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RESEARCH ARTICLE

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Hydraulic properties of peat soils along a bulk density gradient—A meta study

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Abstract

Our understanding of hydraulic properties of peat soils is limited compared with that of mineral substrates. In this study, we aimed to deduce possible alterations of hydraulic properties of peat soils following degradation resulting from peat drainage and aeration. A data set of peat hydraulic properties (188 soil water retention curves [SWRCs], 71 unsaturated hydraulic conductivity curves [UHCs], and 256 saturated hydraulic conductivity [K_s] values) was assembled from the literature; the obtained data originated from peat samples with an organic matter (OM) content ranging from 23 to 97 wt% (weight percent; and according variation in bulk density) representing various degrees of peat degradation. The Mualem-van Genuchten model was employed to describe the SWRCs and UHCs. The results show that the hydraulic parameters of peat soils vary over a wide range confirming the pronounced diversity of peat. Peat decomposition significantly modifies all hydraulic parameters. A bulk density of approximately 0.2 g cm^{-3} was identified as a critical threshold point; above and below this value, macroporosity and hydraulic parameters follow different functions with bulk density. Pedotransfer functions based on physical peat properties (e.g., bulk density and soil depth) separately computed for bog and fen peat have significantly lower mean square errors than functions obtained from the complete data set, which indicates that not only the status of peat decomposition but also the peat-forming plants have a large effect on hydraulic properties. The SWRCs of samples with a bulk density of less than 0.2 g cm^{-3} could be grouped into two to five classes for each peat type (botanical composition). The remaining SWRCs originating from samples with a bulk density of larger than 0.2 g cm^{-3} could be classified into one group. The Mualem-van Genuchten parameter values of α can be used to estimate K_s if no K_s data are available. In conclusion, the derived pedotransfer functions provide a solid instrument to derive hydraulic parameter values from easily measurable quantities; however, additional research is required to reduce uncertainty.

KEYWORDS
hydraulic properties, Mualem-van Genuchten model, peat soil, pedotransfer functions

1 | INTRODUCTION

Peatlands cover only 3% of the earth's land surface but store approximately one-third of the global soil carbon pool (Limpens et al., 2008; Turunen, Tomppo, Tolonen, & Reinikainen, 2002). Drainage and intensive use of peatlands accelerate the mineralization of organic matter (OM; Brandyk, Szatylowicz, Oleszczuk, & Gnatowski, 2002) leading to greenhouse gas emission (e.g., CO_2). Although only 15% of the peatlands have been drained (0.3% of the world's land cover) and are currently being used for agriculture, livestock or forestry, peat extraction, and bioenergy plantations, these drained peat lands are responsible for 6% of anthropogenic CO_2 emissions (Joosten, Tapio-Biström, & Tol, 2012). Peatland drainage can alter physical properties of peat soils (e.g., OM content and pore structure; Rezanezhad et al., 2016), hydrological processes (e.g., infiltration and runoff production; Holden & Burt, 2003; Holden, Evans, Burt, & Horton, 2006), water chemistry (Holden, Chapman, & Labadz, 2004), and vegetation patterns (Fisher, Podniesinski, & Leopold, 1996). Hydraulic properties control the soil moisture, which is in turn one of the main drivers for carbon and nitrogen dynamics, (Kluge, Wessolek, Facklam, Lorenz, & Schwärzel, 2008) as well as solute transport (Liu, Forsmann, Kjærgaard, Saki, & Lennartz, 2017). However, knowledge about hydraulic properties of peat soils remains limited, particularly concerning the unsaturated zone (Wallor, Rosskopf, & Zeitz, 2018; Weiss, Alm, Laiho, & Laine, 1998).

The hydraulic properties of peat soils strongly depend on the pore structure, stage of decomposition, and botanical composition of the peat (Rezanezhad et al., 2016; Schwärzel, Renger, Sauerbrey, & Wessolek, 2002). Compared with mineral soils, peat has a higher OM content, lower bulk density (BD) and contains as high as almost 100% pore space with dead end or isolated pores (Hoag & Price, 1997; Liu et al., 2017; Paavilainen & Päivänen, 1995). Generally, peatland drainage decreases total porosity, accompanied by a shift in pore size distribution (Rezanezhad et al., 2010; Wallor et al., 2018). Macropores are an important feature of pore structure in peat soils (Baird, 1997; Holden, 2009) and have a large effect on hydraulic properties (Baird, 1997; Liu, Janssen, & Lennartz, 2016). During peat decomposition and degradation processes, macroporosity decreases and microporosity increases (Rezanezhad et al., 2010; Silins & Rothwell, 1998), although a higher macroporosity could be observed in strongly decomposed peat than in less decomposed peat (Schindler, Behrendt, & Müller, 2003; Wallor et al., 2018). In addition to pore structure, hydraulic properties of peat soils are highly affected by botanical composition. For example, saturated hydraulic conductivity (K_s) of sphagnum peat often differs from that of sedge peat, even under the same stage of humification (Päivänen, 1973; Rycroft, Williams, & Ingram, 1975). Moreover, botanical arrangement, pore water chemistry, migration of fine peat particles, and gas bubbles strongly affect hydraulic properties of peat soils (Brandyk et al., 2002; Chason & Siegel, 1986; Kettridge & Binley, 2008; Liu & Lennartz, 2015; Ours, Siegel, & Glaser, 1997).

The soil water retention curve (SWRC) and unsaturated hydraulic conductivity (UHC) are essential hydraulic properties for modelling water flow and solute transport under unsaturated conditions with Richards' equation. The well-known Mualem-van Genuchten (MVG) model (for SWRC and UHC) has previously demonstrated suitability for various types of peat soils (Hallema, Périard, Lafond, Gumiere, & Caron, 2015; Schwärzel, Šimůnek, Stoffregen, Wessolek, & Van, 2006; Weiss et al., 1998). Although for specific types of peat soil (e.g., living and slightly decomposed sphagnum), multimodels (e.g., bimodal or trimodal models) seem suitable (Dettmann, Bechtold, Frahm, & Tiemeyer, 2014; Weber, Iden, & Durner, 2017) to describe the UHCs, the MVG model (single domain) has been successfully applied to estimate the unsaturated hydraulic parameters for various peat soils (Gnatowski, Szatyłowicz, Brandyk, & Kechavarzi, 2010; McCarter & Price, 2014; Price et al., 2008; Schwärzel et al., 2006; Silins & Rothwell, 1998). Direct measurements of SWRC and UHC are time-consuming and costly. Pedotransfer functions (PTFs) are commonly employed to estimate the hydraulic parameters of mineral soils from easily measured soil properties such as BD and soil texture (Vereecken et al., 2010). The PTFs of hydraulic parameters have been investigated for less decomposed fen peat with intact plant residues (Weiss et al., 1998), histosols (Wösten, Lilly, Nemes, & Le Bas, 1999), and cultivated fen soils (Wallor et al., 2018); however, these valuable studies only cover a small fraction of the wide range of differently decomposed and degraded peat soils with varying botanical origin (Wallor et al., 2018).

