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Implications for conservation and restoration

Suggested citation referring to the original publication:
Mires and Peat 21 (2018), Art. 23 ,
DOI https://doi.org/10.19189/MaP.2018.OMB.336
ISSN 1819-754X

Physical and hydrological properties of peat as proxies for degradation of South African peatlands: Implications for conservation and restoration

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SUMMARY

The physical and hydrological properties of peat from seven peatlands in northern Maputaland (South Africa) were investigated and related to the degradation processes of peatlands in different hydrogeomorphic settings. The selected peatlands are representative of typical hydrogeomorphic settings and different stages of human modification from natural to severely degraded. Nineteen transects (141 soil corings in total) were examined in order to describe peat properties typical of the distinct hydrogeomorphic settings. We studied degree of decomposition, organic matter content, bulk density, water retention, saturated hydraulic conductivity and hydrophobicity of the peats. From these properties we derived pore size distribution, unsaturated hydraulic conductivity and maximum capillary rise. We found that, after drainage, degradation advances faster in peatlands containing wood peat than in peatlands containing radicell peat. *Eucalyptus* plantations in catchment areas are especially threatening to peatlands in seeps, interdune depressions and unchannelled valley bottoms. All peatlands and their recharge areas require wise management, especially valley-bottom peatlands with swamp forest vegetation. Blocking drainage ditches is indispensable as a first step towards achieving the restoration of drained peatland areas, and further measures may be necessary to enhance the distribution of water. The sensitive swamp forest ecosystems should be given conservation priority.

KEY WORDS: moorsh forming process, swamp forest, restoration, unsaturated hydraulic conductivity

INTRODUCTION

Peatlands in South Africa are important and threatened ecosystems (P. Grundling & Grobler 2005, P. Grundling *et al*. 2017). Land use is a common cause of their degradation (A.T. Grundling *et al*. 2016). Degradation results from drawdown of the local water table due to *Eucalyptus* plantations as well as cultivation practices like drainage, which expose the top peat layers to aerobic conditions (P. Grundling & Blackmore 1998, Pretorius *et al*. 2014, von Roeder 2015, A.T. Grundling *et al*. 2016). Aerobic conditions lead to secondary soil formation in peat, i.e. the formation of horizons characterised by compaction and mineralisation accompanied by alterations of the structure and physical and chemical properties of the peat (Schwärzel 2000, Zeitz & Velty 2002, Ilnicki & Zeitz 2003). Furthermore, it is known that peat compaction and mineralisation lead to a shift in pore size distribution (Ilnicki & Zeitz 2003), changes in water repellence (Szajdak & Szatyłowicz 2010) and decreased total porosity (Kecharvarzi *et al*. 2010), saturated hydraulic conductivity (Kecharvarzi *et al*. 2010) and carbon content (Ilnicki & Zeitz 2003, Glina *et al*. 2018). These soil properties are important regulators for water movements such as lateral flow, infiltration and capillary rise, and also for water storage capacity and carbon sequestration (Rycroft *et al*. 1975, Joosten & Clarke 2002). As a consequence of changes in these soil properties, peatland surface oscillation - a natural mechanism mitigating the exposure of topsoil to aerobic conditions during water table fluctuations - is reduced (Whittington & Price 2006). The reduced capacity of a peatland's surface to oscillate initiates a positive feedback loop, where water table fluctuations increase further and advance the changes in the regulating soil properties (Whittington & Price 2006). For temperate and

Mires and Peat, Volume 21 (2018), Article 23, 1–21, http://www.mires-and-peat.net/, ISSN 1819-754X

boreal peatlands in the northern hemisphere, the influence of degradation on physical soil properties has been extensively studied (Zeitz & Velty 2002, Ilnicki & Zeitz 2003, Zeitz 2003, Whittington & Price 2006). However, little is known about degradation effects in South African peatlands.

A few qualitative studies focusing on peat properties have been conducted in South Africa. Smuts (1996) was the first to investigate carbon content and sequestration in South African peat, with the objective of exploring its potential as biofuel. This idea was soon ruled out, as the peat accumulation rate of about 1 mm per year does not allow long-term sustainable use (P. Grundling *et al*. 2000). P. Grundling *et al*. (1998) investigated many of Maputaland's peatlands, including analyses of water holding capacity and ash content of peats, and highlighting the peatlands' function as water reservoirs. There was also a study of the Vazi peatland complex where *Pinus* plantations caused groundwater deficiency and led to severe peat fires (P. Grundling & Blackmore 1998). Thereafter, there were no further investigations of soil degradation in peatlands until Faul *et al*. (2016) investigated soil physical properties at six peatland sites in northern Maputaland and compared the surface peats of natural and degraded sites. Their results show that pedogenetically altered peat from degraded sites has reduced macropore volume, saturated hydraulic conductivity, hydrophobicity and carbon content, as well as higher bulk density.

Against this background, a closer investigation of the effects of peatland degradation is needed, including consideration of different peatland types and degradation stages. The current study follows up on the work of Faul *et al.* (2016) with an extended dataset and including investigations of unsaturated hydraulic conductivity and maximum capillary rise. These are important soil qualities for water availability after lowering of the water table in peatlands. This study also builds on the work of Gabriel *et al.* (2018), who classified peatland substrates and determined standard soil properties at the same study sites.

The objective of our research is to investigate the effects of drainage on the soil properties of peatlands in different hydromorphic settings, in order to identify type-specific threats and to derive implications for conservation, cultivation and restoration (e.g. rewetting).

METHODS

The study was conducted in the north-eastern part of KwaZulu-Natal Province, South Africa. The study area - the northern part of the Maputaland Coastal Plain (Figure 1) - consists of undulating dunes with a top layer of wind-redistributed sand of Holocene origin (Maud 1980, Botha & Porat 2007). The climate is subtropical–tropical with monthly mean temperatures ranging from 17 °C (June) to 26 °C (February) (Lubbe 1997 in Grobler 2009, Maud 1980). Annual precipitation is about 950 mm and exceeded by potential evapotranspiration, which reaches 2200 mm per annum (Lubbe 1997 in Grobler 2009, Schulze 1997). Thus, peat formation is generally related to groundwater and restricted to certain landscape settings (P. Grundling *et al*. 2013, A.T. Grundling *et al*. 2016) and the corresponding hydrogeomorphic mire types (HGMTs). Five HGMTs are found on the Maputaland Coastal Plain, namely channelled valley bottom (CVB), unchannelled valley bottom (UCVB), interdune depression (ID), seep (SP) and floodplain (FP) (A.T. Grundling 2014). The first three types are the most common (A.T. Grundling 2014, Gabriel *et al*. 2018). Each type provides different hydro-ecological conditions and is inhabited by specialised vegetation communities, which leads to the formation of different botanical peat types (Gabriel *et al*. 2018). In addition to peat, different types of gyttja occur in these systems. Therefore, the term 'peatland substrates' is used to refer to the entirety of the high organic matter substrates investigated in this study.

Substrate stratigraphies of the peatlands were investigated by recording soil profiles at regular intervals along linear transects through the peatlands. Each HGMT was represented by at least one study site (Table 1). The three common types (CVB, UCVB, ID) were investigated in most detail and for each of these types at least one site that was degraded, by drainage and cultivation (CVB, UCVB) or plantations and cattle herding (ID), was included. Only one soil profile was recorded in the rare type FP, in order to study the botanically special raphia peat which is formed from the pneumathodes of the palm *Raphia australis.*

Soil cores were obtained using a Russian peat corer (manufactured by Eijkelkamp), extracting half-cylindrical cores of length 50 cm and diameter 5.2 cm. Field description of the cores was based on the German Soil Mapping Directive 'KA 5' (Ad-hoc-AG Boden 2005) and the botanical peat types identified by Gabriel *et al*. (2018). Special attention was paid to horizons with secondary soil formation, where aerobic conditions had changed the structure and properties of the drained peat layers. When a mire is first drained, a chronological series of soil formation processes known as the moorsh forming process (Ilnicki & Zeitz 2003) is initiated. It starts

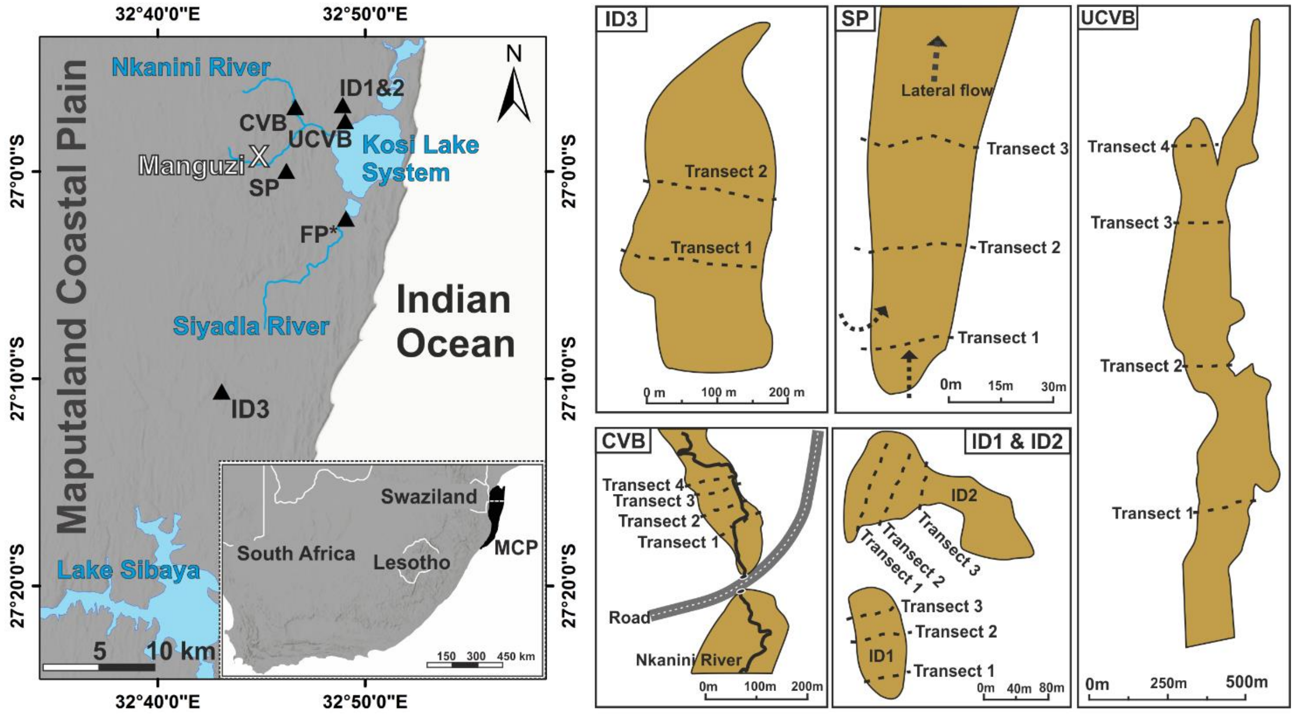


Figure 1. Left: map of the study area around the Kosi Lake System. Right: plan shapes of the individual studied peatlands with broken lines indicating the locations of transects. Only one core was investigated at the FP site which is, therefore, not depicted.

