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Human-induced changes in Indonesian peatlands increase drought severity

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Abstract

Indonesian peatlands are critical to the global carbon cycle, but they also support a large number of local economies. Intense forest clearing and draining in these peatlands is causing severe ecological and environmental impacts. Most studies highlighted increased carbon emission in the region through drought and large-scale fires, further accelerating peatland degradation. Yet, little is known about the long-term impacts of human-induced disturbance on peatland hydrology in the tropics. Here we show that converting natural peat forests to plantations can significantly alter the hydrological system far worse than previously recognized, leading to amplified moisture stress and drought severity. This study quantified how human-induced changes to Indonesian peatlands have affected drought severity. Through field observations and modelling, we demonstrate that canalization doubled drought severity; logging and starting plantations even quadrupled drought severity. Recognizing the importance of peatlands to Indonesia, proper management, and rehabilitating peatlands remain the only viable option for continued plantation use.

1. Introduction

Indonesian peatlands play an important role in the global carbon cycle and the local economy. Despite occupying less than 10% of the country's land area, peatlands hold almost the same amount of carbon stock as mineral soils in Indonesia (Minasny *et al* 2017, Warren *et al* 2017). Because of the growing demand for agricultural land and the availability of peatlands on flat topography, large areas of peatlands have been converted from forest to plantation over the last two decades (Koh *et al* 2011). By 2010, 2.3 million hectares of peat-swamp forests were cleared by large scale agricultural and forestry industries, *about* half *of* the forests in Kalimantan and Sumatra (Koh *et al* 2011). Once cleared, land users often drain sections of peat by building canals (canalization), then start plantations. Furthermore, there is now evidence that smallholder (typically small-scale agriculture less than 10 ha) expansion to peatlands is on the rise (Schoneveld *et al* 2019). Extensive clearing and draining (Abood *et al* 2015, Hohner and Dreschel 2015, Nungesser *et al* 2015, Curtis *et al* 2018, Turner and Mcclenachan 2018) have degraded the peatlands, causing drought-induced wildfire (Taufik *et al* 2017, 2019a), and caused peatland to become a net source of carbon (Baccini *et al* 2017, Wijedasa *et al* 2018).

Many studies have explored how peatland transformation causes large carbon emissions (Baccini *et al* 2017, Wijedasa *et al* 2018; Prananto *et al* 2020). Anthropogenic activities have transformed pristine swamp forests mainly through drainage and land-use change, and both have amplified fire severity (Taufik *et al* 2019a). Studies also looked at the human effect on peatland fires and drought (Page *et al* 2002, Field *et al* 2009). Different drainage systems have affected land-use control of peat decomposition during drought periods (Kwon *et al* 2013, Wang *et al* 2015; Prananto *et al*, 2020). However, the hydrological impacts of peat degradation are often overlooked, although these impacts could be even worse.

Canalization causes an accelerating drop in groundwater levels as reported worldwide (Katimon *et al* 2013, Carlson *et al* 2015, Menberu *et al* 2016, Taufik *et al* 2019a), but the decline in groundwater levels varies among land-use types. The impact of the drainage regime on groundwater dynamics remains a research challenge in canalized tropical peatland. An earlier study suggested that soil-hydrological characteristics control water flow in canalized peatland (Taufik *et al* 2019b), which may influence the pattern of groundwater dynamics. Hardly any research has looked at how different drainage systems impact groundwater dynamics in tropical peatlands. The characteristics of hydrological drought largely depend on groundwater dynamics. This type of drought will have compounding effects by increasing the oxidized peat layer leading to escalating carbon emissions (Carlson *et al* 2015) and increasing wildfire events (Konecny *et al* 2016, Taufik *et al* 2017).

Drought is a natural phenomenon, where its severity is driven by climate variability (climate-induced drought). Humans can amplify drought (human-modified drought), through, for example, water abstraction or dams (Van Loon *et al* 2016). Changes in land use will alter hydrology in peatland, with groundwater levels as the most critical variable in peatland hydrology and ecology (Waddington *et al* 2015). Land-use change in Indonesia typically causes a more significant seasonal water deficit. Therefore, more drought events are expected from transforming the pristine swamp forest. Drought in *a* pristine forest is typically categorized as climate-induced drought, which is driven only by climate variability. With increasing population and socio-economic pressures, this paper aims to answer *two* questions*: How do human-induced changes amplify the climate-induced drought, and to what extent do these changes amplify the drought?* Specifically, this paper addresses the hydrological impacts of canalization on drought amplification. Here, amplification is a measure of how much human-modified drought is greater than climate-induced drought.

This study uses field data and a hydrological model to infer drought severity in natural and human-modified peatlands. Baseline conditions were set using simulated *soil water storage and* groundwater levels under pristine peat forest*, which enables us to identify the typically climate-induced drought*. Daily observed groundwater levels for 11 years *(from 1997 to 2007)* from the peat swamp forest in Sebangau (Hirano *et al* 2012) were used to calibrate the Soil Water Atmospheric Plant (SWAP) model (Van Dam *et al* 2008) to represent the reference condition. Using SWAP, we simulated the long-term change in soil water storage, and groundwater levels from 1980 to 2016 in Sebangau Forest. *We further* extended the simulation to other peatland regions in Kalimantan and Sumatra. These regions were chosen due to prevailing wildfires (Tacconi 2016, Taufik *et al* 2017; World Bank 2016), indicating a greater drought risk.