The shift in hydraulic parameters during peat decomposition and degradation has not been explicitly addressed in earlier studies despite the availability of peat hydraulic data. Compared with the von Post humification (von Post, 1922), BD has been suggested as a proxy for decomposition because of the benefits of being objective, quantitative, and easy to measure (Bloemen, 1983; Frolking et al., 2010). In this study, a data set of peat hydraulic properties was assembled from the literature. The objectives of the study were the following: (a) to explore hydraulic properties of peat soils varying in BD, (b) to evaluate the effect of botanical origin on hydraulic properties of peat soils, and (c) to build PTFs for hydraulic parameters covering a wide range of different peat soil types.

2 | MATERIALS AND METHODS

2.1 | Data collection

We searched the ISI Web of Science (http://apps.webofknowledge.com/) and Scopus database (https://www.scopus.com/) for articles with the terms "peat" AND "soil water retention curve" OR "soil water characteristic curve" OR "moisture retention" and "peat" AND "hydraulic conductivity" OR "macropore flow" OR "preferential flow" in the title, abstract, or keywords. The papers found by this search were refined by the following criteria: (a) the study focused on boreal peat land and reported a detailed description of the study site and the physical properties of investigated peat soils (e.g., BD and OM content), (b) the study was conducted in the laboratory using undisturbed soil samples to determine the SWRC; all studies with repacked peat cores were excluded, and (c) the drying branch of water retention curves was recorded with at least five points.

In total, 24 published studies were selected for this study, which included different types of peat (sphagnum peat, woody peat, and sedge peat) with OM contents ranging from 23 to 97 wt% (weight percent) and corresponding variation in BD (0.01 to 0.76 g cm^{-3}). A database of physical and hydraulic properties of the investigated peat was established containing OM content, bulk density, total porosity, sampling depth, K_s (n = 256), UHCs (n = 71), and SWRCs (n = 188). Details on the data sources are given in Table 1 and Table S1. In most of the studies, the size of undisturbed soil samples was small (from 50 to 633 cm^3) except for Dettmann et al. (2014) who used

TABLE 1 List of publications analysed to compute the database for this study

Reference	Peat type	Depth	Organic matter content	Bulk density	Saturated hydraulic conductivity	Water retention curve	Unsaturated hydraulic conductivity
Boelter, 1968	X[a]	X		X		X	
Brandyk et al., 2002	X		X	X	X	X	X
Dettmann et al., 2014	X	X	X	X	X	X	X
Forsmann, 2014		X	X	X		X	
Hallema et al., 2015		X	X	X	X	X	
Hamamoto et al., 2016	X	X	X	X		X	
Leij et al., 1996 (Unsoda)			X	X	X	X	X
Lewis, Albertson, Xu, & Kiely, 2012	X	X		X	X		
Liu et al., 2016[b]	X	X	X	X	X	X	
Magnusson, 1994	X	X		X		X	
McCarter & Price, 2014	X	X		X	X	X	X
Mclay et al., 1992	X	X	X	X	X	X	
Mustamo, Hyvärinen, Ronkanen, & Kløve, 2016	X	X	X	X	X	X	
Päivänen, 1973	X	X		X	X	X	
Price et al., 2008	X	X	X	X	X	X	X
Rezanezhad et al., 2009	X	X		X	X	X	X
Schindler, Doerner, & Mueller, 2015		X	X	X		X	X
Schwärzel et al., 2002	X	X	X	X		X	X
Schwärzel et al., 2006	X	X	X	X	X	X	X
Silins & Rothwell, 1998	X	X	X	X	X	X	X
Surridge et al., 2005	X	X		X	X		
Thompson & Waddington, 2013	X	X		X		X	
Wallor et al., 2018	X	X		X		X	
Weiss et al., 1998	X	X	X	X		X	

[a]X indicates that data were available from the corresponding publication.

[b]unpublished data. Detailed information see Table S1.

larger columns (diameter of 30 cm and length of 20 cm) to determine the SWRC and UHC.

2.2 | Data processing and analysis

A strong correlation was found between BD and OM content ($r = 0.90$, $p < 0.001$). Therefore, OM content of peat was estimated from BD in cases where no values were reported in the article. The MVG soil hydraulic functions (Equation 1 to Equation 3) were fitted to all measured SWRCs ($n = 188$) and UHCs ($n = 71$):

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + |\alpha h|^n\right]^{-m}, \quad (1)$$

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r), \quad (2)$$

$$K(S_e) = K_s S_e^{\tau}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2, \quad (3)$$

where θ is the volumetric water content ($cm^3\ cm^{-3}$) at pressure head h (cm); θ_r and θ_s are residual and saturated water content, respectively ($cm^3\ cm^{-3}$); α, n and m are empirical parameters, and $m = 1-1/n$; α (cm^{-1}) is related to the inverse of the air entry pressure head; n (>1) describes the pore size distribution affecting the slope of the retention function (van Genuchten, 1980); S_e is the effective saturation, K_s is the saturated hydraulic conductivity ($cm\ h^{-1}$), and τ is an empirical pore connectivity parameter (Schaap & Van, 2006). In this study, θ_r and θ_s were fixed to zero and total porosity, respectively (Weiss et al., 1998). For SWRCs, the parameters α and n were optimized using the nonlinear least squares optimization program RETC (RETention Curve; van Genuchten, Leij, & Yates, 1991). RETC is a computer code for quantifying the hydraulic functions of unsaturated soils. For UHCs, τ and K_s were optimized during the fitting procedure because of the inaccuracy of K_s measurements or missing K_s values in some of the reanalysed papers (Dettmann et al., 2014; Gnatowski et al., 2010; Schwärzel et al., 2002; Schwärzel et al., 2006). The hydraulic parameter values were collected if they were reported in the literature and derived employing a consistent fitting procedure, otherwise the parameters were optimized according to the fitting procedure as given above. The definition of "macropore" is ambiguous in soil science (Carter, Kunelius, & Angers, 1994; Luxmoore, 1981). In this study, the fraction of macropores was computed by the difference between total porosity and volumetric soil water content at 60 cm H_2O pressure head (equivalent pore diameter of 50 µm; Schwärzel et al., 2002; Schindler et al., 2003).

Each sample of the assembled data set comprised physical (e.g., BD, OM, and porosity) as well as hydraulic properties (e.g., K_s, MVG parameters). Continuous PTFs were derived to estimate the MVG parameters ($\log_{10} K_s$, $\log_{10} \alpha$, $\log_{10} n$, and τ) separately (Guber &

Pachepsky, 2010) from independently determined physical properties of peat soils (BD, OM, depth, and botanical peat compositions). Earlier studies have used a similar approach to determine according PTFs (e.g., Vereecken, Feyen, & Maes, 1989; Wallor et al., 2018; Wösten et al., 1999). A stepwise linear regression analysis was conducted, and all statistical analyses and modelling were performed using the default "stats" package of R (R Core Team, 2016).

In order to get more insight into the acquired data base and to test the performance of PTFs, all the SWRCs were grouped according to botanical composition (sphagnum peat, woody peat, and sedge peat) and BD (low, 0.01–0.10 g cm^{-3}; moderate, 0.10–0.20 g cm^{-3}, and high, 0.20–0.76 g cm^{-3}). The variation in some of the obtained groups was still high, and we further split the data set to obtain subgroups of SWRCs according to the physical parameters (BD, OM, and sampling depth) using the Ward hierarchical clustering algorithm (R-package hclust). For each subgroup, a series of pressure heads (0, −10, −30, −60, −100, −200, −300, −600, −1,000, −2,000, −5,000, −10,000, and −15,850 cm H_2O) were selected, and an average measured water content (with standard deviation) at each pressure head was calculated to generate a new SWRC representing the according subgroup. For all newly computed SWRCs, the parameters α and n were optimized using the nonlinear least squares optimization program RETC.

