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Soil water retention and hydraulic conductivity measured in a wide saturation range

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Abstract. Soil hydraulic properties (SHP), particularly soil water retention capacity and hydraulic conductivity of unsaturated soils, are among the key properties that determine the hydrological functioning of terrestrial systems. Some large collections of SHP, such as the UNSODA and HYPRES databases, already exist for more than two decades. They have provided an essential basis for many studies related to the critical zone. Today, SHP can be determined in a wider saturation range and with higher resolution by combining some recently developed laboratory methods. We provide 572 high-quality SHP data sets from undisturbed samples covering a wide range of soil texture, bulk density and organic carbon content. A consistent and rigorous quality filtering ensured that only trustworthy data sets were included. The data collection contains: (i) SHP data: soil water retention and hydraulic conductivity data, determined by the evaporation method and supplemented by retention data obtained by the dew point method and saturated conductivity measurements, (ii) basic soil data: particle size distribution determined by sedimentation analysis and sieving, bulk density and organic carbon content, as well as (iii) meta data including the coordinates of the sampling locations. In addition, for each data set, we provide soil hydraulic parameters for the widely used van Genuchten/Mualem model and for the Peters-Durner-Iden (PDI) model, which accounts for non-capillary retention and conductivity. The data were originally collected to develop and test advanced models of SHP and associated pedotransfer functions. However, we expect that they will be very valuable for various other purposes such as simulation studies or correlation analyses of different soil properties to study their causal relationships.

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1 Introduction

A sound understanding of the hydrological functioning of variably-saturated soils in the environmental cycles is important for numerous applications in agronomy, forestry, water management and other disciplines. The hydrological functioning of soils is controlled by the soil hydraulic properties (SHP), specifically the water retention and hydraulic conductivity characteristics. SHP models are essential to simulate water dynamics, solute transport and energy transfers in the vadose zone using water flow and transport equations. Such SHP models are empirical mathematical representations of the highly non-linear soil hydraulic curves, which are parameterised based on measured SHP data. In order to estimate SHP from more accessible information, pedotransfer functions relate SHP parameters to basic soil properties like soil texture, bulk density, and organic carbon content (C_{org}) (Vereecken et al., 2010; Van Looy et al., 2017).

Fitting non-linear SHP models to observed data and developing pedotransfer functions both require large data collections containing information about SHP measured over a large range of saturation in samples with various combinations of basic soil properties.

Since the application of SHP models in hydrological simulations in the 1980s there is a demand for such parameters (Carsel and Parrish, 1988). Commonly, they are derived for specific SHP models (Vereecken et al., 2010), which is most often the van Genuchten-Mualem model (Van Genuchten, 1980; Mualem, 1976). Due to methodological restrictions, data for such applications were first limited to few points on the soil water retention curve using ceramic pressure plate extractors and pressure-controlled hydraulic conductivity (Brooks and Corey, 1964).

Since the late 1990s, different data collections of SHP and associated basic soil properties have been compiled. They formed the basis to develop various pedotransfer functions. The freely available Unsaturated Soil Hydraulic Database (UNSODA) provided by the U.S. Department of Agriculture comprises nearly 800 SHP data sets from disturbed and undisturbed samples (Nemes et al., 2001). It includes measurements of retention and hydraulic conductivity with different coverage of the saturation range as well as basic soil properties, e.g. information on soil texture or bulk density. UNSODA was an important basis to develop ROSETTA (Schaap et al., 2001; Zhang and Schaap, 2017), which is the most established pedotransfer function to predict the parameters of the van Genuchten/Mualem SHP model. Another prominent large collection of retention and hydraulic conductivity data is the database of the Hydraulic Properties of European Soils (HYPRES) (Wösten et al., 1999) and its further development as the European Hydropedological Data Inventory (EU- HYDI) (Weynants et al., 2013) which is unfortunately not freely available. There are a few more specific SHP data collections, e.g. the HYBRAS data describing Brazilian tropical soils (Ottoni et al., 2018), and the collection by Schindler and Müller (2017) which contains only data measured with the evaporation method (Peters and Durner, 2008; Schindler, 1980). Recently, Gupta et al. (2022) gathered published soil water retention data from 2,702 sites, prepared them for an easy use in land surface modeling and made them commonly accessible.

The existing databases have undoubtedly supported a large number of hydrological studies leading to important conclusions, but they still have some limitations and shortcomings. Often, SHP data only cover a small part of the naturally occurring range

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of soil saturation. Gupta et al. (2022) emphasised that in many cases the retention data series contain only a few pairs of data and lack information in the wet region close to full saturation. Measured saturated hydraulic conductivity (K_{sat}) is included in several data collections, but detailed information about the unsaturated hydraulic conductivity is still rare.

It is technically possible to create pedotransfer functions that only use retention and K_{sat} data (Assouline and Or, 2013). However, in such cases the shape of the hydraulic conductivity curves is predicted only from the water retention curve and scaled to match K_{sat}. Hence, the absolute position of the conductivity curve is solely determined by a single K_{sat} value, which is strongly influenced by soil structure and macropore connectivity. A serious development and rigorous testing of full-range SHP models always requires measured unsaturated hydraulic conductivity data. Zhang et al. (2022) showed impressively how fast a supposedly large number of available SHP data sets can collapse, when they are filtered by predefined data requirements. They initially gathered 19,510 data sets from established data collections and first narrowed it down to 14,997 data sets describing undisturbed samples. They then extracted 1,801 lab measured data sets with information about both soil water retention and hydraulic conductivity. Finally, they extracted data sets with at least six retention and seven conductivity data pairs, each of which contained at least three data pairs close to saturation at matric heads larger than -20 cm. They ended up with 194 data sets accounting for only 1 % of the initial number.