Table 1. Overview of the study sites and transects.

Site name	HGMT	Local name	Coordinates	Size (ha)	Condition and land use	No. trans.	No. prof.
ID1	interdune depression	KwaMazam-bane	26° 56' 52.50" S 32° 48' 54.57" E	0.2	Centre natural; fringe cultivated	3	17
ID2		eMdoni	26° 56' 46.81" S 32° 48' 54.14" E	1.4	Centre natural; fringe cultivated	3	22
ID3		Vazi North	27° 10' 39.58" S 32° 43'3 .83" E	15.0	Degraded; surrounded by *Eucalyptus* plantations; cattle herding,	2	20
UCVB	unchannelled valley bottom	Matitimani	26° 57' 21.50" S 32° 48' 59.83"E	38.6	Transects 1–3: succession; Transect 4: natural, not used	4	31
CVB	channelled valley bottom	Nkanini River	26° 56' 52.89"S 32° 46' 37.99"E	2.0*	Succession; not used	4	39
SP	seep	Nkatwini	26° 59' 58.23"S 32° 46' 12.57"E	0.2	Superficially drained; cultivated	3	11
FP	floodplain	Siyadla River	27° 2' 16.83"S 32° 49' 3.19"E	2–3*	Natural, not used	0	1

* The given size refers, in the case of the CVB site, to the investigated portion of a much larger peatland. In the case of the FP site, it refers to two neighbouring peatland areas on a much more extensive floodplain which may also host other areas with peat substrates.

with formation of a peat shrinkage horizon, which evolves into a peat aggregation horizon then an earthification horizon, and terminates as a grainy moorsh horizon (Table 2). The end product of the process is moorsh - a mineralised peat soil with small-grained structure. In this article, substrate degradation will be described in terms of this sequence, with each horizon belonging to a different degradation stage.

Following the transect corings, one profile per transect was chosen as a site-characteristic profile and its horizons were sampled and analysed in detail. An overview of the soil properties determined and the methods employed is given in Table 3. Substrates encountered within transect corings that were absent from the site-characteristic profile (e.g. saw-sedge peat) were sampled separately.

Carbon content was determined with a True Spec CHN-Analyser and multiplied by the factor 1.88 to convert to organic matter, as suggested by Farmer *et al*. (2014) for tropical peat. This simple conversion is possible because the soils are completely free of inorganic carbon (Gabriel *et al*. 2018).

For horizons that were reachable from the surface, undisturbed samples of substrate were collected for physical soil analyses using 83 cm³ volumetric

Table 2. Horizons of the moorsh formation process, adapted from Ilnicki & Zeitz (2003) and Ad-hoc-AG Boden (2005).

Horizon	**Description**	**Qualifier (in this study)**
Peat shrinkage horizon	Subsoil horizon of drained peatlands, usually directly in transition from non-degraded peat. Oxidation of organic matter and subsidence. Incipient formation of soil structure, vertical cracks.	(shrin.)
Aggregation horizon	Subsoil horizon of drained peatlands. Formation of soil aggregates due to shrinking and swelling; coarse to fine-angular blocky structure, vertical and horizontal shrinkage cracks.	(aggr.)
Earthification horizon	Topsoil horizon of drained peatlands. Formation of crumby, fine-polyhedral to granular soil structure due to mineralisation and humification.	(eart.)
Grainy moorsh horizon	Topsoil horizon of drained peatlands, uusually with intensive tillage. Very fine granular to dusty structure, hard and dry.	(moor.)

Table 3. The laboratory and field methods used: (lab.) = determined in laboratory; (field) = determined in field.

Property	**Method**	**Reference**
Bulk density (lab.)	Drying of volumetric samples (48 hours, 105 °C)	DIN EN 15934: 2012-11
Organic matter (lab.)	Loss on ignition (at 550 °C) TruSpec CHN-Analyser	Schulte & Hopkins (1996) LECO (2016)
Total nitrogen (lab.)	TruSpec CHN-Analyser	LECO (2016)
Saturated hydraulic conductivity K_{sat} (lab.) Saturated hydraulic conductivity K_{sat} (field)	Falling head method Auger hole method	Jury *et al*. (1991) DIN 19682-8:2012-07
Water retention (lab.)	Hanging water column (to pF 2) Pressure pot (to pF 4.2)	Haines (1930) Durner & Iden (2015)
Potential hydrophobicity (lab.)	Water drop penetration time	Doerr (1998)
Degree of decomposition (field)	Squeezing test	von Post (1922)

sample rings; however, it proved impossible to collect undisturbed samples from the fragile earthification horizons.

Saturated hydraulic conductivity was measured on the undisturbed samples using the falling head method of Jury *et al*. (1991). After connecting and sealing a tube of the same diameter on top of a sample ring containing undisturbed substrate, the soil sample was saturated (48 hours). Water was then poured into the tube until the height of the water column above the top surface of the saturated sample was 6 cm. The water started to flow through the substrate and the time required for the height of the water column to decrease from 6 cm to 1 cm was measured in seconds. The saturated hydraulic conductivity was then calculated in cm d^{-1}.

The same samples were subsequently used for water retention analyses. After being saturated with water again, hanging water columns were connected to the samples to apply several pressure (suction) levels up to pF 2.0 (Haines 1930). For pressure levels between pF 2.0 and pF 4.2 the samples were placed on ceramic plates in pressure pots functioning with different stages of air compression (Durner & Iden 2015). The results (residual water contents at distinct pressure levels) were used to model water retention curves in the computer programme RETC (van Genuchten *et al*. 1991), which is based on the following equation from van Genuchten (1980):

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha h)^n]^m} \qquad [1]$$

where $\theta(h)$ = water content at pressure level h, θ_s = water content at saturation, θ_r = residual water content at the permanent wilting point (pF 4.2), α and n are dimensionless empirical shape parameters related to the pore size distribution, and m is calculated as $m = 1 - (1/n)$. Afterwards, the samples were dried for 48 hours at 105 °C to determine bulk density.

Samples of substrates that were not reachable from the surface were taken as volumetric sections cut from the peat cores and were treated in the same way. Peat substrate types not represented in the site-characteristic profiles were sampled separately for the determination of saturated hydraulic conductivity and bulk density. Unfortunately, measurements of water retention could not be realised for these samples.

Using the values of α, n and m from Equation 1, unsaturated hydraulic conductivity K_u was calculated according to the Mualem - van Genuchten model (Mualem 1976, van Genuchten 1980) as:

$$K_u(S_e) = K_{sat} S_e^l [1 - (1 - S_e^{\frac{1}{m}})^m]^2 \qquad [2]$$

$$S_e(h) = \frac{1}{[1+(\alpha h)^n]^m} \qquad [3]$$

where S_e is the effective saturation and l is a dimensionless pore connectivity parameter, estimated at 0.5 by Mualem (1976).

Knowing the unsaturated hydraulic conductivity, the maximum capillary rise z for a substrate was approximated numerically using the following equation from Brandyk *et al*. (1986):

$$z = \sum_{i=1}^{m} \frac{\Delta h}{1+q/K(h_{avi})} \qquad [4]$$

where m is the number of intervals of equal size, Δh is the size interval, q is capillary flow rate, h_{avi} is the average pressure head within the i-th interval = $(h_i + h_{i+1})/2$, and $K(h_{avi})$ is the unsaturated conductivity at that pressure head. Size intervals were calculated in steps of $\Delta h = 10$ cm until a pressure head of $h = 16000$ cm (water column; i.e. pF 4.2) was reached. The pore size distribution was derived from the different pressure levels of the water retention experiment: pF -∞ to 1.8 = wide coarse pores (> 50 µm) ; pF 1.8–2.5 = narrow coarse pores (50–10 µm); pF 2.5–4.2 = mesopores (10–0.2 µm); > pF 4.2 = fine pores (< 0.2 µm), according to Ad-hoc-AG Boden (2005).

For comparison with the laboratory method, saturated hydraulic conductivity was measured in the field using the auger hole method (DIN 19682-8:2012-07). This technique times the refilling with soil water of a perforated tube in a borehole after emptying it. Values cannot be obtained for horizons below the base of the tube, or for unsaturated horizons because the tube refills only up to the current water table level.

The values presented for potential hydrophobicity are medians of five water drop penetration times, tested on air-dry samples according to Doerr (1998).

RESULTS

HGMTs and peatland substrates

The substrates encountered in the different HGMTs ranged from different botanical peat types through amorphous peat to gyttja (Table 4). Amorphous peat was commonly encountered close to the surface in drained peatlands. The qualifiers of the moorsh forming process (Table 2) are added to indicate the degree of degradation. The most common peat types were radicell peat, wood peat and wood-radicell peat, all with median degree of decomposition H6 (von Post 1922). Wood peat predominated in the CVB site, and radicell peat in the ID sites; while radicell, wood and wood-radicell peats were all predominant substrates in the UCVB site. According to Gabriel *et al*. (2017), the current reed-sedge vegetation at the UCVB and CVB sites are succession communities of cleared swamp forest. Therefore, it must be assumed that wood peat would have been more abundant if these sites had been undisturbed. Gyttja substrates were encountered only at the ID and UCVB sites (Gabriel *et al.* 2018).

Secondary soil formation

Degradation horizons occurred at several sites. Site ID3, which is used for cattle herding and surrounded by *Eucalyptus* and *Pinus* plantations, showed the clearest formation of earthification and aggregation horizons. Intense signs of secondary soil formation were also observed at the CVB site, where maintenance of the drainage channels ceased just one year before the field investigation. The channels were partly blocked by vegetation and decomposition products of eroded peat. At the SP site (currently used for agriculture) the top 30 cm consisted of decomposed amorphous peat because of the active drainage, but soil horizons were less clear than at other sites as a result of tillage. Transects UCVB1–3, where succession was in progress following drainage and cultivation spanning a few years, exhibited horizons where radicell peat had formed from reed-sedge vegetation within a layer of amorphous peat in the top decimetre.

