Water-table responses to storms in forested, drained and ditch-blocked tropical peatlands, Sebangau, Kalimantan, Indonesia

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SUMMARY

The effects of hydrological restoration, usually using ditch dams, on water-table responses to storms in drained tropical peatlands are poorly understood. We collected hourly rainfall and water-level data during the dry and wet seasons (August 2019 to January 2020) at a forested peatland (Forested), a drained peatland with ditch dams (Blocked), and a drained peatland without ditch dams (Drained) in Sebangau National Park, Indonesia. Hydraulic conductivity of the surface peat and bulk density of the peat profiles were also measured. The two main components of a Principal Component Analysis (PCA) could explain 62 % to 68 % of the variation of water-table responses to storms at the study sites. The responses were related to the initial water table, the depth and the duration of the storm, and the position within a site with respect to ditches. In Forested, the mean of the post-storm water-level drawdown speed (DSpeed) was 0.039 cm hour^{-1} (SD = 0.024 cm hour^{-1}) when the water table was deeper than 50 cm below the surface but 0.047 cm hour^{-1} (SD = 0.039 cm hour^{-1}) when within the upper 50 cm. In Drained/Blocked, DSpeed varied greatly with depth, distance to ditches, and distance to the main outlet of ditches. Ditch dams alone may not recover the water-table responses to storms in drained tropical peatlands when compared to more intact forested systems.

KEY WORDS: bulk density, climate, drainage, El Niño, hydraulic conductivity, hydrology, rainfall, restoration, wetland

INTRODUCTION

Tropical peatlands cover ~ 1 million km^2 of land (Xu *et al.* 2018, Ruwaimana *et al.* 2020), storing an estimated 102.24 Pg of carbon (Dargie *et al.* 2017, Miettinen *et al.* 2017, Honorio Coronado *et al.* 2021) or around 19 % of the global peatland carbon store (528 Pg of carbon) (Yu *et al.* 2010, Hodgkins *et al.* 2018). They are also important for biodiversity and a range of ecosystem services (Husson *et al.* 2018, Schulz *et al.* 2019, Wijedasa *et al.* 2020). Many tropical peatlands are dome-shaped, ombrotrophic and bounded by open water bodies. Examples include the Sebangau peat dome in Indonesia (Berninger & Siegert 2020) as well as domes in the Cuvette Centrale of the Congo Basin (Davenport *et al.* 2020), Changuinola in the Province of Bocas del Toro, Panamá (Phillips *et al.* 1997) and Pastaza-Marañón, Peru (Roucoux *et al.* 2017). These domes range from 2 km to 20 km in width (Dommain *et al.* 2014, Ishii *et al.* 2016, Dargie *et al.* 2017, Kelly *et al.* 2020), with peat depths typically between 2 m and 12 m at the midpoint of the dome (Page *et al.* 2004, Warren *et al.* 2012, Lähteenoja *et al.* 2013, Hapsari *et al.* 2017). The development of a peat dome has a limit that is related to not only physical but also biochemical factors of the system (Anderson & Muller 1975, Winston 1994, Patterson & Anderson 2000, Anderson & Peace 2017).

Many tropical peatlands have been drained with canals and ditches to lower the water table (Dadap *et al.* 2021, Lilleskov *et al.* 2019). Deepening of water tables makes drained peatlands more prone to fire and ecological degradation (Dohong *et al.* 2017, Putra *et al.* 2018, Agus *et al.* 2020). Some governments have committed to undertake topical peatland restoration and signed the "Brazzaville Declaration", as addressed by representatives of Democratic Republic of the Congo, Republic of the Congo, Republic of Peru and Republic of Indonesia during the Third Partners Meeting of the Global Peatlands Initiative, 21–23 March 2018 (Desai 2017, International Climate Initiative 2021). International Climate Initiative (2021) noted that the commitment to preserve peat carbon should be one of the main drivers behind government investments in peatland restoration. The restoration measures, such as installation of ditch dams, are used to hold water on site by lowering hydraulic gradients (Ritzema *et al.* 2014, Kasih *et al.* 2016, Putra *et al.* 2021).

While several studies have examined tropical peatland water tables (e.g., Wösten *et al.* 2006a, Wösten *et al.* 2006b, Mezbahuddin *et al.* 2015, Cobb *et al.* 2017, Marwanto *et al.* 2018, Cobb & Harvey 2019, Sutikno *et al.* 2019, Deshmukh *et al.* 2021, Putra *et al.* 2021), as far as we are aware there have been no studies examining the effect of different storm variables, such as duration and intensity, on water-table dynamics in tropical peatlands. Such information may help practitioners understand more fully (than just simple seasonal measures of water-table depth) whether ditch blocking promotes restoration of the hydrological functioning of peatlands. Understanding how peatland water tables respond to rainfall events, and the controls on these responses, can also be important for testing and improving models of peatland hydrology, some of which currently do not directly incorporate the contribution of rainfall, at sub-daily scales, to water-table fluctuations. Such models include DigiBog_Hydro used by Putra *et al.* (2022) and the model presented by Urzainki *et al.* (2020). Additionally, such an understanding may aid predictions on how tropical peatlands will respond to different intensities and durations of rainfall under future climate change (Li *et al.* 2007, IPCC 2021).

