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Exploration of the importance of physical properties of Indonesian peatlands to assess critical groundwater table depths, associated drought and fire hazard

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ABSTRACT

Widespread degradation of Indonesian peatlands by deforestation and excessive drainage results into more frequent fires, particularly in El Niño years, which causes: (i) release of enormous amounts of peat soil carbon to the atmosphere, impacting climate, (ii) severe air pollution, affecting human health and air traffic, and (iii) decreased ecosystem services through loss of biodiversity. Groundwater table decline is the main driver of these negative processes and, therefore restoration of peatland hydrology is essential. Although groundwater table depth is critical to counteract peatland degradation, optimal depths are not generic for all peatlands, but depend on peat physical properties (i.e. water retention, unsaturated conductivity), which are related to the degree of peat humification (Fibric, Hemic, Sapric). Unfortunately only few of these peat physical properties are available while they are essential input data in hydrological models required to extend the usually short observed groundwater hydrographs. An experiment with the Soil-Water-Atmosphere-Plant model (SWAP) for two locations in Indonesian peatlands illustrates the impact of the degree of peat humification on physical properties and thereby on calculated groundwater table depth, hydrological drought and associated fires hazards. The Variable Threshold Method is applied to convert groundwater table depths into hydrological drought, and next the modified Keetch-Byram Drought Index (*mKBDI*) is used to assess wildfire hazard. Peat physical properties that reflect higher peat humification (Hemic and Sapric) result into lower water tables during dry periods, in particular during El Niño years, more severe hydrological drought, and an earlier and longer fire season. Using the limited available peat physical properties the importance is demonstrated of initiating a comprehensive programme to build a database of peat physical properties covering different environmental conditions in which tropical peatlands occur. Availability of such a database connected to a long-term monitoring programme, will support the ongoing rewetting, revegetation and revitalisation programme for Indonesian peatlands, which eventually will contribute to sustainable livelihoods for local people and reduce impact on the regional climate.

1. Introduction

Indonesia has about 20–21 Mha of peatland (Wahyunto et al., 2003, 2004, 2006; Page and Rieley, 2016) of which some 13 Mha is located in Sumatra and Kalimantan. Tropical peatlands (Fig. 1) have formed under conditions of high rainfall, poor drainage and frequent waterlogging. These are conditions in which plant residues accumulate faster than they decay. Tropical peatlands, which are important reservoirs of water, carbon and biodiversity, occur mainly along the east coast of Sumatra and in the southern and western coastal regions of Kalimantan. Indonesian peatlands are relatively young, about 5000–10,000 years before present (Neuzil, 1997; Dommain et al., 2011), although some inland peatlands, such as at Danau Sentarum NP in West Kalimantan are over 30,000 years old (Anshari et al., 2001). Originally these areas were covered with peat swamp forest, however, logging, drainage, conversion to industrial plantations, and recurrent fires changed its land use drastically (Dohong et al., 2017). Over the past two decades the main driver has been conversion to oil palm and *Acacia* (pulp) plantations (Miettinen et al., 2016). In 2015, 6.3 Mha of peatland in Western Indonesia have been converted, of which 3.2 Mha for industrial plantations and 3.1 Mha by smallholders (4.8 Mha of these are in Sumatra and 1.5 Mha in Kalimantan). Of the remaining peatland in

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Fig. 1. Intact peat swamp forest near the River Bika in the Upper Kapuas basin, Kalimantan, Indonesia (© Henny A.J. Van Lanen, Wageningen University).

Western Indonesia, 2.9 Mha in Sumatra and Kalimantan is deforested and (severely) degraded, and lies abandoned (Miettinen et al., 2016).

Tropical peat largely consists of water with an organic carbon content (by weight) of 12 to 18%, or more, depending on the clay content of the peat, and a bulk density in the range of 0.07–0.1 g/cm^3. Peat swamps are bordered by streams and have a dome-shaped surface. Draining of peatland through a dense canal system results in peat drying out leading to peat subsidence, including oxidation and enhanced carbon emissions (e.g. Giesen and Nirmala, 2018). In the El Niño year 2015, about 81% of the emissions were calculated to originate from peatland fires (Pribadi and Kurata, 2017). In dry seasons drying out of drained peat may increase hydrological drought, and thereby increase fire risks. This is of particular concern during prolonged El Niño droughts when large areas of peatland may burn (e.g. Taufik et al., 2017). During the latest El Niño in 2015 about 850,000 ha of peatland in Sumatra and Kalimantan were burnt, including commercial plantations, areas managed by smallholders and degraded peat landscapes. One of the consequences was that Indonesia's daily carbon emissions in September–October 2015 were greater than the fossil fuel CO_2 release rate of the European Union (Huijnen et al., 2016). Peat smoulders rather than completely burns and hence a lot of smoke is produced. This smoke is a major health hazard and massively contributes to the ‘haze’ problem that leads to closing of airports, major economic losses and issues with neighbouring countries Singapore and Malaysia (Giesen and Nirmala, 2018). As a result of the 2015 fires about 500,000 persons were hospitalized for respiratory tract illnesses, economic losses in Indonesia were estimated to total at least USD 16 billion (World Bank, 2016) and perhaps as much as USD 47 billion, and 11.3 Tg of carbon was released to the atmosphere (Huijnen et al., 2016).

The massive degradation of Indonesian peatlands and its immense environmental impacts have prompted major concerns about land use changes happening over the last decades. In response to the damaging 2015 peatland fires, the National Peatland Restoration Agency (*Badan Restorasi Gambut* or BRG, https://brg.go.id/) was established by Presidential Decree in January 2016 (PerPres No. 1/2016), with the mandate to coordinate and facilitate restoration of 2.0 Mha of degraded peatland over a period of 5 years (2016–2021). In its peatland restoration efforts, BRG applies three integrated types of intervention, namely Rewetting, Revegetation and Revitalization of livelihoods (the ‘RRR approach’). The decree also requires that every concession should have a MRV (Monitoring, Reporting, and Verification) procedure on collation and assessment of environmental variables.

