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Can the Volume Ratio of Coarse to Fine Particles Explain the Hydraulic Properties of Sandy Soil?

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Hydraulic conductivity (K_s) and effective porosity (ϕ_{eff}) for saturated water flow are essential hydraulic properties for describing fluid and chemical transport in soil and groundwater systems. Typically, K_s is predicted by pedotransfer functions of soil texture and total porosity or ϕ_{eff}. This study shows that a more conceptual approach that uses a volume-weighted ratio of coarser (part of the sand fraction) to finer (clay and organic matter) particles alongside total porosity could explain variations in both K_s and ϕ_{eff} in intact 100-cm^3 samples of 20 sandy surface and subsurface soils with <10% fines (clay + organic matter). The K_s function used was a simple power-law function of the volume-weighted coarse/fine particle ratio with two calibration parameters [A and pore network connectivity (P_{NC})]. The value of the power-law exponent (P_{NC}) in the calibrated function was 1.8, similar to power-law exponents for gas diffusivity and air permeability in unsaturated soil (1.5–2). The second calibration parameter (A) probably depends on the soil classes under consideration, the K_s measurement method, and the sample scale. A sensitivity analyses showed that both K_s and ϕ_{eff} (taken as the volume content of pores larger than 30 µm, that is, drained at –10 kPa of soil water matric potential) are especially sensitive to organic matter content. Besides the water transport parameters, water retention under dry conditions was also closely correlated with the volume-weighted fines content. Therefore, the volume ratio concept seems to be a promising platform for the development of simple, accurate functions for the hydraulic properties of coarse-textured soils.

Abbreviations: ADW$_{50}$, air-dry water content at 50% relative humidity; AIC, Akaike's information criterion; CL, clay fraction; CS, course sand fraction; FS, fine sand fraction; Fvw, volume-weighted fines; K_s, saturated hydraulic conductivity; NSE, Nash–Sutcliffe model efficiency coefficient; OM, organic matter; R_{CF} function; model derived from the ratio of coarse to fine fractions; RMSE, root mean squared error; P$_{NC}$, pore network connectivity; ϕ_{eff}, effective porosity.

S aturated K_s is fundamental for understanding fluid flow in porous media, such as infiltration through topsoil or groundwater movement. Hydrologists base their essential environmental decisions on models of projected K_s. As K_s can span many orders of magnitude, precise estimates of K_s are of critical importance for the suitability and accuracy of any model of water and solute movement. Unfortunately, measurement of K_s is often impractical and, consequently, the literature has presented numerous attempts to predict K_s on the basis of more readily available soil data (Shepherd, 1989).

Hydraulic conductivity represents the ability (or the resistance) to transmit a fluid and it is highly controlled by the soil pore space and soil properties (e.g., texture and bulk density). Characterization of the pore size distribution is to be preferred over that of the particle size distribution; however, the pore size distribution is rarely known and is usually more problematic to obtain than K_s. The particle size distribution has a similar curve to the pore size distribution and, as such,

Core Ideas

- The volume ratio of large to small particles controls intact sand hydraulic properties.

- Simple model explained sand saturated hydraulic conductivity within a factor of two.

- The new concept was also related to effective porosity and water retention points.

- Soil mineral particles larger than 0.1 mm and organic matter need to be considered.

- The volume ratio concepts seem promising for developing pedotransfer functions.

numerous studies use it to obtain K_s. The literature contains several different methods of obtaining K_s from texture. These methods consist of (i) texture fractions or the particle size distribution only (e.g., Alyamani and Sen, 1993; Hazen, 1892; Puckett et al., 1985), (ii) the porosity or the bulk density in addition to the particle size distribution (e.g., Rawls and Brakensiek, 1989; Revil and Cathles, 1999), and (iii) the ϕ_{eff} or active porosity (e.g., Ahuja et al., 1989; Arthur et al., 2012; Schaap et al., 1998).

The ϕ_{eff} for saturated water flow is the pore space contributing to the main water movement (in other words, the pore space with the largest pore radii) and is commonly defined as being close to 'field capacity' around −5 to −33 kPa (Al Majou et al., 2008; Assouline and Or, 2014). Though including the ϕ_{eff} in K_s models evidently increases the predictive accuracy (Schaap et al., 1998), ϕ_{eff} is also fundamental in controlling other soil properties such as gas diffusivity and air permeability (Deepagoda et al., 2011). Unfortunately, ϕ_{eff} is problematic to obtain, as it requires information about the ability of the soil to retain water.

