an exponential functionwas alsomodified forK_h estimation, which performed well when compared to the observed data. The selected models were evaluated using Root Mean Squared Error (RMSE), Nash Sutcliff efficiency, and Coefficient of determination R^2. The Van Genuchtensoil water retention and Mualempore size distribution modelperformed well having 96% model efficiency, RMSE was1.43E-04, and $R^2$0.97. The modified exponential function efficiency was 78%, and RMSE was 3.53E-04 for in-situ $K_h$estimation.

Key Words: In-situ unsaturated hydraulic conductivity, Inverse approach, Exponential Function, Tension Disk Infiltrometer, Soil Moisture Sensors.

1. Introduction

The in-situ soil hydraulic conductivityvaries spatially and temporally depending on the soil, vegetation, and climatic conditions(Russo, Russo, and Laufer 1997) such as soil mineralogy and antecedent soil water content(Warrick and Nielsen 1980).

The number of approaches has been used to understand the soil hydraulic conductivity in the field and laboratory,which depends on soil hydraulic properties. The determination of soil hydraulic properties using traditional methods is very laborious and time-consuming. Moreover,taking the laboratory scale data for in-situ measurement is difficult to be accurately transferred (Waseem, Ajmal, and Kim 2015).Researchers have tested different analytical and numerical inverse methodsfor soil hydraulic parameter estimation(Milly 1988). The inverse approach has widely been practiced for unsaturated hydraulic parameters estimation for the last few decades(COOK 1991; Fashi, Gorji, and Shorafa 2016; Fred Zhang, Ward, and Gee 2004).During the evaluation of inverse method,twelve different scenarios were tested for Van Genuchten- Mualem unsaturated hydraulic conductivity parameters estimation(Mashayekhi et al. 2016). The Van Genuchtenmodel better explains soil water retention function by parameter optimization (Fashi et al. 2016).The in-situ unsaturated hydraulic conductivity was estimated using a multi-flow inverse approach, where HYDRUS software was used for parameters estimation (Nasta, Huynh, and Hopmans 2011).

The in-situ unsaturated hydraulic conductivity was measured from soil capillary pressure head and water content by installing Tensiometers and TDR in different locationsfor comparison with the inverse approach (Hendrayanto, Kosugi, and Mizuyama 1998).

This study is focusingon the evaluation of an inverse approachestimating unsaturatedhydraulic conductivity (Nasta et al., 2011;Vereecken et al., 2010; Van Genuchten, 1978; Van Genuchten and Nielsen, 1985 and Van Genuchten, 1992). The instantaneous soil profile data was used for parameters optimization. In the laboratory,severaltrialswere conducted tocalibrate the effectiveness of the proposed inverse method. The in-situ saturated hydraulic conductivity $K_s$was measured byRenold and Elrick's (1990) method. Which accounts ring diameter and depth, and follows the concept, that field soil water saturation is always less thancomplete saturation ($K_{sat} \geq 2K_s$) (Constantz et al., 1988; Renold and Elrick, 1990; Hillel, 1980, P.179).The soil water content was measured by installing soil moisture sensors SMSand the Gravimetric method.The volumetric soil water content$\theta (cm^3 cm^{-3})$and in-situ saturated hydraulic conductivity K_s wasused in the RETCcomputer codefor parameters estimation (Vereecken et al. 2010).During the parameters estimation, only $n$was optimizedand the remaining parameters left as such for estimating the unsaturated hydraulic conductivityK_h(Abbasi et al. 2003).The in-situ unsaturated hydraulic conductivity $K_h$estimated by inverse approach compared with reference$K_h$measured by Mini disk infiltrometer MDI under varyingsoil conditions.An exponential function for$K_h$estimationwas also proposed by taking laboratory measured saturated hydraulic conductivity K_{sat}in Raats

(1992) function.The number of models has already used for soil unsaturated hydraulic conductivity K_h estimation. These models use different soil hydraulic parameters duringthe inverseapproach (Van Genuchten, 1992). During this study the inverse approach is comprised of optimizing only one soil water retention parameter n(Van Genuchten and Nielsen, 1985; Van Genuchten, 1992), the most sensitive parameter. While the rest of the parameters K_s, θ_r, θ_s , $\alpha, l, and\ m$ left as such.