As part of land degradation studies, extensive research has been conducted on the impact of canal drainage on groundwater table depths, and associated drought and fire hazards (e.g. Wösten et al., 2008a; Hooijer et al., 2010; Takeuchi et al., 2016; Ishii et al., 2016; Taufik et al., 2018). As a result critical groundwater table depths have been derived. For example, Wösten et al. (2008a, 2008b) showed that fire susceptibility of relatively coarse-textured peat material strongly increases when the drainage depth is deeper than 0.40 m below surface. Taufik et al. (2015) found a critical groundwater table depth of 0.85 m below surface when maximum fire danger is reached (clay wetland forest of Southwest Sumatra). Identification of critical groundwater table depths depends on drought and fire risks that people can cope with (Taufik et al., 2018), as well as on peat physical properties (Taufik et al., 2015). These properties are required: (i) to extend the usually rather short time series of observed groundwater table depths, and (ii) to better understand hydrological processes and associated impacts on drought and fire hazard. Peat physical properties are governed by the spaces between organic and mineral particles, which in peats largely depend on the degree of peat humification that is controlled by drainage intensity (uncontrolled, controlled) and possibly rewetting.

In temperate peatlands hydrological processes were examined by Price and co-workers in Canada (Price, 1997; Price and Schlotzhauer, 1999), Holden and co-workers in the United Kingdom (Holden et al., 2004, 2006), and Schothorst in the Netherlands (Schothorst, 1977). In the past these studies were often related to peatland drainage and more recently to peatland restoration. As a consequence, physical properties of temperate peatlands are relatively well known. In contrast, no standard series of physical properties (e.g. water retention curves) are available for tropical peatlands covering the whole range from natural, non-humified peat to fully humified peat. In this context, the objective of this study is to explore for Indonesian peatlands the importance of scarcely available peat physical properties for three calculated, highly relevant land and water management aspects namely groundwater table depth, hydrological drought and associated wildfire hazard. A comprehensive hydrological model and a fire-related drought index are used to quantify these impacts. It is hypothesized that: (i) physical properties (water retention) of tropical peatlands with different humification degrees are not the same, (ii) different humification degrees result into different critical water table depth, hydrological drought and associated fire hazard, which is relevant for rewetting, revegetation and the revitalization of Indonesian peatlands, and (iii) hydrological drought and fire hazard increase with humification degree.

2. Methods and materials

2.1. Genesis of peatlands: influence on physical properties

Typical for peatlands are organic soils or 'Histosols' according the American Soil Taxonomy (USDA, 1975) and FAO (1990). The term has been derived from the Greek *histos*, meaning tissue, and indicates a soil that is rich in fresh or partly humified organic matter. In the humid tropics, regional environmental and topographic conditions have enabled peat to form under high precipitation and poor drainage conditions. Plains were colonised by vegetation composed largely of mangroves and peat swamp forest, all of which provided abundant organic (histic) material which only slowly decays when drained under prevailing anaerobic conditions (Rieley and Page, 1997). Peatlands deviate, e.g. in topography that is a main drive for hydrological conditions, botanical composition, physical characteristics, chemical properties. Peatlands are classified in different ways. One system is based upon the humification degree (Andriesse., 1988).

The degree of humification of the histic material is an important characteristic because it determines many other properties of Histosols (e.g. water retention, hydraulic conductivity, bearing capacity). The USDA Soil Taxonomy (1975) recognises three main classes that define the degree of peat humification, namely Fibric, Hemic, and Sapric. Fibric peats are the least humified and consist of intact fibre. Hemic peats are partially humified and Sapric peats are the most humified. The ten Von Post (1922) classes (H1 – H10) are further refinements of the USDA humification classes, as shown in Table 1.

Over time microbial activity transforms drained peat from Fibric to Hemic, and eventually to Sapric peat. Humification results in a decrease in large spaces and coarse organic material (non-decomposed tree trunks, branches, roots), an increase in small spaces and an increase in bulk density, and consequently in a change in the water retention curve. Despite the fact that information on physical properties of Indonesian peatlands is limited, a comparison can be made with comparable tropical peatlands in Brazil. Da Rocha Campos et al. (2011) concluded that for a peatland in the State of Minas Gerais, Brazil, the water holding capacity, defined as the difference in water content at a pressure head of − 10 kPa and the water content at a pressure head of − 1500 kPa, is high in Fibric peat compared to Hemic and especially Sapric peat. The finding that water holding capacity decreases with increasing degrees of peat humification, allows drawing the hypothetical water retention curve for Indonesian peatlands as shown in Fig. 2.

Based on Fig. 2 it can be hypothesized that when the pressure head drops, i.e. pF increases, less water becomes available in Hemic and Sapric relative to Fibric peats. Consequently the degree of humification, through its changing water holding capacity, is likely to impact

Table 1
Degrees of peat humification.

Classification	Fibre content	Von Post class
Fibric	>66%	H1 to H3
Hemic	33–66%	H4 to H6
Sapric	< 33%	H7 to H10

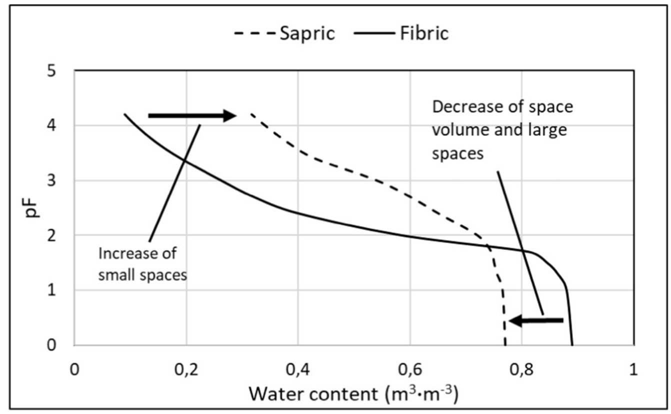

Fig. 2. Hypothetical water retention curves showing the effect of peat humification from Fibric to Sapric. pF equals ^{10}log of absolute value of negative pressure head.

calculated groundwater table depth, hydrological drought and associated wildfire hazard.

