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Rock fragments influence the water retention and hydraulic conductivity of soils

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Abstract

Rock fragments (RFs) influence soil hydraulic properties (SHPs), and knowledge about the SHPs of stony soils is important in vadose zone hydrology. However, experimental evidence on effective SHPs of stony soils is still scarce and mostly restricted to water-saturated conditions and low volumetric contents of RFs. We examined the influence of RFs on SHPs 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 RFs (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 SHPs of stony soils. We used the obtained SHP data to evaluate the performance of models, which predict the effective SHPs of stony soils from SHPs of the background soil. The results highlight the systematic dependency of SHPs on volumetric content of RFs. The difference between modeled and measured SHPs was substantial for cases in which the soil contained a high amount of RFs. Accounting for the moisture content of RFs improved the prediction of the effective water retention curve of stony soils compared with a simple scaling that used only the content of RFs. Among the evaluated models for the effective hydraulic conductivity, the model based on the general effective medium theory 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 (RFs) with an effective diameter >2 mm (Coile, 1953; Nikiforoff, 1948; Poesen & Lavee, 1994). Stony watersheds are widespread around the world, with examples in Europe (Ballabio et al., 2016; Hlaváčiková et al., 2016; Mujtaba et al., 2020; Poesen & Lavee, 1994), New Zealand (Dann et al., 2009), Chile (Verbist et al., 2010), and China (Ma & Shao et al., 2010; Zhou et al., 2021). Existence of RFs 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, RFs influence evapotranspiration (Parajuli et al., 2019), infiltration (Brakensiek & Rawls, 1994;

GEM, general effective medium theory; HCC, hydraulic conductivity; MD, mean deviation; RF, rock fragment; SHP, soil hydraulic property; vG-PDI, van Genuchten–Peters–Durner–Iden; WRC, water retention curve.

van Wesemael et al., 1996), and the generation of surface runoff (Poesen & Lavee, 1994; Sauer & Logsdon, 2002). These effects result from variations in bulk density, pore-size distribution, pore connectivity and, more generally, water retention curve (WRC), and hydraulic conductivity (HCC) of the soil (Li et al., 2020; Naseri et al., 2019; Poesen & Lavee, 1994; Torri et al., 1994). Information about the soil hydraulic properties (SHPs) is required for modeling variably saturated soil water flow using the Richards equation (Richards, 1931).

Efforts to measure the SHPs 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 & Lavee (1994). Coile (1953) was among the pioneers who measured the water content of RFs in a stony soil. Later, Reinhart (1961) assumed impermeable RFs 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 HCC 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 RFs at different soil matric potentials. Their work was followed by studies by Peck & Watson (1979), Bouwer & Rice (1984), and Brakensiek & Rawls (1994) who measured SHPs of stony soils and applied relatively simple models to predict the effective SHPs from properties of the background soil and RF content.

In a more recent study, Fiès et al. (2002) measured WRC for mixtures of soils with different textures and glass fragments representing RFs. 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 RFs for an adequate estimation of water supply and agricultural water demand. However, recent advancements in measurement devices and techniques have resulted in a more accurate quantification of state variables and therefore SHPs of stony soils (Beckers et al., 2016; Naseri et al., 2019; Parajuli et al., 2017). Novák et al. (2011) used numerical simulations of water flow in stony soils to develop an empirical equation for scaling the saturated HCC of stony soils. Hlaváčiková et al. (2016) extended the results to different shapes and positions of RFs. Beckers et al. (2016) measured SHPs 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 HCC and suggested developing new models of describing SHPs of stony soils. The scaling models to calculate saturated conductivity

Core Ideas

- Water retention and hydraulic conductivity curves of stony soils with rock fragments up to 50% (v/v) were measured.
- 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.

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 evaporation method to measure SHPs of a silt loam stony soil with 40% volumetric RF and applied inverse modeling to identify the effective SHPs. 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 SHPs of stony soils, available data are 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 SHPs of packed stony soils with different volumetric contents of RF ranging from 10 to 50% (v/v). The main objectives of our research were to (a) extend the measurement range of SHP soft stony soils to high volumes of RF (i.e., 50% [v/v]), and (b) to evaluate and compare some of the models for scaling SHP at both low and high contents of RFs.