Considering the large variability of naturally occurring soils, many pedotransfer functions are based on data collections that comprise rather limited soil information. Weihermüller et al. (2021) showed that the choice of the pedotransfer function used in a soil hydrological model can have considerable effects on simulated water fluxes. The artificial neural network behind ROSETTA has been trained with 2,134 retention curves, 1,306 K_{sat} values and 235 unsaturated conductivity curves (Schaap et al., 2001; Zhang and Schaap, 2017). Considering the wide use of ROSETTA with more than 1,790 citations (retrieved from Scopus on 20/02/2023) it becomes apparent, that the specific characteristics of only 235 unsaturated hydraulic conductivity data sets have been propagated into a large number of applications and conclusions.

However, pedotransfer functions can only predict the SHP within the range covered by the training dataset. Furthermore, they tend to reflect the individual characteristics of the training data, which are most pronounced in case of small databases. To prevent such bottle neck effects, the basis for pedotransfer applications needs to be further diversified. This requires new and independent, quality-assured SHP data collections. With advanced measuring techniques becoming standard in many soil physical laboratories, it is now much easier to obtain experimental SHP data over a wider range of moisture content and in the desired high quality.

In this paper, we present a collection of 572 new data sets of soil properties (Hohenbrink et al., 2023) that are independent of existing databases. Each data set comprises (i) SHP, and (ii) the basic soil properties soil texture, bulk density and C_{org}. The SHP data meet high quality requirements since they have been determined by combining state-of-the-art laboratory techniques, i.e. evaporation method (Peters and Durner, 2008; Schindler, 1980), dewpoint method (Campbell et al., 2007), and separate K_{sat} measurements. In addition, each data set was subjected to a thorough quality control. The data collection covers a wide range of soil textures. The information on soil texture is provided on two levels: main texture groups in the German and USDA classification system and the sub-classes for silt and sand, respectively.

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In support of the FAIR principles (Wilkinson et al., 2016) we would like to provide free access to this strong foundation for developing powerful SHP models and pedotransfer functions. The data were originally collected to provide a basis for the development of advanced SHP models (Peters et al., 2021, 2023) and related pedotransfer functions. We expect that they will be valuable for various further purposes such as simulation studies and statistical analyses of various soil properties.

2 Materials and Methods

2.1 Data sources

The data sets originate from different laboratories and have been collected for various original purposes. After launching a community initiative for sharing SHP data sets by the Division of Soil Science and Soil Physics at TU Braunschweig, researchers from four institutions participated and provided data. Most of the data had already been used to answer individual research questions at various research sites (Jackisch et al., 2017; Kreiselmeier et al., 2019, 2020; Leuther et al., 2019; Jackisch et al., 2020; Germer and Braun, 2019; Metzger et al., 2021). Further already existing but yet unpublished data sets measured at TU Braunschweig have been reviewed and integrated into the data collection. In addition, we systematically added data from sites with soil characteristics that were missing from the data collection. We took soil samples at these sites and measured their properties explicitly for this data collection.

To select data sets meeting our standards and optimally covering (a) soil texture, (b) bulk density, and (c) C_{org}, the data sets must contain soil water retention and hydraulic conductivity data, measured in the laboratory by the evaporation method, preferably supplemented by dewpoint method data and also measurements of saturated hydraulic conductivity. The data sets should also include information about soil texture, bulk density and C_{org}. We included data sets that lacked some of the preferred information only if they added complementary combinations of basic soil properties to the data collection.

2.2 Soil samples

Each data set is based on one undisturbed soil sample taken in situ with metal cylinders. In 542 cases the sample volume was 250 cm^3, while 30 samples had a volume of 692 cm^3 as indicated in the meta data table of Hohenbrink et al. (2023). For the measurement of C_{org}, soil texture and retention data in the dry range (dewpoint method), disturbed soil (sub)samples were taken. In 363 cases, the disturbed and undisturbed samples are directly assigned to each other by taking the samples in immediate proximity to each other. In the other 209 cases, the disturbed material was taken as a mixed sample, representative of an entire site with several undisturbed sampling points. Consequently, in the latter cases the soil variables derived from the aggregated undisturbed samples have been assigned to more than one data set (indicated in the meta data table). Information about the positions of the sampling sites is available for 555 data sets. It has either been measured by GPS or was taken from aerial images after sampling. The accuracy of the reported sampling locations is smaller than 100 m, which represents the best accuracy class in Gupta et al. (2022).

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2.3 Laboratory measurements

Soil water retention in the wet (defined here as pF < 1.8; $\mathrm{pF} = \log_{10}(-h\ [\mathrm{cm}])$) and medium (defined here as 1.8 < pF < 4.2) moisture range and hydraulic conductivity in the medium moisture range were simultaneously determined with the simplified evaporation method (Peters and Durner, 2008; Schindler, 1980) using the HYPROP device (METER Group, AG, Germany). The evaporation method provides information related to the drying branches of the SHP curves. The air entry points of the tensiometer cups have been used as additional measuring point (Schindler et al., 2010) in cases where the duration of the evaporation experiments was long enough. Soil water retention information has been supplemented in the dry moisture range (defined here as pF > 4.2) by measurements with the dewpoint method (Campbell et al., 2007; Kirste et al., 2019) using the WP4C device (METER Group, Inc., USA). Hydraulic conductivity of the saturated soil was measured in the undisturbed samples either with the falling head or the constant head method using the KSAT device (METER Group, AG, Germany).

Particle size distributions of the disturbed soil samples have been determined by sieving for the sand fractions and sedimentation methods for the silt fractions and clay content (DIN ISO 11277, 2002). Since the data sets originate from various sources, the analyses have been performed following slightly different lab protocols, which, however, are all based on the same principles. Limits between particle size classes were defined by the German soil classification system (Ad-hoc-Arbeitsgruppe Boden, 2005) and afterwards additionally converted to the USDA system using the "soiltexture" R-package (Moeys, 2018). Bulk density of each sample was determined by oven-drying for at least 24 h after the evaporation experiments. C_{org} was determined with high-temperature combustion using different elemental analysers (indicated in the meta data table).

