Rock fragments influence the water retention and hydraulic conductivity of soils

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Core Ideas

- Water retention and hydraulic conductivity curves of stony soils were measured for stony soils with rock fragments up to 50 % (v/v).
- Common models for scaling hydraulic properties of stony soils were evaluated.
- Among the evaluated models of predicting the hydraulic conductivity curve, the GEM performs best.

Keywords

Soil hydraulic properties, water retention curve, hydraulic conductivity, stony soil, evaporation method.

Abstract

Rock fragments (RF) influence soil hydraulic properties (SHP) and knowledge about the SHP of stony soils is important in vadose zone hydrology. However, experimental evidence on effective SHP of stony soils is still scarce and mostly restricted to water-saturated conditions and low volumetric contents of RF. We examined the influence of RF on SHP through a series of measurements. Stony soils were prepared by packing 250 cm^3 cylinders with soils of two textures (sandy loam and silt loam) and with different volumes of RF (up to 50 % v/v) with a diameter of 8-16 mm. Samples were prepared in a way that the background soils (diameter smaller than 2 mm) had identical bulk density. The simplified evaporation method was used to determine the effective SHP of stony soils. We used the obtained SHP data to evaluate the performance of models, which predict the effective SHP of stony soils from SHP of the background soil. The results highlight the systematic dependency of SHP on volumetric content of RF. The difference between modeled and measured SHP was substantial for cases in which the soil contained a high amount of RF. Accounting for the moisture content of RF improved the prediction of the effective WRC of stony soils compared with a simple scaling that used only the content of RF. Among the evaluated models for the effective HCC, the model based on the general effective

medium theory (GEM) showed the best performance, particularly for low RF contents.

1 Introduction

The soils in mountainous areas and floodplains are mostly stony soils. These soils are composed of a background soil with particles of an effective diameter <2 mm and a considerable amount of rock fragments (RF) with an effective diameter >2 mm (Nikiforoff, 1948; Coile, 1952; Poesen and Lavee, 1994). Stony watersheds are widespread around the world with examples in Europe (Ballabio et al., 2016; Poesen and Lavee, 1994, Hlaváčiková et al., 2019; Mujtaba et al., 2020), New Zealand (Dann et al., 2009), Chile (Verbist et al., 2010b), and China (Ma and Shao, 2010; Zhou et al., 2021). Existence of RF in soil alters the hydrological condition of a watershed and knowledge about their impacts is required in vadose zone hydrology, land surface modeling, groundwater recharge prediction and environmental planning. In particular, RF influence evapotranspiration (Parajuli et al., 2019), infiltration (Brakensiek and Rawls, 1994; van Wesemael et al., 1996), and the generation of surface runoff (Sauer and Logsdon, 2002; Poesen and Lavee, 1994). These effects result from variations in bulk density, pore size distribution (PSD), pore connectivity and, more general, water retention curve (WRC), and hydraulic conductivity (HCC) of the soil (Torri et al., 1994; Poesen & Lavee, 1994; Naseri et al., 2019; Li et al., 2020). Information about the soil hydraulic properties (SHP) is required for modeling variably-saturated soil water flow using the Richards equation (Richards, 1931).

Efforts to measure the SHP of stony soils in the field and laboratory date back to the second half of the 20th century. An initial classification of stony soils and their properties was introduced by Nikiforoff (1948) and later by Poesen and Lavee (1994). Coile (1953) was among the pioneers who measured the water content of RF in a stony soil. Later, Reinhart (1961) assumed impermeable RF and used their volumetric content in field samples to correct the moisture content of stony soils. Rawitz (1969) introduced a procedure to measure the moisture content of stony soils in the field using the neutron probe. In an early attempt to measure the hydraulic conductivity of stony soils, Mehuys et al. (1975) proposed a correction factor for the WRC and HCC of stony soils based on the volume and moisture content of RF at different soil matric potentials. Their work was followed by studies by Peck and Watson (1979), Bouwer and Rice (1984), and Brakensiek and Rawls (1994) who measured SHP of stony soils and applied relatively simple models to predict the effective SHP from properties of the background soil and RF content.

