0038-075C/00/16509-718-727
Soil Science

September 2000
Vol. 165, No. 9
Printed in U.S.A.

SCALING OF SATURATED HYDRAULIC CONDUCTIVITY: A COMPARISON OF MODELS

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This study compares eight models for scaling soil-saturated hydraulic conductivity, K_s, using a database of 402 data sets collected from 25 sources in the literature. The database includes data regarding K_s, particle size distribution, soil bulk density, and soil particle density, with textures ranging from sand to heavy clay. The results showed that models based on the nonsimilar media concept and the Kozeny-Carman model performed best for estimating soil K_s using scaling. In contrast, Campbell and Poulsen-Saxton models were not suitable for scaling K_s. The group of models that gave the second best estimation of K_s included Saxton, Cosby, Vereecken, and the complex Brakensiek models. All eight of the models had smaller estimation deviations for sandy soils than for clayey soils. Moreover, the results showed that the sample that had an average of the characteristics of all the samples should be taken as a reference point when scaling K_s, whereas for soil samples with identical texture, it would be better to employ the sample with minimum bulk density as the reference point. The NSMC and Kozeny-Carman models are recommended for scaling K_s. (Soil Science 2000;165:718–727)

Key words: Saturated hydraulic conductivity, scaling model, nonsimilar media concept (NSMC).

MANY hydrologic designs are based on the results of hydrologic modeling. At present, some estimation methods and numerous laboratory and field methods for direct measurement of hydraulic properties are available (Dane, 1980; Gupta et al., 1993; Paige and Hillel, 1993). Saturated hydraulic conductivity (K_s) is a necessary key parameter for analyzing or modeling water flow and chemical transport in subsurface soil. Moreover, a measured value of K_s is usually required as a matching factor in predicting the unsaturated hydraulic conductivity function from soil water characteristic data (van Genuchten, 1980; Mualem, 1992). This parameter is also needed for predicting unsaturated hydraulic conductivity from a large number of the existing one-parameter models (Brooks and Corey, 1966; Campbell, 1974; Mualem, 1976; Alexander and Skaggs, 1986).

Field studies have shown that soil hydraulic characteristics can vary greatly (Nielsen et al., 1973; Mohanty et al., 1991). Spatial variability precludes precise characterization of the hydraulic parameters and, as such, causes difficulty in representing the profile with a deterministic set of hydraulic parameters. To define and quantify the spatial variability, scaling methods based on similar media concepts (Miller and Miller, 1956) and geostatistical methods such as variogram analysis and kriging are two main approaches. Both approaches are capable of providing some spatial pattern of a variable.

Currently, there are three approaches that can be used to estimate K_s: (1) Estimate K_s by generally multiple, nonlinear regression statistics from easily obtainable soil physical and chemical properties such as particle size distribution, bulk density,

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This is Project No. P-97470.

Received Oct 11, 1999; accepted May 8, 2000.

and organic matter content (Rawls et al., 1982). These regression functions are often referred to as pedotransfer functions (Bouma, 1992), and this type includes methods from Cosby et al. (1984), Brakensiek et al. (1984), Saxton et al. (1986), and Vereecken et al. (1990). (2) Develop a physicoempirical relationship between the particle size distribution and K_s. For this purpose Bloemen (1980) describes the particle size distribution using the median grain size M_d and a grain size distribution index (GSDI) and calculates the K_s from these two auxiliary variables. The Campbell (1985) approach is based on the assumption that the particle size distribution is approximately log normally distributed and can be represented by a geometric mean particle size (d_g) and a geometric standard deviation (σ). (3) Methods for estimating K_s in the third group are based on scaling techniques, which can be used to estimate soil hydraulic properties at different locations in a watershed from measurement of these properties at one representative location and limited data at other locations (Ahuja et al., 1984). Similar media concept (SMC) has been used widely as a general theoretical basis for many scaling practices. In this aspect, an important advancement worth mentioning is the presentation of the nonsimilar media concept (NSMC) by Miyazaki (1996). He presented a NSMC-based method of scaling K_s of soils with different bulk densities. Unfortunately, empiricism of the key parameter, i.e. shape factor characterizing NSMC, restricts the applicability of the NSMC approach to practices. Zhuang et al. (2000) proposed an analytic expression for estimating the shape factor τ. It was proved that the expression is flexible in following the physical heterogeneity of soil.