Water retention curves are required for the top (0–30 cm) and sub (> 30 cm) soil. This two layer system applied by Wösten et al. (2008a) is consistent with the 'acrotelm' or surface layer and 'catotelm' or deeper layer concept as used to stratify boreal and temperate peatlands (Ingram, 1978).

Water retention curves for Hemic and Sapric peat were measured in the laboratory of the Indonesian Soil Survey Institute (Pusat Penelitian Tanah, 1986) using 167 cm^3 Kopecky cores (Annex I).

However, water retention curves of Fibric peat are hard to measure with conventional sampling methods using small Kopecky cores. This is because a substantial larger volume of Fibric peat has to be sampled to obtain a characteristic peat water retention curve. Since the Representative Elementary Volume (REV), of Fibric peat should consist of coarse tree remnants, large open spaces and fine parts, these small cores are not suitable. As an alternative to direct measurement, Taufik (2017) and Taufik et al. (2018) used an inverse modelling approach simulating measured groundwater table depths to obtain the water retention curve of Fibric peat (Annex I). Fig. 3 shows the characteristic water retention curves for Fibric, Hemic and Sapric Indonesian peats and they compare well with the hypothetical Fibric and Sapric curves shown in Fig. 2.

2.2. Experiment using the Soil Water Atmosphere Plant model (SWAP)

Two locations (Fig. 4) are studied: Sebangau Forest in the ex-Mega Rice Project area in Central Kalimantan (Hirano et al., 2015), and Air Hitam in the eastern part of Jambi Province in Sumatra (Wösten et al., 2006). The two different locations are selected to investigate if the climate also would have an effect in major Indonesian peat regions. Some details of the two locations are given in Annex I, including time series of observed groundwater table depths used for the inverse modelling approach.

This explorative experiment uses the same three different water retention curves (Fig. 3) for the Sebangau Forest and Air Hitam location (Fig. 4) implying that the influence of physical properties is examined for different weather conditions relevant for Indonesian peatlands. Time series of daily weather data for the two locations were collected from nearby stations for the period 1980–2015 (Annex I). Such a long time-period is necessary to model drought and fire.

The selected SWAP (Soil-Water-Atmosphere-Plant) model is used for: (i) inverse modelling to obtain the water retention curve Fibric peat, and (ii) simulating time series of groundwater table depths for two locations and three different water retention curves (Fibric, Hemic, Sapric peat). SWAP is a one-dimensional, vertically oriented model that

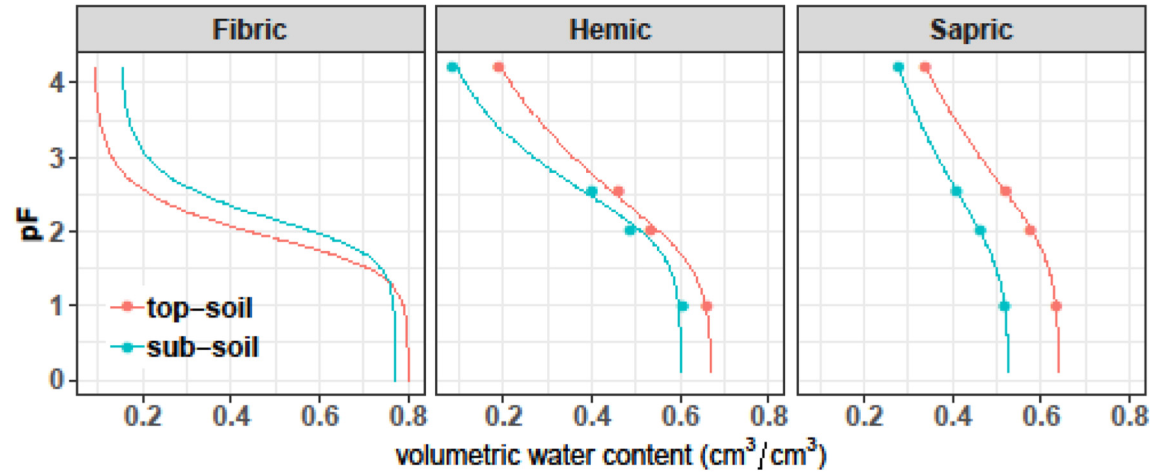

Fig. 3. Water retention curves for top and subsoils of peats with different degrees of peat humification. Left: Fibric peat obtained with inverse modelling; Middle: Hemic peat; Right: Sapric peat. The curves for Hemic and Sapric peat were obtained with direct measurements.

simulates water flow in the unsaturated zone in interaction with vegetation dynamics. It is driven by weather (precipitation, potential evaporation) and subsurface hydrology that connects to the surface water system (Kroes et al., 2017), i.e. peatland streams. To simulate groundwater table depths, SWAP numerically solves soil water flow in each layer using the Richards' approach (Van Dam and Feddes, 2000). The model allows for downward fluxes (percolation), but also upward fluxes (capillary rise), as well as lateral groundwater-stream interaction (both drainage and infiltration).

The SWAP model runs with daily time steps for the period 1980–2015, including a number of strong El Niño years (1982–1983, 1997–1998, 2015). SWAP requires daily weather data, physical properties (soil, subsurface drainage) and vegetation data as input. Water retention curves for the top and subsoil, as shown in Fig. 3, are assigned for Fibric, Hemic and Sapric peat. Because hardly any observed unsaturated hydraulic curves are available for Indonesian peatlands, for both locations and for Fibric, Hemic and Sapric peat, curves are used obtained by Taufik (2017) through inverse modelling. Note that during strong El Niño years not only the wet part of the water retention curve (pF $<$ 2.0) is relevant, but also the dryer part (pF $>$ 3.0). Soil water uptake by roots is assumed to be evenly distributed over layers up to a depth of 100 cm (rooting depth of peat swamp forest).