2. Materials and Methods

2.1 Experimental site, soil analysis, and infiltration measurement.

The tests were conducted in the laboratory (School of Civil and Hydraulic Engineering, Ningxia University) and three different in-situ sites between May and November 2018, where two-stage sampling techniques used. During this technique, each Field (F) was divided into sub-fields cited as location (L) varying in vegetation cover, soil structure and texture, porosity, and soil moisture content. The in-situ tests were conducted in Yinchuan at Jinfeng county, Xixia county, and Yongning county. The double ring infiltrometer DRI and mini-disk infiltrometer MDI used for referencesaturated K_{fs} and unsaturated hydraulic conductivity K_h measurement both in the laboratory and in-situ.During the laboratory experiment, the fine-textured soil was brought from the field and left for drying at room temperature. Then the soil was passed through the net for screening and to get a uniform particle density. After that, the soil was transferred to the box of 5x2x1 meter divided into three portions. Each soil portion was compacted to get uniform bulk density throughout its depth (using the gravimetric method). In the initial stage of the experiment in May 2018, the laboratory tests were conducted. The two DRIs with inner and outer rings of 15 and 30 cm, 30 and 60 cm used at 5 and 10 cm insertion depth and ponding heads. The EC5 soil moisture sensors installed beneath the DRI inner ring for recording the volumetric water content data in the data logger.

The soil texture analysis was conducted using a laser particle size analyzer (Bettersize 2000, Bettersize Instruments Ltd, China), which gives the complete range of soil particles size for obtaining the percentage of sand, silt, and clay. The saturated hydraulic conductivity $K_{sat}\,(cm\ sec^{-1})$was measured in the laboratory by constant head permeameter for each experimental site (taking soil samples to the laboratory) (Reynolds, W. D., &Elrick, D. E. 2002). During this study total, 19 trials were conducted monthly at each site to compare the observed and estimated unsaturated hydraulic conductivity $K_h\,(cm\ sec^{-1})$, and to evaluate the inverse approach using analytical models and modified exponential function This method showed an acceptable goodness of fit using the RETCcomputer code. The optimized parameters used in selected parametric models, including VGM, VGB, BCM, BCB, Gardner& Wooding, proposed Exponential function, and White (1992).

In the first phase of research, parameters were estimated from the experimentallaboratory datafor the calibration of the inverse solution andafter calibration, tested in the field. The statistics of Root Mean Squared Error RMSE, coefficient of determination (R^2), and Nash-Sutcliffe efficiency (NSE) used for the goodness of fit and models comparison.

Table 1. Soil textureanalysis of all sites.

Site	Location	% Clay	% Silt	% Sand	Texture Class	% Gravel > 2mm
Laboratory	Lab	14.94	76.38	8.68	Silt loam	
Yongning county	F1,L1	4.24	47.145	48.61	Fine Sandy Loam	
	F1,L2	4.64	23.37	71.99	Fine Sandy Loam	54.60%
	F1,L3	5.13	27.61	67.26	Fine Sandy Loam	
	F1,L4	5.17	26.53	68.3	Fine Sandy Loam	13 % < 2 mm
Jinfeng county	F2,L1	0.74	5.94	93.32	Sandy	
	F2,L2	4.13	25.75	70.12	Fine Sandy Loam	
	F2,L3	6	34	60	Fine Sandy Loam	
	F2,L4	4.29	24.69	71.02	Fine Sandy Loam	
	F2,L5	21.89	75.68	2.43	Silt loam	

Xixia county	F3,L1	3.58	26.205	70.215	Fine Sandy Loam	
	F3,L2	4.78	26.32	68.9	Fine Sandy Loam	
	F3,L3	6.53	54.79	38.68	Silt loam	
	F3,L4	5.22	36.39	58.39	Fine Sandy Loam	
	F3,L5	11.49	56.095	32.41	Silt loam	
	F3,L6	11.08	74.16	14.76	Silt loam	

F: Field, L: Location, D: Depth, D1, 2, 3: 10, 20, 30 cm.