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 RFs 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 RFs were washed drainage gravels having a round shape 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 RFs and the bulk volume of the background soil were calculated. The target bulk densities of the background soils (without RFs) 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 RFs and the background soils to obtain volumetric RF contents (f) of $f = 0$, 15, 30, and 50% for the silt loam and $f = 0$, 10, 15, 30, and 50% for the sandy loam, respectively. The calculated amounts of RFs and background soils were mixed in the cylinders in three packing steps. In each step of steps, one-third of the calculated weight of RFs and soils were added to the cylinder and mixed carefully. The objective of the packing was to achieve the intended bulk density of the background soil while reaching a homogeneous distribution of the RFs in the sample. Placing of the RFs in the soils was done carefully to prevent any local heterogeneity and overcompaction of the background soil or formation of extra voids in the vicinity of RFs during packing. Care was taken to ensure that the bulk density of the background soil was invariant with the RF contents. We moistened the mixture slightly by spraying it with tap water and pushed it slightly from the top for moderate compaction. Bulk densities of 1.30 (g cm^{-3}) for the sandy loam and 1.42 (g cm^{-3}) for silt loam background soils with errors less than 0.005 g cm^{-3} were obtained for all RF contents. However, it should be noted that small local changes of the internal structure of the system due to the presence of RFs might be inevitable, both in the laboratory and in the field (Fiès et al., 2002; Naseri et al., 2019; Poesen & Lavee, 1994). 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 1 wk in a climate-controlled laboratory with a temperature of 20 ± 1 ˚C.

2.2 | The evaporation method for measuring the SHPs

After saturating the samples, the metal pins were removed carefully and the samples were positioned on the HYPROP device (Meter Group) by placing the two mini-tensiometers in the respective pinholes. HYPROP uses the simplified evaporation method (Schindler, 1980), improved by Peters & Durner (2008b) and Peters et al. (2015) to determine the SHPs. The method has been applied successfully for measuring the SHPs of stony soils (Arias et al., 2019; Beckers et al., 2016; 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 per 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 SHPs, we used the HYPROP-FIT software (Pertassek et al., 2015), which implements the calculation scheme developed by Peters & Durner (2008a) 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 SHPs

We fitted the van Genuchten–Peters–Durner–Iden (vG-PDI) model (Iden & Durner, 2014; Peters, 2013, 2014) to the measured water retention data of the background soil. In the PDI model, the WRC is the sum of the capillary and noncapillary water contents. Although not used in this study, it is worth mentioning that HCC is the sum of capillary conductivity (fully saturated pores), and noncapillary 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 α (–), 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 HCC curve was treated in a simplified manner. The point data of the HCC were limited to pressure heads between approximately −1,000 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.

TABLE 1 The scaling models of water retention curve (WRC) and hydraulic conductivity (HCC) evaluated in this study

Soil hydraulic property	Name	Model	Related references
Water retention	Volume-averaging (porous rock fragment, RF)	$\theta_m(h) = (1-f)\,\theta_{soil} + f\theta_{rock}$	Peters & Klavetter (1988)
	Volume-averaging (nonporous RF)	$\theta_m(h) = (1-f)\,\theta_{soil}$	Bouwer & Rice (1984)
Hydraulic conductivity	Ravina & Magier	$K_r = 1 - f$	Ravina & Magier (1984)
	Maxwell (spherical RF)	$K_r = \frac{2(1-f)}{2+f}$	Peck & Watson (1979), Naseri et al. (2022)
	Novák	$K_r = 1 - a_K f$	Novák et al. (2011)
	GEM	$K_r = (1 - \frac{f}{f_c})^t$	Naseri et al. (2022)

Note. $\theta_m(h)$, effective moisture content of stony soil; f, volumetric content of RF; θ_{rock}, moisture contents of the RF; θ_{soil}, moisture contents of the background soil; K_r, relative hydraulic conductivity of stony soil which is the ratio of the effective hydraulic conductivity of the stony soil to the hydraulic conductivity of background soil; α_K, parameter in Novák's model depending on soil texture and RF size; f_c, critical volumetric RF content; t, shape parameter in the general effective medium theory (GEM) model.