The predominant topsoil horizon of degraded sites was an earthification horizon extending to 5–10 cm depth, usually underlain by aggregation horizons. Aggregation horizons were encountered down to a mean depth of 20 cm, while peat shrinkage horizons reached a mean depth of 25 cm. In some cases, layering of earthification horizons over aggregation horizons over peat shrinkage horizons was observed; whereas in other cases, earthification horizons lay directly over peat shrinkage horizons. Fossil peat degradation horizons, probably resulting from past droughts, were encountered only four times. The appearance and structure of each horizon type is shown in Figure 2.

Organic matter and bulk density

Undegraded peat substrates had high organic matter content (70–95 %), except for raphia peat (Figure 3). Amorphous peat had lower organic matter content, decreasing from 80 % to 50 % as degree of degradation increased. Bulk density was in the range 0.1–0.15 g cm^{-3} for undegraded peat substrates apart

Table 4. Frequencies of horizons belonging to individual substrate types within each HGMT: CVB = channelled valley bottom, UCVB = unchannelled valley bottom, ID = interdune depression, SP = seep, FP = floodplain; n.a. = not applicable.

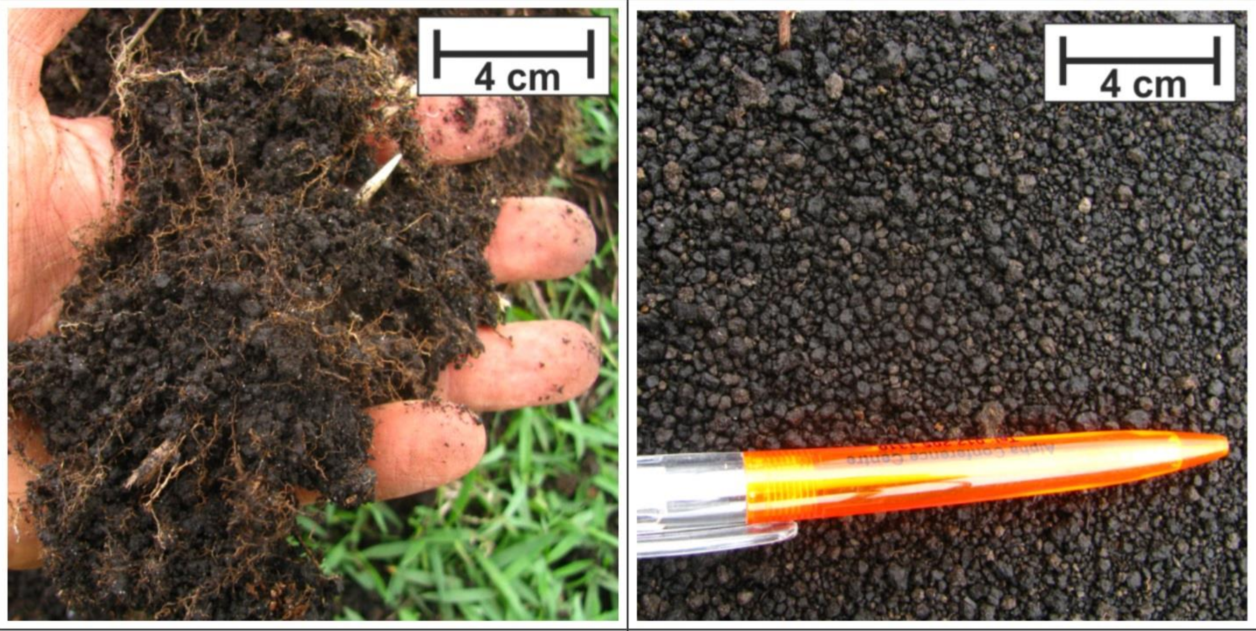
Substrate	**Total**	**CVB**	**UCVB**	**ID**	**SP**	**FP***	**Degree of decomposition (range and median)**
Radicell peat	145	18	49	70	8	-	H3–9, H6
Wood peat	58	28	30	-	-	-	H3–9, H6
Wood-radicell peat	39	9	30	-	-	-	H3–9, H6
Saw-sedge peat	3	-	1	1	1	-	H4–8, H5
Coarse sedge peat	8	3	3	2	-	-	H3–7; H5
Ficus peat	2	-	2	-	-	-	H3–5
Raphia peat	4	-	-	-	-	4	H3–9, H5
Amorphous peat (shrin.)	46	23	11	5	7	-	H9–10, H10
Amorphous peat (aggr.)	36	12	2	19	3	-	H10
Amorphous peat (eart.)	51	14	6	26	5	-	H10
Amorphous peat fossil	4	3	1	-	-	-	H10
Peat-gyttja	68	-	21	47	-	-	n.a.
Organic gyttja	82	-	38	44	-	-	n.a.
Sand gyttja	78	-	27	51	-	-	n.a.

Peat shrinkage horizon

mean extent:	19 cm
mean lower limit:	25 cm
maximum depth:	50 cm

Aggregation horizon

mean extent:	14 cm
mean lower limit:	20 cm
maximum depth:	40 cm



Earthification horizon

mean extent:	7 cm
mean lower limit:	7 cm
maximum depth:	30 cm

Grainy moorsh horizon*

Not encountered in the transects

*image taken in a small depression with a shallow degraded peat layer close to site ID3

Figure 2. Appearance of the structure of degradation horizons. In the top two panes, the yellow lines indicate the upper and lower limits of the horizon described, and the yellow arrows point to cracks.

DOI: 10.19189/MaP.2018.OMB.336

from raphia peat (0.15–0.2 g cm^{-3}), which had higher mineral content (Figure 3). Amorphous peat horizons had much higher bulk densities (0.2–0.3 g cm^{-3}).

Water retention

Of all the undegraded peat substrates, wood peat lost water fastest, with $\theta = 94$ % at pF -∞, $\theta = 67$ % at pF 1.8 and $\theta = 36$ % at pF 4.2 (Figure 4). The curves for other undegraded peat substrates were similar, but their water contents (θ) remained around 10 % higher between pF 1.0 and pF 3.0. The curve for (degraded) amorphous peat (shrin.) was similar to the curves for undegraded peat substrates. Of all the substrates tested, amorphous peat (aggr.) had the lowest initial water content ($\theta = 89$ % at pF -∞) but water losses from this substrate fell behind those from the

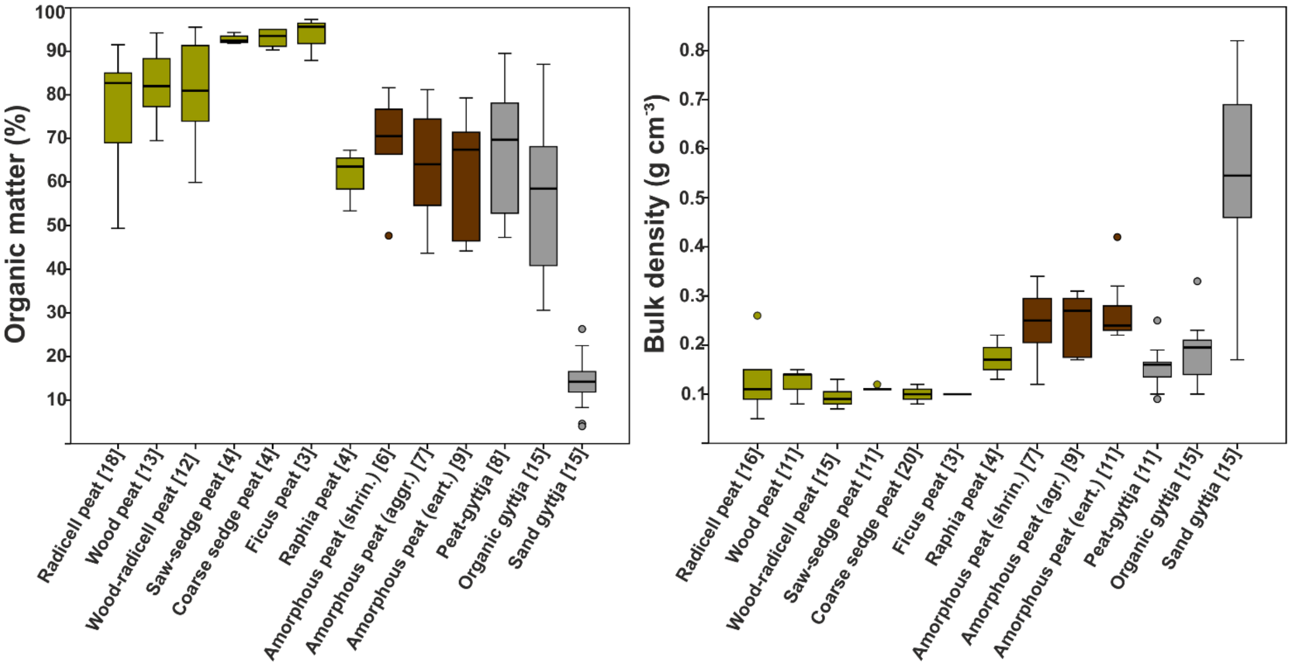


Figure 3. Boxplots of organic matter content and bulk density for each substrate. Boxes with greenish shading represent undegraded peat substrates, those shaded brown represent amorphous peat substrates, and grey shading indicates non-peat substrates.

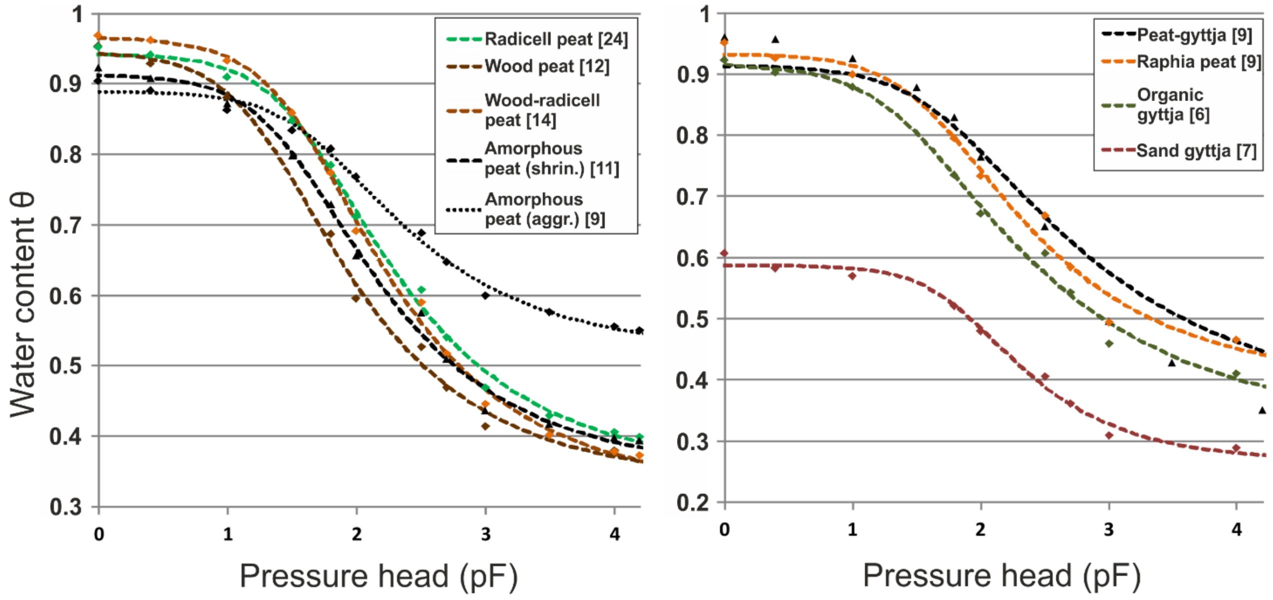


Figure 4. Water retention curves for the different peat substrates.

other peat substrates between pF 1.5 and pF 2.0 and it had by far the highest residual water content ($\theta = 54$ %) at the permanent wilting point (pF 4.2).