The automatic water level control valves (JUNY, model JYN15, ½" Wenzhou Technology Co., Ltd, China), operate at 0.02-1.0 Mpa (0.2 to 10 bar) of applied pressure and water reservoirs kept at the height of > 2 meters. The valve's discharge was calibrated to maintain the required water tension head. Their performance was entirely satisfactory.

The infiltration here recorded from the change in water level in reservoirs designed for constant water supply (rate of water level drop calculated from $R = \Delta L/\Delta t$). The steady-state condition achieved when the change in reading reached to a constant flow rate or < 10% variation in infiltration rate i $(cm\ sec^{-1})$ R for one hour.

$$i = R\frac{A_s}{A_r} \tag{1}$$

where A_s (L^2) is a reservoir area, A_r (L^2) the cylinder or infiltration surface cross-sectional area, L (L) the water level fall, and t (T) time.

*2.2*In-situ Unsaturated hydraulic conductivity

The Mini disk infiltrometer (MDI, Decagone Devices Inc. 2018) is a portable device used for the determination of infiltration parameters at remote locations where other devices are challenging to install (Madsen and Chandler 2007). The MDI is a glass tube of 31 mm diameter and 300 mm long with two portions separated by a rubber septum. The upper bubbler portion controls the suction head ranging from -0.5 to -7 cm and a lower water reservoir of 135 ml with a porous disk at the bottom. The MDI should be placed firmly on a thin layer of sand (Kirkham and Clothier 2000). The MDI allows water to flow through soil micro-pores under negative pressure (tension) excluding macro-pores (having larger radii than the equivalent pore radii of applied tension), cracks, and holes that dominate the saturated flow. This exclusion facilitates the in situ macro-pores characterizations the difference between Ks and Kh (Minasny and George 199

The laboratory and in-situ unsaturated hydraulic conductivityK_h measured by Zhang (1997) method using MDIinfiltration data, which further used for comparison with the inverse approach,

$$I = C_2 t^{0.5} + C_1 t \quad (2)$$

Where C_2 (L$T^{-0.5}$) is soil sorptivity and C_1 (LT¯¹) hydraulic conductivity. The soil K_h (LT¯¹) given as,

$$K_h = \frac{c_2}{A} \quad (3)$$

Where C_2 measured from the slope of cumulative infiltration I vs square root of time $T^{0.5}$using second-order polynomial fitting (Quadratic equation), and A is obtained by relating the Van Genuchten soil parameter to the applied suction head,

$$A = \frac{11.65(n^{0.1}-1)exp[2.92(n-1.9)\alpha h]}{(\alpha r)^{0.91}} n \geq 1.9 \quad (4)$$

$$A = \frac{11.65(n^{0.1}-1)exp[7.5(n-1.9)\alpha h]}{(\alpha r)^{0.91}} n < 1.9 \quad (5)$$

Where α and n are the Van Genuchten soil parameters, h (L) is the suction applied at a disk surface, and r (L) is the radius of infiltrometer disk.

3. Governing equation for water flow and parameter optimization

The measurement ofunsaturated hydraulic conductivity at field scale is not practical due to soil heterogeneity, soil water content, porosity and steady-state flow rate variation(Reynolds and & Elrick 2002). Hence, in practice, the quasi-steady-state flow condition is usually assumed(Angulo-jaramillo 2016).The Richards equation can describe the unsaturated soil hydraulic conductivity as(Richards 1931),

$$C\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z} - K\right) \quad (6)$$

Where t is time (T), K hydraulic conductivity (LT^{-1}), h the soil water pressure head (L), z depth of soil (L), and C the capacity of soil water (L^{-1}) approximated by the SWR curve slope, $\theta(h)$ the volumetric water content (L^3L^{-3}). For the homogenous unsaturated soil($h \leq 0$), the soil water retention can be described:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial \theta}{\partial z} - K\right) \quad (7)$$

where D is hydraulic diffusivity (L^2T^{-1}),

$$D = K\frac{dh}{d\theta} \quad (8)$$

The field K_{fs} of a porous medium is less than true or complete Ks (Hillel, 1980), e.g. $K_{fs} = 0.5K_s$ (Constantz 1998), depending on the natural environmental condition of the porous medium(Bouwer 1986). The change in hydraulic conductivity K is described by the change in soil water content θ and pressure head h with time. we considered the solution for finite domain at θ_L.The initial condition is in term of water content and boundary condition is given as.