Although the first two methods used for estimating K_s perform well in many cases, there seems to be no superior and generally applicable model in these categories. Therefore, attention must first be drawn to the homogeneity of the data, i.e.; all samples must use the same determination method, and second, there must be a model for estimating K_s that is commonly calibrated on individual data sets. The scaling technique is thought to be significant to solving these problems because by using it, some systemic deviation in the measurement or some of the empirical coefficients in the regression expressions fitted using measured data can be avoided. Therefore, the main objective of this study is to compare the prediction quality of different K_s models using scaling.

MODEL DESCRIPTION

NSMC Model

Miyazaki (1996) presented a scaling model of K_s theoretically based on NSMC,

$$\frac{K_s}{K_{s0}} = \left[\frac{\left(\frac{\tau\rho_s}{\rho_b}\right)^{\frac{1}{3}}-1}{\left(\frac{\tau_0\rho_{s0}}{\rho_{b0}}\right)^{\frac{1}{3}}-1}\right]^2 \tag{1}$$

where K_{s0} is the measured saturated hydraulic conductivity of a reference sample with bulk density ρ_{b0}, K_s is the estimated saturated hydraulic conductivity of a soil sample with a bulk density ρ_b, and ρ_s and ρ_{s0} are particle densities of soils investigated and referenced, respectively. Shape factor τ was calculated by Zhuang et al. (2000) with

$$\tau = \left[\frac{\rho_{b0}}{\rho_b}\right]^{\varepsilon}$$

$$\left[1+\left(\frac{\rho_s}{\theta_r\rho_s+\rho_b}-1\right)\exp\left(d_g-d_g\left(1-\theta_r-\frac{\rho_b}{\rho_s}\right)^{-\rho_b}\right)\right]^{-1} \tag{2}$$

where

$$\theta_r = 0.015 + 0.005C + 0.014\rho_b \tag{3}$$

and

$$\varepsilon = \left(\frac{\rho_s-\rho_b}{\rho_{s0}-\rho_{b0}}\right)^{0.5} \tag{4}$$

In Eq. (3), C is the percentage content of a clay particle (<2 μm) of soil. In Eq. (2), d_g is the geometric mean particle diameter in mm, and is calculated with

$$d_g = \exp\left(\sum m_i \ln d_i\right) \tag{5}$$

where d_i is the arithmetic mean diameters for particle-size class i with a mass, m_i. By using Campbell's values, d_i is 0.001 mm for clay, 0.026 mm for silt, and 1.025 mm for sand.

Campbell and Kozeny-Carman Models

Campbell (1985) proposed an equation based on particle size distribution data and on the SMC of Miller and Miller (1956) for estimating K_s. To describe the dependence of the K_s of a soil on its bulk density and particle size distribution, Campbell model here is rewritten as follows:

$$\frac{K_s}{K_{s0}} = \left[(1.3^{b-b_0})\left(\frac{\rho_{b0}^{b_0}}{\rho_b^{b}}\right)\right]^{1.3} \exp[-6.9(C-C_0)-3.7(U-U_0)] \tag{6}$$

where C and C_0 are percentage contents of clay particle (<2 μm) of soil samples investigated and referenced, respectively, U and U_0 are percentage contents of silt (2–50 μm) of soil samples investigated and referenced, respectively. b and b_0 are parameters related to pore-size distributions of soil samples investigated and referenced, respectively, and are calculated with the following formula:

$$b=d_g^{-0.5}+0.2\delta \tag{7}$$

where δ is the geometric standard deviation of particle diameter.

Another model for K_s estimation is the Kozeny-Carman equation (Kozeny, 1927; Carman, 1937), which was given a scaling form by Miyazaki (1996):

$$\frac{K_s}{K_{s0}}=\left(\frac{\rho_{b0}}{\rho_b}\right)^2\left(\frac{\rho_s-\rho_b}{\rho_{s0}-\rho_{b0}}\right)^3 \tag{8}$$

Cosby and Vereecken Models

For the function of Cosby et al. (1984), its scaling form is

$$\frac{K_s}{K_{s0}}=10^{0.126(S-S_0)-0.0064(C-C_0)} \tag{9}$$

where S and S_0 indicate percentage content of sand (50–2000 μm) of soil samples investigated and referenced, respectively.