In comparison with the undegraded peat substrates, peat-gyttja showed delayed water loss (i.e. higher water retention capacity). The water retention characteristics of organic gyttja resembled those of amorphous peat (shrin.). Sand gyttja had the lowest water retention potential, with $\theta = 59$ % at pF -∞ and $\theta = 28$ % at pF 4.2.

Pore size distribution

All substrates except sand gyttja had total pore volumes greater than 90 % (Figure 5). Wood peat had the highest fraction of wide coarse pores (27 %), whereas amorphous peat from aggregation horizons had the lowest (9.6 %). Across all substrates, the volume of narrow coarse pores ranged from 12 % to 18 %. Peat-gyttja had a higher volume of mesopores (30 %) than the other substrates (13–23 %), and amorphous peat from aggregation horizons had the highest volume of fine pores (55 %).

Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) varied greatly between substrates, as well as among different samples of the same substrate. Field measurements could not be completed for unsaturated degradation horizons such as the amorphous peat layers at drained sites; nor for coarse sedge peat, saw-sedge peat and *Ficus* peat because the depth limit of the auger hole method was exceeded.

The peat substrates had higher K_{sat} than the non-peat substrates (Figure 6). Wood peat had the highest K_{sat} values and also the greatest spread. Most previously reported laboratory values lie in the range $3.5–11.6 \times 10^{-5}$ m s^{-1}, but our measurements yielded values up to 1.2×10^{-3} m s^{-1}. Field measurements yielded even higher values with a median around 0.12×10^{-4} m s^{-1} and an extreme of 2.2×10^{-3} m s^{-1}. Field and laboratory values were similar for radicell peat and peat-gyttja, whereas a considerable difference was observed for organic gyttja (field: 1.0×10^{-4} m s^{-1}; laboratory: 1.6×10^{-5} m s^{-1}). Of the undegraded peat substrates, saw-sedge peat and coarse-sedge peat had the lowest values. Among the amorphous peat substrates, an increase from amorphous peat (shrin.) to amorphous peat (aggr.) to amorphous peat (eart.) was observed, accompanied by an increase in spread.

Unsaturated hydraulic conductivity

Wood peat had an extremely high K_u-value of 5.9×10^{-5} m s^{-1} at pF -∞, whereas sand gyttja

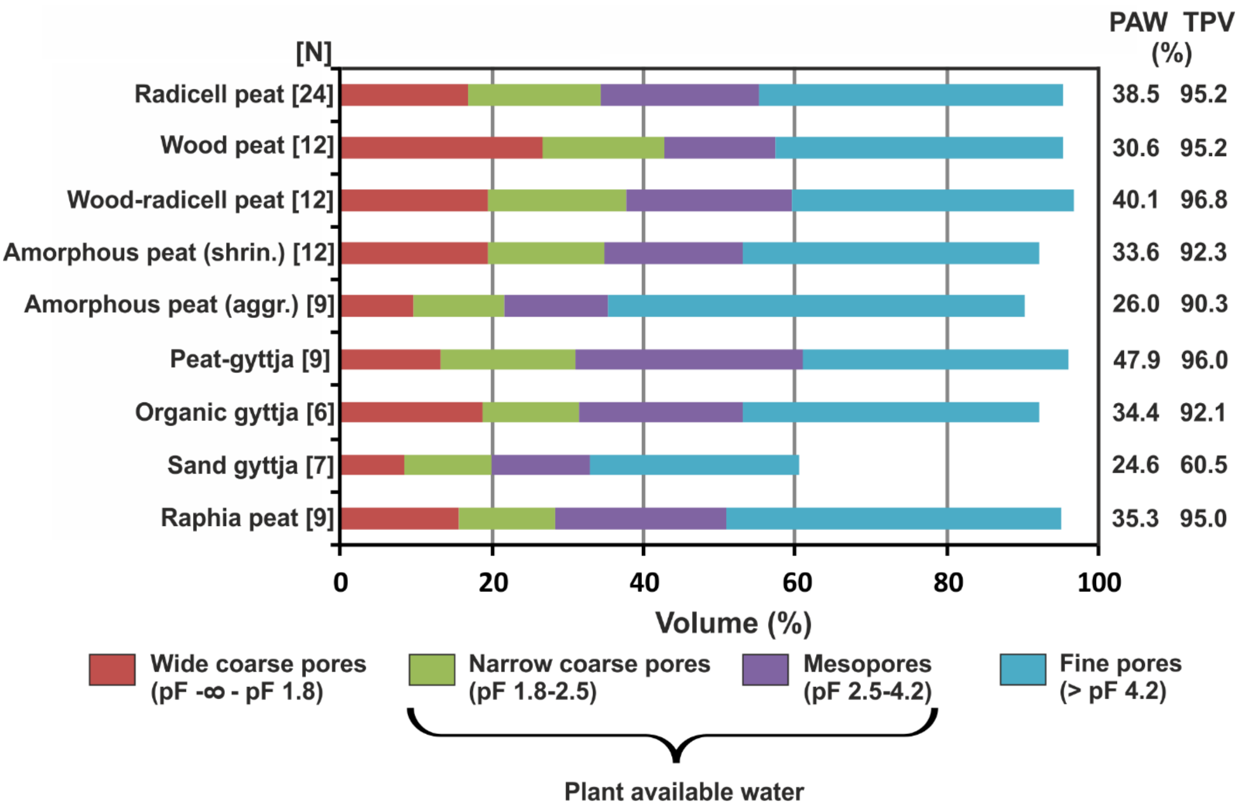


Figure 5. Pore size distribution of each of the substrates. PAW = plant available water; TPV = total pore volume; N = sample size.

(4.4×10^{-6} m s^{-1}) and amorphous peat (aggr.) (1.5×10^{-6} m s^{-1}) had the lowest K_u-values (Figure 7). Between pF 1.5 and pF 2 the K_u-values of all substrates decreased below 1.0×10^{-7} m s^{-1}, with a steeper decrease for the substrates with higher K_u-values at pF -∞.

Maximum capillary rise

The maximum capillary rise (Figure 8) was calculated for different stationary capillary flows q, which represent the evapotranspiration demand (Schwärzel 2000). P. Grundling *et al*. (2015) modelled evaporation rates between 2 mm d^{-1} in winter and up to 6 mm d^{-1} in summer for reed-sedge vegetation in the Mfabeni mire complex. For a better comparison, the results will be described here for $q = 6$ mm d^{-1} at a pressure head of pF 4.2. The greatest capillary rise values were determined for peat-gyttja (173 cm) and raphia peat (158 cm). Amongst the common peat substrates, radicell peat (123 cm) and wood-radicell peat (125 cm) showed similar patterns, whereas the rise for wood peat (107 cm) was smaller. Lower maximum capillary rise values were calculated for amorphous peat (shrin.) (97 cm) and amorphous peat (aggr.) (65 cm). The lowest maximum capillary rise (25 cm) was calculated for amorphous peat (aggr.) from the site characteristic profile at the second transect of Site ID3.

Potential hydrophobicity

The median water drop penetration times for all substrates except sand gyttja were in the strongly or severely hydrophobic categories, and the highest values were in the extremely hydrophobic category (Figure 9). The amplitude of the values is most prominent (please note the logarithmic Y-axis). Of the common peat substrates, radicell peat (2100 seconds) and wood-radicell peat (2700 seconds) showed similar characteristics, whereas the median value for wood peat was 450 seconds. Horizons affected by degradation showed a distinctly different pattern. Whereas the value for amorphous peat (shrin.) was relatively low (186 seconds), potential hydrophobicity increased with degradation, as evidenced by amorphous (aggr.) (1260 seconds) and amorphous peat (eart.) (1620 seconds) (Figure 9).