$$\theta_{(z,t)} = \theta_L(0 \leq z \geq \theta_L)(9)$$

$$(\theta_L > \theta_0)$$

$$\theta_{(t=0)} = \theta_0(10)$$

$$h(z,t) = h_0(t) \qquad z = 0(11)$$

Where θ_0 is the initial water content (cm^3cm^3), θ_L is the final water content (cm^3cm^3), and h is the pressure head (cm) applied at surface $(h > 0)$ for saturated conditions.

3.1 Analytical Models

3.1.1Van Genuchten-Mualemand BurdineModels

The Van GenuchtenSWR function (Van Genucten, 1980) is,

$$S_e = \frac{1}{[1+(\alpha h)^n]^m}. \quad (12)$$

Van Genuchten-MualemVGM and BurdineVGB (1980) unsaturated hydraulic conductivity functions are,

$$K(S_e) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 (m = 1 - 1/n) \quad (13)$$

$$KS_e = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right] \quad (m = 1 - 2/n)(14)$$

Where Se is effective saturation, and n (> 0) is a dimensionless coefficient characterizing pore size distribution, Where l is soil pore tortuosity factor,K_s is saturated hydraulic conductivity (LT^{-1}),(L^{-1}),n, and m areempirical parameters.

3.1.2. Brooks and Corey-Mualem and Burdine Models

The Brooks and Corey SWR is ,

$$S_e = (\theta_e - \theta_r / \theta_s - \theta_r) = \left({h_a}/{h_m}\right)^n \; h_m < h_a, \quad (15)$$

$$S_e = \theta_e = \theta_s = 1 \qquad h_m \geq h_a \quad (16)$$

Where θ_e is effective, θ_r is residual, and θ_s is saturated moisture content, h_a is air entry, and h_m is soil water metric head.

Brooks and Corey-Mualem BCM and Burdine BCB (1966) unsaturated hydraulic conductivity function is given as,

$$K(se) = K_s {S_e}^{\frac{2}{n}+l+2} \quad (17)$$

$$K(S_e) = K_s S_e^{l+1+2/n} \quad (18)$$

3.1.3. Wooding-Gardner Method

Wooding (1968) formulated the three-dimensional infiltration function from tension infiltrometer by approximating steady-state infiltration rate, Q_h (LT^{-1}), from a circular source of a shallow pond with a radius, r (L), at a supplied tension, h (L) in the unsaturated porous medium,

$$Q_{h= K_h[1+4\lambda_c/(\pi r)]} \tag{19}$$

Where K_h is unsaturated hydraulic conductivity at an applied water potential h (L) measured by Eq. (22), and λ_c is the macroscopic capillary length (L), it can be calculated as $\lambda_c = 1/\alpha$. The in-situ unsaturated hydraulic conductivity function used by Gardner (1958) is,

$$K_h = K_s \exp(\alpha h) \qquad \text{if } h_m < h_a \tag{20}$$

Where K_s is the saturated hydraulic conductivity$(L\,T^{-1})$ measured at two steady state fluxes (Ankeny et al., 1991), $h$is the applied water potential(L), and α is a soil parameter relating to the capillary and gravity force during the unsaturated soil water movement (Philip, 1969). In-situ Kh varies due to soil heterogeneity, water content, porosity, and steady-state flow rate variation (Reynold and Elrick 2002). Hence, in practice, the quasi-steady-state flow condition is usually assumed (Angulo-Jaramillo et al., 2016). Observed Khcan evaluate the analytical models for analysis (Jacques et al., 2002). The model prediction ability depends on the accuracy of estimated hydraulic conductivity under varying soil saturation conditions (Ramos and Goncalves, 2006). The following are the models used for laboratory and in-situ K_h estimation.