New measurement devices and techniques have resulted in a more accurate quantification of state variables and therefore SHP of stony soils (Beckers et al., 2016; Parajuli et al., 2017; Naseri et al., 2019). Consequently, there is a recent trend to revise and develop new experimental and analytical approaches to identify SHP of stony soils. Fiès et al. (2002) measured WRC for mixtures of soils with different textures and glass fragments representing RF. They obtained data points of the WRC for mixtures containing different amounts of coarse fragments using the pressure plate apparatus, and reported that the soil water storage of the mixture depends on the volume of coarse inclusions and the texture of the background soil. Cousin et al. (2003) also used the pressure plate method to measure WRC of stony soils. They proposed to correct the WRC of the background soil based on the volumetric content of RF for an adequate estimation of water supply and agricultural water demand. Novák et al. (2011) used numerical simulations of water flow in stony soils to develop an empirical equation for scaling the saturated hydraulic conductivity of stony soils. Hlaváčiková et al. (2016) extended the results to different shapes and positions of RF. Beckers et al. (2016) measured SHP of stony soils made in the laboratory by mixing a clayey soil material with up to 20 % (v/v) glass balls and gravel. They used the experimental data to evaluate the available scaling models of hydraulic conductivity and suggested developing new models of describing SHP of stony soils. The scaling models to calculate saturated conductivity of stony soils were reviewed by Bagarello and Iovino (2007) and later by Beckers et al. (2016) and Naseri et al. (2019, 2020). Arias et al. (2019) used the wind and inverse modeling methods to measure SHP of a silt loam stony soil with 40 % volumetric RF. They reported that using only the volume of RF to scale the WRC of the stony soil is inappropriate. Despite the recent interest in the measurement and modeling of SHP of stony soils, available data is still relatively scarce for variably-saturated soil conditions, and high contents of RF. In addition, the developed models for scaling SHP of stony soils remain insufficiently validated (Naseri et al., 2019). Therefore, in this research we investigated the effective SHP of packed stony soils with different volumetric contents of RF ranging from 10 to 50 % (v/v). Care was taken to ensure that the bulk density of the background soil was invariant with the RF contents. The main objectives of our research were to:

1. Extend the measurement range of SHP of stony soils to high volumes of RF, i.e. 50 % (v/v).

2. Evaluate and compare some of the models for scaling SHP at both low and high contents of RF.

To the best of our knowledge, it is the first time that WRC and HCC of stony soils are measured for such high contents of RF under variably-saturated conditions. Additionally, the performance of some of the models presented in this study has not been evaluated using measured SHP data before.

2 Materials and methods

2.1. Sample preparation

Stony soil samples were prepared by mixing different percentages of the background soil materials and RF in stainless steel cylinders with a height of 5 cm, an inner diameter of 8 cm, and a total volume of 250 cm^3. Background soil textures were sandy loam (63% sand, 29% silt, 8% clay) collected at an agricultural site of the Julius-Kühn-Institute in Braunschweig-Völkenrode and silt loam (7% sand, 78% silt, 15% clay) collected at Groß Gleidingen site near the city of Braunschweig, Lower Saxony, Germany. The soil materials were sampled from a depth of 5-20 cm of the topsoil, cleaned from coarse fragments and roots, and air-dried and sieved through a 2 mm sieve. The RF were washed drainage gravels with an effective diameter of 8-16 mm and a particle density of 2.59 g cm^{-3}. The volume of RF was calculated using their mass and particle density. The required mass of dry RF and the bulk volume of the background soil were calculated. The target bulk densities of the background soils (without RF) were set to 1.42 g cm^{-3} for the sandy loam and 1.30 g cm^{-3} for the silt loam, respectively. Afterward, stony soils were made by mixing different masses of RF and the background soils to obtain volumetric RF contents (f) of f=0, 15, 30, and 50 % for the sandy loam and f=0, 10, 15, 30, and 50 % for the silt loam, respectively. The calculated amounts of RF and background soils were mixed in the cylinders in three packing steps. In each step of steps, one-third of the calculated weight of RF and soils were added to the cylinder, and mixed carefully. Target of the packing was to achieve the intended bulk density of the background soil while reaching a homogeneous distribution of the RF in the sample. Placing of the RF in the soils was done carefully to prevent any local heterogeneity and over-compaction of the background soil or formation of extra voids in the vicinity of RF during packing. We moistened the mixture slightly by spraying it with tap water and pushed it slightly from the top for moderate compaction. Therefore, bulk densities of 1.30 (g cm^{-3}) for the sandy loam, and 1.42 (g cm^{-3}) for silt loam background soils with packing errors less than 0.005 g cm^{-3} were obtained in all of the volumetric RF. However, it should be noted that small local changes of the internal structure of the system due to the presence of RF might be inevitable both in the laboratory and in the field (Poesen and Lavee, 1994; Fiès et al., 2002, Naseri et al., 2019). In order to facilitate installation of the mini-tensiometers especially in the highly stony samples, two metal pins were used as placeholders during packing. Samples were packed in two replicates resulting in 18 evaporation experiments. The samples were saturated from the bottom by putting them in tap water for one week in a climate-controlled laboratory (CCL) with a temperature of 20 ± 1 °C.