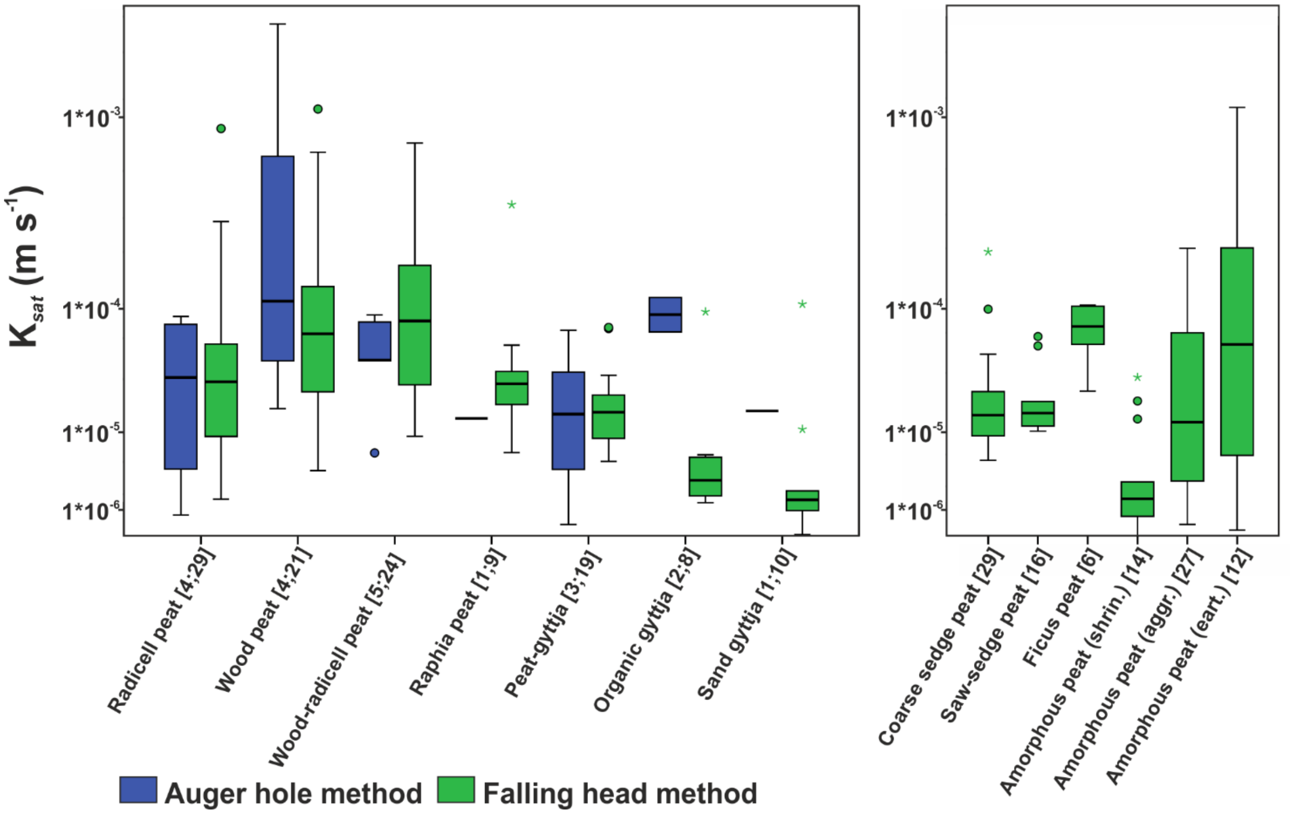


Figure 6. Saturated hydraulic conductivities (K_{sat}) for the different peatland substrates. Left: K_{sat} values for substrates measured in the laboratory and in the field; right: K_{sat} values for substrates measured in the laboratory only. The X-axis indicates substrates with number(s) of samples in square brackets.

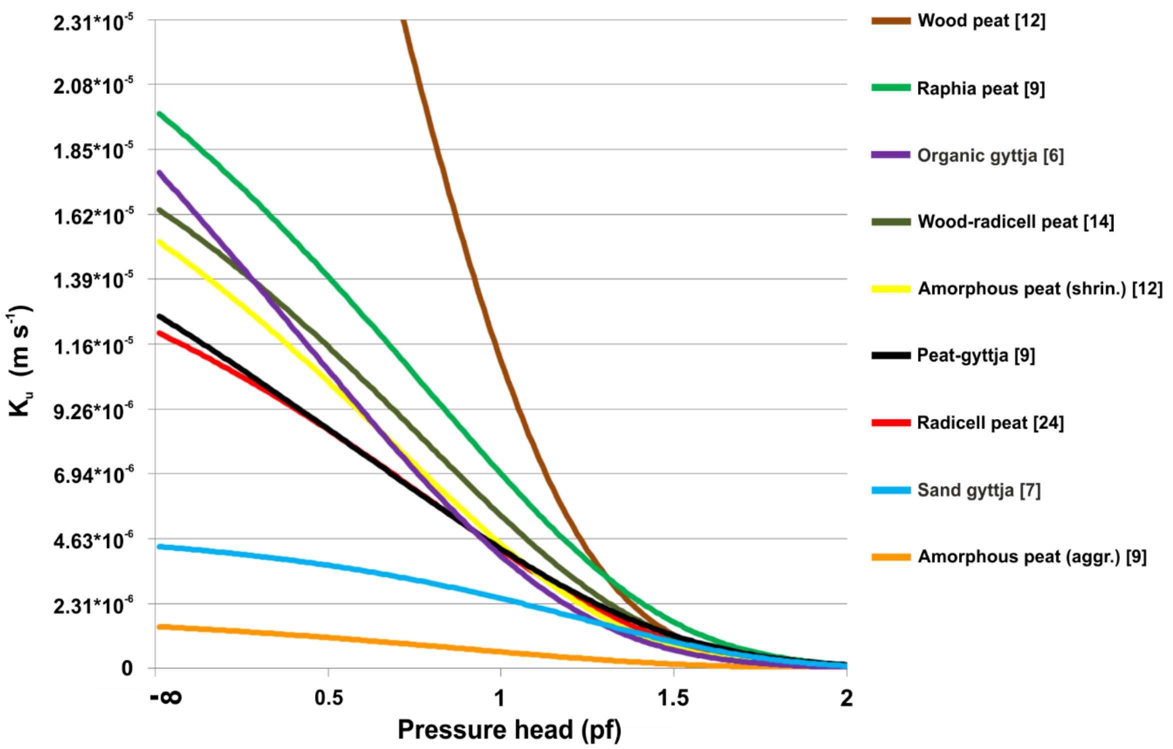


Figure 7. Unsaturated hydraulic conductivities calculated using Equation 2; number of samples [n] in square brackets.

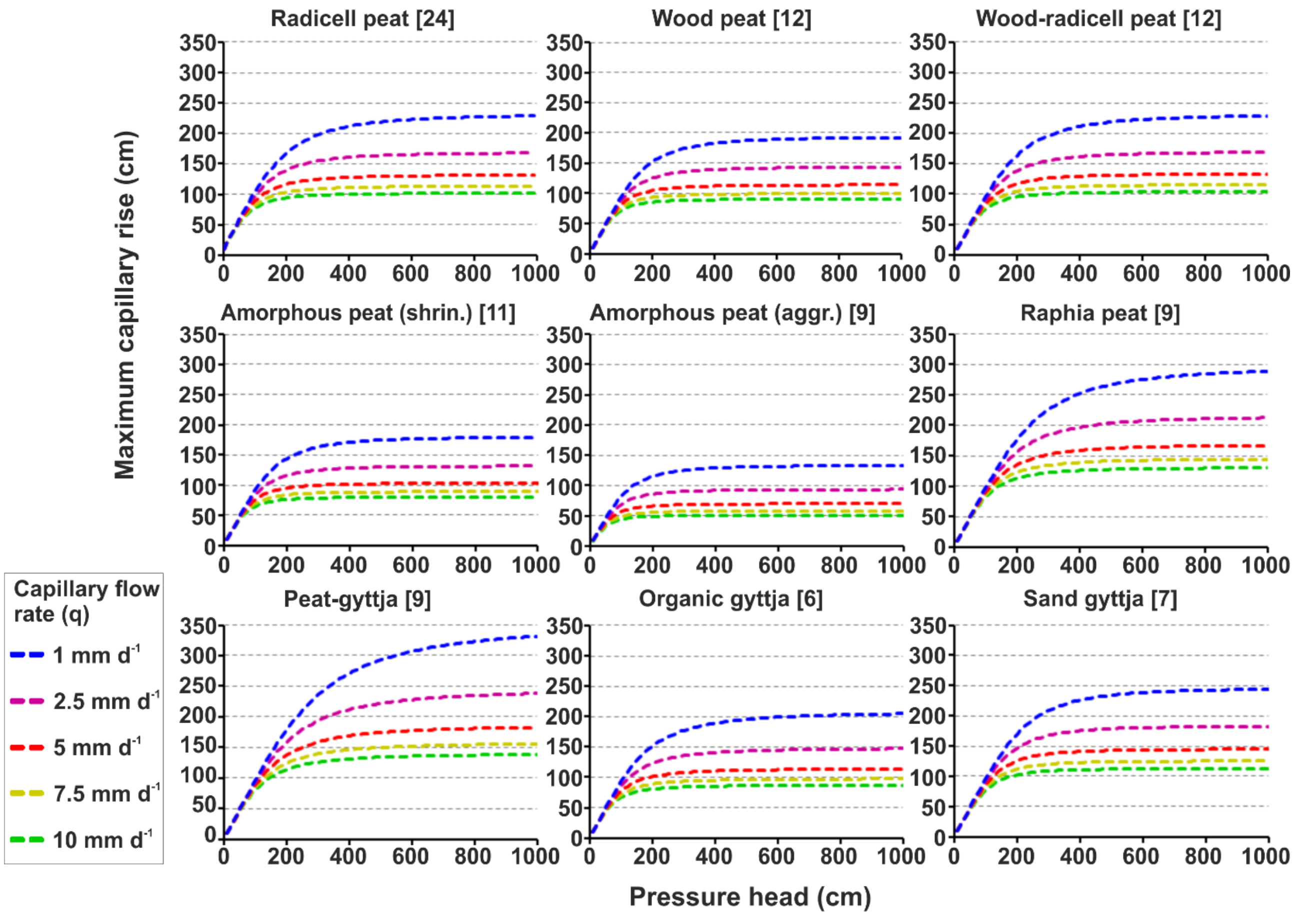


Figure 8. Maximum capillary rise for different substrates. Pressure head: 100 cm = pF 2; 1000 cm = pF 3.