In temperate peatlands the responses of water tables to rainfall events have been found to differ between intact and restored systems, suggesting there is, at least, a very long lag time before the hydrological function recovers (Holden *et al.* 2011, Williamson *et al.* 2017, Kreyling *et al.* 2021). It is therefore hypothesised that the responses of water tables to storms will be different between intact, drained and ditch-dammed tropical peatlands.

This article examines the responses of water tables to storms in the Sebangau tropical peatland, Indonesia, considering the variation of restoration condition among sites (undrained forest, drained and ditch-dammed systems). The main research questions are:

1. What storm variables significantly influence the water-table dynamics in tropical peatlands with different management conditions?
2. How do ditches and ditch dams alter the response of water tables to storms in tropical peatlands?
3. How does the variation in peat properties contribute to the differences in the response of water tables to storms in tropical peatlands?

METHODS

Study sites

We studied three peatland sites in Sebangau, Kalimantan, Indonesia. These were a drained peatland with open ditches (Drained), a peatland where the ditches had dams installed (Blocked), and a relatively intact forested peatland (Forested) (see Putra *et al.* 2021). The monitoring period of this study was between 22 August 2019 and 17 January 2020, covering water-table variations during the late dry and early wet seasons.

The layout of the study sites is presented in Figure 1. The Drained and Blocked sites had been deforested. The ditches in Drained and Blocked were 1.5–2 m deep and 2–4 m wide. There were four ditch dams, constructed in Blocked between 2016 and 2018, still in operation during the study. The Forested site was a relatively intact forested system and it remained intact throughout the monitoring period. Other than that, a single narrow 60 cm deep (but dammed) trench was present in Forested, formed by logs being dragged off the site during former forestry operations in the 1990s, labelled 'Main ditch 1' in Figure 1.

In Drained and Blocked (see Figure 2), the main vegetation cover consisted of *Shorea balangeran*, *Dyera costulata* and *Combretocarpus rotundatus* (Blackham *et al.* 2014, Cattau *et al.* 2015, Husson *et al.* 2018). Some of the vegetation had been replanted gradually as part of restoration efforts since 2003 (based on discussions with local forest rangers). There were more tree saplings in Drained than in Blocked during the study period. The land cover of the driest zones in Drained and Blocked, which had limited water during the dry season, was dominated by ferns (*Polypodiopsida*). Sedge (*Lepironia articulata*) occupied wet zones in both Drained and Blocked. Forested was between a mixed swamp and a low pole densely forested area (see Figure 2), typically populated with *Campnosperma* sp. and *Shorea* sp. (Husson *et al.* 2018, Page *et al.* 1999). In Forested, mature trees were generally 15–25 m tall but there were also plenty of younger trees (5–10 m tall) growing quickly to fill any canopy gaps that emerged.

Putra *et al*. (2021) found that during the end of the dry season (in 2019), water tables at the study sites were deeper than 40 cm from the peat surface and the ditches were dry. It was also found that, in the wet season, water flowed from the peatland to ditches in Drained and Blocked. In Drained, in the wet season, patchy inundation (shallow ponding between 1 and 5 cm) was observed in areas farthest from ditches. In Blocked, in the wet season, large areas around ditches had surface water to depths up to 23 cm. In Forested, for a short period of the wet season (02 January 2020 to 15 January 2020), some shallow inundation (< 10 cm) was noted, especially in microtopographic depressions, while the water-table depths at monitoring wells ranged between 9 and 18 cm.

A topographical survey was conducted to provide absolute water-level profiles across the study sites. The height measurements were undertaken using levelling instruments, implementing a closed traverse section approach. Fibreglass composite rod penetration tests at levelling points (intervals were between 12 and 64 m) across the study sites, supported by peat boring tests at some wells (14 points) and some surface hydraulic conductivity (*K*) test locations (16 points), indicated that the thickness of the peat was at least 2 m throughout. Jaenicke *et al*. (2008) and Page *et al*. (2004) suggested that the