2.2. The evaporation method for measuring the soil hydraulic properties

After saturating the samples, the metal pins were removed carefully and the samples were positioned on the HYPROP^{TM} device (Meter Group, Munich) by placing the two mini-tensiometers in the respective pinholes. HYPROP^{TM} uses the simplified evaporation method (SEM; Schindler, 1980), improved by Peters and Durner (2008a) and Peters et al., (2015) to determine the soil hydraulic properties. The method has been applied successfully for measuring the SHP of stony soils (Beckers et al., 2016; Arias et al., 2019; Naseri et al., 2019). The samples were allowed to evaporate from the top in a laboratory, in which air humidity and temperature are controlled to ensure an almost constant potential evaporation rate. The water loss in the samples was measured by weighing them on a scale with a 0.01 g resolution twice a day, and the dry mass of the soil was determined by oven drying at 105 °C for 24 h after the experiments. For calculating the point data of the SHP, we used the HYPROP-FIT software (Pertassek et al., 2015) which implements the calculation scheme developed by Peters and Durner (2008b) and Peters et al. (2015). In short, point data of the WRC were calculated by assigning the mean water content of the samples, obtained from weighing, to an averaged pressure head, calculated from the tensiometer readings. Point data of the HCC were calculated from the measured gradient of the hydraulic potential and the water flux density across the center of the soil using the Darcy-Buckingham law.

2.3. Parametrization of the SHP

We fitted the van-Genuchten-Peters-Durner-Iden (vG-PDI) model (Peters, 2013, 2014; Iden and Durner, 2014) to the measured water retention data of the background soil. In the PDI model, the WRC is the sum of the capillary and non-capillary water contents. Although not used in this study, it is worth mentioning that hydraulic conductivity is the sum of capillary conductivity (fully saturated pores), and non-capillary conductivity (film and corner flow in partially saturated pores) in the PDI model framework (Peters, 2013). The five adjustable parameters of the vG-PDI model are the residual water content (θ_r) (cm^3 cm^{-3}), the saturated water content (θ_s) (cm^3 cm^{-3}), and the three shape parameters (-), n (-) and m (-). Note that m was treated as being independent from shape parameter n. We used the HYPROP-FIT software (Pertassek et al., 2015) for curve fitting of the water retention data.

The hydraulic conductivity curve was treated in a simplified manner. The point data of the HCC were limited to pressure heads between approximately -1000 cm and -100 cm (pF between 2 and 3; Schofield, 1935), and the data points of the background soil showed a linear trend in the double-logarithmic plot. Therefore, a straight line was fitted to the data points of the background soil and used as a simplified representation of the HCC. By this approach, the best possible match of the WRC data is warranted because the point data of HCC are not accounted for in the objective function minimized during curve fitting. The disadvantage of this is that a parametric description of the full HCC is not achieved and that the models of the WRC and HCC are decoupled. However, this approach leads to a more robust test of the scaling models.

2.4. Models of scaling the WRC and HCC of stony soils

The measured WRC and HCC data of the stony soil samples were used to evaluate the performance of common scaling models for SHP of stony soils. The evaluated models are listed in Table 1. We applied these models to calculate the effective WRC and HCC of the stony soils by scaling the fitted WRC (vG-PDI) and HCC (straight line fit) of each background soil.