2. Materials and methods

2.1. Study area

Six representative peatland regions were assessed: Kampar Peninsula, Air Hitam, and Air Sugihan in Sumatra, and Sebangau Forest, Upper Kapuas, and Kutai Peatlands in Kalimantan (figure 1). We used eleven datasets of observed groundwater levels to calibrate our model. We used the hydrological model called the Soil Water Atmosphere Plant (SWAP) (Kroes *et al* 2008, Van Dam *et al* 2008) to calibrate and simulate groundwater levels (GWLs) using climate data from 1980 to 2016.

We focused on Sebangau Forest as it was used for the calibration of the model under pristine conditions. The peat thickness in Sebangau has been reported by (Hirano *et al* 2015, 2012) to be between 2–3 m. Thick tree debris, with leaf litter, mostly covered the soil surface in the peat swamp forest. The site became a national park in 2006, which has been maintained relatively intact. Vegetation composition was *dominated by the* Anisophylleaceae family (Tuah *et al* 2003) with a canopy height of over 20 m.

We characterized drought in terms of soil water storage (in mm) and groundwater level (in cm), namely the deviation of storage/groundwater levels from normal conditions at the landscape scale in the most vulnerable peatland ecosystems in Indonesia. Soil water storage and groundwater level are critical state variables in the water balance that are affected by drought, and directly affect plant growth and the environment. Hence, these parameters are frequently used in the assessment of hydrological drought (e.g. Tallaksen and Van Lanen 2004, Van Loon 2015).

2.2. Soil Water Atmosphere Plant (SWAP) model

SWAP is a vertically oriented model to simulate water flow in the vadose zone in interaction with vegetation, groundwater and the surface water system (Van Dam *et al* 2008, Kroes *et al* 2017). The domain of the SWAP model spans the *subsurface column* between the groundwater and the soil surface, on which vegetation can grow, and water ponding may occur. The model numerically solves the Richardson-Richards' equation (equation (1)) to simulate water balance and groundwater levels (Van Dam and Feddes 2000). The model input consists of daily rainfall and potential evapotranspiration estimates (top boundary condition). The model requires initial conditions, soil-hydrological characteristics, vegetation properties, and bottom boundary conditions *(canal-groundwater interaction)*.

The Richardson-Richards' equation for soil water flow can be written as:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}\right) + 1\right] - S \qquad (1)$$

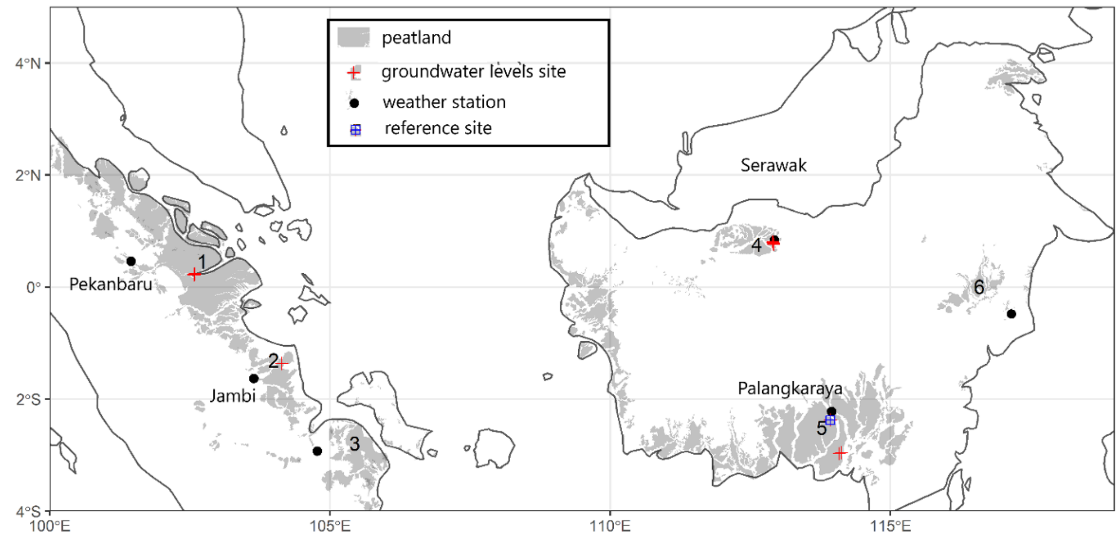

Figure 1. Study sites in the Indonesian peatland on the islands of Sumatra and Borneo. The sites are identified by number in the map: 1. Kampar Peninsula, 2. Air Hitam, 3. Air Sugihan, 4. Upper Kapuas, 5. Sebangau forest, 6. Kutai Peatlands. Locations of groundwater levels monitoring for calibration are indicated by the red plus sign.

where θ denotes soil moisture content (m^3 m^{-3}), t is daily time step (d), z is the elevation (m, positive upwards), and h is pressure head (m). S denotes a sink of the system (d^{-1}), which represents the external losses such as drainage and root water uptake, and $K(\theta)$ is the hydraulic conductivity (m d^{-1}) as a function of water content (θ). The soil moisture and pressure relationship is based on the van Genuchten equation (equation (2)):

$$\theta(h) = \theta_r + \frac{(\theta_r - \theta_r)}{\left[1 + |\alpha h|^n\right]^{1-1/n}} \quad (2)$$

where θ_r and θ_s are the residual and saturated soil moisture content (m^3 m^{-3}), respectively, and α (m^{-1}) and n (−) are shape parameters (Van Genuchten 1980).