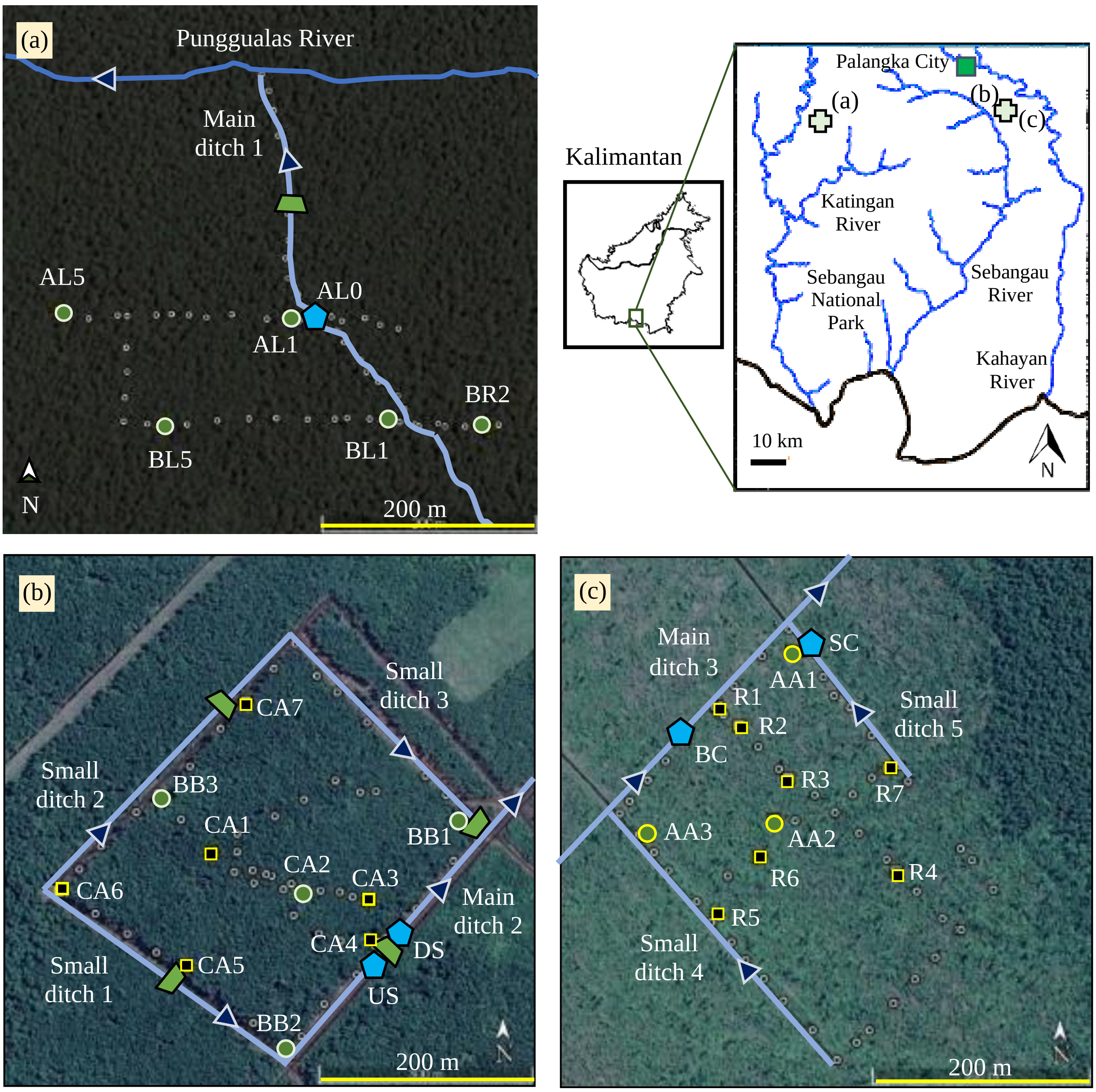

Figure 1. Schematic overview of the study sites, which were Forested (a), Blocked (b) and Drained (c). In the top right map the green square shows the location of Palangka City, and the plus signs are the study site locations. In (a) to (c), larger circles symbolise logger wells, smaller circles are levelling points, squares are testing points, blue pentagons are ditch loggers, and trapezoids are dams. The dark blue continuous line represents a river and the light blue lines are ditches. The main flow directions are shown by arrows. Peat cores were taken at AA1, AA2, AA3, BB1, BB2, BB3, AL0, AL1 and AL5. Surface hydraulic conductivity tests (*K*) in Drained and Blocked were conducted at all logger wells, all points with label CA, and all points with label R. Surface *K* tests in Forested were conducted at Wells AL1 and AL5 only.

mean peat thickness at the Sebangau peat dome was 5.40 m ± 1.08 m but that thickness was up to 9.8 m in some spots.

For the PCA analyses of data collected in Drained and Blocked, the absolute water levels for wells were calculated based on local benchmarks (note that these benchmarks were different from those presented by Putra *et al*. (2021)). The benchmarks were the surface elevations of Well AA2 in Drained and Well BB2 in Blocked (Figure 1), which were the wells with the highest water level at each site in this analysis. The benchmark for Forested was beside Well AL0 (2.3894 °S, 113.4524 °E), as in Putra *et al*. (2021). The elevations of these benchmarks were set at 0 cm.