3.1.4. White Method

White et al. (1992) proposed the following equation for unsaturated hydraulic conductivity,

$$K_h = Q - \frac{4aS^2}{(\theta_e - \theta_i)\pi r} \qquad (21)$$

Where Q is the steady-state infiltration rate ($L\,T^{-1}$) from the bottom of MDI, a is the shape factor varying between 0.5 to $\pi/4$ or 0.55. $S$is the sorptivity($LT^{-0.5}$) at supplied potential, θ_e is the moisture content at supplied potential, and θ_i is the initial moisture content ($L^3 L^{-3}$).

3.1.5.Modified Exponential Function.

Tani (1982), Russo (1988) and Ross &Smettem (1993) proposed a model for SWR using exponential function given as,

$$S_e = [1 + (h_m/h_{m,i})]\exp(-h_m/h_{m,i}) \qquad (22)$$

Where

$$h_{m,i} = -m^{1-m/\alpha} \qquad (23)$$

Where h_m is MDI applied pressure head (cm) and $h_{m,i}$ is air entry head estimated using optimized parameters of VGM, and$m = 1 - 1/n$

Gardner's (1958) concept reproduced after combining with Mualem's (1976) conductivity model for relative hydraulic conductivityK_r (ratio of K_h to K_s) (DANE, J. H; TOPP, G C; CAMPBELL, G S; AL-AMOODI, L; DICK 2002)ane et al., 2002; Raats, 1992).

$$K_r = S_e^l exp(-2h_m/h_{m,i}) \qquad (24)$$

The above K_r function modified for unsaturated hydraulic conductivityestimation in Eq. (25) as,

$$K_h S_e = K_{sat} S_e^l exp\left(-2h_m/h_{m,i}\right) \tag{25}$$

Where K_{sat} is saturated hydraulic conductivity ($L\,T^{-1}$)measured by constant head permeameter,l is soil pore tortuosity factor and $K_h S_e(L\,T^{-1})$is the unsaturated hydraulic conductivity corresponding to effective saturation (S_e) using Eq, (25).

4. Result and Discussions

4.1. Models comparison

The VGM and BCMmodels give the best fit for $K_h$estimation with 0.96 and 0.92 model efficiency as compared to other models in Figure 1,3 andTable 2. The $K_h$estimated by using different models are in good agreement with the observed $K_h$except forthe Laboratory trialno.3, where the VGB, BCM, and BCB resulted no estimationdue to deep cracks throughout the soil depth. The Gardner and Exponential function underestimated the $K_h$but resulted areliable estimates in few cases with model efficiency of 0.79 and 0.78in Figure 1, Table. 2.

The Field 1 hascompact fine sandy loam soil, and limited data was available for parameter optimization.Only VGM, VGB, and BCB gives reliable estimates comparatively,except at location 2, and 4 which have gravels.In F1L2 there was 54.60 % of gravels of 2mm, and 13 % of gravels at F1L4 smaller than 2 mm of size.Thatreduces soil surface area, porosity,increasesresistanceto vertical infiltration,and encourages horizontal infiltration. The $K_h$estimation in-situ conditions by inverse approach is difficult due to water retention parameters fitting.InF1L2, the K_h does not explainwell by all these models in Table 2, becausetheyhave limitations of soil homogeneity and uniform soil water content. The unsaturated hydraulic conductivity K_h estimated by Gardner and Exponential function agreed closely with the observed when using the Van Genucthen retention parameters at a steady infiltration rate ($cm\ sec^{-1}$) Figure 2 and 3.

In Field 2, the soil type varies from sandy to fine sandy loam having deep rooted trees at location 1 and grass cover at location 2, while location 3 and 4 have no vegetation.The BCM, and BCB models resulted overestimation at Location 3, while at location 4, the BCB resulted 0 estimation of K_h in Table 2. The Gardner and Exponential function underestimatedK_h at location 1, 3 and 4,and over estimation at location 2 and 5 where thesoil texture was uniform silt loam.The VGM and BCMmodels performed well at Field 2 with lowest RMSE of 1.43E-04 and 2.15E-4, due to better estimations of soil water retention parameters by the proposed method.