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 SHPs 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 RFs to calculate the water content of the stony soil (Peters & Klavetter, 1988). In this approach, the WRC of the stony soil is the weighted mean of the WRC of the background soil and the RFs. As a special case, if RFs are assumed to be nonporous, 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 RFs (Bouwer & Rice, 1984). For the volume-averaging model by Peters & Klavetter (1988), information about the WRC of RFs 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 $m = 1 - 1/n$ 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), $\alpha = 0.007$ (cm^{-1}), and n = 1.414 (–) for parametrizing the WRC of the RF.

The most frequently used approach of obtaining HCC of stony soils is to scale the HCC of the background soil based on the volumetric content of RFs. This is based on the assumption that RFs 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 & Magier (1984) model that considers RFs as barriers to the water flow to restrict conductivity of the soil. More comprehensive models such as Maxwell, Novák, and general effective medium theory (GEM), not only consider the volumetric content of RFs, but also their shape, orientation, and soil type (Naseri et al., 2020; Novák et al., 2011; Peck & Watson, 1979; Zimmermann & Bodvarsson, 1995). Recently, these models have been evaluated for an ideal case of spherical RFs included in a homogeneous sandy loam background soil by three-dimensional numerical modeling (Naseri et al., 2022). For more information about their advantages, constraints, and assumptions, we refer to Naseri et al. (2019, 2020, 2022) and the references therein.

The two models of WRC were compared using the RMSD. To evaluate the models for HCC presented in Table 1, we scaled the fitted straight line of $\log_{10}(K)$ vs. pF obtained for the background soil by four models and compared the resulting lines by each model to the measured conductivity data of the stony soils. The error of each model was quantified by the RMSD and mean deviation (MD) between the modeled and measured data points of the common log of HCC. The critical volumetric RF content in the GEM model was set as 0.84 with the shape parameter $t = 1.26$ for rounded RFs (Naseri et al., 2022), and in the model of Novák, a value of 1.2 was used for α_K. Novák et al. (2011) estimated that values of α_K vary between 1.1 and 1.32 depending on the soil texture, diameter, and number of RFs in the stony soil.

3 | RESULTS AND DISCUSSION

3.1 | WRCs

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 Figure 1 for the matric

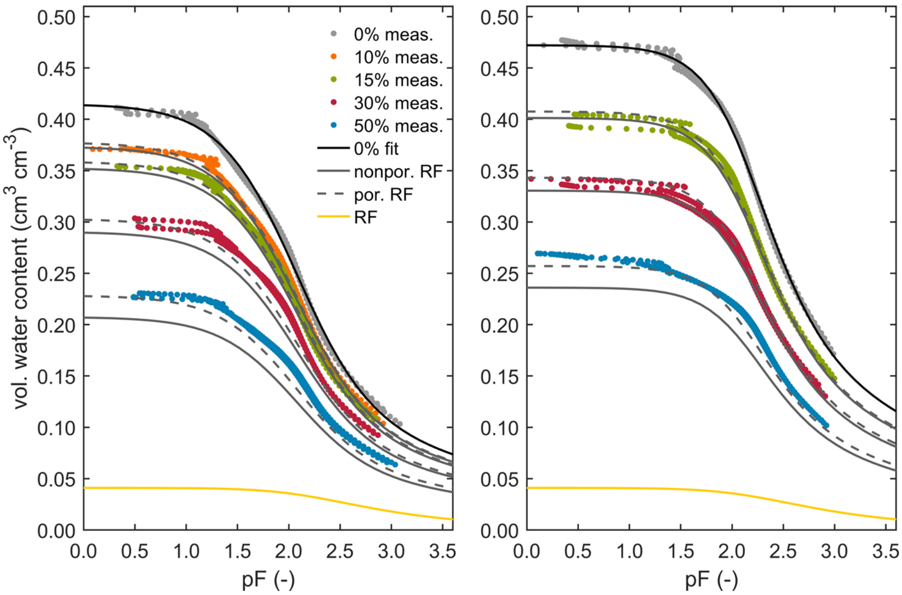

FIGURE 1 Measured water retention data (dots) for the sandy loam (left) and the silt loam (right) with different volumetric rock fragment (RF) contents displayed by color codes. Replicates are shown with the same color. The solid yellow line is the water retention curve (WRC) of RFs, and the solid black line is the van Genuchten–Peters–Durner–Iden WRC model fitted to the measured data points of the background soils. The solid gray lines ("nonpor. RF") show the scaled WRC of stony soils using the model of Bouwer & Rice (1984), and the dashed gray lines ("por. RF") those obtained with the model of Peters & Klavetter (1988), which accounts for water retention of RFs

potentials up to the measurement limit of the mini-tensiometers (i.e., pF ≈ 3).