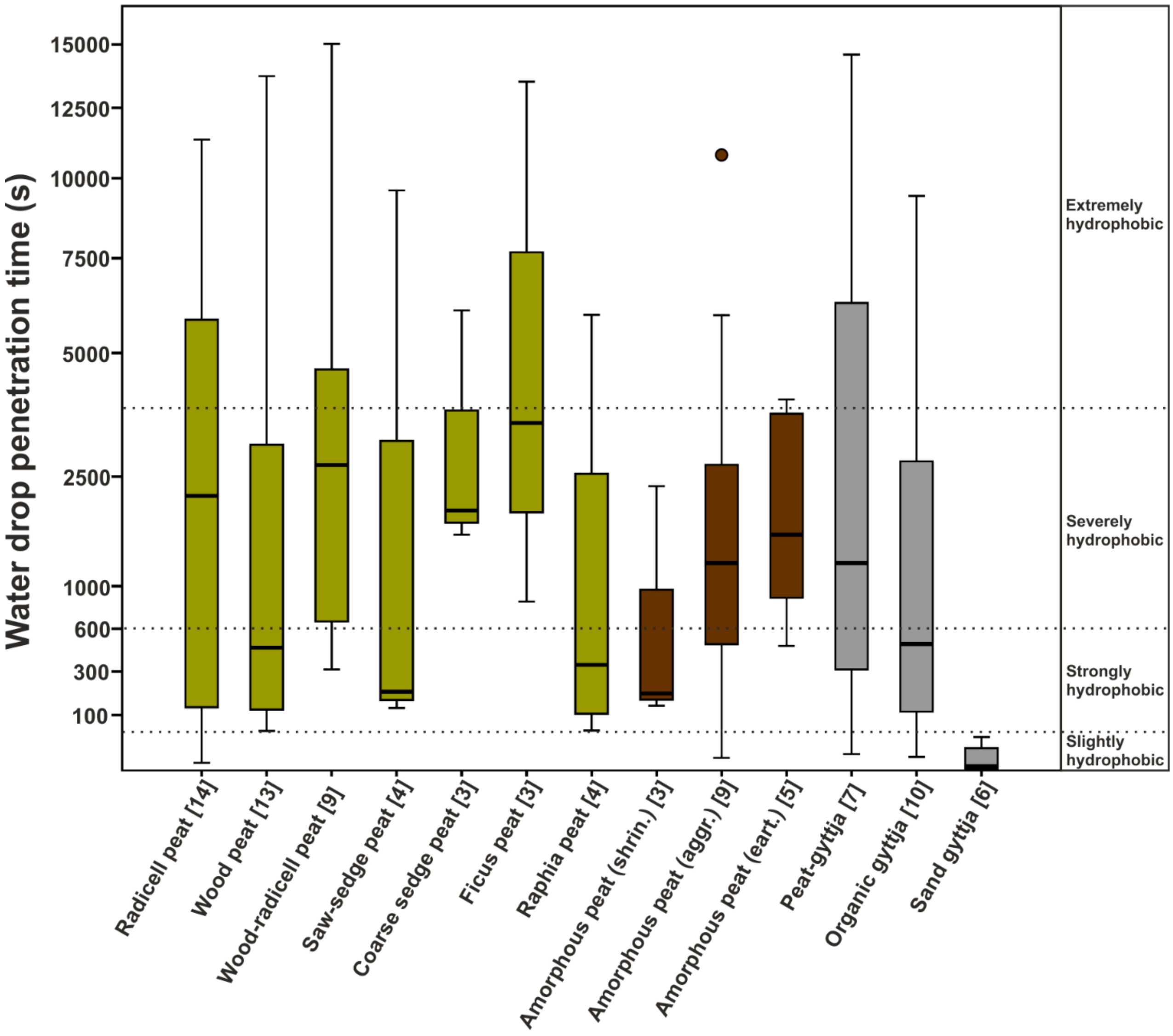


Figure 9. Water drop penetration times for different substrates. Boxes with greenish shading represent undegraded peat substrates; brown indicates amorphous peat; and grey non-peat substrates.

DISCUSSION

Change of peat properties due to degradation

Bulk density and organic matter

The moorsh forming process results from mineralisation and compaction (Zeitz & Velty 2002), which is evidenced by the higher bulk densities of amorphous peat substrates. Unexpectedly, a clear increase in bulk density with degradation intensity was not observed. This may be due to the attendant development of cracks in amorphous peat substrates.

The further the degradation process advances, the more organic matter becomes mineralised. This is visible in the declining content of organic matter for every increase in degradation intensity. Only raphia peat from the FP site showed low values similar to those of degraded peat, as a consequence of fluvial mineral inputs from flood events.

Pore size distribution and water retention

Total porosity decreases with progressing degradation. Furthermore, there is a distinct decline of macropores and an increase of fine pores. Silins & Rothwell (1998, as cited in Holden *et al*. 2004) state that one effect of drainage is the collapse of readily drainable macropores. Zeitz (2001) reports that the volume of narrow coarse pores and mesopores decreases as a consequence of shrinkage, and this is supported by the results of the present study. Studies conducted on peat substrates in central Europe have shown the same pattern (Schwärzel *et al*. 2002, Zeitz & Velty 2002, Schindler *et al*. 2003, Wallor *et al*. 2018). As a consequence, the water storage capacity - an important ecosystem function - declines as well.

The water retention characteristics of organic gyttja and amorphous peat (shrin.) resemble one another, showing that these materials have similar textures, which also makes them difficult to distinguish during fieldwork. Amorphous peat (shrin.), representing the first state of degradation, exhibits lower water content than the common peat substrates at low pressure levels, but similar characteristics at pressure levels above pF 1.5.

Of all the substrates tested except sand gyttja, amorphous peat (aggr.) has the lowest water content at pressure levels below pF 1. Between pF 1 and pF 2 its position in the comparison reverses, and it has the highest water content at high pressure levels.

In the first degradation stage the water retention characteristics of amorphous peat (shrin.) are still similar to those of undegraded peat. However, at a modest degradation stage (amorphous peat (aggr.)), the water retention characteristics are severely affected by alterations in the soil structure. A review of other studies shows that amorphous peat (eart.), representing a stage of major degradation, will have an even lower total pore volume (Zeitz & Velty 2002, Ilnicki & Zeitz 2003, Schindler *et al*. 2003). The formation of cracks and aggregates might increase the volume of coarse pores, but the continuing decomposition of peat compounds leads to a further increase of fine pores, resulting in a net loss of mesopores (Ilnicki & Zeitz 2003, Schindler *et al*. 2003). As mesopores contribute substantially to the available water capacity, peat degradation will also affect vegetation by offering conditions favouring plants that are adapted to drier environments.

Wood peat with a high content of macropores exhibits the fastest water loss of all the peatland substrates examined, as indicated by the shape of its water retention curve. Thus, wood peat dries out the fastest and appears to be the most vulnerable of the substrates to drought.

Saturated hydraulic conductivity

Water movement in the soil takes place in the active pore space, which includes interconnected pores between peat particles but excludes voids and dead-end spaces within the peat particles, such as the remains of plant cells (Quinton *et al*. 2009). The botanical composition of the peat is a major factor in determining its permeability (Rycroft *et al*. 1975). The wide range of K_{sat} values observed for certain substrates in this study originates partly from the heterogeneity of the samples in terms of degree of decomposition and bulk density. These two properties have a major influence on the saturated hydraulic conductivity (Päivänen 1973, Rycroft *et al*. 1975). The uneven distribution of macropores, for example along relict channels of decayed roots, may also be a factor in determining the variations. These preferential flow paths play a crucial role for water movement in the soil (Liu *et al*. 2016).

The low K_{sat} values in saw-sedge peat and coarse sedge peat are likely to be caused by their higher organic gyttja contents, as these substrates are thought to form in shallow open water (Gabriel *et al*. 2017). Wood peat, with the highest amount of macropores, consequently has the highest saturated hydraulic conductivity, as shown by the results of laboratory measurements (median = 7.0×10^{-5} m s^{-1}) and in-situ auger hole tests (median = 1.2×10^{-4} m s^{-1}). The apparently high values measured in the field probably arise from the fact that roots create important preferential flow paths, and soil samples containing thicker roots could not be obtained using sample rings so were not tested in the laboratory.

Other studies on tropical wood peat report K_{sat} values in the same order of magnitude or higher. Kelly *et al.* (2014) found mean K_{sat} values between 3.7×10^{-5} m s^{-1} and 1.6×10^{-4} m s^{-1} in the topsoil and between 1.6×10^{-5} m s^{-1} and 6.3×10^{-5} m s^{-1} in the subsoil of forested tropical peatlands in Peru, while maximum values for topsoil reached 1.1×10^{-3} m s^{-1}. Similarly high values (3.5×10^{-5} m s^{-1}) were reported for ombrogenous peat swamp forests in Kalimantan, Indonesia (Takahashi *et al*. 1997, as cited in Wösten *et al*. 2008). Baird *et al*. (2017), who used piezometers to measure saturated hydraulic conductivity in Panama, even reported values up to 5.5×10^{-3} m s^{-1}. Page *et al*. (2009) state that the mostly fibric and hemic tropical wood peat usually has K_{sat} values above 1.2×10^{-4} m s^{-1}. On the other hand, wood peat from temperate regions is known to have lower K_{sat}, between 9.3×10^{-6} m s^{-1} and 3.9×10^{-5} m s^{-1} (Gabriel & Roßkopf 2014) or around 2.8×10^{-5} m s^{-1} (Gnatowski *et al*. 2010), probably because most wood peat occurring in those latitudes has a higher degree of decomposition (Gnatowski *et al*. 2010). K_{sat} values exceeding 1.2×10^{-4} m s^{-1} are observed in the presence of wide coarse pores related to tree roots. The results indicate the presence of such root pores in at least every few square decimetres within a vertical cross section of a forested peatland. Their contribution to water flow within a peatland consisting of wood peat would be of crucial and much greater importance than that of the bulk of the remaining pores. However, this would only be the case if the root pores formed a connected flow network, and our results do not allow such a conclusion. Other techniques like tracer experiments or non-penetrative methods, focusing on the peatland as a whole, must be applied to investigate this issue. Nonetheless, this leads to the hypothesis that forested peatlands will be more sensitive than other peatland types considered here to aeration after the installation of drainage ditches because water drains from wood peat more rapidly than from other peat types. In addition, the peat between root pores may be more difficult to wet because infiltrating rainwater or rising groundwater will move principally in the root pores.

Another consideration is that, strictly speaking, when K_{sat} exceeds about 1.2×10^{-4} m s^{-1}, the formula for its calculation cannot be applied because the condition of laminar water flow is no longer satisfied. We used calculated K_{sat} values above 1.2×10^{-4} m s^{-1} regardless, in order to allow comparisons with results from other studies.

The collapse and contraction of pores resulting from mineralisation reduced K_{sat} in amorphous peat (shrin.) to 1.3×10^{-6} m s^{-1}. As degradation proceeds, the volume of primary pores between fibres decreases and, at the same time, the volume of secondary pores increases due to aggregation and crack formation. Therefore, the K_{sat} values increased from amorphous peat (shrin.) to amorphous peat (aggr.) (~ 1.2×10^{-5} m s^{-1}) and again to amorphous peat (eart.). (~ 5.8×10^{-5} m s^{-1}). Values of 5.8×10^{-5} m s^{-1} for degraded peat horizons with shrinkage cracks in the soil matrix were also reported by Scholz (1985, as cited in Zeitz 2001, page 90).

Zeitz (2001) states that low K_{sat} values may complicate the rewetting of drained peatlands, as the movement of water from blocked drainage ditches into the peat body is impeded. This problem might also arise in South African peat shrinkage horizons.

Unsaturated hydraulic conductivity and capillary rise

Unsaturated hydraulic conductivity is positively related to soil moisture content because the flow network of connected pores becomes diminished as the water content decreases (Schwärzel *et al*. 2006, Quinton *et al.* 2009). The results of our study indicate that the initial stage of degradation does not have severe consequences for K_u, as the shapes of the curves in Figure 7 for amorphous peat (shrin.) and most of the undegraded peat substrates are similar. However, a distinct decline in K_u is observed between amorphous peat (shrin.) and amorphous peat (aggr.) due to the reduced volume of narrow coarse pores and mesopores. There are implications for peatland restoration; Zeitz (2001) identifies reduced K_u as another of the problems for water distribution into the areas around blocked drainage ditches. Ilnicki & Zeitz (2003) and Zeitz (2003) show a gradual decline of K_u with degradation through earthification horizons to grainy moorsh horizons. On the other hand, Schwärzel *et al*. (2002) state that K_u values at low pressure levels up to pF 2 are higher in very degraded grainy moorsh horizons due to a greater volume of macropores. The high K_u values for wood peat at pressure levels below pF 1.5 are a consequence of its high volume of coarse pores.