As shown in our data and hydrological literature, the variation of phreatic groundwater of peatlands in Indonesia is less than 2 m (Wösten *et al* 2016, Hirano *et al* 2015). This led to using a soil profile of 4 m (figure S1) for modelling, in which the bottom should be well below the deepest simulated groundwater level. The model assumed that the plant roots are evenly distributed up to 100 cm depth. For the bottom boundary condition, we defined canal water levels and drainage resistances. The daily outputs of the SWAP model are time series of soil moisture, groundwater levels, and hydrological fluxes. The drainage fluxes were calculated using the following equation:

$$q_{dr}(t) = \frac{H(t) - CWL}{\gamma} \quad (3)$$

where: q_{dr} is the drainage flux to the surface water system for day t (m/day); H is the groundwater height (m, positive upward) for day t; CWL is the canal water level (m below soil surface) that is dependent on the season, and γ is the constant drainage resistance (unit = days).

q_{gr} (t) and H(t) were sequentially simulated by solving the water flow equation (equation (1)) that considers precipitation as input and actual transpiration and drainage as output. These fluxes are included in the sink term.

2.3. Data source and analysis

2.3.1. Climate and hydrology data

We used daily meteorological data from nearby weather stations (figure 1) for each of the six selected peatland regions for 37 years (1980–2016). We identified six meteorological stations (source: http://dataonline.bmkg.go.id), three in Sumatra (i.e. WMO ID stations 96 109 in Pekanbaru, 96 195 in Jambi, and 96 223 in Palembang), and the other three in Kalimantan (i.e. WMO ID station 96 655 in Palangkaraya, 96 565 in Putussibau, 96 607 in Samarinda). With this meteorological data, we calculated the potential evapotranspiration based on the Penman-Monteith approach (Allen *et al* 1998). As the approach requires a lot of weather variables, in case of missing data, we followed procedures in (Allen *et al* 1998) to fill the time gaps.

In total, eleven datasets of observed groundwater levels (including in Sebangau) from different sites in Indonesian peatlands (figure 1, plus sign) were used to calibrate the SWAP model. The datasets, also including information about land-use types, were collected from numerous literature sources (Suppl. Material table 1). According to the datasets, five existing land-use types were identified including pristine forest (PF, 2 sites), drained forest (DF, 2 sites), restored forest (RF, 2 sites), logged forest (LF, 3 sites), and drained acacia (DA, 2 sites). Soil-hydrological properties for peat soils were obtained from the Indonesian Soil Survey Institute (Pusat Penelitian Tanah 1986) (figure S2(a)). These properties were used as a starting point to adapt soil water retention curves based upon the Van Genuchten equation (equation (2)). *These curves were adjusted in a stepwise manner to eventually fit observed water tables.* figure S2(b) provides the soil water retention curves we used. Taufik *et al* (2019b) described this inverse modelling approach.

2.3.2. Model calibration and performance

At each site, two key drainage parameters of SWAP, namely canal water levels, and drainage resistance, were calibrated. Drainage resistance represents the resistance of the subsurface, which controls how fast groundwater can flow to surface water (such as natural rivers or canals in peatlands). We used a manual calibration approach and expert knowledge based upon field experience to fine-tune the canal water levels and the drainage resistance. The model performance was assessed by three-statistical goodness-of-fit indicators (Bennett *et al* 2013), including the correlation coefficient (r), percent bias (pbias), and index of agreement (d) (Suppl. Material table 2). The correlation coefficient, ranging from -1 to 1, is an indicator of the strength of the linear relationship between the observed and simulated values. If r equals zero, it means that no linear relationship occurs. Percent bias (pbias) measures the average model simulation bias (overestimation or underestimation). Index of agreement (d) explains the degree of model prediction error. The model performance is good if $d > 0.85$ and pbias $\pm 15\%$ (Moriasi *et al* 2015).

2.3.3. Hydrological simulation

We simulated soil water storage changes and groundwater levels for the five land-use types (table 1) in six peatland regions with daily climate data back to 1980 from a nearby meteorological station. Land-use of pristine forest (PF) represents pristine peatlands conditions where drought is solely driven by climate variability (climate-induced drought). Other land-use types are typical of human intervention (human-modified drought). We ran SWAP with several assumptions, including: (i) the soil hydrological parameters were the same as those resulting from calibration, (ii) static mature land-use. The static land-use enabled us to investigate the influence of climate variability on drought. By comparing *soil* water storage changes and groundwater levels from different land-use types, we can identify the effect of land-use change. To help validate the impacts of drainage and land-use types on groundwater levels, an independent sample t-test was performed with the Welch' test (Dag *et al* 2018) using $\alpha = 1\%$.