Soil organic matter (OM) is also included in various models to predict the K_s, as OM may contribute to higher K_s because of its effect on structural formation, such as supporting the stability of aggregates (Tisdall and Oades, 1982). However, the degree of aggregation and the resulting macropores are usually attributed to clay particles and not necessarily to OM (Horn et al., 1994). The content of OM in the soil is known to increase the specific surface area and water retention (Arthur et al., 2015; Jensen et al., 2015) and, as a result, several studies have found OM and K_s to be negatively correlated (e.g., Nemes et al., 2005; Wösten et al., 1999). For sandy soils with limited or no aggregation, the particle size distribution and the particle arrangement mainly control the K_s. Large particles leave behind large pores, and small particles create small pores (Arya and Paris, 1981). Since a soil matrix is a mix of large and small pores, the pore sizes, and thereby the ϕ_{eff} for sandy soils, are likely to be related to the ratio between large and small particles.

Soil texture is considered to be one of the easier accessible soil properties to measure compared with the soil hydraulic properties, but more theoretical K_s models also include the particle surface areas, such as the well-known Kozeny–Carman equation. The specific surface area is rarely available; however, several studies have found that there is a strong relationship between the water adsorbed to the soil particles under air-dry conditions (≤ -10,000 kPa) and the specific surface area (e.g., Arthur et al., 2013; Resurreccion et al., 2011), and between the air-dry soil water content, and the clay and OM content (e.g., Poeplau et al., 2015; Wäldchen et al., 2012).

The main objective of this study was to present a new concept for descriptions of K_s and ϕ_{eff} for sandy soils by using a volumetric-based ratio between the fine (mineral and organic) and coarse particles of the soil.

MATERIALS AND METHODS

Two datasets were used for data analysis. The first dataset consisted of 20 soil samples from the Danish Soil Library (Hansen, 1976) and supplementary materials selected on the basis of their content of fines (OM + clay) between 2 and 10%. The soils are intact soils from arable land representing sandy agricultural soils across Denmark. At each sampling location, intact soil cores of 100 cm³ were collected together with bulk soil. The intact cores were used to determine soil water retention, saturated K_s, and bulk density, and the bulk soil was used to determine organic C and texture. Table 1 presents the ranges of the physical soil parameters of Dataset 1. Additionally, to determine the air-dry water content, a second soil dataset was used, comprising 45 bulk soils, 15 from Dataset 1 and 30 from other locations in Denmark (de Jonge et al., 2004; Moldrup et al., 2001; Olesen et al., 1999). Table 2 presents the ranges of the soil physical parameters of Dataset 2.

Soil water retention data for determining ϕ_{eff} were measured in hanging water columns connected to sandboxes at −10 kPa as described by Dane and Hopmans (2002). The matric potential at air-dry conditions was determined on bulk samples that had been kept in a humidity controlled room (50% relative humidity) for several weeks to ensure equilibrium, and the corresponding water content was determined by oven-drying the samples at 105°C for 24 h. Saturated K_s was performed bottom-up at 20°C following a similar concept described by Klute and Dirksen (1986), with values ranging across two orders of magnitude from 6 to 352 μm s⁻¹ (Table 1).

The total soil organic C was determined on a LECO C analyzer (LECO Corporation, St. Joseph, MI) coupled to an infrared CO_2 detector. Soil texture was determined by a combination of hydrometer methods and mechanical sieving (Gee and Or, 2002), following the International Soil Science Society standards where the silt fraction is 2 to 20 μm, fine sand is 20 to 200 μm, and coarse sand is 200 to 2000 μm. Table 1 gives the ranges for the different texture fractions and OM. The bulk density was determined by oven-drying the soil samples at 105°C for 24 h, and the bulk density varied from 1.36 to 1.71 g cm⁻³.

Table 1. Ranges of soil physical parameters for Dataset 1 (20 soils) used to develop functions for saturated hydraulic conductivity and effective porosity.

Parameter	Min.	Max.	Mean
Bulk density, g cm⁻³	1.36	1.71	1.49
Total porosity, m³ m⁻³	0.368	0.483	0.437
Effective porosity at −10 kPa, m³ m⁻³	0.10	0.366	0.234
Clay content, %	1.6	7.6	4.4
Organic matter content, %	0.30	4.10	1.73
Fine sand, %	6.8	93.6	44.0
Coarse sand, %	0.4	82.0	45.4
Saturated hydraulic conductivity, μm s⁻¹	6.0	352	74.2

Table 2. Ranges of soil physical parameters for Dataset 2 (45 soils) used to develop a function for air-dry soil water retention.