Rainfall and water-level data

Rainfall data were obtained from two automatic gauges. A Davis Vantage Pro2 raingauge was installed at Tumbang Nusa Camp (2.3556 °S, 114.0896 °E), which was 2.7 km from Drained and 3.5 km from Blocked; and a Qingdao Tlead AW003 raingauge was located at Punggualas Camp

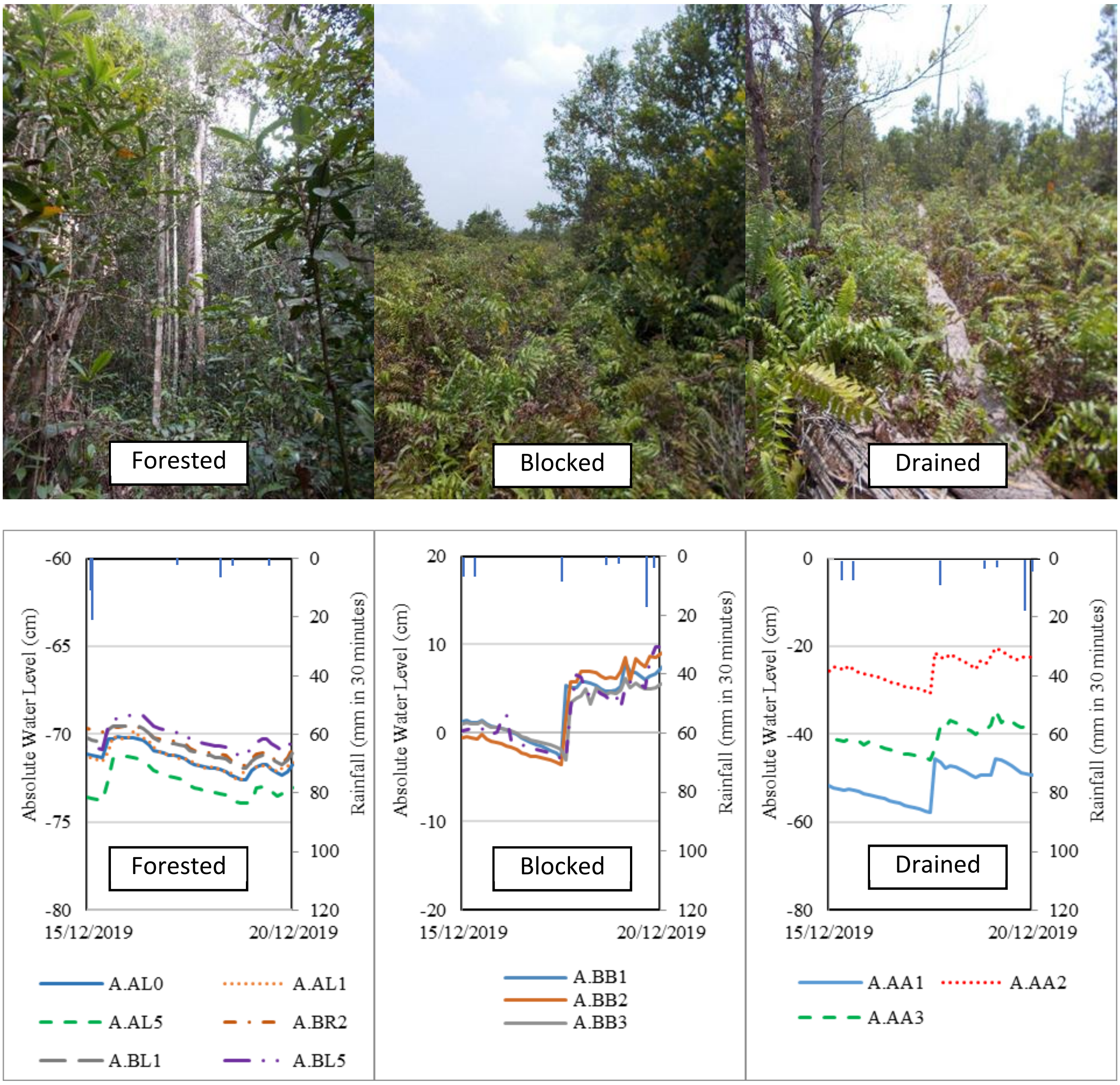

Figure 2. Above: general views across the study sites Forested (08 November 2019), Blocked (18 October 2019) and Drained (03 December 2019). Below: example water-level time series for the period 15–20 December 2019. The water-level time series have different vertical (absolute water-level) scales, based on the benchmarks of Putra *et al*. (2021). Lines represent automatic logger data and blue bars on the secondary vertical axis are rainfall data.

(2.3865 °S, 113.4453 °E), 0.8 km from Forested. The distance between the two raingauges was ~70 km Rainfall data were collected at 30-minute intervals. Water-level data were collected at 180-minute intervals from automatically-logged monitoring wells, of which 13 were in the peat at various distances from the ditches and four were in the ditches themselves (Figure 1). The water-table loggers (In-situ Level TROLL 500) were vented, but the ditch water-level loggers (Schlumberger Diver) were non-vented and accompanied by a barometric pressure logger installed above the ground. The monitoring wells were lined with perforated plastic tubing that was 6.4 cm in diameter and 200 cm deep. The 2 m long groundwater pipes (monitoring wells) were not anchored to the substrate underlying the peat. The top of the tubing was 50 cm above the ground surface, allowing access to the well during periods when the peatland was inundated.