The common method of choice to scale the WRC of the stony soil is to use the composite-porosity or the volume-averaging of the background soil and RF to calculate the water content of the stony soil (Peters and Klavetter, 1988). In this approach, the WRC of the stony soil is the weighted mean of the WRC of the background soil and the RF. As a special case, if RF are assumed to be non-porous, their role is only to reduce the WRC of the background soil by the factor $(1 - f)$, where f (v/v) is the volumetric content of RF (Bouwer and Rice, 1984). For the volume-averaging model by Peters and Klavetter (1988), information about the WRC of RF is required. Parajuli et al. (2017) measured WRC of some types of low porous RF (Dolostone, limestone and two fine sandstones) and described them by the van Genuchten model. We fitted the van Genuchten model with the constraint $m = 1 - \frac{1}{n}$ to the mean of the respective four retention curves $\theta(h)$ and used the parameters $\theta_s = 0.041$ (v/v), $\theta_r = 0.0$ (v/v), =0.007 (cm^{-1}), and $n = 1.414$ (-) for parametrizing the WRC of the RF.

The most frequently used approach of obtaining hydraulic conductivity of stony soils is to scale the HCC of the background soil based on the volumetric content of RF. This is based on the assumption that RF are impermeable or that their contribution to the effective conductivity is negligible, an assumption that we adopt here for the sake of simplicity and due to the absence of the required data. The simplest scaling model is the Ravina and Magier (1984) model that considers RF as barriers to the water flow to restrict conductivity of the soil. More comprehensive models such as Maxwell, Novák, and GEM, not only consider the volumetric content of RF, but also their shape, orientation, and soil type (Peck and Watson, 1979; Zimmermann and Bodvarsson, 1995; Novák et al., 2011; Naseri et al., 2020). Recently, these models have been evaluated for an ideal case of spherical RF included in a homogeneous sandy loam background soil by 3D numerical modeling (Naseri et al., 2021). For more information about their advantages, constraints, and assumptions, we refer to Naseri et al. (2019, 2020, and 2021) and the references therein.

Table 1: The scaling models of WRC and HCC evaluated in our study.

SHP
Water Retention
Hydraulic Conductivity
$\theta_m(h)$: effective moisture content of stony soil, f: volumetric content of RF, θ_{rock}: moisture contents of the R

In order to evaluate the models in Table 1, we scaled the straight lines of $\log_{10}(K)$ vs pF obtained for the background soils by the models and compared the resulting lines to the measured conductivity data of the stony soils. The error of each model was calculated/quantified by the average deviation (d_{avg}) between the modeled and measured data points of the common log of hydraulic conductivity.

3 Results and Discussion

3.1 Water retention curves (WRC)

The measured data points of the WRC and the fitted vG-PDI model to the background soil and the scaled WRC for stony soils are illustrated in Fig. 1 for the matric potentials up to the measurement limit of the mini-tensiometers (i.e. pF ≈ 3).

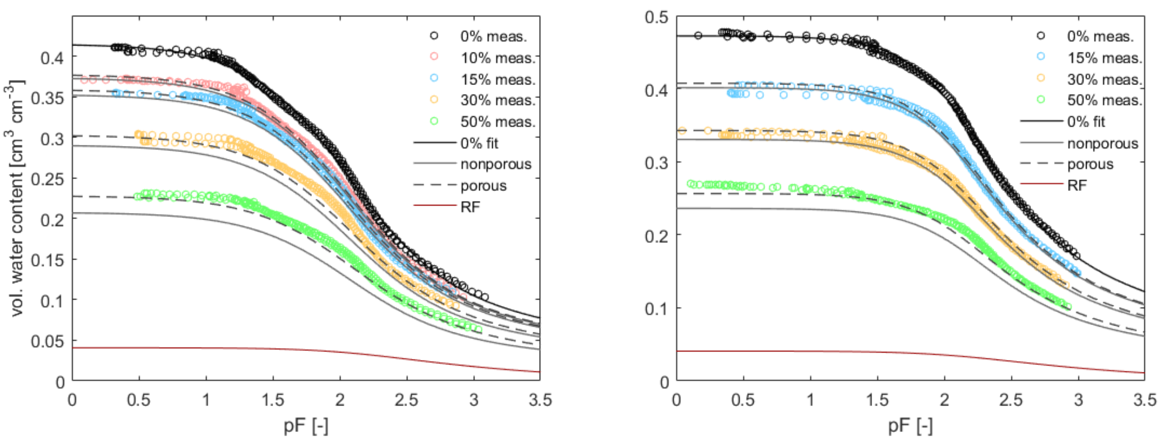


Figure 1: Measured water retention data (circles) for the sandy loam (left) and the silt loam (right) soils with different volumetric RF contents displayed by color codes. Replicates are shown with the same color. The solid red line is the WRC of RF and the solid black line is the vG-PDI WRC model fitted to the measured data points of the background soils (0 % fit). The solid gray lines (nonporous) show the scaled WRC of stony soils using the model of Bouwer and Rice, and dashed gray lines (porous) show the scaled WRC by considering the WRC of RF.