Parameter	Min.	Max.	Mean
Air dry water content at 50% relative humidity, %	0.2	3.7	1.2
Clay content, %	1.6	38.2	11.8
Organic matter content, %	0.3	3.3	1.5

Model Development and Theoretical Considerations

Pedotransfer functions for K_s typically include finer particles such as the clay content or the finest 10% of the total particle size distribution because of their pore network blocking ability and their contribution to the formation of aggregates (Cronican and Gribb, 2004; Horn et al., 1994). On the basis of soil samples collected from both top and subsurface soils consisting of 1 to 41% clay content, Puckett et al. (1985) found a strong exponential correlation between clay content and K_s:

$$K_s = 43.6\exp\left(-0.1975\text{CL}\right), \qquad [1]$$

where K_s is given as $\mu m \ s^{-1}$ and CL is the gravimetric clay content (kg kg^{-1}). Although using a single texture parameter may provide estimations within a few orders of magnitude of the actual value, it should not be able to describe the dynamics of the K_s within a texture group (such as sandy soils).

Hydraulic conductivity is a function of the soil matrix, and the soil matrix includes assorted particle sizes and shapes, structures such as aggregates, compaction, and particle arrangements. Bulk density or porosity comprises the compaction, and sandy soils have a limited degree of aggregates (i.e., the sandy soils are more or less structure-free). The new concept for predicting K_s for sandy soils is based on the consideration that K_s can be expressed as a ratio between the large particles (sand) and the fines (clay and OM). The sand particles promote the built-up of well-connected active pore networks, whereas the fines block the network. The sand fraction comprises a large particle size range (20–2000 μm) and, as such, sand alone cannot describe the dynamics and variation of K_s for sandy soils, and thus it is necessary to separate the sand fractions into elements and only include the particles that contribute as facilitators of the active pore network. We therefore suggest a power function for K_s based on the ratio between coarse and fine particles, where (i) the nominator includes the coarse sand fraction and a part (the larger particles) of the fine sand fraction; (ii) the denominator includes the clay fraction and the OM fraction, the latter normalized for the lower density of organics compared with minerals; and (iii) the power function is multiplied by a term that takes both unit conversion and the compaction level (in form of the soil total porosity) into account. The resulting equation for K_s is written as:

$$K_s = A\phi\left(\frac{\text{CS}+B\text{FS}}{\text{CL}+R_D\text{OM}}\right)^{P_{\text{NC}}}, \qquad [2]$$

where ϕ is the total porosity (m^3 m^{-3}); CS, FS, CL, and OM are the fractions of coarse sand, fine sand, clay, and OM respectively (kg kg^{-1}), and A and P_{NC} are the fitting parameters, where P_{NC} is the pore network connectivity parameter describing the mixing of fine and large particles and the tortuosity. The parameter B indicates the particle sizes considered within the fine sand fractions (20–200 μm), and R_D indicates the relative density, considering that OM has a lower specific gravity than the solid particles.

Depending on the degree of compaction, the pore size is expected to be typically ~20% of the particle size (Hamamoto et al., 2011). The ϕ_{eff} for sandy soils is positively correlated to the K_s, and the ϕ_{eff} is expected to be close to the air-filled pore space under field conditions, defined as –10 kPa, corresponding to a minimum pore size contributing to the main flow of water of 30 μm (Al Majou et al., 2008; Assouline and Or, 2014). The particles of fine sand (20–200 μm) consist of particles contributing to both pore spaces above and below 30 μm. Using the assumption of pore size being around one-fifth of particle size (Hamamoto et al., 2011), the new K_s concept only considers the particles above 150 μm to form pores larger than 30 μm. Therefore, the B parameter (part of the fine sand fraction considered in the model) is set to 25% ($B = 0.25$).

Although studies typically use gravimetric considerations of the texture to describe K_s and pore space (Arya and Paris, 1981; Cronican and Gribb, 2004), several studies have found that because of the lower specific gravity of OM, a volumetric consideration of OM is preferable to gravimetric because of its large influence on water retention and specific surface area (Jensen et al., 2015; Moldrup et al., 2007; Naveed et al., 2012). On the basis of these assumptions, the ratio of fine and coarse particles affecting the active pores can be given as:

$$R_{CF} = \left(\frac{\text{CS}+0.25\text{FS}}{\text{CL}+2.65\text{OM}}\right), \qquad [3]$$

where 2.65 (the ratio of densities, R_D, in Eq. [2]) accounts for OM having a specific gravity of 1 g cm^{-3} compared with the soil particles of 2.65 g cm^{-3}. This will correspond to assuming silicate clays with a particle density similar to that of quartz. We note that this value may need to be adjusted if other types of clay minerals are dominant.