The upper boundary condition of SWAP consists of daily time series of precipitation and evaporation (Annex I). SWAP simulates actual daily evapotranspiration and soil moisture contents by combining reference evapotranspiration according the Penman-Monteith FAO method (Allen et al., 1998) with crop coefficients converting reference evaporation to potential evapotranspiration for peat swamp forest. No change in vegetation development of the peat swamp forest is assumed as well as a canopy that fully covers the soil surface.

At the lower boundary, SWAP simulates soil drainage fluxes driven by differences between groundwater table depths and surface water (stream) levels (below soil surface). Based on field experience at both locations, surface water depths of 50 cm (wet season), 100 cm (dry season), and 150 cm (dry season of strong El Niño years) are used. SWAP simulations result in time series of daily groundwater table

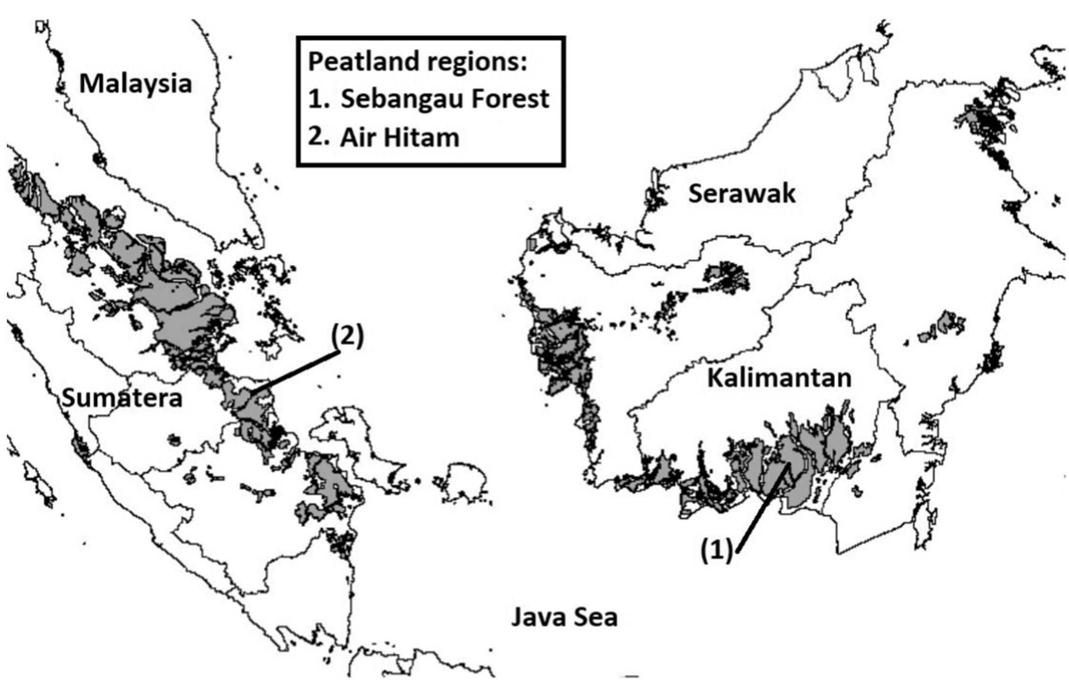

Fig. 4. Study locations in Indonesian peatland: 1. Sebangau Forest, and 2. Air Hitam.

depths for the period 1980–2015.

2.3. Drought identification and assessment of fire hazard

Drought duration is obtained with the Variable Threshold Method (VTM), which identifies water deficits (drought) in different domains of the water cycle (e.g. soil moisture, groundwater, and discharge) (Yevjevich, 1967; Hisdal et al., 2004; Van Loon et al., 2010). In this study, groundwater table depth is used to identify (hydrological) drought (Tallaksen and Van Lanen, 2004). VTM uses a pre-defined variable threshold level and drought events start when groundwater table depths falls below the threshold value and ends when it is equal or rises above the threshold value. In this study, thresholds were derived from 80th percentile of groundwater table depths (Van Loon and Van Lanen, 2012; Taufik, 2017; Taufik et al., 2018). First the variable threshold value is calculated for each month using all groundwater table depths for that specific month (1980–2015). Thresholds are separately calculated for each location. Then, groundwater table depths in each year are confronted with monthly thresholds of Fibric peat to determine duration of periods with groundwater table depths below the threshold. Additionally, severity of droughts is determined from the average deviation of the groundwater table depth from the threshold (e.g. Taufik, 2017; Taufik et al., 2018). Use of thresholds of Fibric peat as reference means that change of drought duration and severity for a specific location can be interpreted as decrease or increase due to differences in physical properties, i.e. Hemic or Sapric relative to Fibric peat representing degrees of humification. Differences in drought duration and severity for the same peat but for the two locations can be attributed to differences in climate.

The modified Keetch-Byram Drought Index (*mKBDI*) is used to assess daily fire hazard (Ainuddin and Ampun, 2008). Taufik et al. (2015) describe how the daily *mKBDI* (moisture deficiency relevant for fire hazard) is calculated using the daily: (i) drought factor, (ii) rainfall factor, and (iii) water table factor. Input data are daily maximum air temperature, daily rainfall, and daily groundwater table depth. Temperature and rainfall data for the two locations for the period 1980–2015 have been measured, and groundwater table depths are simulated using the SWAP model. The average annual rainfall in the drought factor is been set at 2500 mm/yr, which is representative for Indonesian peatlands.

The *mKBDI* is scaled from zero to 203 mm. Prolonged extremely wet spells increase soil moisture to eventually reach saturation, therefore *mKBDI* is at minimum (i.e. 0), whereas long-lasting hot and dry spells create favourable conditions for *mKBDI* to reach its maximum value (i.e. 203 mm). The *mKBDI* is used to assign a fire hazard class to each day in the record 1980–2015, i.e. Low, Moderate, and High. The fire hazard class limits used in this study follow previous research in Southeast Asia (Ainuddin and Ampun, 2008; Taufik et al., 2015) and are as follows: Low: $mKBDI < 100$, Moderate: $100 \leq mKBDI \leq 150$, and High: $mKBDI > 150$. In this study $\alpha_H = 10.64$ and $\beta_H = 0.283$ as obtained by Taufik et al. (2015) for a site at East Sumatra not far from Air Hitam.