The performance of PTFs were tested by deriving the MVG parameter values and plotting the resulting SWRCs for each group/subgroup employing average values of the MVG parameter as they were obtained by using the PTF on each individual experimental data set from the respective group/subgroups. The UHCs were generated in a similar fashion.

3 | RESULTS

3.1 | Descriptive statistics for the hydraulic parameter values

The MVG model appropriately described all of the tested SWRCs and UHCs with a fitting criterion of $r^2 \geq 0.95$ (Table S2). Table 2 gives the statistical description of the hydraulic parameters of peat soils. The saturated hydraulic conductivity had a very broad range irrespective of peat types, with values ($\log_{10}K_s$) varying from −2.8 to 3.1 cm h^{-1}. The parameter values of the MVG model ranged for $\log_{10}\alpha$ from −2.7 to 2.5 cm^{-1} and the maximum value were obtained for woody peat; the values of τ varied from −5.2 to 1. The values of n had a smaller variance ($\log_{10} n$; from 0.01 to 0.45) than that of α and τ. Among the peat types, the smallest variance of n was obtained from woody peat samples. Some extreme values of n (n > 2) were observed for less decomposed sphagnum peat.

3.2 | Variability of hydraulic parameter values along density gradients

Although total porosity of peat decreased proportionally with increasing BD from 0.01 to 0.76 g cm^{-3} (Figure 1a), macroporosity only decreased as BD increased from 0.01 to 0.2 g cm^{-3} (Figure 1b). For the increase in BD from 0.20 to 0.76 g cm^{-3}, no clear tendency was observed for macroporosity.

TABLE 2 Mean values and range of parameters of the physical (bulk density, BD, g cm^{-3}; organic matter content, OM, wt%; and Porosity, vol%) and hydraulic parameters (saturated hydraulic conductivity, K_s, cm h^{-1} and Mualem-van Genuchten parameters α, cm^{-1}, n, τ) for the different peat types

Peat type	Parameters	Mean value	Standard deviation	Minimum value	Maximum value
Sphagnum	BD	0.08	0.04	0.01	0.20
	OM	89.5	3.5	73.9	93.3
	Porosity	91.9	2.8	82.0	98.0
	$\log_{10}(K_s)$	0.68	1.19	−2.08	3.06
	$\log_{10}(\alpha)$	−0.72	0.67	−2.41	1.02
	$\log_{10}(n)$	0.13	0.07	0.01	0.45
	τ	−2.60	1.63	−5.22	1.06
Woody	BD	0.13	0.04	0.02	0.21
	OM	89.6	3.02	85.5	98.0
	Porosity	89.5	4.2	82.2	98.6
	$\log_{10}(K_s)$	0.76	1.46	−2.07	3.02
	$\log_{10}(\alpha)$	−0.43	1.28	−1.98	2.48
	$\log_{10}(n)$	0.09	0.03	0.03	0.17
	τ	−4.19	1.95	−4.99	0.97
Sedge	BD	0.24	0.16	0.02	0.76
	OM	79.5	16.2	20.5	91.1
	Porosity	83.9	7.6	68.4	95.0
	$\log_{10}(K_s)$	−0.03	0.82	−2.77	1.86
	$\log_{10}(\alpha)$	−1.50	0.50	−2.68	−0.41
	$\log_{10}(n)$	0.08	0.04	0.02	0.17
	τ	0.37	1.18	−2.43	3.02
All	BD	0.18	0.16	0.01	0.76
	OM	83.2	15.1	20.5	99.0
	Porosity	87.2	7.5	62.0	98.6
	$\log_{10}(K_s)$	0.45	1.27	−2.77	3.06
	$\log_{10}(\alpha)$	−1.08	0.83	−2.68	2.48
	$\log_{10}(n)$	0.10	0.06	0.01	0.45
	τ	−1.62	2.15	−5.22	1.06

All peat types include some other peat types and unknown peat type (not mentioned in the literatures).

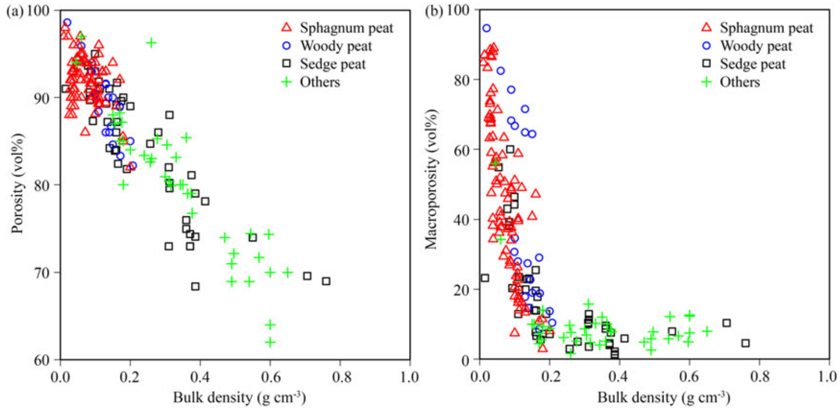

FIGURE 1 Total (a) porosity and (b) macroporosity (equivalent pore diameter of 50 μm) of peat soils as a function of bulk density

A negative Pearson's correlation coefficient was found between BD and total porosity, $\log_{10}K_s$, $\log_{10}\alpha$, and $\log_{10}n$ (Table 3). The correlation between BD and $\log_{10}K_s$ was moderate; however, if only peat soils with a BD of less than 0.2 g cm^{-3} were considered, the correlation was stronger (Pearson's correlation coefficient of 0.67, $p < 0.01$). With an increase in dry BD from 0.2 to 0.76 g cm^{-3}, no correlation was found between BD and K_s (Pearson's correlation coefficient of 0.06, $p = 0.72$). For peat soils with different botanical compositions, K_s differed and followed different functions as BD increased from 0.01 to 0.76 g cm^{-3} (Figure 2). With respect to the MVG model, the values of $\log_{10}\alpha$ decreased gradually with BD up to a value of 0.2 g cm^{-3}; a further increase in BD led to a considerable increase in $\log_{10}\alpha$ (Pearson's correlation coefficient of 0.37, $p < 0.01$; Figure 2). A moderate correlation was found between $\log_{10}n$ and BD. The parameter τ had a strong positive correlation with BD (Table 3). Generally, negative values of τ were observed in less decomposed peat (sphagnum peat and woody peat), and the positive value of 0.5 occurred for highly degraded peat (Figure 2).

3.3 | Pedotransfer functions

Different PTFs for hydraulic parameters of peat were established based on soil physical properties. The best fitted models are given in Table 4. The derived PTFs based on the individual peat types had a significantly lower mean square error (MSE) than those taking all peat types into account. The measured as well as estimated hydraulic parameter values are shown in Figure 3. The PTFs for K_s and α were acceptable with coefficients of determination of 0.59 and 0.73, respectively. Figure 3 reveals a low performance of PTFs for n and τ. High values of n were underestimated, and the values of τ obtained from sphagnum peat were not captured by the derived PTF. A high correlation was observed between the measured and PTF-estimated soil water content with a concordance correlation coefficient of 0.94 (Figure 4; Table S3). The concordance correlation coefficient decreased with increasing tensions (Table S3). The root MSE of soil water content (measured and estimated) at selected pressure heads ranged from 0.03 to 0.12 (Table S3).