The new concept for predicting K_s from the ratio between coarse and fine particles is then given as:

$$K_s = A\phi\left(R_{CF}\right)^{P_{\text{NC}}} \qquad [4]$$

Equation [4] is hereafter denoted as the R_{CF} function. The least squares method was used to obtain the best fit for fitting parameter A and the pore network connectivity parameter P_{NC} of Eq. [4] (the R_{CF} model).

Statistical Analyses

Three statistical performance measures were used to compare and evaluate the K_s functions: Akaike's information criterion (AIC), the Nash–Sutcliffe model efficiency coefficient (NSE), and the root mean squared error (RMSE). These performance measures were chosen because they complement each other. Any performance measure has pros and cons, thus it is difficult to use only a single measure to evaluate and compare performances objectively across models.

The AIC takes the number of model parameters into account. When model complexity is increased by including more model parameters, the more complex model will typically yield a

better fit to the observations. However, the better fit might just be a result of overconditioning, caused by the increased number of degrees of model freedom. This complicates objective comparisons across models with different numbers of model parameters, so the AIC measure addresses this issue (Akaike, 1973; Carrera and Neuman, 1986; Hwang et al., 2002):

$$AIC = n\left\{\ln(2\pi) + \ln\left[\frac{\sum_{i=1}^{n}(M_i - O_i)^2}{n-k}\right] + 1\right\} + k \qquad [5]$$

where M is the model prediction, O is the observed measurement, k is the number of model parameters, and n is the number of observations and corresponding model predictions. The AIC is a relative measure conditional on the dataset. It ranges from $-\infty$ to ∞, whereas a smaller or more negative AIC indicates better model performance. Because the AIC measure is relative, the measure is not useable between datasets and thus the evaluated models have to be tested on identical observational data. The AIC has been used in a number of studies developing and comparing pedotransfer functions for soil fluid phase parameters, including soil water retention (Minasny et al., 1999) and the soil–gas diffusion coefficient (Moldrup et al., 2004).

The NSE performance measure does not account for the number of model parameters but, in contrast to the AIC, the NSE expresses an absolute measure of model performance (Moriasi et al., 2007; Nash and Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(M_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad [6]$$

where M is the model prediction, O is the observed measurement, and n is the number of observations and corresponding model predictions. The NSE has methodical similarities to the coefficient of determination R^2 obtained from simple linear regression. However, the NSE evaluates performance according to the bisector line (the 1:1 line in a scatter-plot); consequently, the NSE punishes systematic model bias, unlike R^2. The NSE ranges from $-\infty$ to 1, where NSE = 1 is a perfect match between the model and observations, NSE = 0 tells us that the model predictions are just as accurate as the mean of the observations, and if NSE is negative, it is better to use the mean value of the observations as a predictor rather than the model itself.

The NSE expresses the model's performance without information about the model's uncertainty. As compensation, the RMSE of prediction is used to evaluate the average prediction uncertainty (Hyndman and Koehler, 2006):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2} \qquad [7]$$

where M is the model prediction, O is the observed measurement, and n is the number of observations and the corresponding model predictions. The RMSE is a widely used measure of accuracy and is useful when comparing model performance.

However, the measure is scale-dependent, which complicates comparisons between datasets with different scales.

RESULTS AND DISCUSSION
Volume-Based Ratio of Coarse to Fine Particles and its Impact on Hydraulic Properties

The sand fraction covers a wide range of particle sizes, and the corresponding pore sizes and pore networks contributing to the main water movement are, for sandy soils, primarily controlled by the largest particles of a soil matrix. If we compare the sandy soils from Dataset 1 (Table 1) and the model by Puckett et al. (1985) Eq. [1], Fig. 1a confirms that although the model was accurate for some of the soils, a K_s model that only includes the finest particle fraction cannot differentiate between coarse and fine sandy soils. For this model, the largest deviation between modeled and observed K_s was found for the soils with the highest content of coarse sand.

Figure 1b shows the fit of measured versus predicted $\log(K_s)$ grouped by coarse sand and OM, and the best-fit parameters were found to be 3.1 and 1.8 for A and P_{NC}, respectively (see Table 3). Equation [8] gives the calibrated function for describing K_s:

$$K_s = 3.1\phi\left(\frac{CS + 0.25FS}{CL + 2.65OM}\right)^{1.8} \qquad [8]$$

As we have a near perfect match between modeled and measured (NSE = 0.91) and an accuracy of RMSE = 0.15, it is evident that using a ratio of coarse and fine particles to describe the active pore space for the main water flow enables the possibility of describing the dynamics of K_s values. The pore network connectivity parameter P_{NC} is a function that relates to the mixing of large and small particles and to the water flow network (tortuosity). The calibrated value was 1.8, which resembles the findings of similar power functions of active pore space describing pore connectivity and tortuosity for convection and diffusion in porous media, with P_{NC} usually being around 2 (e.g., Hazen, 1892; Moldrup et al., 2000; 2007). Note that the value of A (3.1) is specifically for Dataset 1. It is well known that K_s depends on both the measurement method and the sample scale (Dane and Hopmans, 2002), and will also be related to the interval of texture (soil classes) considered. Therefore, the high accuracy for the R_{CF} function seen in Fig. 1b and Table 3 is promising as a proof of concept but does not represent a general model for predicting K_s across soil type, measurement methods, and scales. In addition, in the case of a layered or stratified soil or groundwater system, the K_s should be evaluated for each layer with the layer-specific texture and total porosity. A harmonic mean of K_s can then be used to describe the effective K_s for the entire sandy soil or groundwater system.

The soils with the largest OM content were found at the lower half of the K_s values compared with the soils with less OM. The reasoning for the negative correlation between K_s and OM is probably caused by its impact on pore size distribution, which agrees with similar findings by Nemes et al. (2005). In Fig. 1c, the R_{CF} function was fitted to the K_s data when OM was not
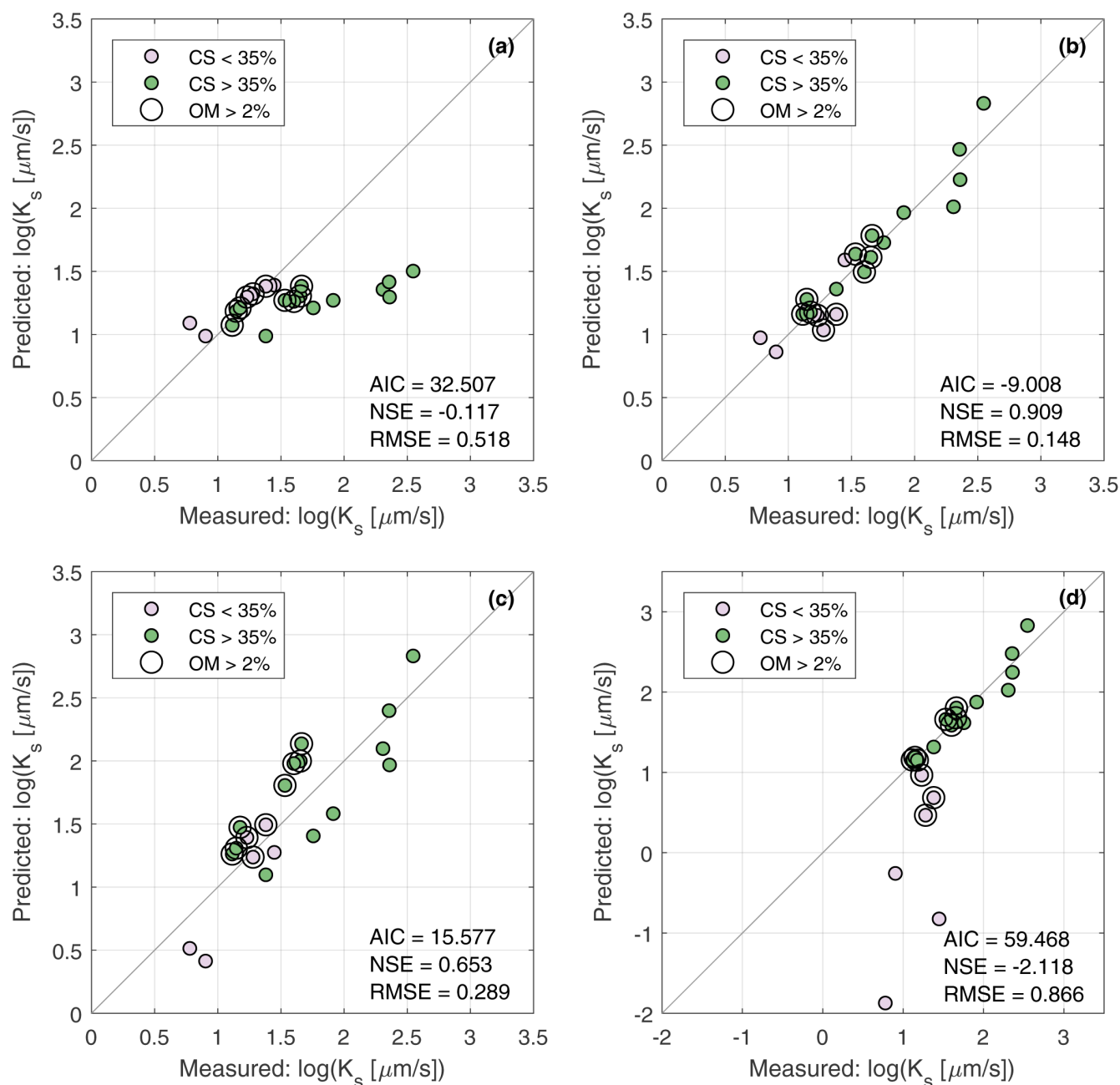
Fig. 1. Comparison of measured and predicted saturated hydraulic conductivity (K_s) grouped by coarse sand and organic matter (OM) for (a) the Puckett model (Eq. [1]), (b) the coarse–fine ratio (R_{CF}) model (Eq. [2]), (c) the R_{CF} model without OM as input (setting $R_D = 0$ in Eq.[2]), and (d) the R_{CF} model without fine sand as input (setting $B = 0$ in Eq. [2]). Akaike's information criterion (AIC), the Nash–Sutcliffe model efficiency coefficient (NSE), and root mean square error (RMSE) are error indices, given in Eq. [5–7], respectively.