For the function of Vereecken et al. (1990), its scaling expression is

$$\frac{K_s}{K_{s0}}=\exp\left[-0.96\ln\left(\frac{C}{C_0}\right)-0.66\ln\left(\frac{S}{S_0}\right)-0.46\ln\left(\frac{OM}{OM_0}\right)-8.43(\rho_b-\rho_{b0})\right] \tag{10}$$

where OM and OM_0 represent contents of organic matter of soil samples investigated and referenced, respectively.

Brakensiek and Saxton Models

The expression of Brakensiek et al. (1984) is transformed into

$$\frac{K_s}{K_{s0}}=\exp(x) \tag{11}$$

with

$$\begin{aligned}x&=19.52348(\phi-\phi_0)-0.028212(C-C_0)\\&+0.00018107(S^2-S_0^2)-0.0094125(C^2-C_0^2)\\&-8.395215(\phi^2-\phi_0^2)+0.077718(\phi S-\phi_0 S_0)\\&-0.00298(S^2\phi^2-S_0^2\phi_0^2)-0.019492(C^2\phi^2\\&-C_0^2\phi_0^2)+0.0000173(S^2C-S_0^2C_0)\\&+0.02733(C^2\phi-C_0^2\phi_0)+0.001434(S^2\phi-S_0^2\phi_0)\\&-0.0000035(C^2S-C_0^2S_0)\end{aligned} \tag{12}$$

where ϕ and ϕ_0 are the total porosity of soil samples investigated and referenced, respectively.

The scaling form for the function of Saxton et al. (1986) is identical to Eq. (11), except that:

$$x=-0.0755(S-S_0)+\frac{-3.895+0.03671S-0.1103C+0.00087546C^2}{0.332-0.0007251S+0.1276\log_{10}C}-\frac{-3.895+0.03671S_0-0.1103C_0+0.00087546C_0^2}{0.332-0.0007251S_0+0.1276\log_{10}C_0} \tag{13}$$

Poulsen-Saxton Model

Poulsen et al. (1998) presented a model for estimating K_s. Its scaling form is

$$\frac{K_s}{K_{s0}}=\left(\frac{\theta_s-\theta_e}{\theta_{s0}-\theta_{e0}}\right)^{3.15}\left(\frac{\theta_{s0}}{\theta_s}\right)^{2.10} \tag{14}$$

where θ_s and θ_{s0} are the saturated volumetric water content of soil samples investigated and referenced, respectively. θ_e and θ_{e0} are the volumetric water content of soil samples investigated and referenced, respectively, at −10 kPa of water potential. To avoid the difficulty of measuring θ_s and θ_e, and to make Eq. (14) ready for predicting K_s by means of easily measured physical properties of soil, in this study we tried to replace these two parameters by the values estimated by means of the functions of Saxton (1986):

$$\theta_s=0.332-0.0007251\,S+0.1276\,Log_{10}C \tag{15}$$

and

$$\theta_e=\exp\left(\frac{2.302-\ln A}{B}\right) \tag{16}$$

with

$$\begin{aligned}A=&100\exp(-4.396-0.0715C\\&-0.000488S^2-0.00004285CS^2)\end{aligned} \tag{17}$$

and

$$B=-3.14-0.00222C^2-0.00003484CS^2 \tag{18}$$

Hereafter, we will call Eq. (14) combined with Eqs. (15) to (18) the Poulsen-Saxton model.

DATABASE AND STATISTICAL EVALUATION OF MODELS

The 402 sets of data used in this study were obtained from published articles specified in Table 1. The data sets include data such as K_s; particle-size distribution or fractions of sand, silt, and clay; and particle density and bulk density of soils with 11 types of textures from sand to heavy clay. Where data regarding particle density were not included in data sets, we adopted the usual value, 2.65 Mg m^{-3}, in the scaling processes.