Some visual examples of rainfall and water-level time series data are presented in Figure 2. Storm events were identified from the rainfall data. A rainfall event was defined as a series of 30-minute rainfall values separated by periods of zero rainfall at the beginning and end of the event. If there were two or more rainfall events within 24 hours, these were considered as a single storm event. If there was a single rainfall event (no other rainfall event within 24 hours before and after) followed by any increase of water table at any well (within 24 hours after the rainfall event), that single rainfall event was considered as a storm event. If the water table at any well continuously decreased for 24 hours after the single rainfall event, the single rainfall event was discarded. The number of storms included in a principal components analysis (see below, subsection ‘Storm-event data analysis’) was different for each well, as a storm did not always result in a rise in water table at all wells. In total, for the whole monitoring period, there were 87 identified storm events in Drained, 142 in Blocked, and 151 in Forested. The storm variables listed in Table 1 were then extracted for each identified storm event.

The water-level recession patterns during the periods without rain were extracted from the records from the automatically logged wells (13 wells) and from the ditches (at the Main ditch 3 monitoring point (BC) in Drained and downstream of the main-dam monitoring point (DS) in Blocked, see Figure 1). Water-level drawdown was calculated by subtracting water level at time j from the water level at time i during the recession period, where time j equals time i plus 3 hours. Water-level drawdown speed (DSpeed) was calculated by dividing the water-level drawdown value by 3 hours. The hydraulic head difference (HHead) was calculated by subtracting the water level at the ditch (at point BC in Drained and DS in Blocked) from the peatland water level. A negative HHead value indicates that the ditch water level was higher than the peatland water level at that specific time.

Storm-event data analysis

The storm variables listed in Table 1 were included in a principal component analysis (PCA) (Westra *et al.* 2007, Jolliffe & Cadima 2016, Maity 2018, Lai & Kuok 2019), to identify the main controls on the overall variation of the water table in response to storms. The PCA was also used to establish whether the set of variables which were significantly correlated to the top two principal components were different for each land management condition.

For each analysis, a matrix with individual storms on the x-axis and the eleven storm variables on the y-axis was processed using the R package FactoMineR (Lê *et al.* 2008), following the protocol of Kassambara (2017). The PCA was conducted to examine the responses of water tables to storms in all three peatland sites (Drained, Blocked and Forested), for two water-table categories (shallow: water table within 50 cm of the surface; and deep: water table more than 50 cm below the surface). If the water-table rise crossed the 50-cm level, and if the rise above the 50-cm level was larger than the rise below, that water-table rise was included in the shallow category. The PCAs were conducted for individual wells to examine spatial variations in the response of water tables to storms but only included the shallow water-table category, because the number of storms recorded in the deep water-table category was less than fifteen at each well. Rainfall rates greater than 7 mm hour^{-1} in Drained and Blocked were associated with surface inundation during shallow water-table conditions and were not included in the analysis.

Dry bulk density and hydraulic conductivity

In order to support the interpretation of the PCA results, three peat cores were extracted from each site (Figure 1) and sampled for dry bulk density and organic matter content. The sample locations were chosen to capture the spatial variability of peat properties with reference to the layout of the ditches. The cores were extracted in 50 cm sections, up to 200 cm deep, using a Russian peat sampler (Eijkelkamp Soil and Water 2020) of 52 mm internal diameter. The cores were stored in PVC casings, wrapped with cling film, and transported to the soil laboratory at the University of Palangka Raya. The samples were then cut into 2 cm lengths for the dry bulk density determination, although longer samples up to 10 cm in length were used if the peat was too fibric (poorly decomposed). The bulk density samples were dried at 105 °C for at least 24 hours (Chambers *et al.* 2011). Organic matter content was determined for samples of 2 cm length taken at upper depths of 2 cm, 23 cm, 46 cm, 96 cm, 146 cm and 196 cm from the top of each peat core. However, the samples at 23 cm depth for BB3 (Figure 1), at 146 cm for AL1 and at 2 cm for AL5 were not tested for organic matter because they were too fibric. The samples were heated in the soil furnace at 850–900 °C (Hoogsteen *et al.* 2015) to remove organics (for at least 5 hours) and later weighed at room temperature (25 °C).

Minidisk tension infiltrometers of 4.4 cm diameter (Meter Group 2020) were used to measure saturated hydraulic conductivity at, and close to, the peatland surface. The infiltrometer tests were conducted at the peat surface in the Drained (ten locations), Blocked (eleven locations) and Forested (Points AL1 and AL5 only) sites (see Figure 1). Six ‘sub-surface’ tests, at 20 cm below the original surface, were conducted at Points CA1, CA2, CA3, CA4, R2 and R3. The top peat was carefully removed to undertake the sampling with minimal disturbance of the peat at 20 cm below the surface. At least two pressure head states were required to calculate near-saturated hydraulic conductivity values using the technique outlined by Reynolds & Elrick (1991) and Baird (1997); pressure heads of 0 cm and -1 cm were used in this study.