2.3.4. Drought identification

The hydrological drought was characterized by investigating a time series of simulated hydrological variables using monthly variable threshold levels. Here we identified drought for soil water storage change and groundwater levels. We used the 80th percentile of the duration curve for each variable as the threshold (Taufik *et al* 2017). A drought is identified when the soil water storage or groundwater level is below the threshold for at least two consecutive months. Each pristine peatland has its own thresholds, which correspond to the 80th percentile, to accommodate rainfall differences across the regions. In this study, drought severity is defined as the mean annual deviation of storage/groundwater levels, which is the cumulative daily deviation in storage/groundwater levels from the threshold during drought events divided by the number of years (37 years).

We chose groundwater levels from the pristine forest (PF) in each region as a reference to identify changes in drought severity with other land-use types. For each land-use type, we compared the results against the reference (i.e. PF) to quantify the contribution of human intervention to drought severity. Further, we calculated an area-weighted severity based on the proportion of plantation compared to the pristine forest for each province, where the peatland exists. The land-use proportion was derived from (Miettinen *et al* 2016). All statistical analyses were conducted using R statistical software version 3.6.

3. Results and discussions

3.1. Hydrological model performance in simulating groundwater levels

The hydrological model, SWAP, was able to simulate the dynamics of groundwater levels in Indonesian peatland successfully. The model performance varied across land-uses, and we chose the best five (figure 2) out of the 11 datasets (Suppl. Material table 1) to represent different land-use types. An underestimated high water table was observed in the pristine forest (figure 2(a)), restored forest (figure 2(b)), and logged forest (figure 2(d)), in particular during the wet season. The pbias value indicates this underestimation (-9% to -2.6%). On the other hand, overestimation was observed in the drained forest, especially for the low water table (12.7%). Overall, the SWAP model showed a good performance in simulating groundwater levels as shown by the performance metrics (high correlation value, r, and the index agreement, d). The underestimated ponding for pristine forest is not a major issue as our study focused on the impact of peatland transformation in dry periods.

Table 1. Definition of land-use types used in this study, including two key input parameters for the SWAP model. Namely, typical canal/river water levels (CWL) for different seasons and drainage resistance across land-use types in peatland. Both parameters were fitted through calibration. In drained acacia plantation, the calibration was performed under controlled canal levels, where canal blocking exists as part of water management. For pristine forest, surface water levels relate to rivers, instead of canals.

Land-use type	Code	Definition	Typical seasonal canal/river water levels (cm)*			Drainage
			Wet	Inter-mediate	dry	resistance (day)
Pristine forest	PF	Undrained peat swamp forest	−50	−60	−100	500
Restored forest	RF	an area of peat that has been cleared and canal-ized, then reforested	−50	−80	−110	400
Drained forest	DF	an area of canalized nat-ural peat forest within a plantation	−50	−80	−120	300
Logged drained forest	LF	A canalized peat swamp forest that has been logged	−50	−100	−120	200
Drained acacia	DA	a peat swamp forest that has been cleared, canalized, and has a mature acacia plantation	−70	−100	−130	200

Note: the value represents the minimum levels that could occur. For PF, we used the natural river to represent natural conditions.

Table 2. Groundwater drought characteristics under pristine condition (climate-induced drought) in six peatland regions.

no	Region	Island	Number of events	Average Duration (days)	Severity, i.e. average annual deviation (cm)
1	Kampar Peninsula	Sumatra	10	150	1041
2	Air Hitam	Sumatra	4	216	672
3	Air Sugihan	Sumatra	7	117	675
4	Upper Kapuas	Kalimantan	7	136	984
5	Sebangau Forest	Kalimantan	4	164	621
6	Kutai Peatlands	Kalimantan	5	191	747

3.2. Climate-induced drought

Groundwater drought has long been an important feature of tropical peatland. We combined observations and simulation modelling to examine drought severity under baseline conditions (climate-induced drought) in the six Indonesian peatlands. Our simulation showed that droughts under pristine conditions occurred infrequently in all regions throughout 1980–2016. Events were hardly detected in Air Hitam and Sebangau Forest, with only four hydrological drought events in the 37-year simulation (figure 3, PF), whereas twice as many events were found for Kampar Peninsula. Although few in number and relatively low in severity in terms of annual deviations, droughts in the Air Hitam and Sebangau Forest typically lasted longer than four months (table 2). In contrast, more drought events were monitored for *soil* water storage (7 events), but events were shorter than those of groundwater drought.

3.3. Anthropogenic influence on drought amplification

Drought severity changes markedly, however, mainly when the impact of human activity from canalization is considered (figure 4(b)). To investigate how canalization has amplified drought, we compared drought severity in a restored forest (RF) and drained forest (DF), to pristine forest. Canalization (RF and DF) made groundwater droughts twice as severe (amplification factor of around two) as they would have been under pristine forest conditions. In regions with a strong monsoon, as with Air Sugihan and Kutai, amplification was more than twice, as confirmed by the drought events (figure 3). Drainage in Air Sugihan and Kutai led to three-times more frequent drought. The simulation also showed that peatland restoration could reduce drought amplification by at least 19% (compare DF and RF). Amplification of soil moisture drought (figure 4(b), *soil* water storage) was not as severe as shown for groundwater drought.