For both soils, the data points of the two replicates show high compatibility. This confirms the good replicability of our packing and measurement methods for obtaining the WRC data for all volumetric contents of RF within the measurement range. Soil water content does not change significantly near saturation, but water content is not constant for pF < 1, in particular for the silt loam with f=50 % (v/v). The slight slope near saturation might be an indicator of widening the PSD towards the existence of more macrospores in the soil structure when the amount of RF in soils are high (Torri et al., 1994; Fiès et al., 2002; Naseri et al., 2019). As the figure shows the scaling of the water content in the saturated and dry ranges is proportional to the volumetric content of RF.

We evaluated the applicability of the volume-averaging model (Peters and Klavetter, 1988) in the scaling of WRC of the background soils for different volumes of RF. The solid gray lines in Fig. 1 indicate the scaled WRC by assuming nonporous RF (Bouwer and Rice model). As it is visible, this model results in a systematic underestimation of the WRC of stony soils. The mismatch between the measured data points and scaled curves (solid gray lines) increases with increasing RF content. This indicates that water retention in the RF cannot be neglected. The dashed gray lines in Fig. 1 present the scaled WRC that include the water content of RF in the volume-averaging model. According to the figure, scaling the WRC improves substantially by accounting for water storage in the RF. Specifically, the quality of match increases significantly for the highly stony soils. Our results are in accordance with Parajuli et al. (2017). Therefore, we conclude that accounting for water storage in RF improves the prediction of the effective WRC of stony soils.

3.2 Unsaturated hydraulic conductivity

The measured hydraulic conductivity data points of both soils and with different volumetric content of RF are illustrated in Fig. 2. The hydraulic conductivity data are shown on linear and logarithmic scales.