included as an input parameter (setting $R_D = 0$ in Eq. [2] and thus omitting the term 2.65OM in Eq. [3]). The results show that the prediction accuracy is lower (NSE = 0.653, RMSE = 0.289), and it is more likely to overpredict the K_s for the soils with large OM content.

Similarly, the R_{CF} function was tested without the input of fine sand particles (setting $B = 0$ in Eq. [2] and thus omitting the term 0.25FS in Eq. [3]) to evaluate whether fine sand is compulsory as an input parameter, as this fraction creates considerably smaller pores than the coarse sand. The model result (Fig. 1d) showed a lack of ability to capture the dynamics and variability of K_s for soils with <35% coarse sand, and the results resemble

that of the Puckett model (Fig. 1a, Eq. [1]). This further supports that particles >150 µm are the ones that mainly create the active water flow pores.

Table 3. Optimized (P_{NC} and A) and preset (B and R_D) parameter values for the new saturated hydraulic conductivity model concept [Eq. 2], based on the 20 soils from Dataset 1 (Table 1).

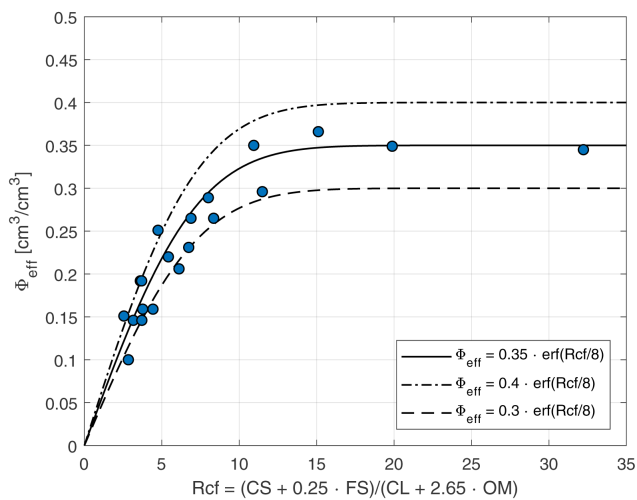| Model	Parameter values				Figure number
	P_{NC}	A	B	R_D	
Primary model	1.8	3.1	0.25	2.65	1b
Omitting organic matter	2.0	0.56	0.25	0	1c
Omitting fine sand	1.7	4.7	0	2.65	1d

Fig. 2. Effective porosity (ϕ_{eff}) as a function of the ratio between the coarse and fine particles (R_{CF}; Eq. [3]). The three model curves are the ϕ_{eff} function (Eq. [9]) with a total porosity of 0.3, 0.35, and 0.4 cm³ cm⁻³, respectively.

Table 3 gives the optimized parameter values for the three different versions of the new concept. Based on model accuracy evaluated by the NSE and RMSE (Table 3), we conclude that both fine sand and OM (because of their network blocking and water-holding ability) are imperative for correctly describing the saturated K_s of sandy soils.

Effective Porosity and Model Sensitivity

The ϕ_{eff} is defined as the pore space of the main water flow, and a strong correlation between the ϕ_{eff} and K_s has been found. In this study, we proposed that pores larger than 30 μm control the pore space contributing to the main flow, corresponding to −10 kPa. The ϕ_{eff} showed a quite wide range, from about 0.1 to 0.4 m³ m⁻³.