The K_h was overestimated by VGM, VGB, BCM, and BCB at Field 3 location 3,except Gardner and Exponential functionthat underestimated$K_h$when compared to the observed data due to soil hardness and deep-rootedlonggrass.The grass effects the pore uniformity,especially the micro-pore capillaritywhich reduces infiltration. At location 4 the infiltration test was conducted in a maize field, while locations 1 and 2 were barren with fine sandy loam soil. In field 3 the models gave reasonable estimates of K_h(figure 1 and 3) except for the White model whichoverestimatedK_h. This model depends on soil sorptivity andassumes a steady infiltration rate ($cm\ sec^{-1}$) from the disk surface. When usingsuchtypes of models in the field, proper estimation of soil sorptivity and steady infiltration rate is required.

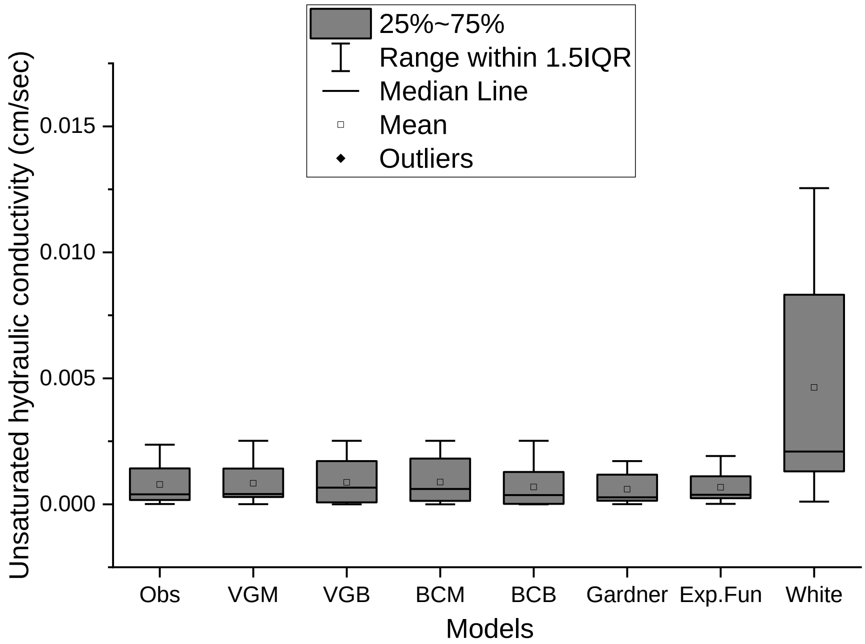

Figure1.Comparison of observed and estimated unsaturated K_h ($cm\ sec^{-1}$) by using different models.

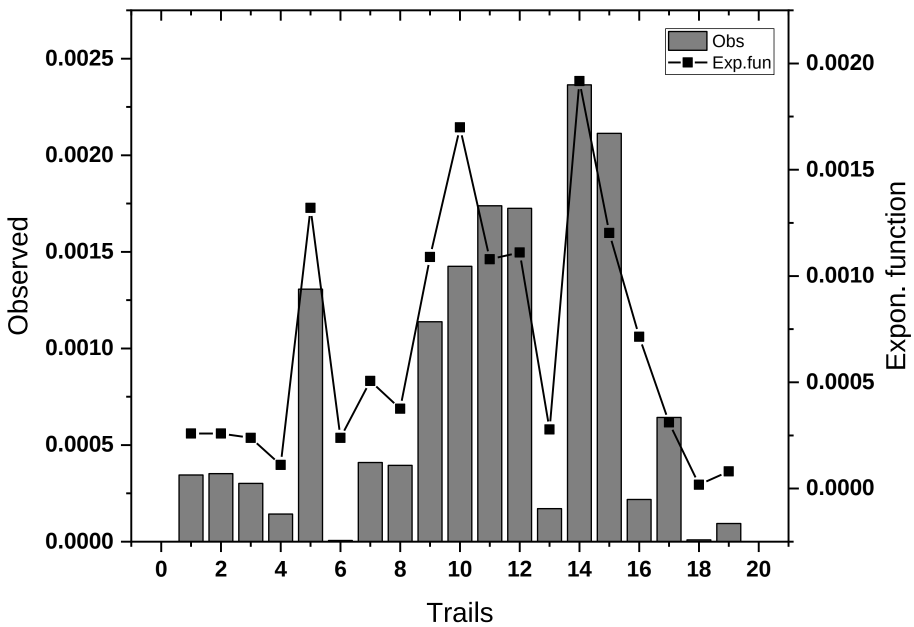

Figure2.Comparison of observed and estimated K_h ($cm\ sec^{-1}$) by using Exponential function