3.4 | Groups of SWRCs

For peat soils with a BD of less than 0.2 g cm^{-3}, the SWRCs of each peat type (sphagnum, woody, and sedge) exhibited a wide variance and could be grouped into two to five subgroups (Figure 5). For highly degraded peat soils (BD > 0.2 g cm^{-3}), the SWRCs varied less, and they were classified into one group (Figure 5h). In some cases, mostly for sphagnum peat and woody peat, two subgroups of SWRCs according to sampling depth or BD were identified (e.g., Figure 5a,c–e; Table S4). The observed differences can be confirmed from the optimized MVG parameter values (Table 5). For all peat types, the MVG parameter values (α and n) decreased with increasing BD (e.g., sphagnum Group I to V; Table 5). For highly degraded peat soils (Figure 5h), α and n are significantly lower than for other subgroups.

The performance of the PTFs for different groups of SWRCs can be assessed from Figure 5 and Table 5. A good performance of PTFs

TABLE 3 Correlation coefficients of soil physical properties (Bulk density, BD; organic matter content, OM; porosity; and depth) and hydraulic parameters of peat soils (saturated hydraulic conductivity, K_s; α, n, and τ derived from the optimization of the Mualem-van Genuchten model)

	BD	OM	Porosity	Depth	K_s	α	n	τ
BD	1.00							
OM	−0.89**	1.00						
Porosity	−0.91**	0.77**	1.00					
Depth	−0.12	0.22**	0.09	1.00				
K_s	−0.47**	0.25**	0.39*	−0.30*	1.00			
α	−0.53**	0.31**	0.51**	−0.30**	0.70**	1.00		
n	−0.41**	0.31**	0.34**	−0.09	0.49**	0.18*	1.00	
τ	0.64**	−0.57**	−0.56**	0.11	−0.45**	−0.74**	−0.12	1.00

Log-transformation were performed on K_s, α, and n, not the whole dataset.

* Correlation is significant at the 0.05 level and ** correlation is significant at the 0.01 level.

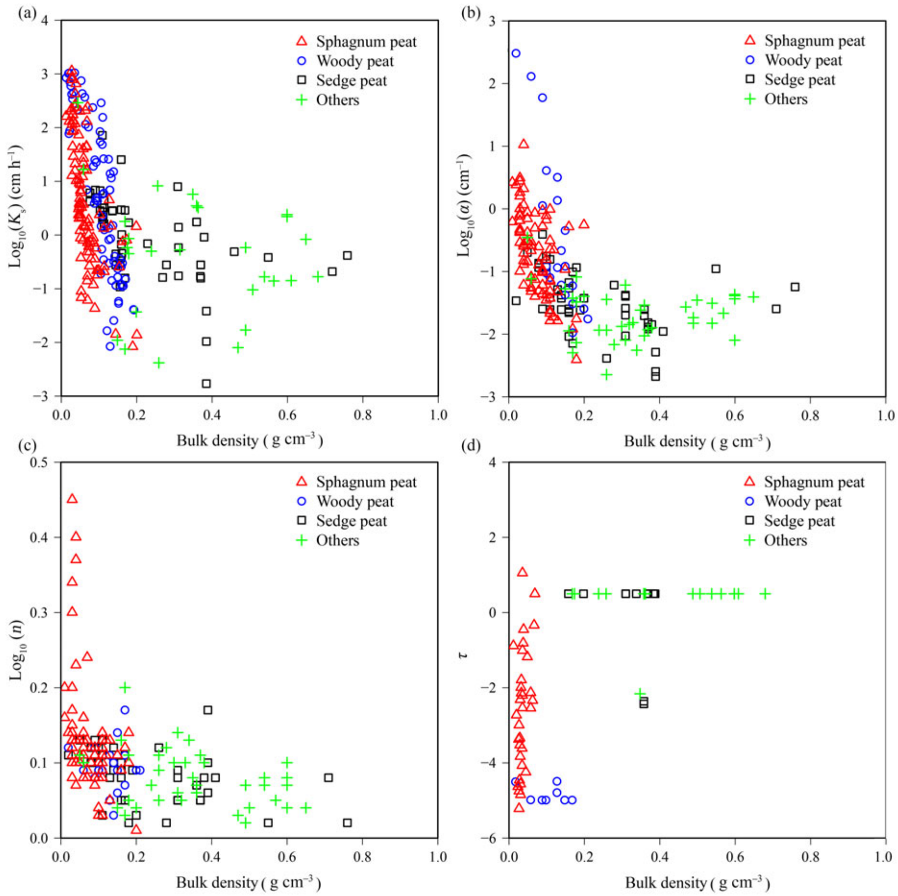

FIGURE 2 Hydraulic parameter values (saturated hydraulic conductivity, K_s; Mualem-van Genuchten parameters, α, n, and τ) of peat soils as a function of bulk density

TABLE 4 Results of the linear regression analysis in which the hydraulic parameters (K_s, cm h^{-1}; α, cm^{-1}; n, τ derived from Mualem-van Genuchten model) were the dependent variables and the physical properties (bulk density, BD, g cm^{-3}; organic matter content, OM, wt%; and depth, cm) were the explanatory variables

Peat type	Bulk density	Parameters	Model	R^2	MSE	*p* value
Sphagnum	≤0.2	$\log_{10}(K_s)$	3.362–55.113 × BD + 172.728 × BD^2	0.53	0.648	0.000
		$\log_{10}(\alpha)$	4.497–7.493 × BD-0.046 × OM-0.021 × Depth	0.57	0.181	0.000
		$\log_{10}(n)$	0.182–0.714 × BD	0.16	0.003	0.000
		τ	−5.086 + 67.880 × BD	0.26	2.165	0.003
Woody	≤0.2	$\log_{10}(K_s)$	3.538–26.542 × BD	0.73	0.585	0.000
		$\log_{10}(\alpha)$	2.799–18.846 × BD-0.027 × Depth	0.76	0.351	0.000
		$\log_{10}(n)$	0.634–0.006 × OM	0.33	0.001	0.008
		τ	−4.84	-	0.044	-
Sedge	≤0.2	$\log_{10}(K_s)$	1.561–9.432 × BD	0.21	0.316	0.008
		$\log_{10}(\alpha)$	−0.575-13.441 × BD^2–0.011 × Depth	0.53	0.080	0.000
		$\log_{10}(n)$	0.124–1.766 × BD^2	0.34	0.001	0.001
		τ	0.5	0.38	0.000	0.014
All types	>0.2	$\log_{10}(K_s)^a$	1.935–15.802 × BD + 19.552 × BD^2	0.40	1.184	0.000
		$\log_{10}(\alpha)$	−1.994 + 1.191 × BD^2	0.15	0.119	0.001
		$\log_{10}(n)$	0.089–0.088 × BD^2	0.11	0.001	0.020
		τ	0.5	-	1.113	-
All data	≤0.76	θ_s	0.950–0.437 × BD	0.82	0.001	0.000
		$\log_{10}(K_s)$	1.935–15.802 × BD + 19.552 × BD^2	0.40	0.956	0.000
		$\log_{10}(\alpha)$	0.326–9.135 × BD + 10.420 × BD^2–0.014 × Depth	0.56	0.305	0.000
		$\log_{10}(n)$	0.153–0.422 × BD + 0.450 × BD^2	0.22	0.003	0.000
		τ	−3.024 + 7.242 × BD	0.40	2.720	0.000

Note. MSE: mean square error.