Table 1. Hydrological variables extracted from the storm profiles.

Variables	Units	Description
Storm variables		
Initial-vars		Variables that are related to conditions before the water table started to rise
• rR	mm	Storm rainfall before rise (storm rainfall sum before first water-level rise)
• dLS	hour	Duration from the last rainfall event to first rainfall in this storm
• dSR	hour	Duration from first rainfall to first rise in water level
• dP2	hour	Duration from first rainfall to peak rainfall
Rising-vars		Variables that were related to conditions between the start of rise and the water-table peak
• dSP	hour	Duration from first rainfall to peak water level
• dPP	hour	Duration from peak rainfall to peak water level
• dRP	hour	Duration from first rise in water level to peak water level
Peak-vars		Variables that were related to peak rainfall conditions
• 30MP	mm hour^{-1}	Peak rainfall intensity in 30 minutes interval
• 1HP	mm hour^{-1}	Peak rainfall intensity in hourly interval
• pR	mm	Storm rainfall before peak (storm rainfall sum before peak water level was reached)
Unique variable		Variable that cannot be grouped with others
• sRI	mm hour^{-1}	Storm rainfall intensity (total storm rainfall depth divided by storm duration)
Recession variables		
• DSpeed	cm hour^{-1}	Result of (water level at time j minus at time i) divided by (time j minus time i), where $j > i$
• HHead	cm	Result of subtracting (water level at the lowest ditch) from (water level at well) for time i

RESULTS

Overall, water levels in the peatlands had different responses to storms, depending on the initial water-table condition, the depth-duration patterns of the storm, and the position with respect to ditches. The timing and magnitude of water-table increase in response to storm events were unique for each monitoring well. Table 2 shows the mean values of the storm variables for each monitoring well during the shallow water-table condition.

During the shallow water-table condition, the Storm rainfall intensity (sRI), Storm rainfall before rise (rR), Duration from peak rainfall to peak water level (dPP), and Duration from first rise in water level to peak water level (dRP) in Forested appeared to be almost 2–3 times those in Drained and Blocked. In Forested, the Storm rainfall before peak (pR) was around twice the Storm rainfall before rise (rR), but in Drained and Blocked, the pR data were mostly 5–8 times the rR data.

Generally, a rainfall event with a higher intensity was required for it to be associated with a rise of water table in Forested than in Drained and Blocked. A rainfall event with a low intensity (below the mean storm rainfall intensity in Table 2) tended not to result in a water-table rise in Forested. These conditions could be caused by different of interception rates between Forested and Drained/Blocked, which will be discussed more in the 'Storm variables that are influential to water-table variations' subsection.

Storm controls on water-table response between sites

Figure 3 shows the contribution of each storm variable to Principal Components 1 and 2 (PC1 and PC2). The responses to storms varied between the sites, and the responses when the water table was deep differed from the responses when the water table was shallow (Figure 3). For the site and season (shallow/deep water table) categories, PC1 and PC2 represented the variation in the responses to storms by between 62 % (Drained-deep) and 68 % (Forested-shallow). In terms of the contributions of individual variables to PC1 and PC2, the eleven storm variables can be placed in three groups plus a further individual variable (each variable had a unique response for each category of the analysis, see Figure 3). The groups are Initial-vars, Rising-vars and Peak-vars, whereas the ungrouped variable is sRI (Storm rainfall intensity) (see Table 1). In general, Rising-vars and Peak-vars were important and gave substantial contributions to PC1 and PC2, while Initial-vars did not. Storm rainfall intensity was important and provided substantial contributions to PC1 and PC2 for Forested-deep, Blocked-shallow, and Drained-shallow, but not for other categories.

The vector directions for the storm variables varied among categories of analysis. The vectors that contributed positively to both PC1 and PC2 are presented with a darker colour in Figure 3 (see the blue scale bar). For Forested-deep, Peak-vars and Storm rainfall intensity contributed positively to both PC1 and PC2 but Rising-vars contributed positively to PC1 only. The responses in Drained were different from those in Forested and Blocked because no storm variables contributed positively to PC1 except for dSR (the duration from first rainfall to first water-level rise), which contributed only 3 % of the variance. In Drained-deep, Rising-vars contributed strongly to PC1 and Peak-vars to PC2, but in Drained-shallow, the reverse was the case.