2.4 Fitting models to measured SHP data

The results of all SHP measurements have been compiled with HYPROP- FIT (Pertassek et al., 2015), a software to organize and evaluate raw data from the simplified evaporation method, the dewpoint method and individual K_{sat} measurements. Since manual adjustments to the raw data is required, all resulting retention and hydraulic conductivity points have been re-checked for plausibility by the same expert for consistency. In a few cases, individual dewpoint measurements that were clearly inconsistent were omitted from the original sources. The original binary HYPROP-FIT files are provided by Hohenbrink et al. (2023) to ensure transparency on all manual adjustments. The final series of measured retention and hydraulic conductivity data were exported from HYPROP-FIT to csv-files for further data processing, which was mainly performed in R (R Core Team, 2020).

For direct access to resulting SHP model parameters, we fitted two models to the measured soil water retention and hydraulic conductivity data using SHYPFIT 2. 0 (Peters and Durner, 2015). The first model is the well-established van Genuchten/Mualem (VGM) model (Van Genuchten, 1980; Mualem, 1976). The second model is the recent version of the Peters-Durner-Iden (PDI) model with the VGM model as the basic function (Peters et al., 2021, 2023). The PDI model specifically considers (i) capillary water in completely filled pores and (ii) non-capillary water in thin films on particle surfaces and in corners and ducts of the pore system. The explicit consideration of non-capillary water yields more realistic retention

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and hydraulic conductivity curves in the medium and dry moisture range. Furthermore, the description of hydraulic conductivity in the dry range includes an effective component that reflects isothermal vapour flux (Peters, 2013). Unlike VGM and common models of SHP, where the relative hydraulic conductivity curve is scaled by the saturated conductivity K_s, the new PDI model structure allows absolute conductivity prediction based on the water retention curve. This enables a more realistic conductivity prediction under nearly saturated conditions (Peters et al., 2023). Additionally, we constrained the conductivity model by a maximum pore radius close to saturation, referring to an equivalent water tension of $h = -6$ cm (Iden et al., 2015). We refer to Peters et al. (2023) for a more detailed description of the applied version of the PDI model.

Retention and conductivity parameters were estimated simultaneously. Retention points measured with the dewpoint method were weighted ten times higher than those obtained with the evaporation method because the latter have a much higher frequency. Weights of hydraulic conductivity data were defined in a way that their ratio to the mean retention data weights was 16 to 10,000 following Peters (2013). We neglected measured K_{sat} values in the parameter optimization process, since they mainly reflect effects of soil structure (Weynants et al., 2009), which is not considered in the unimodal SHP models.

For the VGM model six parameters were estimated (residual and saturation water contents θ_r (-) and θ_s (-), the shape parameters α (cm^{-1}) and n (-), the tortuosity parameter λ (-), and the saturated hydraulic conductivity parameter K_s (cm d^{-1})). The predefined parameter limits are listed in Table 1. The upper limits for θ_r and θ_s were defined as a fraction of porosity Φ to ensure physical consistency. For the PDI model, five parameters (θ_r, θ_s, α, n and λ) were estimated. The same settings for the fitting algorithms as in Peters et al. (2023) were used. The parameter K_s in the PDI frame was calculated from the water retention curve and equals the hydraulic conductivity of the saturated bulk soil excluding the soil macropore network.

Table 1: Upper and lower parameter boundaries defined for parameter estimation. Note that the parameter boundaries for θ_r and θ_s are defined individually as a fraction of the porosity Φ. The boundaries for θ_r and λ differ between both models to ensure physical consistency.

	VGM		PDI	
	lower	upper	lower	upper
α (cm^{-1})	10^{-5}	0.5	10^{-5}	0.5
n (-)	1.01	8.00	1.01	8.00
θ_r (-)	0.0	$0.25 \cdot \Phi$	0.0	$0.75 \cdot \Phi$
θ_s (-)	0.2	Φ	0.2	Φ
K_s (cm d^{-1})	10^{-2}	10^{5}	-	-
λ (-)	$1 - \frac{2}{1-\frac{1}{n}}$ *	10	-1	10

* parameter constrained guaranteed physical consistency and allowed maximum flexibility

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3 Data description

The content of the data collection consists of (i) meta data (file: MetaData.csv), (ii) basic soil properties (BasicProp.csv), and (iii) SHP including measured points of the retention curve and hydraulic conductivity curve (RetMeas.csv, CondMeas.csv), optimized parameter sets for two SHP models (Param.csv) and data series resulting from both SHP models (HydCurves.csv). Each data set is labelled by a unique Sample-ID for easy joining of the different data tables.

3.1 Meta data

The meta data table summarizes relevant information about the availability of the single variables in each data set. All 572 data sets contain SHP measurements by the evaporation method, 499 contain at least one dew point measurement and 409 data sets include K_{sat} measurements (Table 2). In 370 data sets all three kinds of SHP information are available. In case of the basic soil properties, soil texture and bulk density are available for all data sets and C_{org} is contained in 488 cases. Complete information about all variables (SHP and basic soil properties) is available for 315 data sets (57 %).

The data collection contains location information for each data set (Figure 1). Most of the samples have been taken in Central Europe (n = 508) and only few data sets come from Canada (n = 29), Japan (n = 5) and Israel (n = 30). The sampling sites are not arranged systematically, since the region of sampling has not been a criterion for data collection. They are rather clustered in the regions where the data contributing institutions have performed field work.