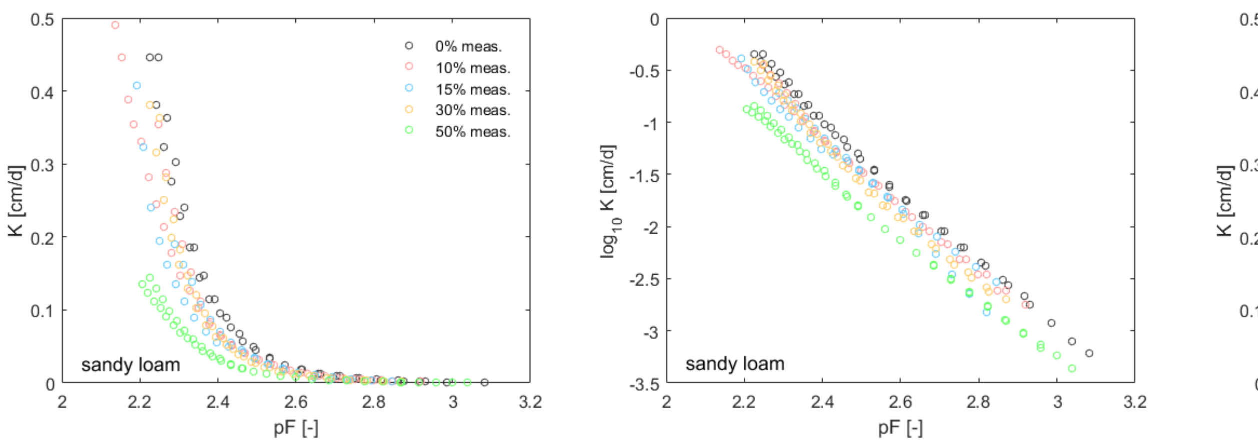


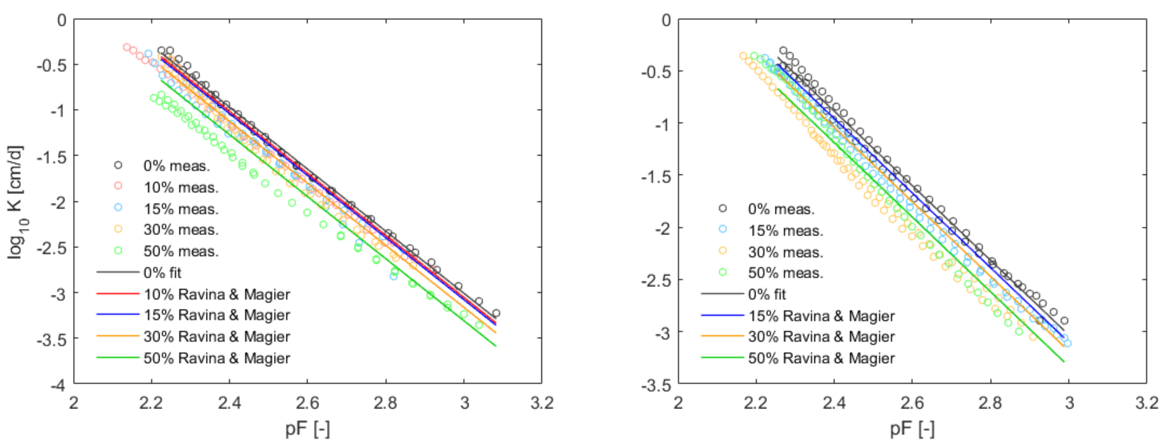
Figure 2: Measured conductivity data (circles) in linear (left) and logarithmic (right) scales for the sandy loam and silt loam soils with different volumes of RF displayed by color codes.

As the figure shows, the decrease in conductivity by an increase of the volumetric RF is obvious for both soils in the measured range of matric potentials from pF ≈ 2 to pF ≈ 3. The trend of reduction in conductivity is evident for the stony soils with low volumes of RF. Interestingly, a countertrend is visible for the sandy loam soil with f=30 % and for the silt loam soil with f=50 % (v/v), opposed to theoretical expectation, their conductivities do not decrease as expected. In these few cases, the reduction of the conductivity in the matric potentials up to $pF \approx 2.4$ for the sandy loam and pF ≈ 2.6 for the silt loam soil is lower compared to other stony soils with smaller values of f. The reason could be a more probable presence of macropores in soil for higher amounts of RF. This is also supported by the WRC of the silt loam. It has been noted that RF boost the development of macropores in the vicinity of the RF (Sekucia et al., 2020). The existence of macropores may compensate the imposed reduction of conductivity, which results from the decrease of the cross-sectional area of flow by RF. This causes a lower than expected reduction in the conductivity. However, hydraulic conductivity of these soils follow the expected trend when film and micropore flow become the dominant contributing mechanisms of the water flow in soil (Naseri et al., 2019).

Furthermore, for higher amounts of RF, the HCC shows a more nonlinear behavior compared to the HCC of the background soil. This presents a challenge when using the available scaling models to calculate hydraulic conductivity of stony soils.

3.3 Evaluation of the Ravina and Magier, Maxwell, Novák, and GEM models using the measured hydraulic conductivity data

Figure 3 illustrates the measured data points of hydraulic conductivity, the straight line fitted to the data of the background soil, and the calculated values of effective HCC using the scaling models (Table 1).