Storm controls on water-table response between wells

The responses of water tables to storms varied spatially within sites. Table 3 shows the contribution of each storm variable to PC1 and PC2 at each well during shallow water-table conditions. The variances of the response to storms at individual wells accounted for by PC1 and PC2 were between 64.1 % (at AA3) and 73.9 % (at AL1). For wells in Drained, during the shallow water-table condition, the storm variables with the largest contribution were generally the Rising-vars, showing the dominant effect of storm duration over storm intensity. The Peak-vars provided the largest contribution to the water-table variations at wells in Blocked during shallow water-table conditions, suggesting that storm intensity contributed more than storm duration. Initial-vars did not provide substantial contributions to water-table variations at any site.

In Drained, the contributions of storm variables to the variation in PC1 and PC2 at wells near to ditches (AA1 and AA3) were different from those at the more distant well AA2 (Table 3). The duration from first rainfall to peak water level (dSP) provided the largest contribution to variance in PC1 and PC2 at AA1 and AA3, while the duration from first rise in water level to peak water level (dRP) provided the greatest contribution at AA2. In Blocked, the contributions of storm variables to the variation of the water table at the well close to the main ditch outlet (BB1) were different from those at more distant wells (CA2 and BB3). Although all of the wells in Blocked contributed strongly to water-table response from Storm rainfall before peak (pR), CA2 and BB3 had low contributions from Initial-vars and high contributions from Storm rainfall intensity. In Forested, storm response at all wells had strong

Table 2. Mean values of storm variables for each monitoring well during shallow water-table conditions. Standard deviations are in square brackets. The variable codes are as given in Table 1. Column ns contains the number of storms included in the PCA.

Well	Location	ns	sRI (mm hour^{-1})	30MP (mm hour^{-1})	1HP (mm hour^{-1})	rR (mm)	pR (mm)	dLS (hour)	dSR (hour)	dSP (hour)	dPP (hour)	dRP (hour)	dP2 (hour)
AA1	Drained	15	3.8[2.9]	14.3[11.1]	19.2[16.9]	4.9[8.5]	34.9[28.9]	23.0[14.1]	2.0[2.8]	11.0[6.1]	9.4[5.8]	9.0[5.9]	1.6[1.9]
AA2	Drained	15	2.9[2.3]	9.5[6.7]	12.5[9.5]	1.1[2.2]	22.3[18.3]	22.1[14.7]	1.2[2.1]	7.4[3.4]	5.6[3.6]	6.2[3.5]	1.8[2.0]
AA3	Drained	19	3.4[2.8]	12.0[10.9]	15.9[16.4]	3.7[6.8]	27.3[27.4]	20.9[13.5]	3.2[7.4]	11.7[8.1]	10.2[8.5]	8.5[6.2]	1.4[1.8]
BB1	Blocked	17	3.4[2.9]	10.3[9.1]	14.8[15.9]	3.3[7.2]	27.0[28.3]	21.5[14.2]	1.2[2.1]	11.1[8.6]	9.6[8.9]	9.9[9.0]	1.5[1.8]
BB2	Blocked	23	3.1[2.7]	10.3[10.6]	13.8[15.6]	3.2[7.5]	24.9[26.5]	20.1[13.6]	1.3[2.8]	9.3[4.5]	7.8[4.5]	8.0[4.8]	1.5[1.8]
BB3	Blocked	20	3.2[2.7]	11.2[10.9]	15.0[16.2]	5.0[8.4]	28.8[27.9]	21.9[13.5]	2.6[5.2]	15.3[9.4]	14.1[9.2]	12.8[8.7]	1.2[1.4]
CA2	Blocked	22	2.8[2.7]	8.4[8.9]	11.9[15.1]	3.4[7.5]	21.0[26.8]	20.2[12.8]	1.2[1.7]	10.1[8.0]	9.1[7.8]	8.9[7.0]	1.0[1.3]
AL0	Forested	19	8.7[12.5]	11.7[11.0]	15.6[16.4]	10.7[20.4]	25.0[23.6]	39.7[28.8]	1.6[2.0]	27.9[14.9]	26.2[14.4]	26.4[14.6]	1.7[2.0]
AL1	Forested	20	9.2[12.5]	10.9[11.1]	14.6[16.5]	11.4[22.2]	23.6[24.3]	41.6[27.3]	1.4[2.0]	23.0[17.2]	21.4[16.5]	21.6[16.4]	1.5[2.0]
AL5	Forested	17	9.5[13.0]	12.3[11.5]	16.6[17.1]	5.1[10.5]	27.3[25.1]	43.6[28.6]	1.2[2.1]	28.1[14.5]	26.3[13.8]	26.8[14.5]	1.8[2.0]
BL1	Forested	23	8.5[11.5]	10.6[10.4]	14.0[15.4]	9.1[18.7]	21.6[22.6]	37.9[27.4]	1.7[1.9]	21.1[12.7]	19.7[12.4]	19.4[12.1]	1.4[1.9]
BL5	Forested	23	8.5[11.5]	10.6[10.4]	14.0[15.4]	9.0[18.7]	21.4[22.7]	37.6[27.7]	1.7[2.1]	24.4[16.9]	22.9[16.4]	22.7[16.1]	1.4[1.9]
BR2	Forested	22	8.7[11.7]	11.0[10.4]	14.5[15.5]	10.0[19.0]	22.5[22.7]	37.2[27.8]	1.9[2.1]	13.4[30.7]	18.0[11.1]	17.6[10.6]	1.5[1.9]