Capillary rise is closely related to unsaturated hydraulic conductivity (Brandyk *et al*. 1986). The values for maximum rise derived in this study are somewhat higher than values from other studies, e.g. 70–160 cm in Ilnicki & Zeitz (2003), suggesting over-estimation of K_{sat} in this study. Zeitz (2001) and Ilnicki & Zeitz (2003) have reported maximum heights of < 10 cm for earthified and grainy moorsh horizons. Unfortunately, no earthified horizons could be examined in this study. The maximum capillary rise of 25 cm for the sample from Site ID3, which is representative only of the second most severe degradation type in this study, makes the literature values of < 10 cm for severely degraded topsoils seem realistic for South African peatlands. The change of water availability in degraded topsoil horizons also entails a vegetation change. In colder climates, peat forming vegetation like *Sphagnum* mosses might be replaced by vegetation which does not accumulate as peat (Eggelsmann *et al*. 1993). It is unknown whether this is also the case for South African reed-sedge and swamp forest mires but the possibility should be considered, e.g., in the case of interdune depressions affected by afforestation.

Because the top 20–30 cm of peatland typically shows several different horizons, especially if degraded, it is difficult to interpret the results for unsaturated hydraulic conductivity and capillary rise directly. Rather, they serve to indicate tendencies and, therefore, have a value for comparative evaluation. Among the three common peat types, wood peat has the lowest maximum capillary rise. Consequently, the HGMTs with high occurrence of wood peat (CVB and UCVB) are at greater risk of their surfaces drying out than the ID sites, where peat gyttja and radicell peat display higher capillary rises at the same pressure head levels.

Hydrophobicity

In organic soils, hydrophobicity (= water repellency) is closely negatively related to soil moisture and occurs when the soil moisture content falls below a critical value (Dekker & Ritsema 1999, Brandyk *et al*. 2003). Winarna *et al*. (2016) derived values for two tropical peatlands in Indonesia, whose soils turned hydrophobic when the gravimetric water content (water content as a fraction of peat dry weight) fell below 260 % and 160 %, respectively. Water repellence determined by the water drop penetration time test on air-dry substrate samples reflects the potential hydrophobicity (Dekker & Ritsema 1999), which decreases with decomposition because hydrophobic components such as lipids and waxes within the peat also become decomposed (Doerr *et al*. 2000). Amorphous peat substrates, which are still strongly to severely hydrophobic, are less water repellent than most undegraded substrates. As a consequence, water repellence is especially strong in recently drained peatlands, and will contribute to maintaining aeration facilitating fast decomposition because it hampers rewetting by rain or capillary rise (Doerr *et al*. 2000). In the course of ongoing decomposition, hydrophobicity gradually increases again. However, we could not confirm the assumption of Stegmann & Zeitz (2001) that hydrophobicity increases with degradation to values above those for dry undegraded peat. At least, this property does not seem to be a limiting factor for restoration efforts.

Degradation stages and recovery prospects

The study sites displayed different intensities of degradation, from shallow peat shrinkage horizons to dry earthification horizons up to 30 cm thick.

Amorphous peat without cracks and soil structure was a typical feature in the topsoil horizons of Transects UCVB1 and UCVB2. As these areas were in succession after cultivation, it seems that degradation during the period of drainage did not reach a point where the formation of soil structure was irreversible. However, the exact period of cultivation and drainage is not known to the authors, so further interpretations cannot be made. A new radicell peat layer is currently being formed by the reed-sedge succession vegetation, within the topsoil horizons of amorphous peat. The greatest hydrological alteration in amorphous peat (shrin.) is the decrease of saturated hydraulic conductivity. A full recovery of hydrological properties will depend on how successfully the new input of radicells by succession vegetation re-establishes the macropore system.

The second degradation stage, indicated by amorphous peat (aggr.), already implicates alterations in soil structure (and, hence, hydrological properties) which are expected to be irreversible (Schumann & Joosten 2008). The reduced total pore space means that water storage capacity is lowered; this further reduces the capacity for capillary rise, which might be detrimental to plants during droughts. These trends intensify in amorphous peat (eart.) horizons which, furthermore, are likely to hamper rewetting efforts because they present preferential flow paths capable of continuously discharging water, due to their high K_{sat} values.

Amorphous peat (moor.) - the most severely degraded type - was not encountered in our transects, indicating that drainage was not maintained for long enough to reach this state. However, it is known from other sites in South Africa such as the Vazi peatland, which dried profoundly as a consequence of *Pinus* plantations and was later afflicted several times by peat fires (P. Grundling & Blackmore 1998). Once such a stage is reached, natural recovery is impossible, as vegetation cannot recolonise the harsh, bare burned areas because of their high salt content, high temperatures and evaporation rates.

Subsidence and peat surface oscillation

Subsidence is a consequence of consolidation (loss of buoyancy), shrinkage and peat oxidation. The rate of subsidence depends on temperature and is higher in warmer climates (Wösten *et al*. 1997). In a comparable study, these authors observed an average subsidence rate of about 3 cm per year in Malaysian peat swamp forest with an average water table depth of 50 cm. In addition to water table depth and temperature, the third driver for peat subsidence is time. The rate of subsidence is usually high during the first years of drainage due to consolidation, and declines to a rather constant value in the following years (Wösten *et al*. 1997, Zeitz 2003, Hooijer *et al*. 2012). This occurs, on the one hand, because the recalcitrance of the remaining substance increases with advancing decomposition (Bader *et al.* 2018). On the other hand, reduction of the coarse pore space reduces the aeration (Wösten *et al*. 1997, Zeitz 2003, Hooijer *et al*. 2012). In the results of the current study, this decline can be seen in the sequence of mean organic matter contents: 79 % for undegraded peat, 69 % for amorphous peat (shrin.), 64 % for amorphous peat (aggr.) and 62 % for amorphous peat (eart.).

Therefore, undegraded substrates will subside considerably when drained for the first time, and the progress of subsidence will slow down with increasing degradation intensity. A higher subsidence rate is expected for wood peat, as the coarse pores enhance aeration and reduce capillary rise.

Degraded peatlands with compacted and compressed surface horizons have reduced buoyancy and, therefore, reduced peat surface oscillations (Stegmann & Zeitz 2001, Whittington & Price 2006). The dominating factor for surface oscillations in natural peatlands is the peat forming vegetation (Stegmann *et al*. 2001). P. Grundling *et al*. (2012) measured water table fluctuations of 40 cm in the South African Mfabeni mire complex during a period of two years. At the same time they recorded peat surface oscillation of about 10 cm in reed-sedge dominated parts, whereas no significant oscillations were noted in forested parts. They concluded that the weight of swamp forest vegetation, the deep anchorage of the roots and the absence of aerenchymatous tissues reduced oscillations to almost zero. The only peatlands in Maputaland with the capacity to mitigate mineralisation during droughts are, consequently, those with reed-sedge vegetation.

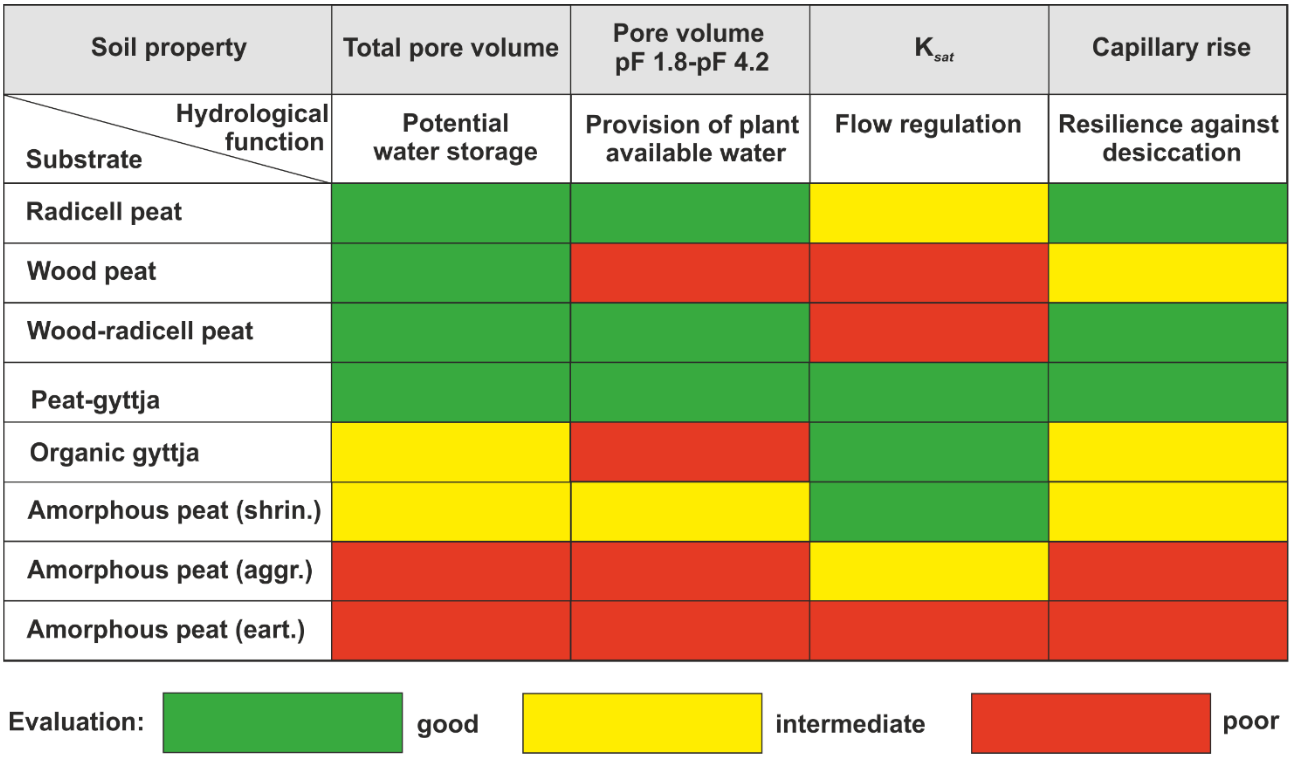
Consequences of degradation; threats to HGMTs

Direct comparisons between the different substrate types investigated show that unfavourable soil properties related to the hydrological soil functions make wood peat, amongst the undegraded substrates, the one which is most vulnerable to degradation (Figure 10). Amongst the degraded substrates, a gradual deterioration with degradation intensity is observed.