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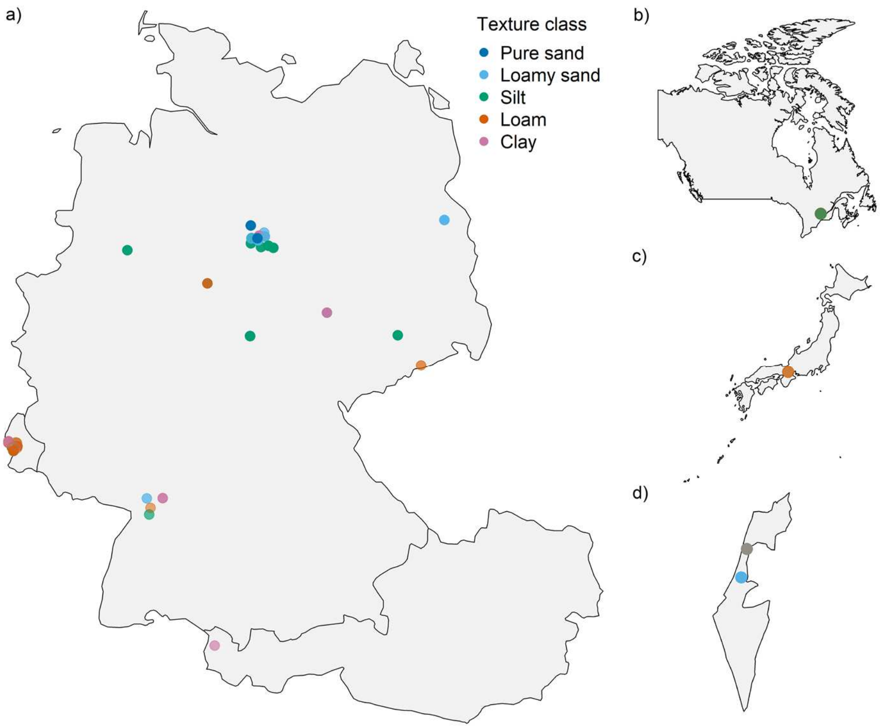

Figure 1: Locations of the sampling sites in (a) Luxembourg, Germany and Austria, (b) Canada, (c) Japan, and (d) Israel. Please note that the map scales differ, as the maps should only provide a broad overview.

Table 2: Availability of the key variables in the data collection.

Measured variable	Number of data sets	
	available	not available
SHP by Evaporation method	572	0
SHP by air entry point of tensiometers	286	286
Retention data by dew point method	499	73
Separately measured K_{sat}	409	163
Bulk density	572	0
Texture main groups (SSC)	572	0
Texture subgroups	569	3
C_{org}	488	84

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3.2 Basic soil properties

The data collection covers a wide range of soil textures, including soils with up to 65 % clay and 93 % silt and 100 % sand (positons of symbols in the soil texture triangle, Figure 2a and 2b). It covers the textures most frequently found in natural soils. The main textural classes according to the German classification (Ad-hoc-Arbeitsgruppe Boden, 2005) account for 217 (sand), 146 (silt), 122 (loam) and 88 (clay) data sets. The sandy soils are further subdivided into 39 pure sands and 178 loamy sands, as the SHP usually have the highest variation within the sand texture class. The two areas in the soil texture triangle with the lowest data coverage are sandy clay and sandy silt soils.

The bulk densities of the samples vary between 0.37 g cm^{-3} and 1.89 g cm^{-3} with a median of 1.40 g cm^{-3}. High bulk densities mainly occurred in sandy soils while silty clay soils were less dense (Figure 2a). In general, soil bulk density scattered across the texture triangle, which is reflected by rather weak but significant Pearson correlations (p-value <0.05) between bulk density and the sand ($r = 0.41$), silt ($r = -0.24$) and clay ($r = -0.50$) contents, respectively.

C_{org} in the samples ranges from 0.04 % to 19.26 % with a median of 1.44 %. The maximum values mainly occurred in silty clay, loam and silty sand soils. Smaller C_{org} values were associated with sand and silt soils (Figure 2b). C_{org} and bulk density were negatively correlated (r=-0.76; Fig. 2c).

In addition to the standard soil texture classification by sand, silt and clay fractions, the subgroups (coarse, middle, fine) for silt and sand are also provided (Figure 3). Most silt soils contain a maximum fraction of coarse silt (20 µm - 63 µm), while the loamy sands are mainly dominated by the fine sand fraction (63 µm - 200 µm).

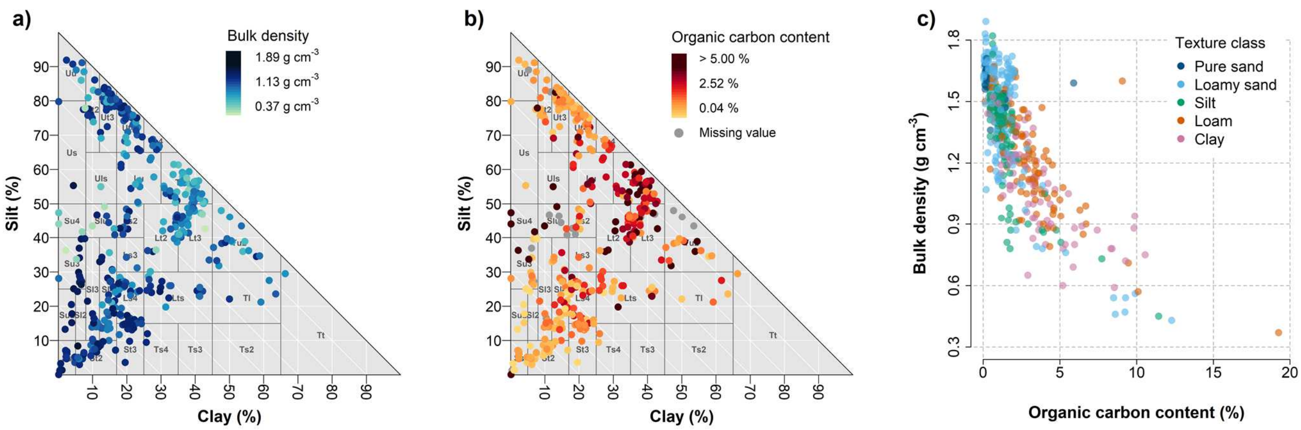

Figure 2: Distributions of (a) bulk density and (b) organic carbon content in the texture triangle and (c) the negative correlation between them.