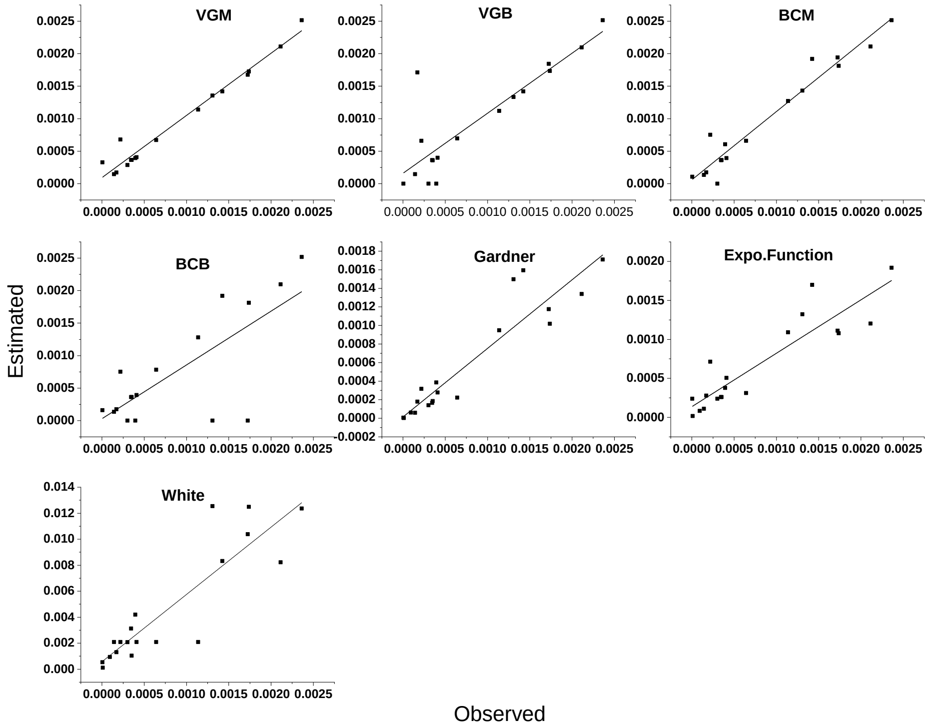

Figure3. Linear fit of the observed and estimated K_h $(cm\ sec^{-1})$ using selected models.

able 2. observed and estimated unsatuarated hydraulic conductivity Kh $(cm\ sec^{-1})$ by different models at actual water content $\theta_e\,(cm^3cm^{-3})$.

Site	ObseKh	VGM	VGB	BCM	BCB	Gardner	Exp. fun	White
L1	3.45E-04	3.63E-04	3.61E-04	3.61E-04	3.61E-04	1.65E-04	2.59E-04	3.12E-03
T2	3.53E-04	3.65E-04	3.58E-04	3.62E-04	3.62E-04	1.86E-04	2.59E-04	1.03E-03
T3	3.01E-04	2.85E-04	0.00E+00	0.00E+00	0.00E+00	1.39E-04	2.38E-04	2.07E-03
T4	1.43E-04	1.46E-04	1.46E-04	1.34E-04	1.34E-04	6.00E-05	1.11E-04	2.09E-03
F1,L1	1.31E-03	1.36E-03	1.33E-03	1.43E-03	0.00E+00	1.50E-03	1.32E-03	1.25E-02
F1,L2	6.40E-06	3.29E-04	0.00E+00	1.05E-04	1.60E-04	5.99E-06	2.38E-04	5.24E-04
F1,L3	4.10E-04	4.05E-04	3.98E-04	3.94E-04	3.94E-04	2.78E-04	5.06E-04	2.09E-03
F1,L4	3.95E-04	3.92E-04	0.00E+00	6.05E-04	0.00E+00	3.85E-04	3.76E-04	4.19E-03
F2,L1	1.14E-03	1.14E-03	1.12E-03	1.27E-03	1.28E-03	9.47E-04	1.09E-03	2.09E-03
F2,L2	1.43E-03	1.42E-03	1.42E-03	1.92E-03	1.92E-03	1.59E-03	1.70E-03	8.32E-03
F2,L3	1.74E-03	1.72E-03	1.73E-03	1.81E-03	1.81E-03	1.02E-03	1.08E-03	1.25E-02
F2,L4	1.73E-03	1.68E-03	1.84E-03	1.94E-03	0.00E+00	1.17E-03	1.11E-03	1.04E-02