[a]All peat soils with bulk density ranging from 0.01 to 0.76 g cm^{-3}.

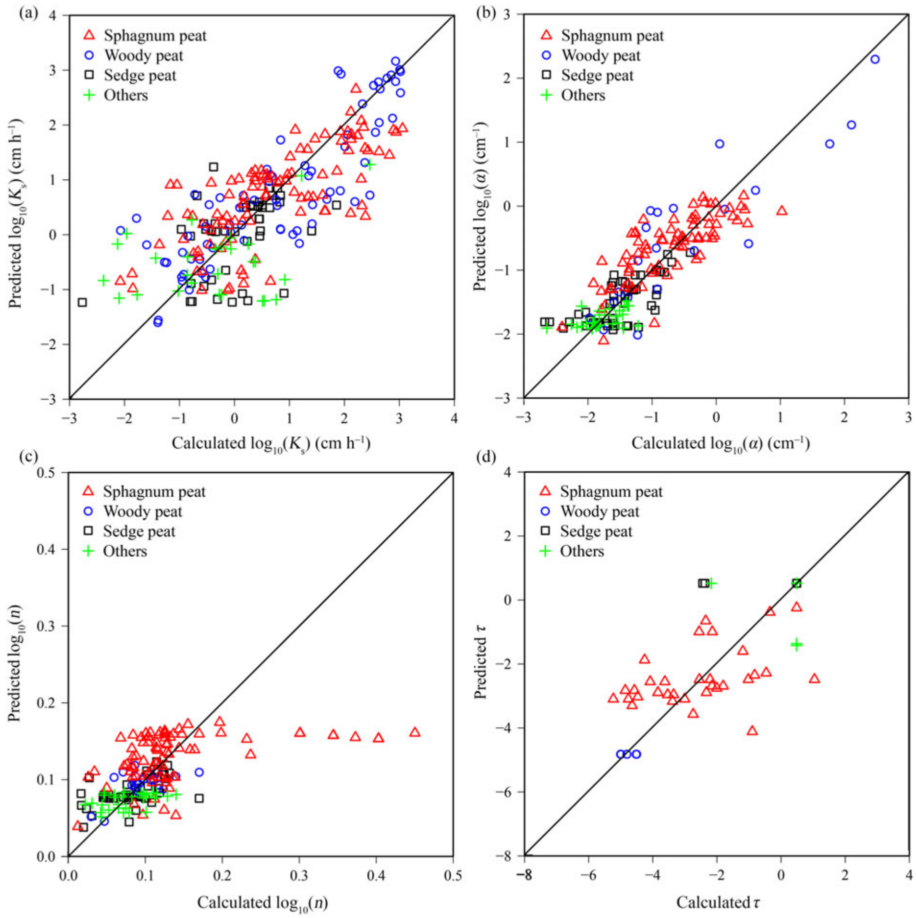

FIGURE 3 Relationships between parameter values derived from the optimization of the Mualem-van Genuchten model (calculated) and from pedotransfer functions (predicted)

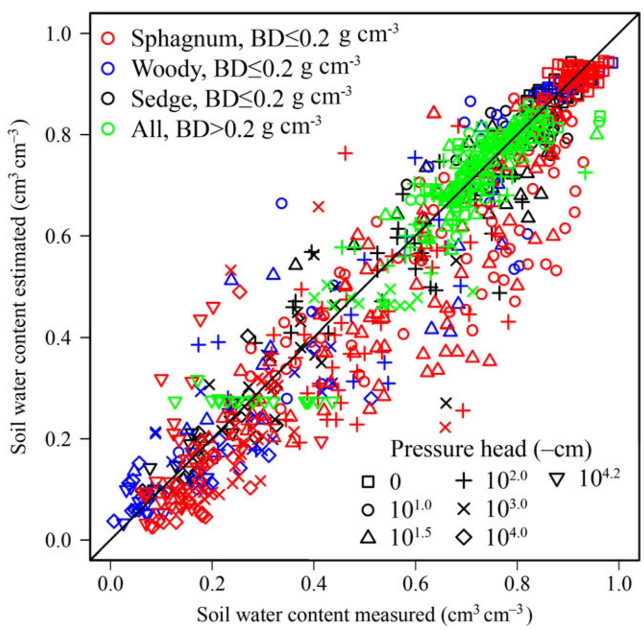

FIGURE 4 Relationship between measured and estimated soil water contents at selected pressure heads and for different peat types

was generally observed for sedge peat and highly degraded peat (BD > 0.2 g cm^{-3}). In other cases, mostly for sphagnum and woody peat soils (BD ≤ 0.2 g cm^{-3}), the performance of the PTFs was lower.

4 | DISCUSSION

4.1 | Pore structure and saturated hydraulic conductivity

Hydraulic conductivity of soils is largely controlled by pore structure (e.g., porosity, pore size distribution, and pore continuity), which is also true for peat soils (Baird, 1997; Holden, 2009; Liu et al., 2016; Surridge, Baird, & Heathwaite, 2005). As one important feature of pore structure, macroporosity not only controls the hydraulic conductivity of peat soils but also affects the soil available water for plants (Schindler et al., 2003). The calculated macroporosity of peat soils (BD > 0.2 g cm^{-3}) ranged from 0.01 to 0.16 cm^3 cm^{-3}, which is comparable with values reported in a previous study based on an investigation of hydraulic properties of fen peat from 30 soil profiles (Wallor et al., 2018). In a few studies, macroporosity initially decreased with peat degradation (BD increasing from 0.15 to 0.27 g cm^{-3}) and then increased with further peat degradation (BD > 0.27 g cm^{-3}; Schindler et al., 2003; Wallor et al., 2018). That pattern was not confirmed by the database of this study. With the beginning of decomposition of plant residues and soil compaction, a clear reduction of macroporosity occurred. With the further mineralization of organic matter, macroporosity remained almost constant because of the generation of secondary macropore space (e.g., root and worm channels;