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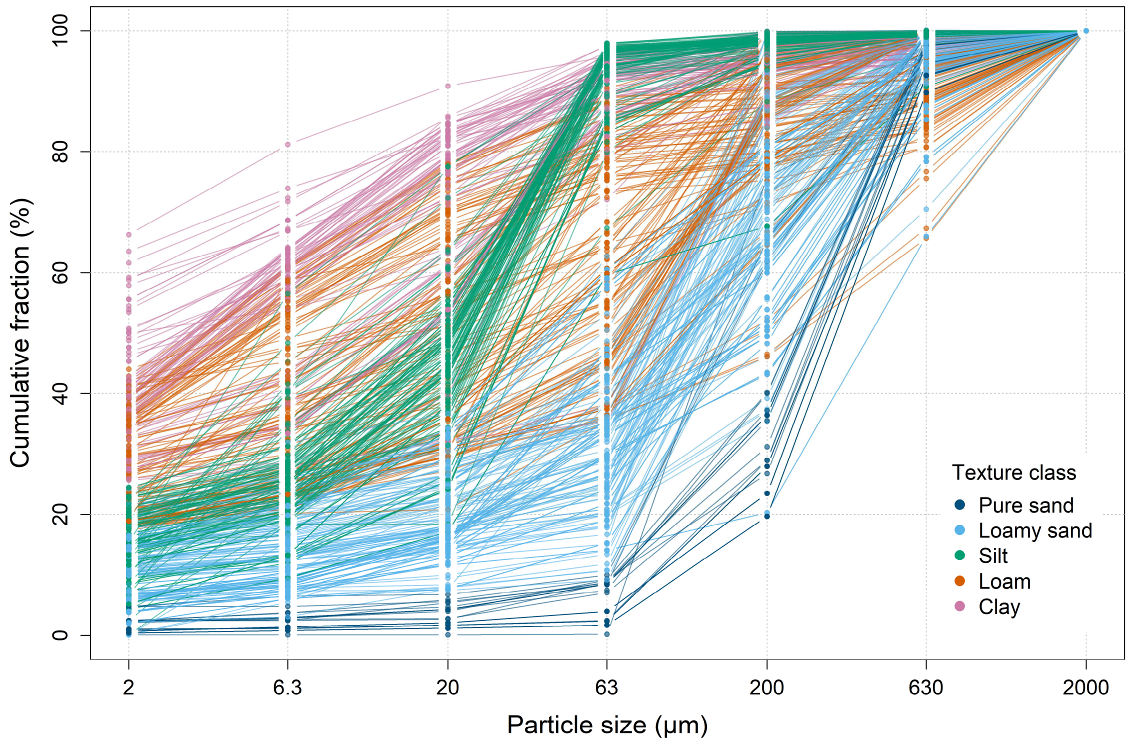

235 **Figure 3: Cumulative particle size distributions of the 572 samples, different textures are distinguished by colour codes. The texture classification refers to the German classification system (Ad-hoc-Arbeitsgruppe Boden, 2005), but USDA texture classes are also provided in the data collection.**

3.3 Measured soil hydraulic data

The measured SHP are shown in Figure 4. The retention data cover almost the entire range between full water saturation and oven dryness. The highest data coverage is available in the wet and medium saturation range with pF < 3.2, where the data stem from the simplified evaporation method (circles in Figure 4). Half of the data sets contain one additional data point between pF 3.0 and pF 4.0 which originates from the air entry pressure of the porous tensiometers cup (triangles in Figure 4). In 499 data sets at least one data pair between pF 4.0 and pF 6.3 determined by the dewpoint method exists (squares in Figure 4). The number of dewpoint measurements for single samples ranges between 1 and 8 with a median of 3. Hydraulic conductivity data obtained by the evaporation method range mostly from pF 1.0 to pF 3.2. Again, one single conductivity data point originates from the air-entry of the porous cup for about half of the data sets. A separately measured K_{sat} is available for 409 data sets (diamonds in Figure 4). The data collection neither contains conductivity data in the range close to saturation (pF <1), nor in the dry range. Currently, there is no standard laboratory method to determine hydraulic conductivity in this range.