The goodness of the models for scaling the K_s of various soils was evaluated by deviation times (DT), which were calculated as follows:

$$Log_{10}\,DT = \left\{\frac{1}{n}\sum_{i=1}^{n}\left[Log_{10}\left(\frac{K_s^p}{K_s}\right)\right]^2\right\}^{0.5} \quad (19)$$

where K_s, K_s^p are saturated hydraulic conductivity measured and predicted by the scaling models, respectively. A larger DT value means greater estimation deviation, and lower efficiency of the model.

TABLE 1

Sources of data used in the analyses

Reference No.	Texture	n	Sources
1	SCL—SiL	10	Ma et al. (1998)
2	S	8	Laboski et al. (1998)
3	HC	10	Kim et al. (1999)
4	L—SC	22	Zhuang et al. (2000)
5	SL—CL	30	Ohnuki and Yoshinaga (1995)
6	LS—SCL	42	Puckett et al. (1985)
7	LS—Si	20	Toyomitsu et al. (1996)
8	SC	20	Hayano et al. (1997)
9	LS	7	Coultas and Calhoun (1976)
10	SL	4	Yabe et al. (1992)
11	LS—Si	4	Rudolf et al. (1990)
12	S	6	Wu et al. (1996)
13	Si	4	Mwendera and Feyen (1993)
14	SiC	5	McAfee et al. (1989)
15	LS—SCL	5	Olaolu (1978)
16	LS—CL	8	Onstad et al. (1984)
17	L	7	Kanwar et al. (1985)
18	SCL—SC	27	Southard and Buol (1988)
19	SL—C	10	Radcliffe et al. (1990)
20	SL—Si	14	Habecker et al. (1990)
21	LS	6	Dane (1980)
22	SCL—C	27	John et al. (1985)
23	SL	10	Jeong et al. (1994a)
24	SCL—SiC	8	Jeong et al. (1994b)
25	S—C	90	Grismer (1989)

S: sand; L: loam; C: clay; Si: silt; LS: loamy sand; SL: sandy loam; SiL: silty loam; SiC: silty clay; SCL: sandy clay loam; CL: caly loam. HC: heavy clay. n indicates number of data.

RESULTS AND DISCUSSION

Estimation Accuracy

Figure 1 shows how well the eight models performed in scaling K_s of soils with textures ranging from heavy clay to sand. Table 2 lists DT values of the eight models in scaling K_s of the 402 soil samples from 25 references. From these results, it can be seen that different models had different accuracy in scaling K_s. Generally speaking, for soils of all textures, NSMC models had smallest estimation deviation in terms of the mean DT, but some models were superior to NSMC models for some specific soils. The second best model was Kozeny-Carman's, whereas models of Cosby and Saxton ranked third. Models of Poulsen-Saxton (P-S) and Campbell had larger DT values compared with other models, including Vereecken's and Brakensiek's models. For the Campbell model, the large estimation deviation, especially when scaling K_s of clayey soils, presumably resulted from the unfeasibility of use of the parameter, *b*, because *b* trends to become unusually large in the case of clayey soil. For the worst performance of Poulsen-Saxton (P-S) model, it is difficult to distinguish which of the followings, such as inaccurate estimations of θ_s and θ_e by means of Eq. (15) to (18), and inflexibility of Eq. (14) presented by Poulsen, resulted in the larger estimation deviation of K_s. Unlike other models, the Cosby, Saxton, and Poulsen-Saxton models do not have bulk density or porosity as a factor in the scaling processes; thus, their sometimes superior performances, especially for the Cosby and Saxton models, should be attributable to the better quality of the empirical regression pedo-transfer functions (Cosby et al., 1984; Saxton et al., 1986). Nevertheless, values of the DT could presumably be reduced by integrating additional independent variables, such as bulk density and organic matter content of soil, into the K_s models. Therefore, NSMC, Kozeny-Carman, Vereecken, and Brakensiek models should be recommended for use in investigations of K_s in fields or watersheds or to underlie the approaches to developing new models for estimating K_s in the future.