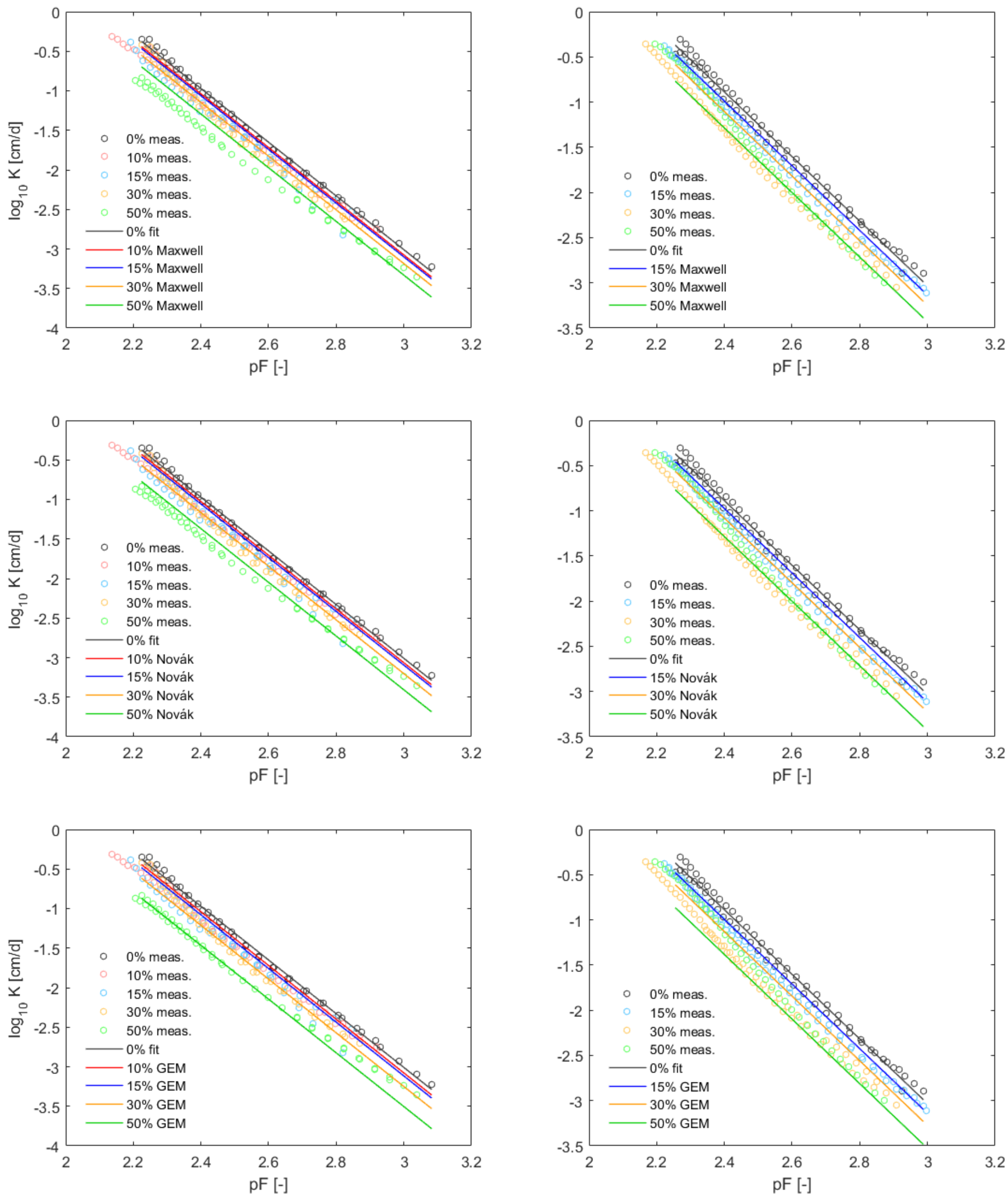


Figure 3: The scaled hydraulic conductivities (solid lines) obtained by the scaling

models of Ravina and Magier, Maxwell, Novák, and GEM for sandy loam (left) and silt loam (right) soils and different values of f shown by different color codes. Circles also present the measured data points of hydraulic conductivity for different values of f.

According to the Fig. 3, the models show dissimilar results in scaling the HCC of background soils, in particular for high volumetric RF. The general assumption with scaling HCC of the background soil to calculate the HCC of stony soils is that the HCC of stony soil is described by the same functions as the HCC of the background soil. Although the assumption might hold true for stony soils with low volumes of RF, in highly stony soils the HCC becomes more nonlinear. That explains the discrepancies between the modeled and measured conductivities. The resulting values of d_{avg} for the four evaluated scaling models and two background soils with different volumes of RF are presented in Table 2. The value of d_{avg} is an indicator of the performance of the scaling model in predicting the measured data points of hydraulic conductivity.

Table 2 Performance of the evaluated scaling models of conductivity quantified by the average deviation (d_{avg}). The values of d_{avg} are shown for both background soils with different volumes of RF. The model with best performance in each volumetric content of RF has the lowest value of d_{avg} shown in bold.