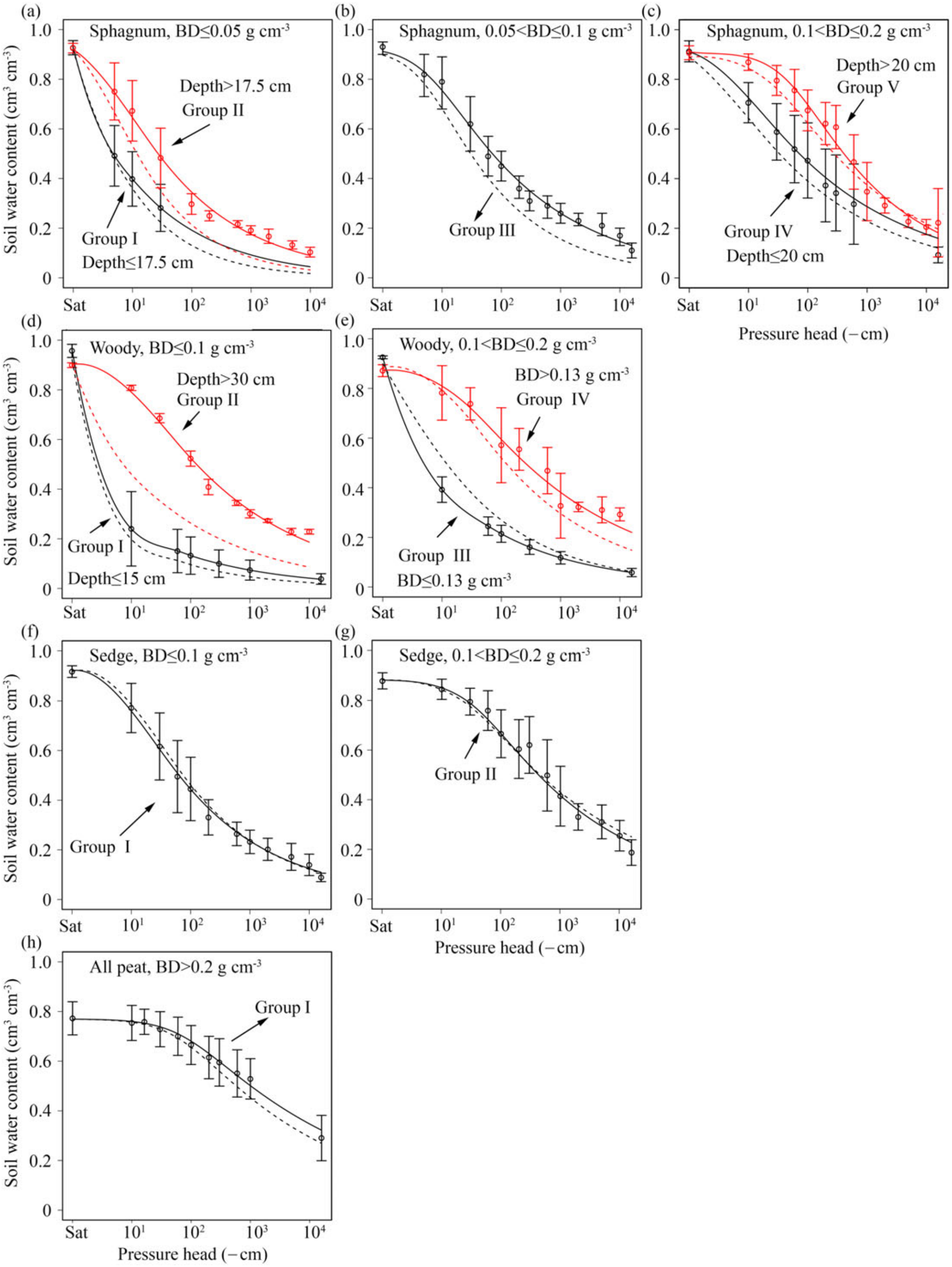

FIGURE 5 Different groups of soil water retention curves (SWRCs) according to peat types, bulk density, and depth. Different colours indicate different subgroups within one group of SWRCs. The open circles are observed SWRCs. Solid lines are from the optimization of the Mualem-van Genuchten model to mean measured values (using RETC), dashed lines were produced from averaging the MVG parameter values as they were obtained by using the PTFs on each individual experimental data set. The error bars denote standard deviation

Liu & Lennartz, 2015; Liu et al., 2016). This sequence supports results for a single site investigated by Schwärzel et al. (2002).

Saturated hydraulic properties of peat soils are highly affected by the stage of peat decomposition and botanical composition (Letts, Roulet, Comer, Skarupa, & Verseghy, 2000; Rezanezhad et al., 2016). Both K_s and macroporosity decreased dramatically during initial stages of peat decomposition and the according increase in BD (below values of 0.2 g cm^{-3}), indicating that K_s of less decomposed peat soils was primarily affected by the macroporosity as generated by the peat forming plants. With a further mineralization of peat soils, both macroporosity and K_s were not correlated with bulk density, although the variance of K_s was much higher than the variance of macroporosity. This finding is consistent with previous studies by Siegel and Glaser (2006) who stated that K_s does not decrease necessarily with an increase of BD because of the secondary porosity in peat. The large variance of hydraulic conductivity at this stage could

TABLE 5 Hydraulic parameter values (θs, $cm^3\ cm^{-3}$; α, cm^{-1}; K_s, $cm\ h^{-1}$; n; and τ) derived from optimising the Mualem-van Genuchten model (MVG) and employing pedotransfer functions (PTFs) for subgroups of SWRCs and UHCs (see Figures 5 and 7)

Peat types	Groups	Bulk density	Models	θs	α	n	τ	K_s	K_s'[a]
Sphagnum	I	BD ≤ 0.05	MVG	0.93	1.393	1.32	−4.40	576.26	
			PTF	0.94	0.784	1.45	−2.90	58.41	131.06
	II		MVG	0.92	0.277	1.29			
			PTF	0.93	0.327	1.42			
	III	0.05 < BD ≤ 0.1	MVG	0.93	0.163	1.25	−1.79	718.92	
			PTF	0.92	0.184	1.34	−0.89	4.13	37.33
	IV	0.1 < BD ≤0.2	MVG	0.91	0.222	1.21			
			PTF	0.89	0.364	1.23			
	V		MVG	0.91	0.020	1.28			
			PTF	0.89	0.040	1.23			
Woody	I	BD ≤ 0.1	MVG	0.96	21.38	1.26	−4.69	40.12	
			PTF	0.92	23.52	1.23	−4.84	55.77	104.05
	II		MVG	0.90	0.103	1.23			
			PTF	0.91	0.670	1.24			
	III	0.1 < BD ≤0.2	MVG	0.92	2.518	1.26	−5.66	20.74	
			PTF	0.90	0.729	1.25	−4.84	0.49	4.84
	IV		MVG	0.87	0.062	1.20			
			PTF	0.88	0.069	1.25			
Sedge	I	BD ≤ 0.1	MVG	0.92	0.133	1.28			
			PTF	0.92	0.099	1.30			
	II	0.1 < BD ≤ 0.2	MVG	0.88	0.029	1.22	0.50	1.95	
			PTF	0.88	0.038	1.21	0.50	0.91	1.36
All	I	BD > 0.2	MVG	0.77	0.014	1.16	0.50	0.23	
			PTF	*0.77*	*0.016*	*1.19*	*0.50*	*0.05*	*0.20*

Note. BD: bulk density (g cm^{-3}).

[a]K_s' values were estimated from α in the same line (equations are in Figure 6b and Figure S3)

be explained by the heterogeneous distribution of secondary macroporosity (root channels and earthworm holes) and pore structure (pore size and pore continuity). In addition, differences in land use/cover is another factor possibly causing strong variance of K_s. Among all the different land use/covers (natural, forest, grass, and cultivated peatland), hydraulic properties of peat soils in grassland had the smallest variance (Table S5). Although K_s values may be affected by the measurement methods (Figure S1), we assume the soil intrinsic properties (e.g., pore structure and peat type) are the key factors controlling K_s (Rosa & Larocque, 2008). It has been also reported that pore structure and K_s of peat soils were affected by swelling–shrinkage cycles (Brandyk et al., 2002). Most peat soils shrink when dried, which leads to an underestimation of the soil water content at high pressure heads if volume changes are ignored (Schwärzel et al., 2002). This effect may be of minor importance for highly degraded peat soils because shrinkage in these soils is less (Kechavarzi, Dawson, & Leeds-Harrison, 2010). In most of the analysed individual studies, the shrinkage information was not given; therefore, the shrinkage phenomenon cannot be discussed in detail in this study.