Selection of Reference Points of Scaling

A measured reference point is one of the components essential for the scaling process. Adoption of this reference point could alleviate systematic error. It is, however, worth under-

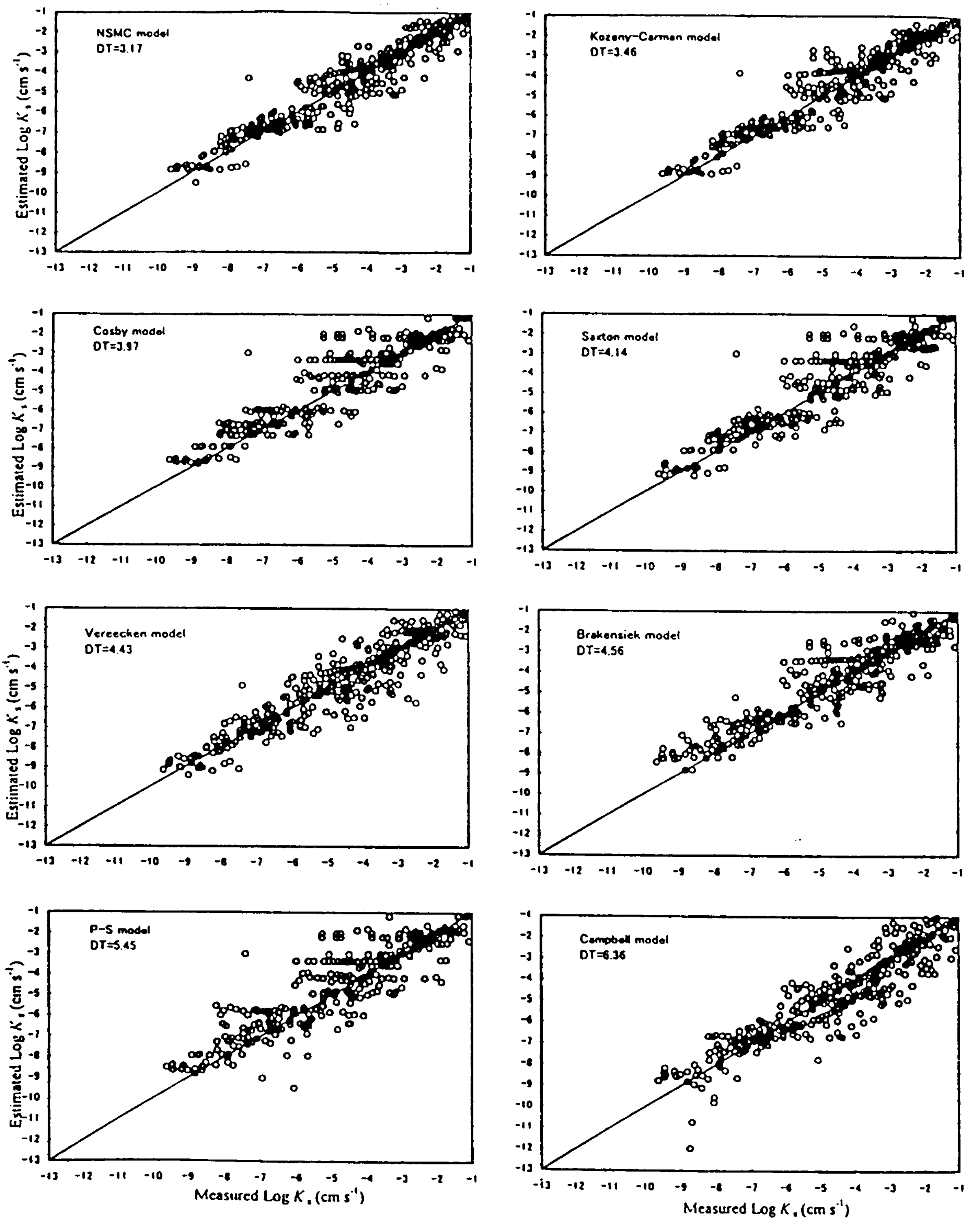

Fig. 1. Comparison of values of LogK_s measured and estimated by means of the eight models

standing whether any point is suitable to act as a reference point, or what differences would be introduced for the ultimate estimation results caused by adoption of different reference points. In this study, two types of data sets were involved: (i) that soil samples have identical texture but different bulk densities; (ii) that soil samples are different both in texture and in bulk density. The data of the latter type were obtained for soil samples collected from soil profiles in fields or from watersheds.