As Indonesian peatlands are often used for plantations, our next simulations explored the compounding interference, land-use change, in addition to canalization. This simulation included a logged forest (LF) and a mature drained acacia plantation (DA) in the comparison. The drainage system significantly influenced *soil* water storage and groundwater levels in transformed peatlands. Significant effects were evident, particularly during the dry season ($p < 0.001$). For instance, groundwater levels in *the* logged forest and drained acacia were significantly lower (∼30%) relative to the undisturbed forest

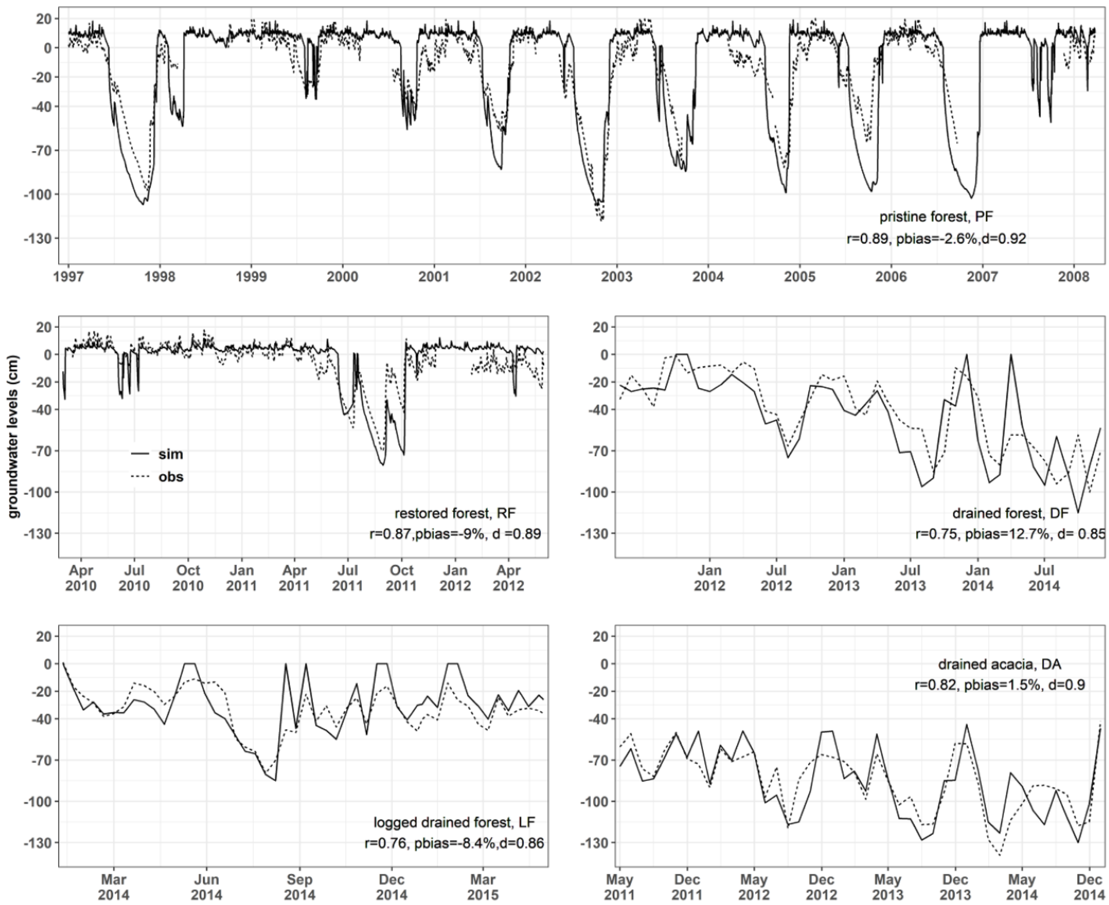

Figure 2. Hydrograph of groundwater levels for five land-use types (different timescales): (a) pristine forest (PF), (b) restored forest (RF), (c) drained forest (DF), (d) logged forest (LF), and (e) drained acacia (DA). The dotted line represents the observed groundwater levels, whereas the solid line is the simulation. In each graph, three statistical metrics are presented namely (i) correlation coefficient, r, (ii) percent of bias, pbias, and (iii) index of agreement, d.

(figure 4(a)). Logging and plantations further amplified drought relative to PF across all peatland regions. In Air Hitam and Kutai Peatlands, logging amplified the groundwater drought severity by more than four times. Amplification further increased when the peatland is converted to acacia plantation (DA) (figure 4(b), DA, groundwater levels). On average, across all regions, drought severity was amplified by 2.5 in logged forests, and 2.8 in acacia plantations for soil moisture drought, and even worse for drought in groundwater (3.6 for LF, and 4.8 for DA). The amplified severity is linearly connected to the increased drought frequency, as shown in LF and DA. The largest amplification (>5 times higher) was observed in the monsoonal climate region, such as in Air Sugihan, Sebangau, and Kutai.