We hypothesize there is also a relationship between the ϕ_{eff} for saturated water flow and the interaction between the coarse and fine particles. When R_{CF} is small, the soil consists of mostly fine pores and particles, and the resulting ϕ_{eff} is small; when R_{CF} is large, the soil is coarse textured and, as such, the ϕ_{eff} is large with the total porosity as upper limit. Because of the steep observed increase in ϕ_{eff} at lower R_{CF} values followed by an almost constant ϕ_{eff} at higher R_{CF} values, we found that the ϕ_{eff} was best described by the error function (*erf*) of R_{CF} (see Fig. 2). The best fitting equation Eq. [9] gives the ϕ_{eff} as a fraction of the total porosity and also correctly assumes that when R_{CF} approaches zero (no coarse particles present), the ϕ_{eff} for water flow will also approach zero:

$$\phi_{eff} = \phi erf\left(\frac{R_{CF}}{8}\right). \tag{9}$$

In Fig. 2, it is evident that the ratio of coarse and fine particles can accurately describe the variability of the ϕ_{eff}, but this concept is less dynamic when $R_{CF} > 8$, as a large R_{CF} will result in ϕ_{eff} being close to the total porosity. As the ϕ_{eff} in this study was defined at -10 kPa, which corresponded to expected field conditions (Al Majou et al., 2008; Assouline and Or, 2014), this also opens up for the possibility for determination of other key soil properties closely related to ϕ_{eff} such as plant-available water or the soil oxygen diffusion coefficient (Moldrup et al., 2000; 2001).

In a model sensitivity analysis, we tested how OM influences the new model concept. The expected influence of OM on K_s (Fig. 3a) and ϕ_{eff} (Fig. 3b) were generally significant. A 4% change in OM decreased the K_s value by nearly two orders of magnitude and significantly decreased the air-filled pore space at −10 kPa.
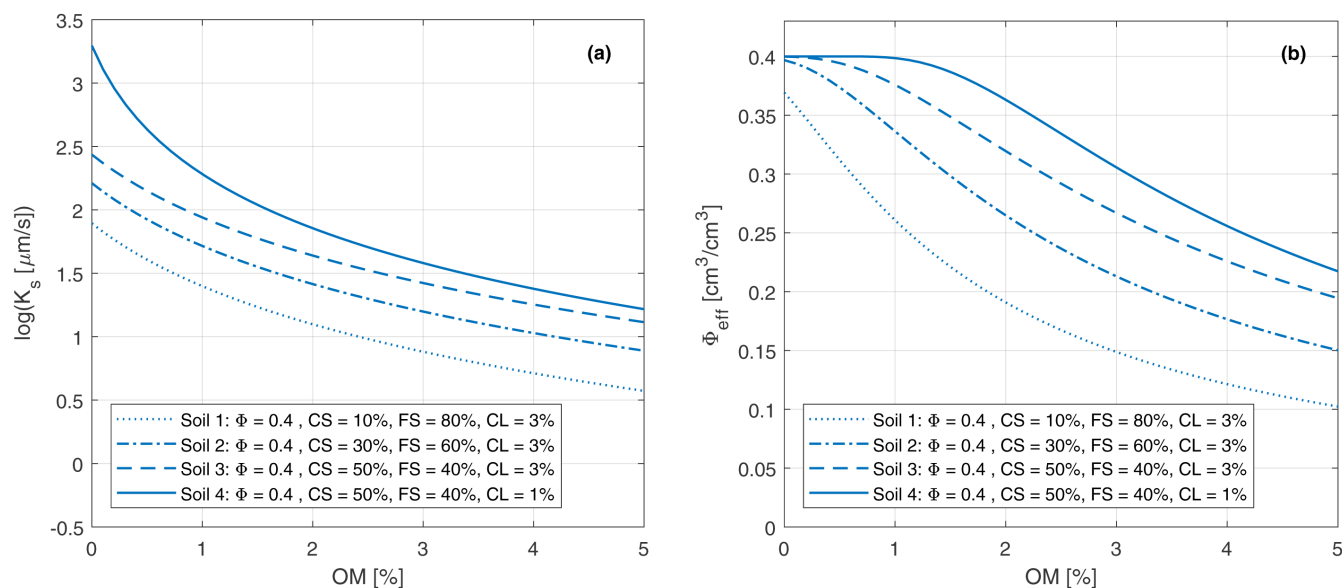

Fig. 3. Model sensitivity analyses with focus on effect of organic matter content (OM). (a) The coarse–fine ratio (R_{CF})–based K_s function (Eq. [2], Eq. [4]) with four different sets of parameter values for total porosity, and coarse sand and clay contents, (b) the R_{CF}–based effective porosity (ϕ_{eff}) function (Eq. [3] and Eq. [9]) with four sets of parameter values for total porosity, and coarse sand and clay contents.