For the first type of data sets, Fig. 2 compares differences caused by using different reference points to scale K_s from various models. When

TABLE 2

Values of deviation times (DT) of K_s estimated by various models with scaling method

Reference No.	NSMC	Kozeny-Carman	Cosby	Saxton	Vereecken	Brakensiek	Poulsen-Saxton	Campbell
1	1.77	2.61	1.94	2.22	2.05	2.86	5.41	2.44
2	1.30	1.36	1.29	1.35	1.44	1.35	1.26	1.29
3	3.13	4.15	3.37	3.37	3.53	6.41	3.37	3646.70
4	5.47	25.00	53.04	53.04	5.72	25.64	53.04	78.02
5	3.20	3.39	2.80	4.03	4.07	4.01	4.51	10.12
6	3.19	3.20	3.23	3.01	3.45	4.93	3.56	3.40
7	6.45	6.84	6.44	6.15	11.17	6.77	7.50	7.97
8	2.43	15.87	21.98	21.98	4.69	19.84	21.98	5.02
9	7.31	7.60	18.10	18.85	233.94	7.96	17.97	11.52
10	1.98	1.99	1.76	2.57	2.63	2.23	1.61	2.30
11	1.87	1.75	1.91	2.01	3.34	9.14	67.10	4.15
12	1.47	1.44	1.64	1.65	1.50	1.68	1.73	3.14
13	6.61	1.51	1.33	1.33	3.20	1.94	1.33	2.51
14	2.36	2.42	3.16	3.07	2.18	2.30	2.26	2.56
15	1.75	1.70	1.41	3.07	2.94	7.71	1.63	5.48
16	4.30	4.19	2.45	2.53	5.39	2.20	2.53	3.69
17	2.34	2.04	1.54	1.96	3.38	2.70	1.52	2.47
18	9.68	9.64	7.26	7.81	11.08	6.58	6.89	7.24
19	2.13	2.12	2.40	3.43	2.56	4.57	2.21	3.54
20	3.18	3.12	12.14	7.27	4.74	9.66	75.18	8.38
21	1.93	1.92	2.14	1.87	2.79	1.93	2.47	2.00
22	5.65	6.43	11.83	11.83	10.29	4.13	11.83	24.80
23	2.16	1.43	1.44	1.27	2.44	1.39	1.68	2.22
24	6.41	6.15	14.13	9.15	5.16	18.43	27.00	7.88
25	5.06	5.02	6.79	6.24	5.85	5.40	8.29	4.78
Mean	3.17	3.46	3.97	4.14	4.43	4.56	5.45	6.36

using the soil sample with minimum bulk density as a reference point, NSMC and Vereecken models clearly performed best, whereas Campbell and Brakensiek models had larger deviations. In comparison, when using a reference point whose bulk density approximates the averaged bulk density of the soil samples from one of the reference sources, values of the DT of NSMC and Vereecken models increased (Fig. 2B). Scaling accuracy of other models was improved. In Fig. 2C, the sample with maximum bulk density was used as reference point. It can easily be seen that scaling efficiency of all models decreased, but the Vereecken model still performed better than others. To sum up, for NSMC models, it would be better to select soil samples with minimum bulk density or any samples whose bulk density is smaller than the average bulk density of all samples as a reference point. Vereecken model had situation similar to that of NSMC model. For Campbell, Kozeny-Carman and Brakensiek models, it seemed to be better to use sample whose bulk density approximates the averaged value of all samples as a reference point when scaling K_s.

For the second type of data sets used in the scaling process of this study, we used samples whose clay content approximated the averaged clay content of soil samples of the individual reference sources as a reference point. Our purpose was that using samples with either the most or least clay particles would increase the estimation deviation of K_s.