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 RFs within the measurement range. Although the water content of each stony soil does not change markedly near saturation, it is not constant for pF < 1, in particular for the silt loam stony soil with a high volume of RFs (f = 50% v/v). The slight slope near saturation might be an indicator of widening the pore size distribution towards the existence of more macrospores in the soil structure when the amount of RFs in soils is high (Fiès et al., 2002; Naseri et al., 2019; Torri et al., 1994). 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 & Klavetter, 1988) in the scaling of WRC of the background soils for different volumes of RF. The solid gray lines in Figure 1 indicate the scaled WRC by assuming nonporous RF (Bouwer and Rice model), and the dashed gray lines show the scaled WRC including the water content of RF in the volume-averaging model (model of Peters & Klavetter, 1988). For evaluating and comparing the performance of two models, the values of RMSD are given in Table 2.

According to Figure 1, the Bouwer & Rice (1984) model results in a systematic underestimation of the WRC of stony soils. Additionally, the mismatch between the measured data points and scaled curves (solid gray lines) increases with increasing RF content shown by the values of RMSD in Table 2. This indicates that water retention in the RFs cannot be neglected and the error in predictions grows as the volumetric RFs in soil increases. According to Figure 1 and Table 2, scaling the WRC improves substantially by accounting for water storage in the RFs. Specifically, the quality of match increases significantly for the highly stony soils where values of RMSD decrease significantly. For instance, in the silt loam stony soil with 50% RF (v/v), value of RMSD declines from 0.025 to 0.008 for the Peters & Klavetter (1988) model. Our results are in accordance with Parajuli et al. (2017). Therefore, we conclude that accounting for water storage in RFs improves the prediction of the effective WRC of stony soils.

3.2 | Unsaturated HCC

The measured HCC data points of both soils and with different volumetric content of RFs are illustrated in Figure 2. The HCC data are shown on linear and logarithmic scales.

As the figure shows, the decrease in conductivity by an increase of the volumetric RFs 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 RFs. 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

TABLE 2 Calculated values of the RMSD to compare the scaling models of water retention curve (WRC) for nonporous rock fragment (RF) (Bouwer & Rice, 1984) and porous RF (Peters & Klavetter, 1988) for sandy loam and silt loam stony soils with different volumes of RF

		Scaling model	
Background soil	Volumetric content of RF, *f* (%)	Nonporous RF (Bouwer & Rice, 1984)	Porous RF (Peters & Klavetter, 1988)
Sandy loam	10	0.004	0.002
	15	0.007	0.003
	30	0.016	0.008
	50	0.024	0.009
Silt loam	15	0.005	0.006
	30	0.006	0.005
	50	0.025	0.008