Background soil	Volumetric content of RF, f (%)	Scaling model			
		Ravina and Magier	Maxwell	Novák	GEM
sandy loam	10	0.1583	**0.1269**	0.1486	0.1347
	15	0.1335	0.1021	0.1179	**0.0964**
	30	0.0391	-0.0216	**0.0002**	-0.0478
	50	0.1507	0.0538	0.0538	**-0.0432**
silt loam	15	0.0951	0.0637	0.0795	**0.0581**
	30	0.2435	0.1828	0.2045	**0.1566**
	50	**-0.0057**	-0.1026	-0.1026	-0.1996

The values of d_{avg} in Table 2 are mostly positive (modeled values of hydraulic conductivity are greater than measured) for stony soils with low volumes of RF, which shows the tendency of all models to underestimate the reduction of hydraulic conductivity. All models underestimate the reduction in the hydraulic conductivity for sandy loam with values of f up to 15 % (v/v), and silt loam with values of f up to 30 % (v/v). For the silt loam stony soils, the hydraulic conductivity is underestimated for high RF content. This highlights the role of texture of the background in reducing hydraulic conductivity depending on the volume of RF, which should be taken into account in the scaling models. Different reductions in the saturated hydraulic conductivity for stony soils with similar RF contents and various soil textures is reported through numerical simulations by Novák et al. (2011). The simple linear scaling using the Ravina and

Magier model underestimates the reduction in the HCC in sandy loam stony soils. This indicates that reduction in the measured hydraulic conductivity is stronger than expected by the factor $(1 - f)$ and hints at a higher tortuosity of flow paths caused by the presence of RF. Naseri et al. (2021) also reported identical results by comparing the Ravina and Magier model results and the HCC identified through 3D simulated experiments. However, despite the underestimation of the reduction in conductivity in stony soils with low values of *f*, this model has the lowest d_{avg} in the silt loam stony soil with f=50 % (v/v). Therefore, although the scaling model of Ravina and Magier does not predict the hydraulic conductivity in stony soils with low RF contents accurately, applying it for highly stony soils seemed to be more reliable. The other three models tend to overestimate the reduction in conductivity in highly stony soils. It should be noted that an accurate determination of the parameter   in the linear-scaling model of Novák is necessary to obtain improved estimations of conductivity by this model (Hlaváčiková et al., 2016; Naseri et al., 2021). Although the results of the Maxwell model are acceptable for all values of *f*, the GEM model is the best among the evaluated models to calculate hydraulic conductivity of stony soils with low volumetric RF and the method of choice based on the results in our research. For stony soils with 30 % and 50 % (v/v) RF, the models of Novák and Maxwell yield a better match to the measured values of hydraulic conductivity. However, the GEM model still shows a better performance in the sandy loam stony soil with f=50 %.

4 Conclusions

In our study, we successfully measured the SHP of stony soils for pressure heads up to pF $\approx$ 3.0. Scaling of the WRC shows that the reduction in the water content by RF in our experiments is lower than a simple shift by $(1-f)$. Accounting for the WRC of RF in the mixing model of Peters and Klavetter (1988) resulted in an excellent match to the measured data. This result suggests that not only the volume of RF, but also their moisture content has a considerable impact on the effective WRC, and should be considered.

For scaling the hydraulic conductivity, the models slightly under- or overestimated the reduction in conductivity. The error of these scaling models is related to their fundamental assumptions. For instance, they assume the background soil to be homogeneous regardless of the embedded amount of RF. However, our results confirm that pores size distribution of the background soil varies especially in highly stony soils even in packed samples with identical bulk densities. Therefore, we suggest to develop and apply models, which account for the influence of RF content on bulk density of the background soil and the resulting impact on the pore-size distribution and SHP. Our results imply that among the evaluated scaling models of HCC the GEM model showed the best performance when the soil contains low volumes of RF up to $\approx$ 30 % (v/v). Furthermore, the development of macropores caused by the presence of RF influenced water retention and flow in the wetter range of SHP.

In this research, we extended the experimental data of unsaturated flow conditions to soils with high volumes of RF. Measuring properties of these systems for higher RF contents, different sizes, types, arrangements, and shapes needs further experiments. The role of permeable RF on the conductivity of stony soils especially at lower matric potentials is still an open question for future research, although respective models exist (Naseri et al., 2020). In highly stony soils, a potential source of error is the high local heterogeneity of the flow field. At the interface of two RF or background soil and RF some water might be attracted by capillarity and result in higher moisture content in the vicinity of RF surface (Berger, 1976). Therefore, larger experimental setups and more measurement sensors are required to characterize the local heterogeneity of flow fields in such systems. Finally, the validation of models under field conditions is necessary to improve their predictability potential in theoretical and practical applications.

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