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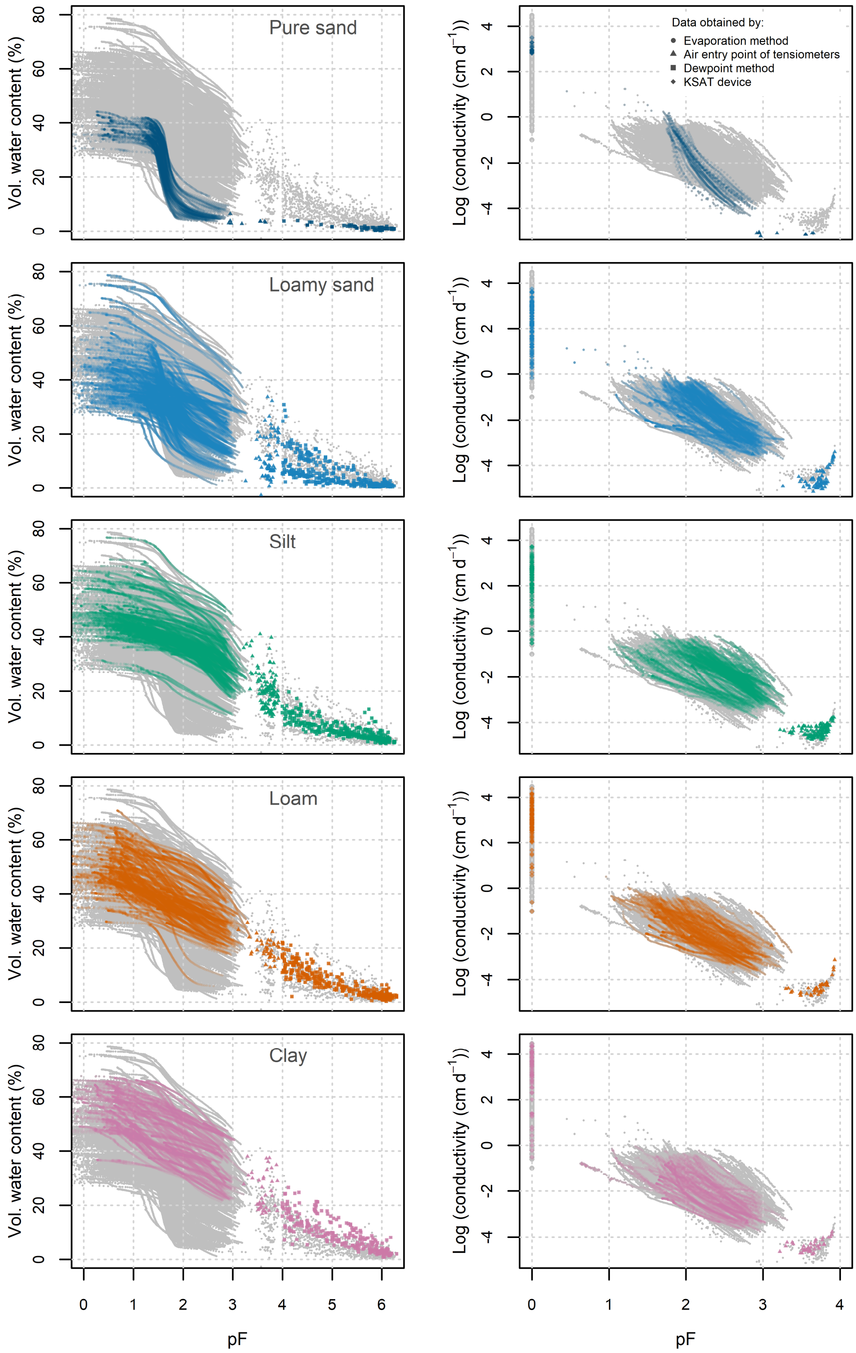

250 **Figure 4: Soil water retention (left) and hydraulic conductivity (right) measured with different laboratory methods. Grey symbols in the background show all measured values. Data series for single texture classes are summarized in sub-plots and indicated by colour codes. Please note the different pF ranges for the retention and conductivity curves.**

3.4 Fitted SHP models

The distributions of the fitted model parameters for both VGM and PDI (data provided in table "Param.csv" in Hohenbrink et al. (2023), but not shown here) mostly cover the predefined range of plausible parameters (Table 1). The constraining boundaries were only hit in 5 cases with the exception of parameter λ of the PDI model (154 cases in which bounds were hit). The fitted water retention curves (Figure 5a and 5c) reflect the main characteristics of the measured SHP described above (Figure 4). Retention curves from both models are similar in the wet to medium range. However, in the medium to dry moisture range they systematically differ. The retention curves described by VGM approach a residual water content, while those from the PDI model linearly reach zero saturation at pF = 6.8, which reflects the matric potential at oven dryness (Schneider and Goss, 2012).The hydraulic conductivity curves described by VGM (Figure 5b) vary over a wide range. While it is difficult to relate them to texture visually, those of the PDI model (Figure 5d) are more closely related to texture and span a much narrower range for each texture class. The variation among the curves decreases towards the dry end of the saturation range. Especially in the dry range, the hydraulic conductivity increases along the texture gradient from pure sand via loamy sand, silt and loam to clay. This phenomenon results from the PDI model structure, where hydraulic conductivity in the dry range is directly derived from the water content at $\mathrm{pF} = 5.0$ (Peters et al., 2021). At $\mathrm{pF} > 5.5$ the hydraulic conductivity of the PDI is dominated by the isothermal vapour conductivity for all textures.

Common soil hydrological key properties to evaluate the ability of a soil to support plant growth can be derived from the fitted water retention curves : the water content at field capacity (θ at pF = 1.8) and at the permanent wilting point (θ at pF = 4.2) as well as the resulting plant available water content ($\theta(\mathrm{pF} = 1.8) - \theta(\mathrm{pF} = 4.2)$). Figure 6 shows these values in the texture triangle derived from the PDI retention curves. The water content at both field capacity (Figure 6a) and wilting point (Figure 6b) roughly increases from sandy soils towards soils with finer textures. However, apart from this very general distinction, the values of both variables vary widely over the texture triangle. The same pattern applies to the values of plant available water content, which varies between the extremes of 3.8 % (v/v) in pure sand up to 49.2 % (v/v) in the fine-textured soils.