Adaptability of the Scaling Models to Textures

Table 1 shows that most soil textures, from sand to heavy clay, were used in this study. Since hydraulic models are usually texture adaptable, adaptability of the eight scaling models to soil textures was examined. In the evaluation, the parameter, $Log(K_s^p/K_s)$, was used. Results are listed in Table 3 against the geometric mean diameter (d_g) of soil particles. Evidently, most of the eight models performed better for soils with d_g larger than 0.4 mm. This value is actually equivalent for soil textures such as sand or loamy sand. In the case of estimating the K_s of loamy soil, different models were shown with different adaptability to soil textures. In Table 3, one point worth noting is that all eight models had smaller deviations in estimating the K_s of soils with texture of sandy clay loam. The reason for this remains unknown.

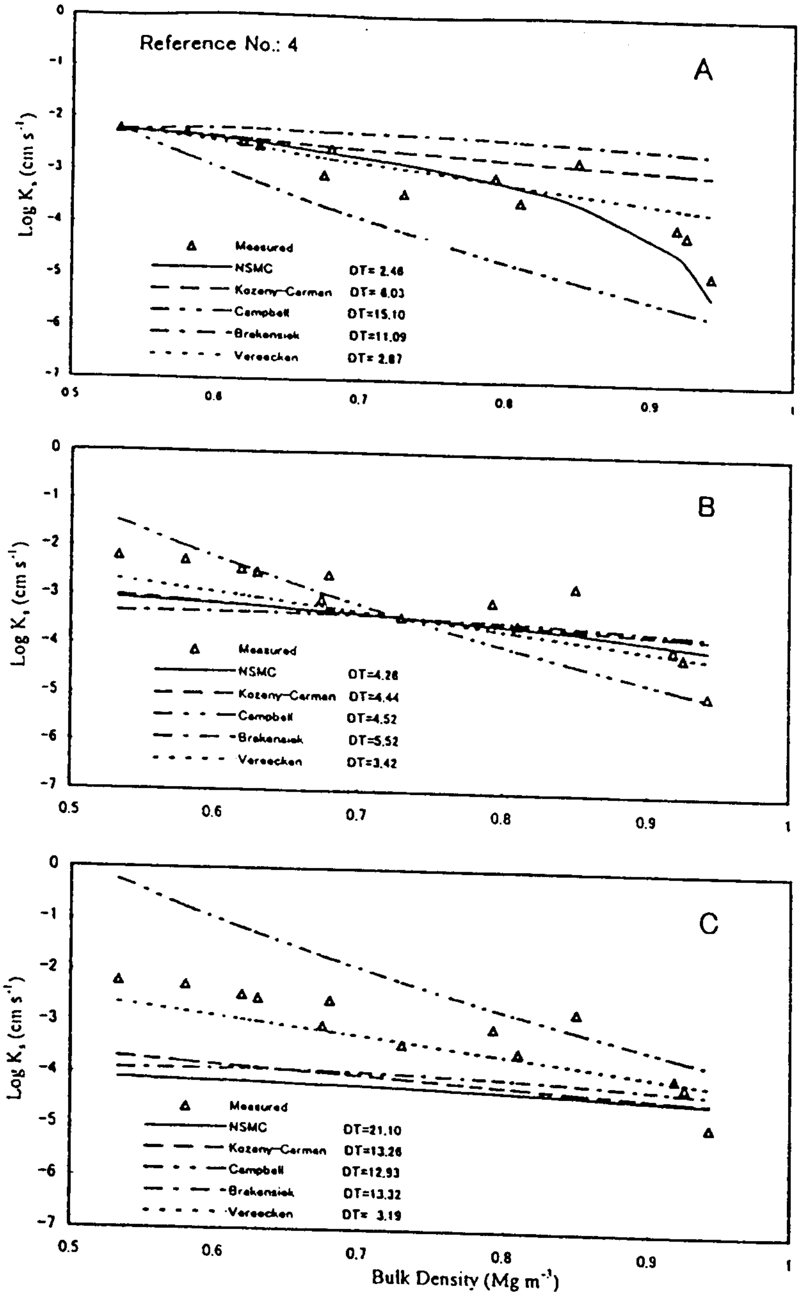

Fig. 2. Effects of selection of reference sample in terms of bulk density of soil on results of K_s estimated by various models. A: minimum bulk density; B: averaged bulk density; C: maximum bulk density.