Further Links to Water Retention

The new R_{CF} concept is already closely linked to the wet part of the soil water retention curve via its relationship to ϕ_{eff} (defined as total porosity minus volumetric water content at a given soil water matric potential; Eq. [9]). We will also look at potentially useful links to the dry part of the water retention curve. Using clay and OM together with sand in a simple model concept complicates the applicability, as sand may be easier to obtain through a simple sieve analysis compared with clay and OM, which require an additional time-extensive analysis. Several studies over the last few years have identified clay and OM as being estimated with high accuracy by means of the soil water content under air-dry conditions (e.g., Arthur et al., 2015; Poeplau et al., 2015). Arthur et al. (2015) identified a series of equations as a function of humidity for estimating the clay content based on water content and OM. In relation to this work, for the 45 soils from Dataset 2, we compared (Table 2) between the water content at 50% relative humidity and the volume-weighted fines content (clay + 2.65 OM), and found a strong positive correlation of $R^2 = 0.94$ (Fig. 4), as given in Eq. [10]:

$$F_{VW} = 12.2 \, ADW_{50} + 1.39 \qquad [10]$$

where F_{VW} is the volume-weighted fines (clay + 2.65 OM) and ADW_{50} is the air-dry water content at 50% relative humidity (kg kg^{-1}).

With strong links to both K_s and water retention properties, the concept of volume-weighted fines and the ratio of coarse sand and fine sand seems to be highly promising for platforming predictions of hydraulic properties for coarser-textured soils. We recognize that so far, the results are based on relatively small datasets and further proof of concept is needed to develop actual pedotransfer functions. Furthermore, to take a future perspective, a sieve with 150-μm mesh, a balance or a scale, an oven to determine the air-dry water content, and a hygrometer to determine and control the humidity may be all that is needed to determine both the saturated K_s and the ϕ_{eff} with good accuracy.

CONCLUSIONS

This paper has presented a new concept for describing saturated K_s and ϕ_{eff} in sandy soil. The prediction is based on a volume-weighted ratio (R_{CF}) between the coarser particles (coarse sand and part of the fine sand promoting the build-up of well-connected macropore networks) and the network-blocking fine particles (clay and OM). The R_{CF}–based K_s function also includes a pore network connectivity parameter (P_{NC}) that could be considered as a constant and has a value close to 2, as expected from other transport parameters such as gas diffusion and permeability.

The R_{CF}–based K_s function (Eq. [4]) was successfully implemented for 20 differently textured, compacted, and intact sandy soils with 2 to 10% fines, with a maximum deviation between measured and model-estimated K_s of only a factor of 2. A similar function (Eq. [9])could also describe the ϕ_{eff} for saturated water flow with high accuracy. Finally, a strong link between the fines part of the R_{CF} expression and the dry part of the soil water retention curve (water contents under air-dry conditions) was shown for a second dataset of 45 differently textured soils.

In perspective, the new R_{CF}–based function for K_s, ϕ_{eff}, and additional points on the soil water retention curve need to be further tested and optimized for larger sandy soil databases, but this should only be based on measurements with comparable laboratory or field methods and at a comparable measurement scale.

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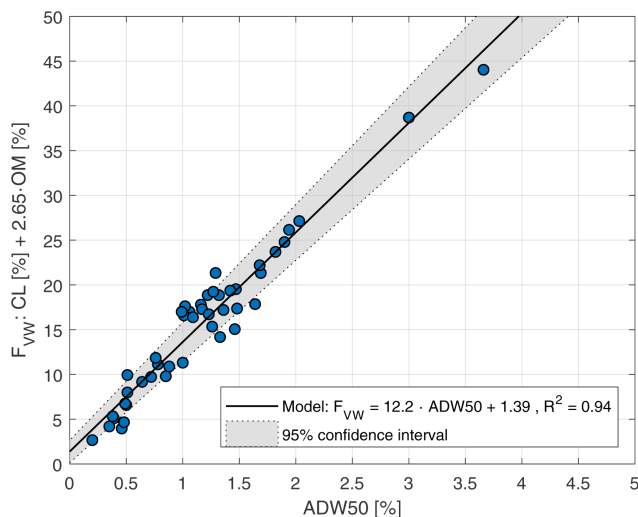
Fig. 4. Relationship between organic matter (OM)-weighted fines content (F_{VW} = CL + 2.65 OM) and air-dry water content at 50% relative humidity (ADW$_{50}$), where CL is gravimetric clay content.

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