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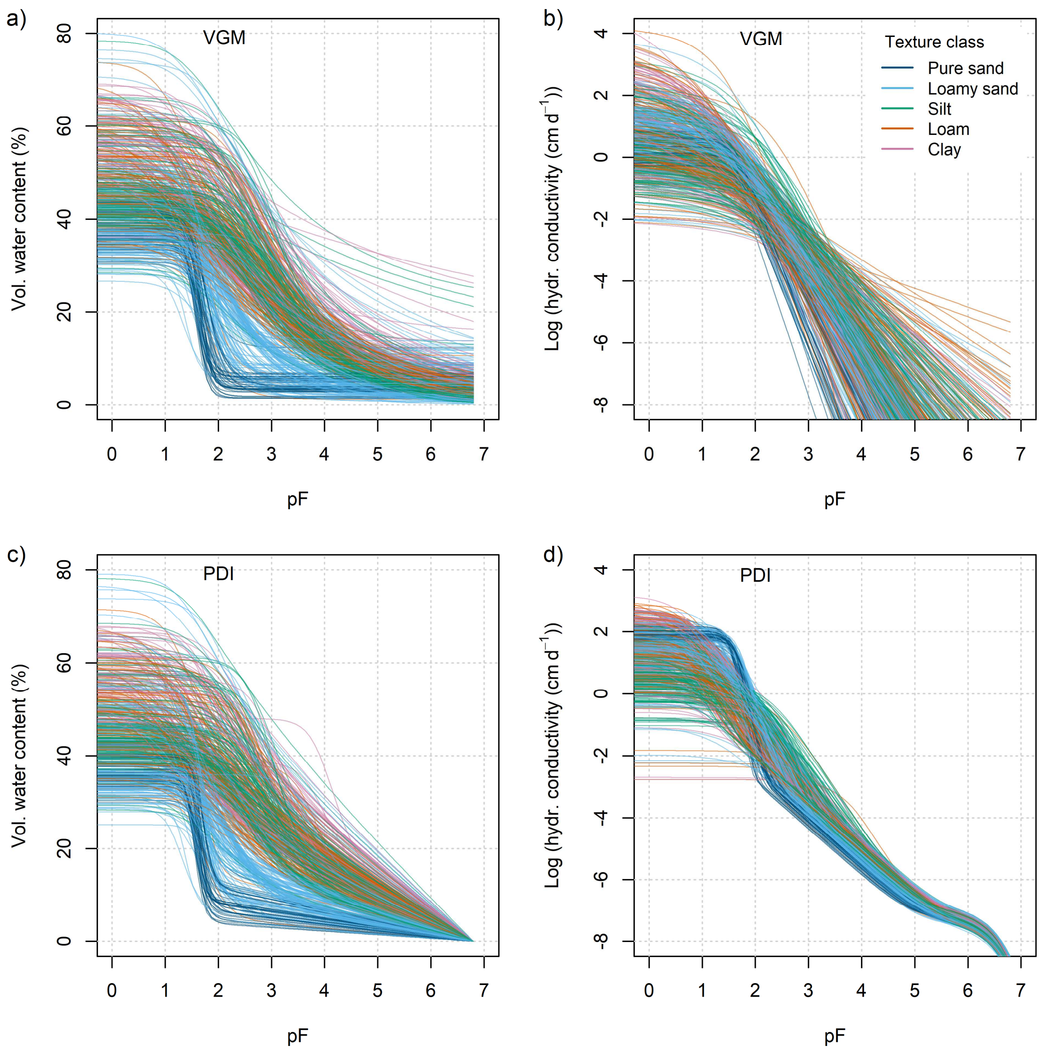

Figure 5: Retention curves (left) and hydraulic conductivity curves (right) for the van Genuchten- Mualem model (a and b) and the PDI model with van Genuchten basic function (c and d). Soil texture classes are indicated by different colour codes.

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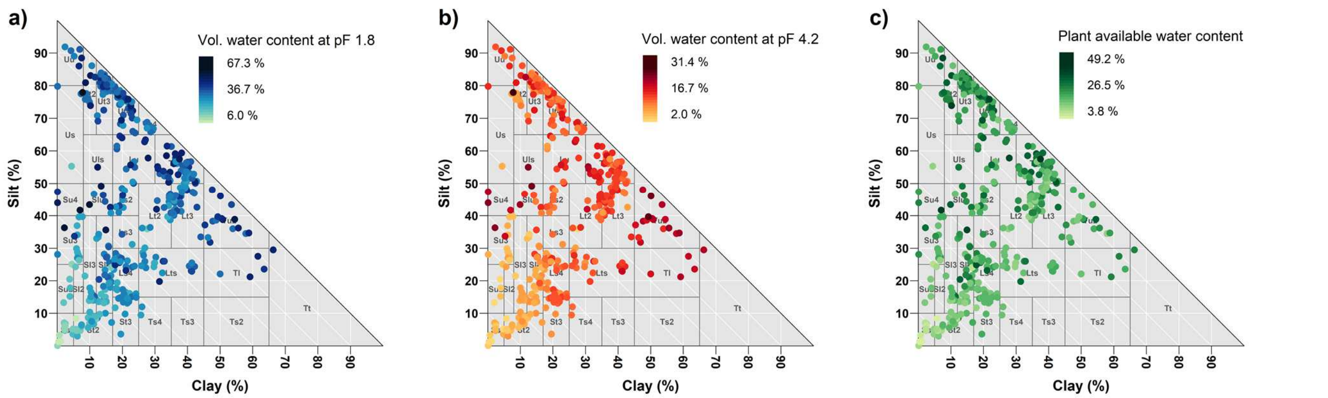

Figure 6: Volumetric water contents at (a) field capacity, (b) the plant wilting point and (c) the resulting plant available water scattered on the soil texture triangle. The values provided in the data collection are calculated from retention curves described by the PDI model.

4 Discussion

4.1 New applications arising from the data collection

The combination of different state-of-the-art methods to measure soil water retention and hydraulic conductivity yields a unique SHP data collection. Especially, the denser coverage of a wider range of saturation compared to existing data collections makes this one valuable for new applications. For example, the retention data in the dry range measured with the dewpoint method represent essential information to develop retention models that overcome the concept of a residual water content, which has been shown to be not physically consistent (e.g. Schneider and Goss, 2012; Tuller and Or, 2005; Nimmo, 1991). Furthermore, this data collection provides measurements of both saturated and unsaturated hydraulic conductivity for each of the 572 samples in high resolution and over a wide range of saturation. This supports the development and improvement of hydraulic conductivity models.