For clayey soils whose d_g are smaller than 0.01 mm, it was difficult to obtain accurate estimations of K_s by means of the models. For example, most of models tended to overestimate the values of K_s, whereas the Campbell model was found to more likely result in substantial underestimation. This is assumed to be the result of the neglect of the soil structural regime in the formulation of the models. The pore size, shape, and orientation of soils, especially heavy soils, depend substantially on soil structural regime and bulk density. Soil structures can produce many coarse pores and, as a result, are prime factors influencing hydraulic conductivity. Therefore, to incorporate bulk density into the specific matching factors is, undoubtedly, conducive to reducing the variability of the K_s predicted by the individual models. This was evidenced further by the comparison results of the models in this study. Thus, NSMC, Kozeny-Carman, Vereeçken, and Brakensiek models should be recommended for use in the modeling practices of soil hydraulics, or for preferential improvements in the future. To incorporate soil structural regimes into the present models for K_s

TABLE 3

Values of $Log(K_s^p / K_s)$ of the eight models for soils with different d_g

d_g (mm)	NSMC	Kozeny-Carman	Campbell	Cosby	Saxton	Brakensiek	Vereecken	Poulsen-Saxton
< 0.01	0.295	0.357	−1.570	0.624	0.625	0.315	0.068	0.493
0.01–0.02	0.162	0.402	− 0.526	0.570	0.577	0.493	0.246	0.558
0.02–0.03	0.039	0.050	0.176	− 0.116	− 0.208	− 0.171	0.034	− 0.184
0.03–0.04	− 0.064	0.164	0.066	0.214	0.143	0.195	0.051	0.212
0.04–0.05	− 0.222	− 0.176	− 0.168	− 0.112	− 0.299	− 0.091	− 0.340	− 0.121
0.05–0.06	− 0.230	− 0.105	− 0.255	0.260	0.115	0.048	− 0.472	0.330
0.06–0.10	− 0.041	− 0.047	− 0.012	− 0.011	− 0.084	0.083	− 0.135	0.041
0.10–0.20	0.235	0.180	0.060	0.267	0.124	0.190	0.001	0.385
0.20–0.40	0.081	− 0.038	0.104	0.405	0.390	0.436	− 0.347	0.471
0.40–0.70	− 0.139	− 0.159	− 0.018	0.025	0.030	0.150	− 0.249	0.133
0.70–1.00	0.071	0.070	0.106	0.096	0.115	0.106	0.119	0.075

*Different values of d_g are equivalent to different soil textures. For example, < 0.01 mm—Clay; 0.01–0.02 mm—Silty clay loam; 0.02–0.03 mm—Silt to Clay loam; 0.03–0.04 mm—Silty loam; 0.04–0.05 mm—Sandy clay; 0.05–0.06 mm—Loam; 0.06–0.10 mm—Sandy clay loam; 0.10–0.20 mm—Sandy loam; 0.20–0.40 mm—Sandy loam to Loamy sand; 0.40–0.70 mm—Loamy sand to Sand; 0.70–1.00 mm—Sand.

estimation is a research topic that should be emphasized for improving model quality.

CONCLUSION

To reduce the systematic errors resulting from measuring methods or the inherent uncertainty of the models for estimating K_s, the reliability of the eight models for scaling K_s was tested. Although none of the tested models had a consistently better prediction for all textural classes, NSMC models generally performed best. The second best model was shown to be Kozeny-Carman model, followed by Saxton, Cosby, Vereecken and Brakensiek models. Unfortunately, Campbell and Poulsen-Saxton models were found unsuitable to a scaling practice, especially for soil samples that include wide textural classes.

In addition, because of inherent drawbacks in the models—even the NSMC and Kozeny-Carman models—selection of the reference point for scaling K_s still exerts a significant influence on the resulting prediction of K_s. The results of this study showed that it would be better to select a sample with the average characteristics of the samples as a reference point, but for NSMC models, when the texture is identical for all samples, the sample with minimum bulk density should be taken as the reference point.

ACKNOWLEDGMENTS

This work was supported by a postdoctoral fellowship from the Japan Society for the Promotion of Science (JSPS). We are also grateful to "The Hundred-Talents Program" of The Chinese Academy of Sciences for support of this research project.

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