3. Results

The influence of physical properties, i.e. different degrees of peat humification and associated differences in water retention curves, on calculated groundwater table depth, hydrological drought and fire hazard is illustrated for two climatically different locations in Indonesia.

3.1. Groundwater table depth

Time series of daily groundwater table depths over the period 1980–2015 are simulated for a location in Kalimantan and in Sumatra (Fig. 4). Calculations are made for peatlands at three stages of humification: Fibric, Hemic and Sapric (Fig. 5).

Groundwater table depth is in particular relevant in dry periods during strong El Niño years. As a consequence, focus is on the years 1982–1983, and 2014–2015, which are known to be warm ENSO years (e.g. Taufik, 2017; Taufik et al., 2018). Fig. 5 shows simulated daily groundwater table depths for two of these years for the Sebangau Forest and Air Hitam. Water table depth strongly fluctuates, as also has been observed in the field (e.g. Hirano et al., 2012, 2015; Taufik et al., 2018). At both locations, groundwater is at soil surface during wet periods, which is common by the end of the wet season (end February–March), while also drying out of the peat is clearly observed. For the period 1982–1983, the first year shows a stronger decline of water tables than the second year, whereas in the period 2014–2015, clearly the latter has the deepest groundwater tables.

3.2. Hydrological drought

Simulated time series of groundwater table depths for the Sebangau Forest and Air Hitam are used to identify drought characteristics (i.e. drought in groundwater) applying the Variable Threshold Method as described in Section 2.3. The onset, end, drought duration and the severity of events in strong El Niño years are presented in Table 2. The longest drought in the Sebangau Forest occurred in the years 1997–1998, which lasted 298 days (total of two events, which have a short interruption around the turn of the year), whereas in Air Hitam it occurred in 2015 and it lasted 314 days (Fibric peat conditions).

When Hemic or Sapric water retention curves are used instead of the Fibric curve, drought severity increases for all cases. Differences vary between 8–34% for the Sebangau Forest and 4–39% for Air Hitam. Drought duration decreases when using Fibric curves ranging between 13–35% for the Sebangau Forest and 20–36% for Air Hitam (Table 2).

3.3. Fire hazard

Simulated time series of daily groundwater table depths for the Sebangau Forest and Air Hitam are also used to compute the modified Keetch-Byran Index, *mKBDI*, as a measure for fire hazard (Section 2.3). The fire hazard for the dry season of the strong El Niño years 1982 and 2015 is presented in Fig. 6 for the two selected peatland locations.

Fire hazard starts to increase from June onwards at both locations and both years. After a while it reaches a maximum (i.e. 203) in these years for all cases. Differences, when using humified Hemic and Sapric peat curves instead of the Fibric curves are larger for the Sebangau Forest than for Air Hitam. In the Sebangau Forest, in both years, moderate and high fire hazard levels are reached about one month earlier when using the humified peat curves (Fig. 6), implying an earlier start of the fire season. This early start is caused by drought beginning in mid-June, whereas this happens only early July for Fibric peat (Table 2). Moderate fire hazards also finish 1–1.5 months earlier when applying the humified peat curves in the Sebangau Forest, which is in accordance with the drought assessment. In Air Hitam, in 1982, the fire season starts also about one month earlier (Fig. 6). The recovery of fire hazards during that year is approximately identical for the different peat water retention curves, which does not reflect the earlier recovery from drought (Table 2). Differences in the 2015 fire hazards for the different peat curves are almost negligible in Air Hitam. An exception is the hazard in November 2015 where a moderate hazard still continues when Fibric curves are used. For humified peat in Air Hitam the hazard is already low.

4. Discussion

4.1. Key findings

This study shows that water retention curves reflecting different degrees of peat humification have a marked influence on groundwater tables, hydrological drought and fire hazard. Groundwater tables fall