An additional advantage of this data collection is that it is based on undisturbed samples exhibiting features of natural soils. Thereby it can be tested whether SHP models are suitable to describe the SHP for more practical applications. When an SHP model is only developed and tested with packed soil columns or with samples from few carefully selected sites, it might behave less robust in “real world” applications.

The VGM and PDI parameters provided in the data collection have been estimated with state-of-the-art techniques. Both parameter sets can be valuable to develop and test simulation models and to perform simulation studies. We have intentionally omitted the measured K_{sat} values during parameter estimation. Considering K_{sat} in combination with unimodal SHP models usually causes an overestimation of hydraulic conductivity close to saturation since the K_{sat} information mainly reflects the impact of soil structure (Durner, 1994; Peters et al., 2023). The K_s parameter derived for the PDI can thus be interpreted as the conductivity of the soil matrix only, excluding effects of soil structure similarly to Weynants et al. (2009) and as further discussed in Fatichi et al. (2020). It is now possible to further investigate the relation between K_s of the soil matrix and K_{sat} of the entire soil including structure effects based on the parameters provided.

Besides the commonly used fractions of sand, silt and clay to classify soil texture, the subgroups for sand and silt are also provided in the data collection. The effect of the resolution of particle size classification on SHP has rarely been investigated, and common pedotransfer functions only consider the main texture groups as predictor variables. However, SHPs are expected to differ significantly when the sand fraction is dominated by either fine sand or coarse sand. Based on the presented data collection, such questions can be investigated in detail and potentially more accurate pedotransfer functions can be developed.

4.2 Limitations of the data collection and further research needs

Although the data collection enables many different applications, it has some limitations that must be considered when analysing the data and interpreting the results. The single data sets are not completely statistically independent from each other for the following main reasons: (i) many samples stem from identical sites; (ii) some data sets exhibit identical texture and C_{org} values, because in some cases only few aggregated disturbed samples representative for a whole site have been taken; (iii) the analyses have been performed in five different laboratories. However, by closely following the guidelines of the experiments a high degree of standardisation in the laboratory protocols could be achieved.

In some situations, it might be reasonable to thin out the data by keeping only data sets assumed to be statistically independent. However, whether this is necessary depends on the particular research question and the applied data analysing technique. We have decided to include all available data sets, provide enough meta information to evaluate the statistical dependencies, and leave it up to the user to decide how to handle it.

Another feature of the data that users have to cope with is the unbalanced distribution of the datasets in terms of basic soil properties. For example, Luvisols with silt contents between 70 % and 85 % are overrepresented in the data collection due to their agricultural importance which leads to more frequent soil analyses. In contrast, there are data gaps for the sandy clay and sandy silt texture classes, because they do occur more sparsely in nature and are generally less intensively investigated. The unbalanced distribution of the data can be especially challenging for the development of pedotransfer functions. This problem can be best solved by supplementing the data collection by additional measurements.

At the level of individual datasets, the gaps in the hydraulic conductivity series near saturation and under dry conditions are another important limitation. Such data are needed to parameterize existing models in a way that they become more reliable in the respective saturation ranges. More comprehensive hydraulic conductivity data is also required to develop new SHP models. Therefore, we identify a need for developing and establishing new standard methods to measure hydraulic conductivity close to saturation (Sarkar et al., 2019b, a) and in the dry range.

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5 Data availability

The data collection is hosted in the repository GFZ Data Services (Hohenbrink et al, 2023). It can be accessed via https://doi.org/10.5880/fidgeo.2023.012. The final DOI will be registered when the paper is accepted, temporary data access to Hohenbrink et al. (2023) via https://dataservices.gfz-potsdam.de/panmetaworks/review/5c617cd2664ea4d03e81301b5bc2236f0c9620ca0bed66c726d2e424d166fd85/. The rights of use are defined by a creative common licence (CC BY 4.0). The data collection in the repository includes all data presented in this paper. Further information and materials such as small volumes of air dried reserve soil samples can be provided by the corresponding author or the second author (Conrad.Jackisch@tbt.tu-freiberg.de) upon request.

6 Summary and conclusions

Motivated by a need for detailed soil water retention and hydraulic conductivity data, we have launched a community initiative to collect data of SHP measured using state-of-the-art techniques. After rigorous quality filtering, our data collection contained soil water retention and hydraulic conductivity data sets determined with the simplified evaporation method, the dewpoint method and separate K_{sat} measurements for 572 undisturbed soil samples. The data sets are supplemented with basic soil properties including particle size distribution obtained by sieving and sedimentation analyses, as well as bulk density and organic carbon contents. In addition to the experimental data, we provide parameter sets and tabulated water retention and conductivity curves over the whole moisture range for two models of SHP: the well-established van Genuchten-Mualem model, and the recent version of the PDI model.

The data collection can be used in its current form or integrated into existing data collections. All data sets were acquired directly from the original sources, which makes the data collection completely independent of the existing pool of data on SHP and thus contributes to their diversification. In particular, the hydraulic conductivity series will substantially expand the existing inventory of SHP data.

We expect that this data collection can serve as an independent, new and therefore unexplored benchmark reference to evaluate already existing SHP models and pedotransfer functions. Due to the high resolution of measured data compared to existing databases and the extended range of saturation, it is also an ideal basis to develop and test new advanced SHP models and pedotransfer functions. It is also well suited to verify findings and conclusions that have so far emerged from the existing data collections.

Author contributions

TH compiled and analysed the data, created the figures, and drafted the manuscript. All co-authors contributed to the final version. AP adapted the PDI model and the fitting software, was involved in building the data collection, and supervised the project. CJ supported in structuring the data collection. JM, JK, FL, and CJ provided already existing data sets and evaluated them initially. KG and MN collected samples with new combinations of basic soil properties, performed laboratory measurements, and evaluated them initially. WD and SI supported the data preparation and analyses.

Competing Interests

Conrad Jackisch is a member of the editorial board of Earth System Science Data. The authors have also no other competing interests to declare.

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