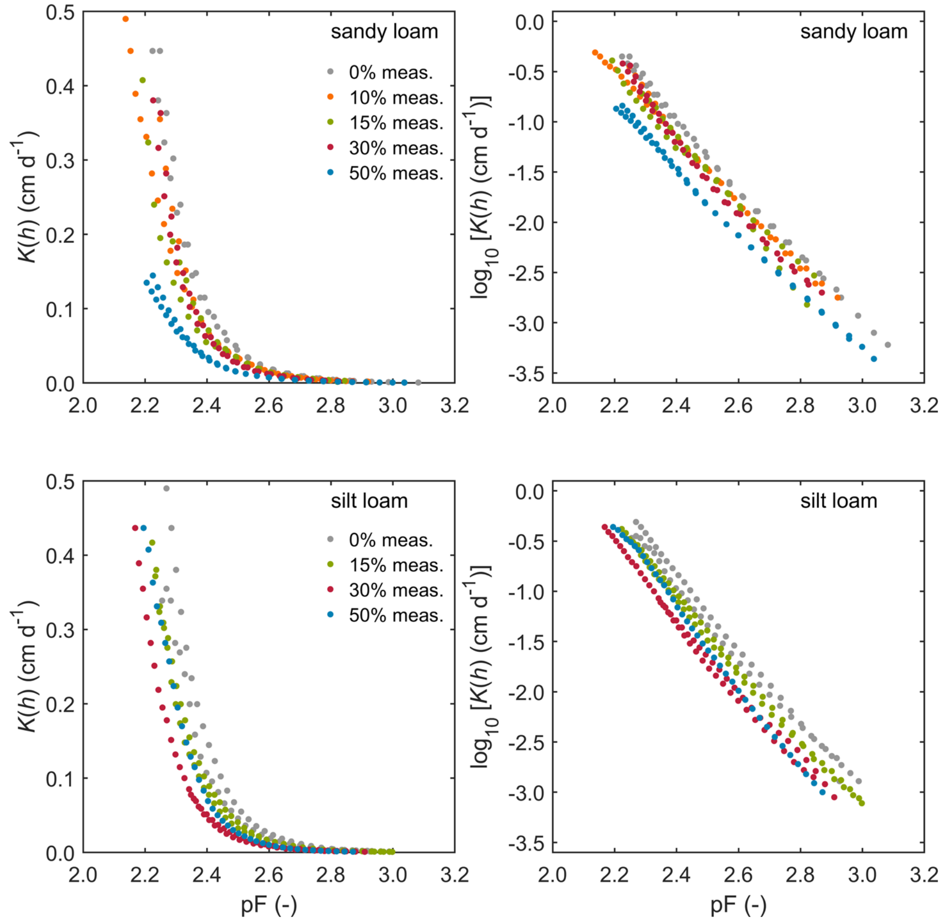

FIGURE 2 Measured (meas.) conductivity data, $K(h)$, (dots) in linear (left) and logarithmic (right) scales for the sandy loam and silt loam soils. The different volumes of rock fragments are displayed by color codes

decrease as expected. In these few cases, the reduction of the conductivity in the matric potentials up to pF ≈ 2.4 for the sandy loam and pF ≈ 2.6 for the silt loam soil is lower compared with other stony soils with smaller values of *f*. The reason could be a more probable presence of macropores in soil for higher amounts of RFs. This is also supported by the WRC of the silt loam. It has been noted that RFs boost the development of macropores in the vicinity of the RFs (Sekucia et al., 2020). The existence of macropores may compensate for the imposed reduction of conductivity, which results from the decrease of the cross-sectional area of flow by RFs. This causes a lower-than-expected reduction in the conductivity. However, HCC of these soils follows the expected trend when film and micropore flow become the dominant contributing mechanisms of the water flow in soil (Naseri et al., 2019).

TABLE 3 Performance of the evaluated scaling models of conductivity quantified by the mean deviation (MD) and RMSD

Background soil	Volumetric content of RF, *f* (%)	MD Ravina & Magier	MD Maxwell	MD Novák	MD GEM	RMSD Ravina & Magier	RMSD Maxwell	RMSD Novák	RMSD GEM
Sandy loam	10	0.1583	**0.1269**	0.1486	0.1347	0.1785	**0.1513**	0.1699	0.1579
	15	0.1335	0.1021	0.1179	**0.0964**	0.1569	0.1312	0.1438	**0.1268**
	30	0.0391	−0.0216	**0.0002**	-0.0478	0.0888	0.0826	**0.0797**	0.0929
	50	0.1507	0.0538	0.0538	**−0.0432**	0.1724	0.0996	0.0996	**0.0943**
Silt loam	15	0.0951	0.0637	0.0795	**0.0581**	0.1057	0.0787	0.0920	**0.0742**
	30	0.2435	0.1828	0.2045	**0.1566**	0.2516	0.1935	0.2142	**0.1690**
	50	**−0.0057**	−0.1026	−0.1026	−0.1996	**0.1066**	0.1478	0.1478	0.2262

Note. The values of MD and RMSD are shown for both background soils with different volumes of rock fragment (RF). The model with best performance for each volumetric content of RF has the lowest RMSD and absolute value of MD and is highlighted by bold letters. GEM, general effective medium theory model.