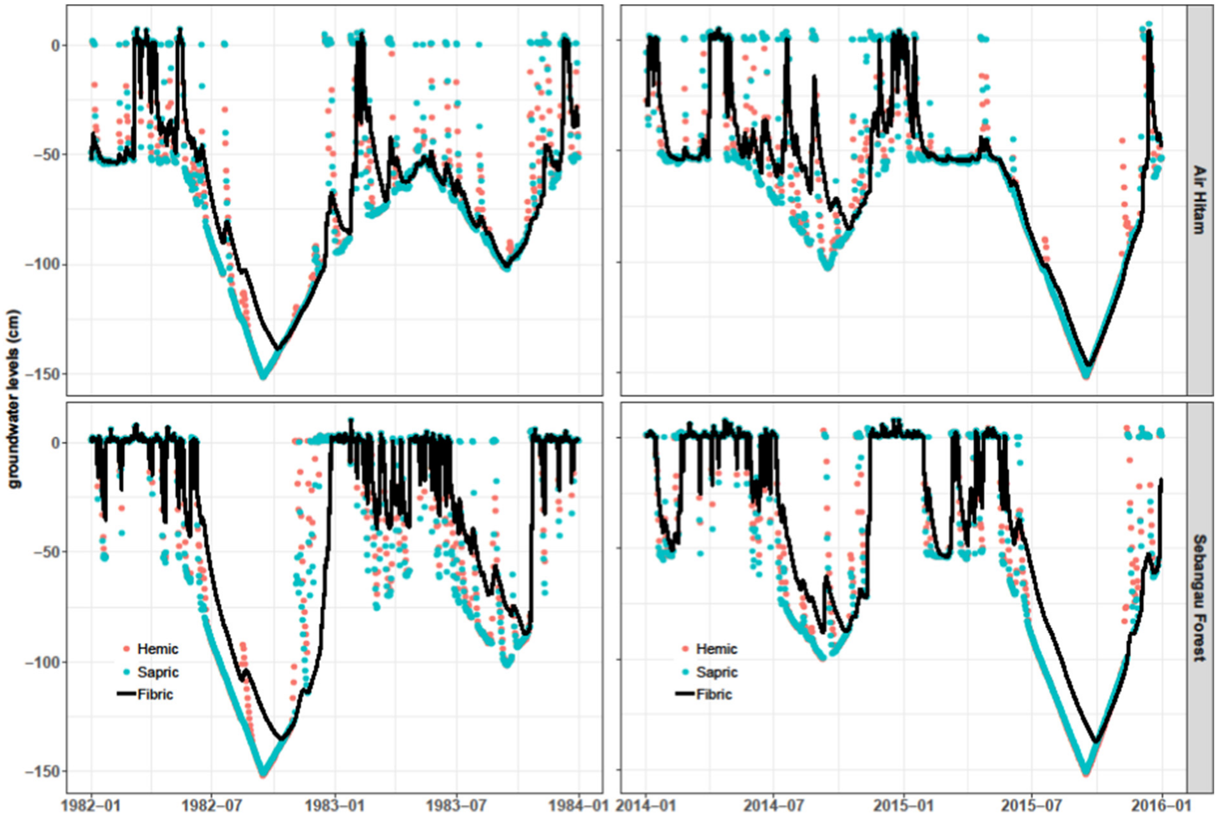

Fig. 5. Simulated groundwater table depths (cm below soil surface) for Fibric, Hemic and Sapric peat in the warm ENSO years 1982–1983 and 2015. Top: Air Hitam, and Bottom Sebangau Forest.

Table 2
Drought characteristics in terms of duration and severity for Fibric, Hemic and Sapric peat, and percent change relative to Sapric peat for two Indonesian peatlands.

	Drought		Drought characteristics			
	Onset	End	Duration (day)	% change	Severity (cm)	% change
Sebangau Forest						
Fibric peat	4-7-1982	26-12-1982	175	–	37	–
	26-5-1997	23-12-1997	211	–	33	–
	10-1-1998	7-4-1998	87	–	44	–
	4-7-2015	1-1-2016	181	–	31	–
Hemic peat	11-6-1982	2-11-1982	144	−18	40	8
	9-7-1997	23-11-1997	137	−35	43	30
	20-1-1998	6-4-1998	76	−13	53	21
	16-6-2015	12-11-2015	149	−18	41	30
Sapric peat	10-6-1982	5-11-1982	148	−15	43	15
	8-7-1997	23-11-1997	138	−35	45	34
	20-1-1998	6-4-1998	76	−13	53	21
	16-6-2015	13-11-2015	150	−17	41	30
Air Hitam						
Fibric peat	7-7-1982	3-2-1983	211	–	34	–
	28-3-1983	1-6-1983	65	–	13	–
	16-6-1997	10-3-1998	267	–	39	–
	2-2-2015	13-12-2015	314	–	21	–
Hemic peat	25-7-1982	16-12-1982	144	−32	46	36
	10-6-1997	28-11-1997	171	−36	40	4
	8-2-2015	19-4-2015	70	–	7	–
	6-6-2015	6-11-2015	153	−29[a]	34	20[a]
Sapric peat	24-7-1982	16-12-1982	145	−31	47	39
	9-6-1997	2-12-1997	176	−34	40	11
	8-2-2015	19-4-2015	70	–	7	–
	6-6-2015	4-12-2015	181	−20[a]	33	20[a]

[a] % change refers to the total duration and severity of the two drought events in 2015.