F2,L5	1.71E-04	1.71E-04	1.71E-03	1.75E-04	1.75E-04	1.78E-04	2.78E-04	1.30E-03
F3,L1	2.36E-03	2.52E-03	2.52E-03	2.52E-03	2.52E-03	1.71E-03	1.92E-03	1.24E-02
F3,L2	2.11E-03	2.11E-03	2.10E-03	2.11E-03	2.10E-03	1.34E-03	1.20E-03	8.22E-03
F3,L3	2.18E-04	6.80E-04	6.60E-04	7.53E-04	7.53E-04	3.16E-04	7.14E-04	2.09E-03
F3,L4	6.43E-04	6.72E-04	6.95E-04	6.60E-04	7.81E-04	2.22E-04	3.11E-04	2.08E-03
F3,L5	9.37E-06	5.18E-06	6.21E-06	6.42E-06	1.74E-05	2.53E-06	1.77E-05	1.05E-04
F3,L6	9.38E-05	4.86E-05	7.38E-05	8.31-05	2.01E-04	6.13E-05	8.10E-05	9.41E-04
RMSE	***	1.43E-04	4.10E-04	2.15E-04	5.71E-04	3.44E-04	3.53E-04	5.34E-03
NSE	***	0.96	0.70	0.92	0.41	0.79	0.78	0.00
R^2	***	0.97	0.75	0.95	0.56	0.87	0.82	0.89

*θ_e is water content at steady-state flow below MDI, Observed data by using MDI (Zhang method). VGM (Van Genuchten-Mualem), VGB (Van Genuchten-Burdine), BCM (Brooks and Corey-Mualem), BCB (Brooks and Corey-Burdine), Expo. Fun (Exponential Function). Root Mean Squared Error (RMSE), Nash-Sutcliffe efficiency (NSE) and Coefficient of determination R^2

5. Conclusions

The proposed inverse approachfor unsaturated hydraulic conductivity K_h ($cm\ sec^{-1}$) estimation performed well for in-situ application except for a few cases. During parameter optimization,theK_h ($cm\ sec^{-1}$) estimated by VGM and BCM corresponded well with the observed data having 0.96 and 0.92 model efficiency. Van Genuchten retention function is more powerful and gives the best results,as compared to other methods.At F3L5, L6, and F1L2, the hydraulic parameters could not be optimized well due to soil hardness throughout the depth. During such soil conditions, there was a significant variation between observed and estimated K_h using an inverse approach, and only a direct measurement is recommended.

The inverseapproachhas limitations of homogeneous soil, uniform porosity, and uniform initial soil moisture, which is not possible in in-situ conditions.The soil water retention parameters obtained from parameter optimization corresponded well, especially in

Van Genuchtenmodel. Using the proposed inverse method only for Van Genuchten parameters optimization will give a better estimation of K_h in in-situ conditions.

Using such an approach, explain well the in-situ phenomena and requires repetitions at each location to get the best results. The number of optimized parameters was limited to only n in this study, which can be increased to, i.e., $\alpha, l, K_s, \theta_s,\ and\ m$.

The Gardner and exponential function estimated well the K_h when compared to VGB, BCB and White models. The Gardner and exponential function model efficiency was 0.79 and 0.78, while theVGB,BCB and white models efficiency was 0.70, 0.41, and 0. The White modelis not recommended as it depends on soil sorptivity for K_h estimation. The direct method of mini-disk infiltrometer for in-situ unsaturated hydraulic conductivity measurement is more efficient and robust.

Conflict of Interest

There is no conflict of interest

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