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

3.3 | Evaluation of the Ravina & Magier, Maxwell, Novák, and GEM models using the measured HCC data

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

According to Figure 3, the models show dissimilar results in scaling the HCC of background soils, in particular for high volumetric RFs. 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 RFs, in highly stony soils, the HCC becomes more nonlinear. That explains the discrepancies between the modeled and measured values of HCC for the evaluated models. The resulting values of RMSD and MD for the four evaluated scaling models and two background soils with different volumes of RF are presented in Table 3. These values are indicators of the performance of each scaling model in predicting the measured data points of HCC.

The values of MD in Table 3 are mostly positive (modeled values of HCC are greater than measured) for stony soils with low volumes of RFs, which shows the tendency of all models to underestimate the reduction of HCC. All models underestimate the reduction in the HCC 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 reduction in HCC is overestimated for high RF content. This highlights the role of texture of the background in reducing HCC depending on the volume of RFs, which should be taken into account in the scaling models. Different reductions in the saturated HCC for stony soils with similar RF contents and various soil textures are reported through numerical simulations by Novák et al. (2011). The simple linear scaling using the Ravina & Magier model underestimates the reduction in the HCC in sandy loam stony soils. This indicates that reduction in the measured HCC is stronger than expected by the factor $(1 - f)$ and hints at a higher tortuosity of flow paths caused by the presence of RFs. Naseri et al. (2022) also reported identical results by comparing the Ravina & Magier model results and the HCC identified through three-dimensional simulated experiments. However, despite the underestimation of the reduction in conductivity in stony soils with low values of f, this model has the lowest MD and RMSD values in the silt loam stony soil with $f = 50\%$ (v/v). Therefore, although the scaling model of Ravina & Magier does not predict the HCC 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. For the linear-scaling model of Novák in our study, an average value of 1.2 was applied for α_K. An accurate determination of this parameter is necessary to obtain correct estimations of conductivity for Novák's model (Hlaváčiková et al., 2016; Naseri et al., 2022). According to the values of RMSD and MD (Table 3), 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 HCC of stony soils with low volumetric RFs 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 HCC. However, the GEM model still shows a better performance in the sandy loam stony soil with $f = 50\%$.