The consequences of drainage and water abstraction are evaluated for the different HGMTs according to the following factors: soil qualities, hydrological setting and potential for peat surface oscillation (Figure 11).

The high drainability and low maximum capillary rise of wood peat make CVB and UCVB peatlands with swamp forest vegetation the most vulnerable HGMTs to drainage. The consequences are high losses of carbon storage, losses in water storage, compaction and subsidence. ID peatlands are hardly vulnerable to drainage due to their hydrological settings, as drainage ditches cannot practically be installed without removing a whole dune ridge. The capacity for peat surface oscillation in UCVB peatlands with reed-sedge vegetation makes the peat adjacent to drained areas less vulnerable in cases where the peatland is only partly drained. Ditch blocking during the low to medium degradation stages will result in a positive response with recovery of hydrological functions and a continuation of peat formation. In severe degradation states, however, drainage along desiccation cracks can continue.

In the case of groundwater lowering, e.g. by water abstraction through *Eucalyptus* plantations or during droughts, UCVB is the most vulnerable HGMT, as wood peat is very prone to desiccation on account of its low capillary rise and good drainability. Furthermore, ID peatlands with major layers of organic gyttja are endangered due to the lower



Soil property	Total pore volume	Pore volume pF 1.8-pF 4.2	K_{sat}	Capillary rise
Hydrological function / Substrate	Potential water storage	Provision of plant available water	Flow regulation	Resilience against desiccation
Radicell peat	🟩	🟩	🟨	🟩
Wood peat	🟩	🟥	🟥	🟨
Wood-radicell peat	🟩	🟩	🟥	🟩
Peat-gyttja	🟩	🟩	🟩	🟩
Organic gyttja	🟨	🟥	🟩	🟨
Amorphous peat (shrin.)	🟨	🟨	🟩	🟨
Amorphous peat (aggr.)	🟥	🟥	🟨	🟥
Amorphous peat (eart.)	🟥	🟥	🟥	🟥

Evaluation: 🟩 **good** 🟨 **intermediate** 🟥 **poor**

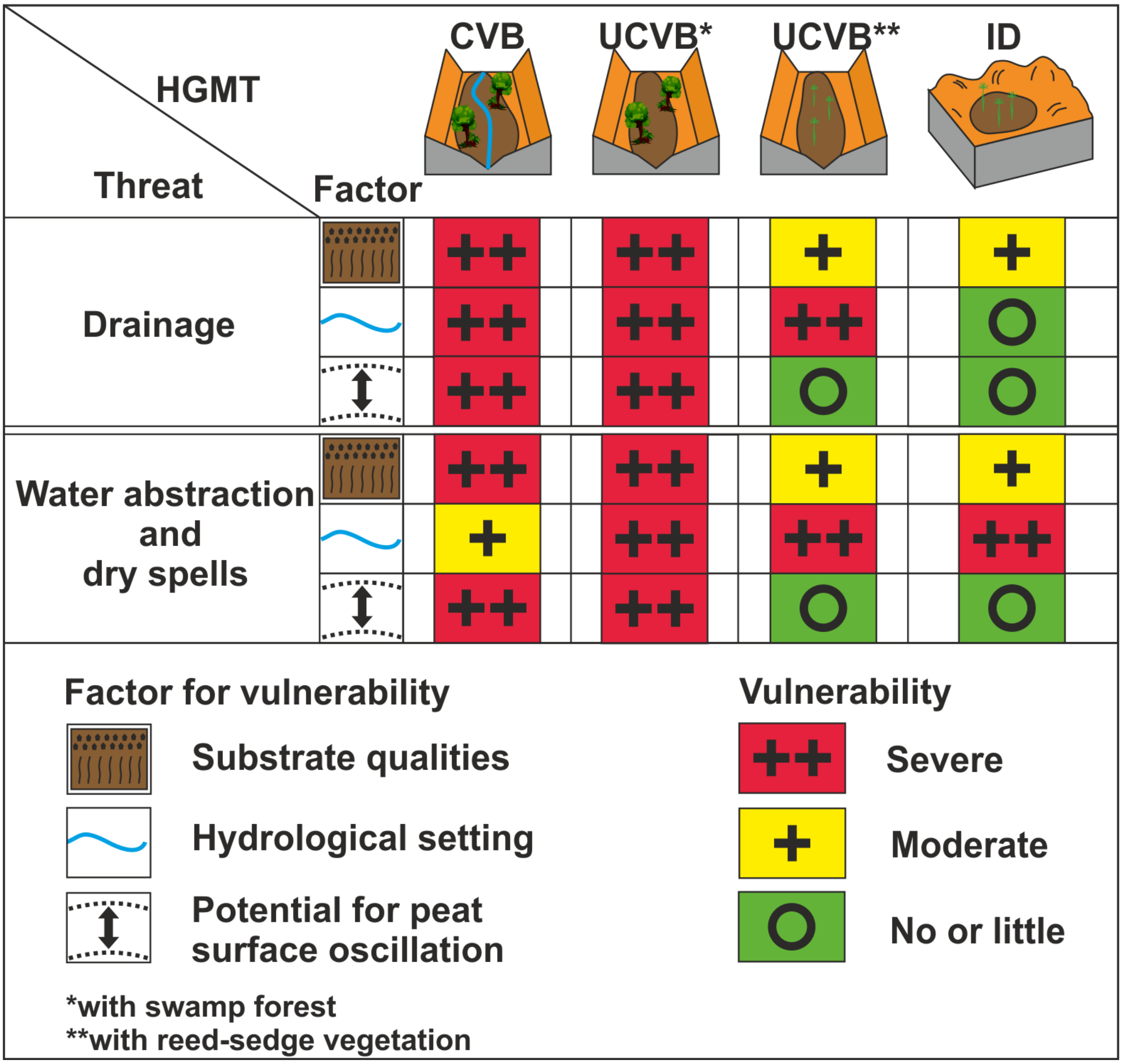
Figure 10. Comparison of the peatland substrates examined here, according to their soil physical properties and evaluation of their hydrological functions. For amorphous peat (eart.), ‘provision of plant available water’ and ‘capillary rise’ were evaluated on the basis of information from literature (Zeitz 2001, |Zeitz & Velty 2002, Schäfer 1996, Schindler *et al*. 2003).

maximum capillary rise in this substrate type, and this is especially the case for cultivated and turbated sites with organic gyttja topsoil. The hydrological setting of CVB peatlands mitigates threats arising from groundwater abstraction because they are usually situated below the local groundwater table and rely on groundwater discharge at the upper fringe of the peat body; unlike the other HGMTs, which rely on groundwater throughflow in situations where the peatland water table is at the same level as the local groundwater table (A.T. Grundling 2014).

The lack of capacity for peat surface oscillation in CVB peatlands and in UCVB peatlands with swamp forest vegetation places these two HGMTs amongst those that are more vulnerable to groundwater lowering.

CONCLUSIONS

As the hydrogeomorphic settings of Maputaland's peatlands mean that they depend on groundwater rather than on rainwater, they are hydrologically dependent on their surroundings. Therefore, management of their water sources is essential. Afforestation in the recharge areas of interdune depressions, seeps and valley bottoms causes degradation of peatlands belonging to these HGMTs. Peatlands containing wood peat that occur in channelled and unchannelled valley bottoms are the ones where the fastest degradation is expected after drainage. Therefore, conservation priority should be afforded to the CVB and UCVB peatland types. Cultivation of peatlands in valley bottoms should



Threat	Factor	HGMT CVB	UCVB*	UCVB**	ID
Drainage	▨	++	++	+	+
	~	++	++	++	O
	↕	++	++	O	O
Water abstraction and dry spells	▨	++	++	+	+
	~	+	++	++	++
	↕	++	++	O	O

Factor for vulnerability

▨ Substrate qualities
~ Hydrological setting
↕ Potential for peat surface oscillation

Vulnerability

++ Severe
\+ Moderate
O No or little

*with swamp forest
**with reed-sedge vegetation

Figure 11. Summary overview of the hydrological vulnerability of different HGMTs.

abandon drainage and, preferably, be located along the peatland fringes where the natural water table is at the desired depth. In interdune depressions, cultivation along the fringes is again preferable for the peatland, as the organic material of raised beds is exposed to aerobic conditions.

Concerning water and carbon storage functions, conservation priority should be given to natural peatlands, where drainage would lead to higher losses than in peatlands that are already degraded.

For restoration purposes, the causes of degradation need to be reversed first. The following interventions can be considered initially:

- Block drains, even on a seasonal basis, to rewet the peat but still allow subsistence agriculture.
- Protect areas with exposed (bare) peat by mulching to conserve moisture.
- Deactivate any erosion points and do not burn waste/dry vegetation on degraded peat.
- Remove plantations that are close to ID peatlands.

Rewetting measures must be monitored properly. If drainage ditches are blocked downslope and the topsoil still remains dry in some parts of the peatland, it has to be supposed that water is continuing to drain through desiccation cracks. In that case, in order to prevent water loss via the cracks, it is suggested that a barrier should be installed in the degraded subsoil, with orientation perpendicular to the flow direction and extending from one side of the peatland to the other. This barrier should be as deep as the degraded topsoil horizon and consist of a substrate with low hydraulic conductivity (e.g. amorphous peat (shrin.)) taken from the topsoil of the degraded peatland. Such interventions should not be initiated until a wise use programme aimed at educating local communities, building capacity and changing land use behaviour is in place.

ACKNOWLEDGEMENTS

This study was realised within the DAAD project “Alliance for Wetlands - Research and Restoration” (AllWet-RES, Project No. 55516208) and financed through the BMBF (German Federal Ministry of Education and Research). We would like to thank Dr Jan Sliva for initiating the project. The first author also thanks the Elsa Neumann studying fund of the State of Berlin for supporting his work with a scholarship. We further thank Nhlanhla Masinga, Silidile Tembe, Lulu Pretorius and Kilian Walz for their support during fieldwork; also Yvonne Dessels and Dr Bataung Kunene (both at the University of the Free State), and Ines Dutschke (Humboldt-Universität zu Berlin), for supporting and facilitating the laboratory work in Berlin. Thanks also to Carolina Rodríguez for comments on the manuscript; Jason Sauer for correcting the spelling mistakes; and finally the two reviewers, the article editor and Dr Olivia Bragg whose comments and suggestions improved the quality of the manuscript.

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Submitted 01 Feb 2018, revision 01 Oct 2018
Editor: Bartłomiej Glina

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