4.2 | MVG model parameters

The estimated parameter values for α had a broader range for peat soils ($\log_{10}\alpha$, −2.68 to 2.48 cm^{-1}) than for mineral soils ($\log_{10}\alpha$, −2.30 to −1.45 cm^{-1}) as estimated by the Rosetta database (Schaap, Leij, & Van, 2001). In contrast, n values for peat soils (from 1.03 to 2.82) compare with those of mineral soils (1.2 to 3.2; Schaap et al., 2001). The variance of α values was greater than that of n in peat soils, particularly for less degraded and pristine peat. In contrast, a high variance for α was observed for degraded peat soils by Wallor et al. (2018), who investigated hydraulic properties of degraded peat soils with BD of larger than 0.15 g cm^{-3}. The highest values for α were generally obtained from less decomposed wooden peat samples (Silins & Rothwell, 1998) and several sphagnum peat soils. This finding is consistent with a previous study in which the α value of woody peat was found to be higher than that of moss (Gnatowski et al., 2010). But even within the same peat type and at similar BD values, α shows a high variability, indicating the general heterogeneity of the medium (Silins & Rothwell, 1998).

Peat decomposition and degradation processes significantly altered the MVG model parameters. $\log_{10}\alpha$ decreased with increasing BD (Table 5) confirming previous studies for fen peat soils (Schwärzel et al., 2006; Weiss et al., 1998), bogs (Silins & Rothwell, 1998), and cultivated peatland (Hallema et al., 2015). Nevertheless, this finding was not supported by Wallor et al. (2018), who found weak correlation between $\log_{10}\alpha$ and BD in cultivated peat. The reason probably was that their study was limited to highly degraded peat soils (BD > 0.15 g cm^{-3}). In this study, the strong negative correlation between α and BD (Table 3) suggests that α is significantly affected by peat degradation processes.

Setting the parameter τ to 0.5 is common practice for mineral soils (Mualem, 1976). However, negative values were always obtained from peat soils (Dettmann et al., 2014). From the database in this study, negative values of τ were generally obtained for less decomposed sphagnum peat and woody peat (Figure 2). For highly degraded peat soils, τ set to 0.5 was generally suitable to fit UHCs using the MVG model. The parameter τ accounts for pore continuity and tortuosity. Compared with a positive τ, a negative value of τ can cause less of a drop in hydraulic conductivity as water content decreases, resulting

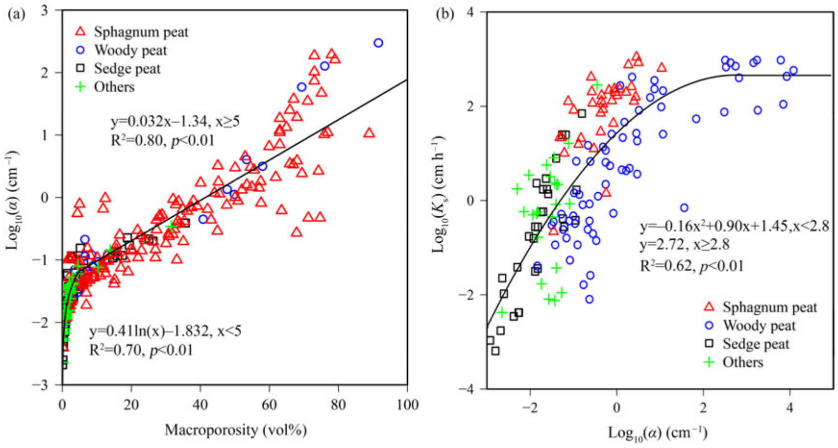

FIGURE 6 Scatter plots of (a) Mualem-van Genuchten parameter $\log_{10}\alpha$ as a function of macroporosity (equivalent pore diameter of 300 µm); (b) $\log_{10}\alpha$ against saturated hydraulic conductivity ($\log_{10}K_s$)

in a higher hydraulic conductivity at a given negative pressure head (Gnatowski et al., 2010). Our finding indicates that pore connectivity is reduced and tortuosity increased during peat decomposition and degradation (Rezanezhad et al., 2010). Setting τ to 0.5 would greatly underestimate the UHC of less decomposed and pristine peat.

4.3 | Relation between the saturated hydraulic conductivity and $\log_{10}\alpha$

$\log_{10}\alpha$ was more sensitive to large macropores (equivalent circular diameter of 300 µm; difference between total porosity and volumetric soil water content at −10 cm H_2O pressure head) than to the pores with an equivalent circular diameter of 50 µm (Figure 6a and Figure S2), because the air entry value corresponds to the potential at which air truly enters the largest pore (Nemati, Caron, Banton, & Tardif, 2002). The smallest air entry values (greater α values) were generally obtained for less decomposed or pristine peat soils because of a greater fraction of macropore space. As the peat soil is mineralized, the size of the largest pores is reduced, leading to an increase in air entry value (lower α value). This observation is consistent with previous studies demonstrating a more pronounced resistance to air entry in peat soils with a high BD (Gnatowski et al., 2010; Kechavarzi et al., 2010). The relationships between $\log_{10}\alpha$ and $\log_{10}K_s$ differed when different peat types were considered (Figure S3). A strong parabolic relationship was found between $\log_{10}\alpha$ and $\log_{10}K_s$ (Figure 6b) if the entire data set was considered. Similar findings were reported in earlier studies for mineral soils (Guarracino, 2007) and peat soils (Kettridge et al., 2016). The strong parabolic relationship can help to estimate K_s from α if no K_s data are available.

4.4 | PTFs for SWRCs

The botanical composition of peat soils plays an important role for hydraulic properties. However, in the widely used database UNSODA (Leij, Alves, Van, & Williams, 1996) and other PTFs (Wösten et al., 1999), botanical information is neglected, resulting in a low performance if estimating the hydraulic properties for organic soils. Building PTFs for individual peat types significantly decreased the MSE for all the hydraulic parameters in this study (Table 4). The performance of PTFs for $\log_{10}\alpha$ were better than PTFs for n. The results confirm investigations by Weiss et al. (1998) and Wallor et al. (2018) who reported that $\log_{10}\alpha$ is more sensitive to BD or soil depth than n. Considering the groups of SWRCs, the performance of PTFs for sphagnum peat and woody peat soils (BD $\leq$ 0.2 g cm^{-3}) was generally lower than for other groups. The reason is that for the sphagnum and woody peat, variation was very high, and two types of SWRCs were always identified (subgroups; BD and sampling depth depending). However, in the PTFs, the MVG parameters α and n are more sensitive to BD than sampling depth. This finding indicates a large variance of hydraulic properties of peat soils at a comparable degradation stage (Rycroft et al., 1975; Silins & Rothwell, 1998).