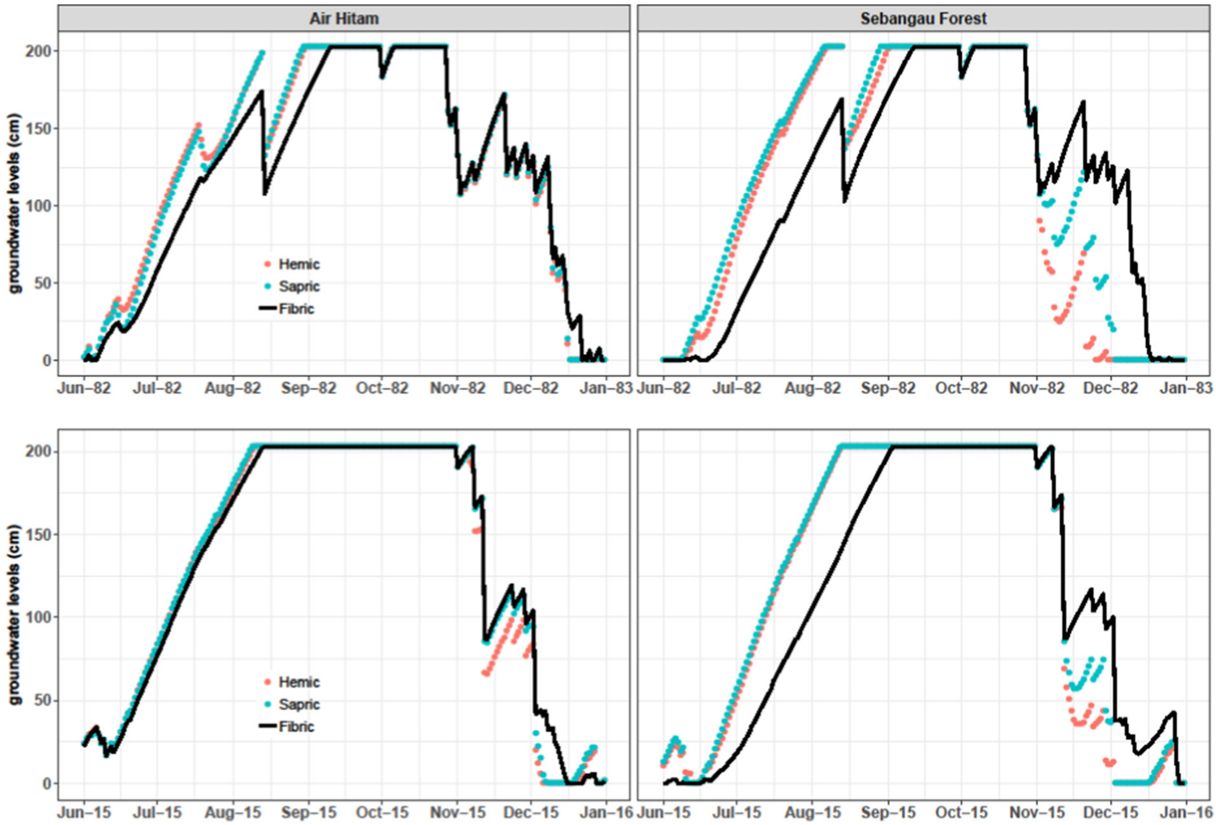

Fig. 6. Wildfire hazard for Fibric, Hemic and Sapric peat in the warm ENSO years 1982 and 2015 using the modified Keetch-Byran Index (*mKBDI*). Left: Sebangau Forest, and Right: Air Hitam Fire hazard is classified as follows: Low: mKBDI < 100, Moderate: 100 ≤ mKBDI ≤150, and High: mKBDI > 150.

quicker when the peat is humified (Hemic and Sapric). Differences between Hemic and Sapric peat relative to non-humified peat (Fibric) are rather small, in particular in the falling part of the groundwater hydrograph. Groundwater tables in humified peatlands are more flashy and recover quicker after rain (Fig. 5). A decline of the groundwater table causes a drop in the pressure head implying that soil water is released from the peat. The higher water holding capacity of non-humified peat relative to humified peat (Figs. 2 and 3) governs that per unit of water table drawdown more water is released. Accordingly, when peat has to supply water to cover a certain evaporation demand, the groundwater table in a non-humified peat (Fibric) drops slower than in humified peat (Hemic and Sapric). On the other hand, during wet periods less water is required to rise groundwater tables in humified peatlands, which explains the quicker recovery after rain and in general the more flashy behaviour. The deeper groundwater tables in humified peat during dry periods, particularly in strong El Niño years, lead to more severe hydrological drought than in non-humified peat (Table 2). An increase of drought duration for humified peatlands was also anticipated, but did not happen because most drought events had a slighter later onset than the non-humified peat and an earlier end of drought due to quicker recovery. Differences in groundwater tables affect the fire season, expressed in terms of a moderate or high fire hazard. The fire season is about 2 month longer in Sebangau Forest and 1 month in Air Hitam when using Hemic and Sapric peat water retention curves (humified peatlands) instead of Fibric curves (non-humified peatlands).

4.2. Relation to existing findings

There is little knowledge on the influence of peat humification on physical properties of tropical peatlands. Da Rocha Campos et al. (2011) confirm the higher water holding capacity of non-humified tropical peat in Brazil, as we hypothesized (Fig. 2) and as obtained from observations and inverse modelling for Indonesian conditions (Fig. 3). Wösten et al. (2008a, 2008b) found a critical drainage depth of 0.40 m below soil surface for relatively coarse-textured peat material below which fire hazard strongly increases. Taufik et al. (2015) reported for tropical clayey peatland in Sumatra a critical groundwater table depth of 0.85 m below soil surface when maximum fire danger is reached. This study indicates that the critical groundwater table depth, i.e. the depth that the High fire hazard level (*mKBDI* = 150 mm) is reached, is slightly deeper (depth varying from 0.93 to 1.11 m soil surface) than the above-mentioned levels, and depends on the degree of humification and location. Humified peatlands (Hemic and Sapric) have a somewhat deeper critical groundwater table depth than the non-humified peat (Fibric). The climate conditions in Sebangau Forest also result in marginally lower critical depth than in Air Hitam.

4.3. Limitations

The widely used Soil-Water-Atmosphere-Plant (SWAP) model (Kroes et al., 2017) is used to quantify impacts of physical properties of Indonesian peatlands. Although the SWAP model which has been downloaded for over 30 applications in Indonesia (http://www.swap.alterra.nl/), has high potential to reliably simulate soil water flow, groundwater table depth and drainage to the surface water system, findings can be affected by, for example, the definition of the surface water regime as a boundary condition (Section 2.2). The deepest surface water level for the dry period in El Niño years is set at 150 cm, implying that groundwater table depths below 150 cm depth are counteracted by infiltration from streams. Coupling SWAP to a saturated groundwater flow model (Xu et al., 2012) or using another coupled soil water – groundwater flow model (e.g. SIMGRO, Querner and Van Lanen, 2010) could overcome this limitation. However, such a coupled soil water – groundwater model requires spatially-distributed hydraulic properties of the groundwater system (e.g. saturated hydraulic conductivity, storativity), which usually are not available for the studied data scarce locations in Indonesia. Also use of the Penman-Monteith equation in combination with a crop coefficient (Section 2.2) to calculate potential evapotranspiration of peat swamp forests is an approximation of potential water losses from these diverse peatlands. The limited availability of physical properties for tropical peatlands still prevents to carry out a formal uncertainty analysis at this stage. However, by using different water retention curves for Fibric, Hemic and Sapric peat it is demonstrated that results are sensitive to these input parameters, which clearly support the conclusion that more of these properties need to be collated.

In this study, hydrological drought is assessed instead of the more frequently used meteorological drought. Taufik et al. (2017) proofed that groundwater needs to be included to improve the assessment of drought and fire hazard (see also Section 2.3). The 80th percentile of the groundwater table depths is selected as threshold (Section 2.3). This chosen 80th percentile lies within the range of the 70–95% percentile that commonly is used for drought studies (e.g. Andreadis et al., 2005; Fleig et al., 2006). With a more extreme threshold, i.e. 95th percentile, drought severity would be smaller and with a less extreme threshold the opposite would happen. However, it would not change the order of the studied examples (Van Loon and Van Lanen, 2012; Heudorfer and Stahl, 2016), implying that the drought severity for Hemic and Sapric peat remains higher than for Fibric peat (Table 2).