Intensive land-use change has occurred in Sumatra and Kalimantan. Potential impacts of these changes on drought severity were analyzed, which reveals that regional drought severity in Sumatra peatland is three times higher than in Kalimantan (Suppl. Material table 3). This is likely caused by hydrophobic conditions in Sumatra that are more favorable for smoldering peat wildfire (Huang and Rein 2017, Taufik *et al* 2017) and the high occurrence of canalized plantations in Sumatra compared to Kalimantan. This *condition* was reflected in reality, when in 2015, wildfires burnt 10.9% of peatland in Sumatra, compared to 6.3% in Kalimantan (Tacconi 2016; World Bank 2016). Another study report that carbon emissions from plantations in Sumatra were three times higher than those in Kalimantan (12.2 Mt C yr^{-1}) due to peat oxidation (Miettinen *et al* 2017).

3.4. Discussion

The outcome of *our* analyses provides new insights previously not considered on droughts in tropical peatlands. Using climate station data, (Field *et al* 2009) noted an escalated drought-related forest fire in Indonesia due to human activities. Their work mainly focused on a typical meteorological drought, which depends on climate data only, and did not consider the groundwater drought addressed in this study. More recent work, Taufik *et al* 2017) used global climate data to detect amplified fires due to hydrological drought in Borneo, whereas here, local data are used. The influence of drainage on hydrological regimes addressed in our work revealed an *essential* feature of peatland that has been discussed by (Kwon *et al* 2013) in Indonesia and (Wang *et al*