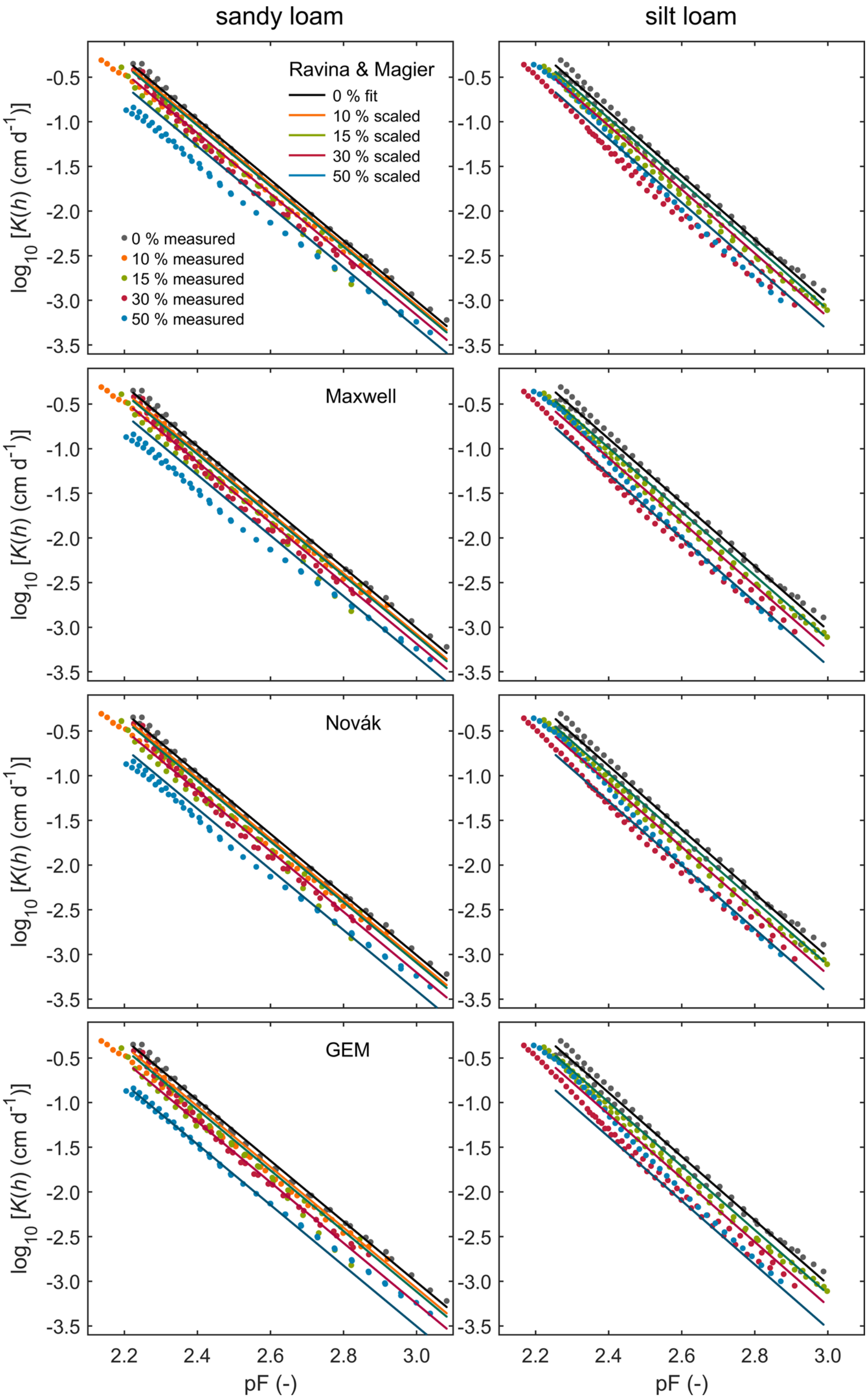

FIGURE 3 Illustration of hydraulic conductivities, $K(h)$: the straight black line fitted to the hydraulic conductivity of background soil in logarithmic scale (0% fit) and scaled hydraulic conductivities (solid lines with different color codes) obtained by the scaling models of Ravina & Magier, Maxwell, Novák, and general effective medium theory (GEM) for sandy loam (left) and silt loam (right) soils and different values of f (volumetric content of rock fragments). Colored dots also present the measured data points of hydraulic conductivity for different values of f

4 | CONCLUSIONS

In our study, we successfully measured the SHPs of stony soils for pressure heads up to pF ≈ 3.0. Scaling of the WRC shows that the reduction in the water content by RFs in our experiments is lower than a simple shift by $(1-f)$. Accounting for the WRC of RFs in the mixing model of Peters & Klavetter (1988) resulted in an excellent match to the measured data. This result suggests that not only the volume of RFs but also their moisture content has a considerable impact on the effective WRC and should be considered. The amount of influence for a soil depends on the characteristics of RFs, such as their volumetric content, size, effective porosity, pore-size distribution, and so on.

For scaling the HCC, 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 invariant with the embedded amount of RFs. However, our results confirm that pore-size distribution of the background soil varies, particularly in highly stony soils, and even in packed samples with identical bulk densities. Therefore, we suggest to develop and apply models that account for the influence of RF content on bulk density of the background soil and the resulting impact on the pore-size distribution and SHPs. 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 ~30% (v/v). Furthermore, the development of macropores caused by the presence of RFs influenced water retention and flow in the wetter range of SHPs.

In this research, we extended the experimental data of unsaturated flow conditions to soils with high volumes of RFs. Measuring properties of these systems for higher RF contents and different sizes, types, arrangements, and shapes needs further experiments. The role of permeable RFs on the conductivity of stony soils, especially at lower matric potentials where soil becomes drier, 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 RFs or a background soil and RF, some water might be attracted by capillarity and result in higher moisture content in the vicinity of the 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. This research extends our knowledge to calculate effective hydraulic properties of highly stony soils in large-scale hydrological models. However, the validation of models under field conditions is necessary to improve their predictability potential in theoretical and practical applications.

AUTHOR CONTRIBUTIONS

Mahyar Naseri: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – original draft; Writing – review & editing. Deep C. Joshi: Formal analysis; Software; Visualization. Sascha C. Iden: Formal analysis; Methodology; Writing – review & editing. Wolfgang Durner: Funding acquisition; Project administration; Resources; Software; Supervision; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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