The Keetch-Byran Drought Index (*mKBDI*) is applied to investigate fire hazard in this study and the groundwater table depth is integrated into the fire hazard assessment (Section 2.3). Currently, the coefficients α_H and β_H are only available for one site in Sumatra not far from Air Hitam. As shown by Taufik et al. (2015) changes in α_H and β_H up to 50% do not have a large influence on the frequency of occurrence of the high fire class.

4.4. Importance of physical properties of tropical peatlands

All studies on water and solute transport in soils require information on soil physical properties, that is, the water retention and unsaturated hydraulic conductivity curves for the different soil layers that together constitute the soil profile. Over the years, databases of these properties have been developed at the national scale (The Netherlands: Staring Series, Wösten et al., 2001; Brazil: HYBRAS, Ottoni et al., 2018), continental scale (European Union: HYPRES, Wösten et al., 1999) and global scale (UNSODA, Nemes et al., 2001). Unfortunately, such a database is still lacking for Indonesian soils while this study shows that it is a prerequisite for the assessment of critical groundwater depths, hydrological drought and fire hazard. Consequently, it is recommended to bring together existing measured soil physical properties for Indonesian soils in a central database. Setting up such a database for both mineral and organic soils also illustrates for which soils data are already available and for which they are missing, thus allowing targeting future soil physical measurement efforts. For sure, such a database for Indonesian soils will find many grateful end users studying for instance, plant growth, irrigation, drainage and optimization of surface water management.

As mentioned in Section 2.2, classical Kopecky rings (100–200 cm^3) are far too small to measure the water retention curve of in particular Fibric peat with all non-humified vegetation parts (REV is substantially larger). Likely, samples taken are biased to finer parts of Fibric peat, which resemble Hemic and Sapric peat. Consequently, using water retention curves using these samples will lead to calculation of too deep groundwater tables in dry periods, and to an overestimation of drought severity and fire hazard. Since conventional measurement techniques do not apply for peats, novel creative laboratory and field measurement techniques are required to adequately measure the physical properties of peats. In this respect lessons can be learned from, for instance, physical measurements on clay soils that started already some decades ago (e.g. Bouma and Wösten, 1979). These soils develop cracks upon drying, which close after rewetting and water can flow both through cracks and soil matrix. Targeted soil physical measurement techniques have been developed to obtain in this case representative soil physical properties used as input in revised soil water flow models considering presence of cracks in clay soils during dry periods. For example, Van Stiphout et al. (1987) used large undisturbed clay samples (6000 cm^3) to measure flow through cracks as a function of soil moisture and next to simulate with a revised SWAP model, the transient amount of water flowing through clay cracks thus bypassing the soil matrix.

Targeted measurement of physical properties of peats should not be an exercise on its own but rather be part of a long-term monitoring programme at several monitoring/experimental locations representative for Indonesian peatlands. Locations should be well-equipped to measure environmental fluxes (e.g. evapotranspiration, surface water discharge, CO_2 emissions) and state variables (e.g. moisture profiles, groundwater table depths, stream levels, CO_2 concentrations). These measurements are crucial to understand the environmental impact of drastic changes in land use occurring in Southeast Asia, and in particular in some regions in Indonesia. At the same time, collected data can be used to test models that simulate environmental fluxes and state variables, which subsequently can be applied to explore various land use and climate change projections. This requires a strong cooperation between natural and social scientists, policy makers, and local stakeholders resulting in co-creation of knowledge fine-tuned to their needs. The 2016 Presidential Decree requires that every concession in Indonesia should use a MRV (Monitoring, Reporting, and Verification) procedure thereby stimulating the initiation and implementation of the proposed comprehensive monitoring initiative. BRG efforts to implement Rewetting, Revegetation and Revitalization of livelihoods in an integrated way (the 'RRR approach') are well aligned with this. BRG specifically mentions laboratory and field measurement of water retention curves of peat as a research need.

5. Conclusions

In Indonesia, thorough knowledge of critical groundwater table depth is decisive to combat extensive peatland degradation, and hence reduce drought severity and frequent fires leading to severe air pollution and reduced ecosystems services. This study provides evidence that physical properties of peats are essential to reliably simulate groundwater table depths in peatlands. Modelling is required because long time series of observed groundwater table depths are lacking. It is demonstrated that water retention curves of peat swamp forest with different degrees of humification (Fibric, Hemic, Sapric) have a distinct effect on groundwater tables in dry periods, particular in El Niño years. This results in hydrological droughts of humified peat that are 20–30% more severe in 2015. Furthermore, in 1982 and 2015 the fire season in these peats starts earlier and lasts 1–2 month longer. Measured soil physical properties in Indonesia are sparse and hard to access. Consequently, it is beneficial to develop a publicly available database with standard series of soil physical properties both for organic and mineral soils, comparable to what has been done elsewhere at different scales. Such a database can support Indonesia to better cope with the environmental challenges it faces (e.g. impact of land use change). Innovative soil physical field measurement techniques need to be developed for Indonesian peats, because conventional methods do not apply. Samples should be undisturbed and large to adequately represent the heterogeneity, in particular of non-humified Fibric peat. Lessons can be learned from measurement techniques developed for clay soils.

It is recommended that systematic collation of soil physical properties is part of a comprehensive monitoring programme measuring environmental fluxes and state variables at representative sites in Indonesian peatlands. This programme can take advantage of the recent

Indonesian Presidential Decree that requires every concession to perform Monitoring, Reporting, and Verification (MRV). The programme can be the basis for a concerted action of policy makers, scientists (both natural and social), public sector, private sector (e.g. plantations) and local stakeholders to develop sustainable scenarios, incl. pathways for future developments in peatlands.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.04.001.

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