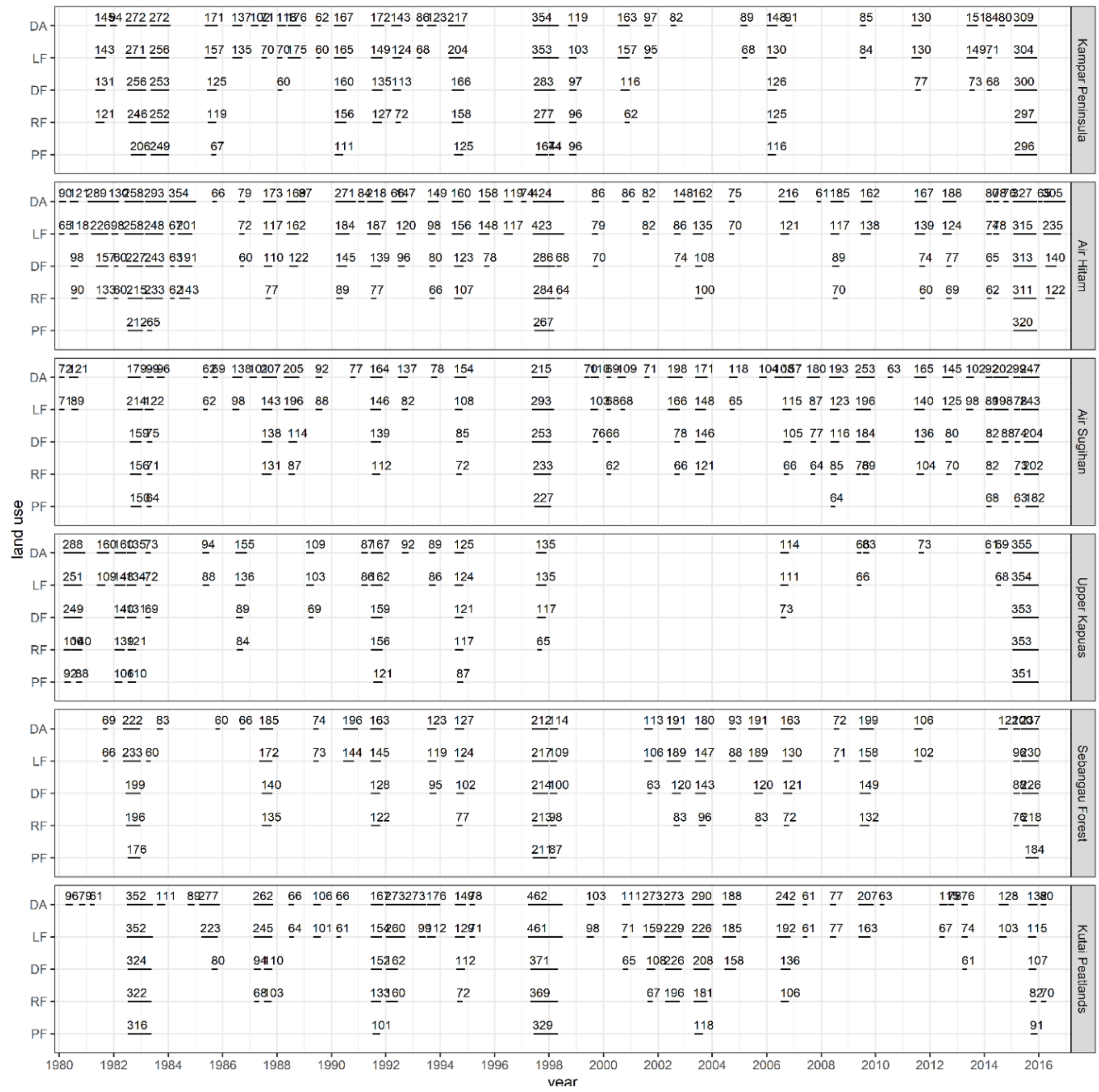

Figure 3. Temporal pattern of drought in groundwater across Indonesian peatland for 1980–2016 assuming no land-use change over time. Starts and ends of the black lines indicate the onset and the termination of drought, with the number above the line gives the duration of drought. A drought has to last at least two consecutive months. Overlapping numbers indicate that events are close to each other. The *y*-axis consecutively lists pristine condition (PF), RF—restored forest; DF—drained forest; LF—logged forest; DA—drained acacia.

Table 3. Frequency of drought (number of events in period 1980–2016) in groundwater across land-use types and peatland regions.

NO	Region	Pristine Forest (PF)	Restored Forest (RF)	Drained Forest (DF)	Logged Forest (LF)	Drained Acacia (DA)
1	Kampar Peninsula	10	13	17	25	31
2	Air Hitam	4	21	27	33	41
3	Air Sugihan	7	20	21	30	40
4	Upper Kapuas	7	9	11	17	21
5	Sebangau Forest	4	13	15	22	25
6	Kutai Peatlands	5	13	16	27	35
	Average	6.2	14.8	17.8	25.7	32.2

2015) in the USA. However, this study focused on drought as part of the hydrological cycle. Studies that addressed the impact of drainage on fires (Konecny *et al* 2016, Taufik *et al* 2019a, 2019b) focused on how the drainage system controls peat ecology, whereas our approach links to the impacts of the drainage system on the hydrological balance among land-use types, the associated drought in *soil* moisture, and groundwater.

There are limitations *to* this study. Firstly, the calibration of the SWAP model was performed under drainage with canal blocking. The deepest CWL was −130 cm during the dry season, but this may be a bit too high. Another study noted

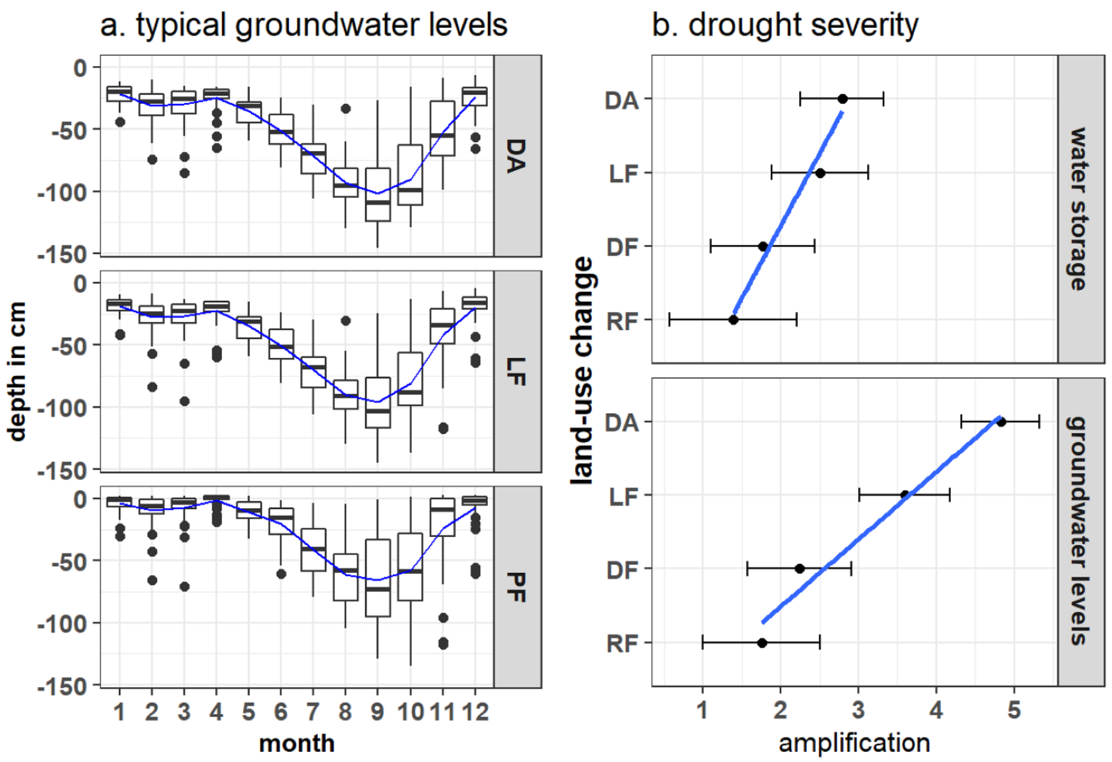

Figure 4. Anthropogenic (land-use change and drainage) influence on hydrological regimes. (a) typical simulated groundwater levels (boxplot) in relation to disturbance from pristine condition (PF) to drained acacia (DA) for period 1980–2016 in Sebangau peatland. A blue line represents monthly average groundwater levels. The boxes indicate the median, and the 25 and 75% quantiles. The whiskers represent 10 and 90% of quantiles. The dots indicate outliers. (b) predicted values of drought amplification (± standard error) in relation to disturbance, with trend lines obtained through linear regression. Two variables; changes in root-zone water storage and groundwater levels, represent drought in the hydrological cycle (soil moisture drought and hydrological drought). Amplification [dimensionless] is calculated relative to the baseline (pristine forest). The numbers on the *x*-axis represent severity amplification. The *y*-axis consecutively lists converted PF categories (RF—restored forest; DF—drained forest; LF—logged forest; DA—drained acacia).