It has been shown earlier that substantial correlations often exist among the MVG parameters, which increases ambiguity in the relationships between the MVG parameters and soil properties (Vereecken et al., 2010). In addition, the relationships between MVG parameters and soil properties are too complex to be accurately described (Tomasella, Pachepsky, Crestana, & Rawls, 2003). The two reasons may lead to low accuracy in water retention predictions by applying the continuous PTFs. Hence, in the future, additional information (e.g., water content at selected pressure heads; morphological properties; Vereecken et al., 2010) should be considered in the PTFs to improve the estimates of hydraulic properties using PTFs.

4.5 | PTFs for UHCs

Only 71 UHCs were available (compared with 188 SWRCs). The UHCs could be classified into six groups according to the botanical composition and BD (Figure 7; no subgroups were formed because of limited data). The parameter values for K_s and τ as obtained from optimizing the MVG model to the average UHCs (solid line in Figure 7) and PTFs (black dashed lines in Figure 7) are given in Table 5. Interestingly, the description of the measured UHCs could be improved using K_s values as computed from the relation presented in Figure 6b and Figure S3 (red dotted lines in Figure 7). The correct determination of K_s is crucial for the accuracy of depicting measured UHC values. It is possible that a stronger data base is needed to get better predictions for K_s.

Adding the information of percentage of mineral soil fraction as well as size and orientation of plant residues such as bark pieces

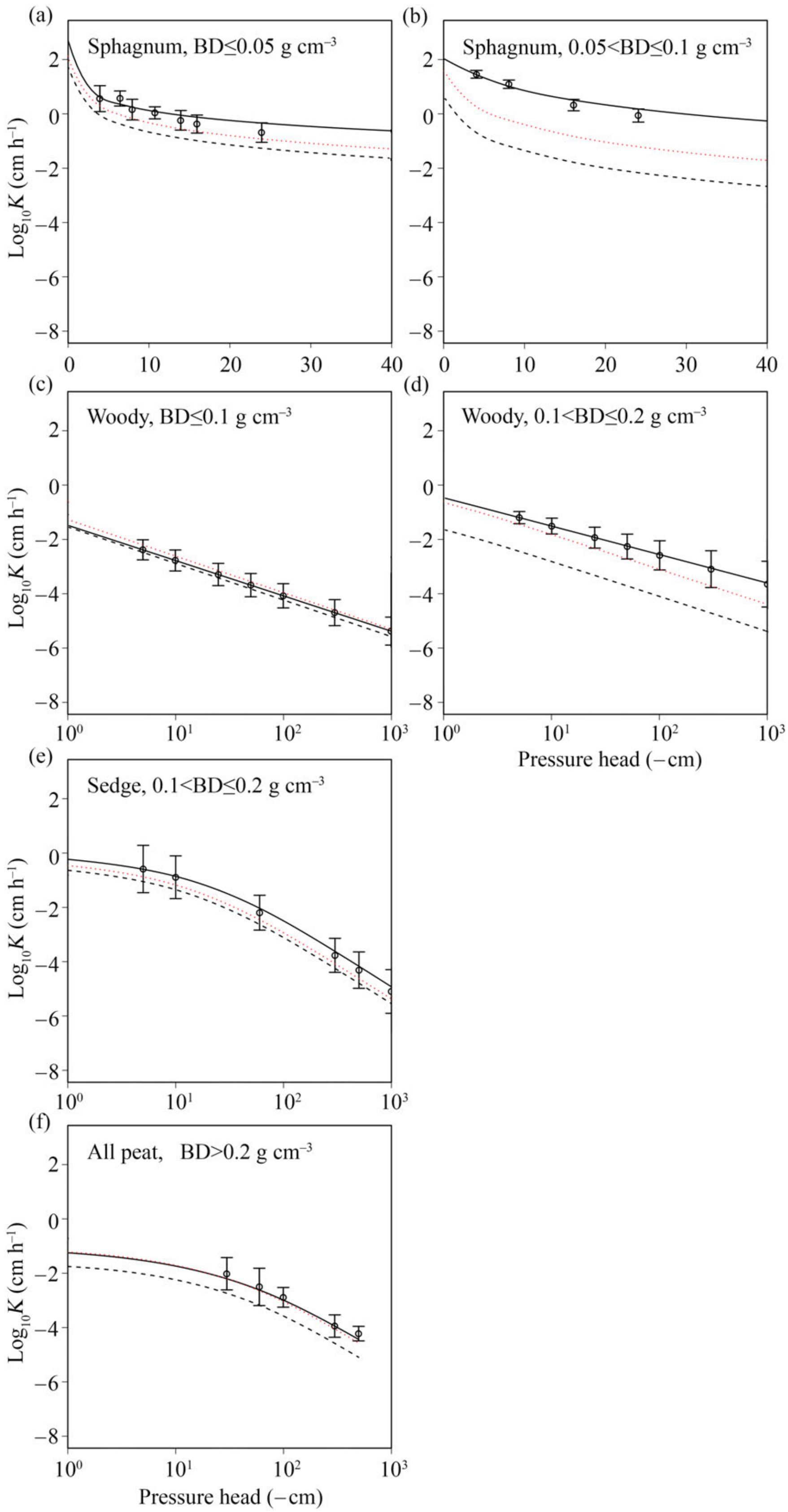

FIGURE 7 Different groups of unsaturated hydraulic conductivity curves (UHCs) according to peat types and bulk density. The open circles are observed UHCs. Solid lines are from the optimization of the Mualem-van Genuchten model to the mean measured values, dashed lines are generated from pedotransfer functions (PTFs, τ, and K_s; Table 5) and red dotted lines are from a mixed model (τ from PTF and K_s' estimated from α; Table 5; Figure S3). The error bars denote standard deviation

may improve the estimation of parameters (Wösten et al., 1999). For instance, increasing the size of bark particles in peat soils did not change the air-filled porosity, but decreased the pore efficiency (tortuosity) and thereby the hydraulic conductivity (Caron & Nkongolo, 2004; Nkongolo & Caron, 1999).

5 | CONCLUSIONS

Soil degradation resulting from peatland drainage significantly alters the physical and hydraulic properties of peat soils. Peat degradation causes a decrease in macroporosity and K_s, but results in an increase in air entry value, pore size classes, and pore tortuosity (α, n, and τ; MVG model). BD as a proxy for the degree of peat decomposition and degradation can be used to predict the hydraulic properties of peat soils. The various hydraulic parameters of peat soils show different patterns along with a varying bulk density. A BD value of around 0.2 g cm^{-3} seems to be a threshold; peat soils with higher values tend to behave more like mineral soils with respect to hydraulic properties. This also implies that less degraded and pristine peat soils (e.g., BD < 0.1 g cm^{-3}) may suffer a more dramatic change after peatland drainage. The obtained PTFs have good predictive abilities for the hydraulic properties of peat soils (e.g., K_s and α) over a wide range of peat types, which better enable us to parameterize hydrological models (e.g., HYDRUS) for water flow in peat soils under variable saturated conditions. The separate consideration of fen and bog peat significantly improves the accuracy of PTFs suggesting that accounting for both the botanical origin as well as the BD (respectively peat decomposition) strengthens the reliability and representativeness of water flux simulations employing physically based hydraulic models. Future (experimental) studies shall focus on a possible bimodal shape of the SWRC in the near saturation range and a resulting macropore flow as has been observed for mineral soils.

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SUPPORTING INFORMATION

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