that groundwater levels were somewhat deeper than 130 cm (Takeuchi *et al* 2016). This implies that drought amplification in our study may be exaggerated to some extent under uncontrolled drainage, in particular during an intense El Niño event. Second, we assumed that land-use was stationary under current climate variability to analyse groundwater levels dynamics. The modelling approach used a mature forest that represents potential and ideal growing conditions, whereas vegetation was not always in ideal conditions due to various water and environmental stresses (Allen *et al* 2005, Sun *et al* 2011, Anda *et al* 2015). Data from more sophisticated evapotranspiration methods that would reflect land cover development, including stresses, such as data from flux towers (e.g. Sun *et al* 2011) covering various land-use types may better represent evapotranspiration. Non-stationarity is challenging to address, as the aim of our work is to calculate drought amplification due to anthropogenic influence, in which we need to define pristine condition and the modified ones. However, as the calculation is over similar soil and climate conditions, the response of their physiology to climate variability is almost the same. Third, the length of the model calibration period is rather short (on average, almost 3 years). A short period of groundwater levels data for calibration may disregard the influence of climate extremes on the dynamics of groundwater levels. Long-term monitoring of the water table, particularly in human-modified peatlands will reduce the uncertainty in the calibrated parameters. Lastly, further work is necessary on water retention curve of peatland. In our work, we obtained soil retention data from the Sebangau peatlands. An earlier study noted that peat water retention varies with peat humification degree (Taufik *et al* 2019b).

4. Conclusions and policy recommendation

We discovered that climate-induced drought is infrequently observed in Indonesian peatland during the last four decades. Pristine forest was used as a baseline to quantify drought amplification due to different drainage practices. Our approach using the hydrological model SWAP was based on two key variables, namely the drainage resistance, which is mainly driven by the density of canals, and canal water levels. With drainage through rather deep canals, more water is lost from the fields as the drainage resistance of the peat is significantly reduced. For instance, the drainage resistance of drained acacia (DA) plantation is less than half than *that of pristine forest, which implies that groundwater in DA is more easily transported towards the drainage system than in pristine forest. This leads to lower groundwater levels. The lowering of groundwater levels accelerates the drying of root zone layers, which intensifies soil moisture drought. Prolonged dry spells under drained conditions accelerate groundwater drawdown, which leads to more groundwater drought events. Our findings revealed that the amplification of groundwater drought (in groundwater levels) is at least twice that in pristine forest. In addition, more drought events are expected due to the peatland transformation. Drought frequency during the last decade in transformed peatland is at least three times that in pristine conditions (*figure 3).

The potential impacts of the land use change in Sumatra and Kalimantan on future drought severity revealed that regional drought severity in Sumatra peatland is three times higher than in Kalimantan likely because less canalized plantations occur in the latter.

Degradation of Indonesian peatlands will continue to have significant climate and social impacts in Southeast Asia. Its impact on hydrological drought (soil moisture and groundwater) can now be disclosed. Canalization and associated land-use change caused a series of compounding effects. Canalization doubled drought severity; logging and starting plantations quadrupled drought severity. Plantations on peatland are an essential part of the local economy; however, sustained exploitation will only make impacts worse (Abood *et al* 2015, Hohner and Dreschel 2015, Turner and Mcclenachan 2018). In 2016, the Indonesian Government established Badan Restorasi Gambut (the peat restoration agency), with a goal to restore 20 000 square kilometers of peatland by 2020. This initiative, coupled with regulations to maintain high water tables (minimum −40 cm depth, based on the Presidential Decree No. 71/2014), is a good start. If we are to stop peatlands releasing carbon into the atmosphere, and to maintain peat quality for use in plantations, more is needed. We need contemporary water management practices that can rehabilitate the peatland hydrological function, prevent floods during extreme precipitation, and avert prolonged droughts. Shallow subsurface drainage, possibly in combination with controlled canal levees, for example, can remove excess surface water and allow peat to be used for plantations, without dropping groundwater levels through canalization.

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Conflict of interests

The authors declare no competing interests.

Data availability statement

- The data that support the findings of this study are available from the corresponding author upon reasonable request.
- Climate data from six weather stations are available online (http://dataonline.bmkg.go.id).

Author contributions

MT, BM, and HVL conceived and implemented the research. MT performed the data analysis and generated all figures. MT and BM wrote the initial version of the manuscript. All authors contributed to interpreting the results, discussions and associated improvement of this manuscript.

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