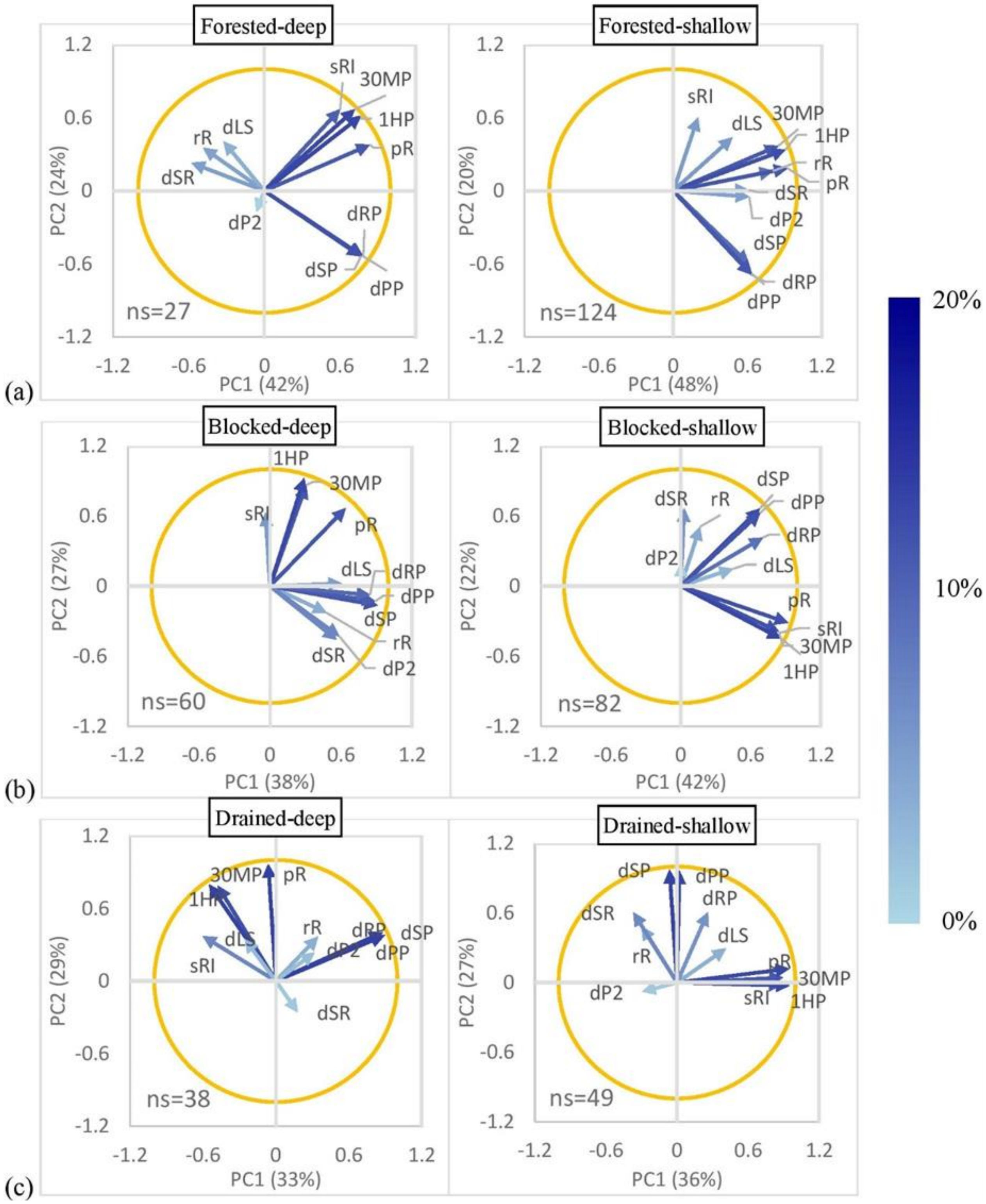

Figure 3. Principal Components 1 and 2 (PC1 and PC2) with the distribution of each hydrological variable for the three sites. The variable codes are provided in Table 1. The left-hand panels show the variations under deep water-table conditions (deep/dry period), while the right-hand panels show the shallower water-table conditions (shallow/wet period). The percentage attributed to the axes indicates the variance that is represented by the PC. The arrows show the direction and the quality of representation for each variable to PC1 and PC2 within the maximum quality radius of 1 (yellow circle). The colour of the arrows shows the contribution of each variable to PC1 and PC2, in which the shaded bar indicates the percentage of the contributions. The number of storms (ns) used in the analysis for each location is stated.

contributions to PC1 and PC2 from Rising-vars and Peak-vars, and low contributions from Initial-vars and Storm rainfall intensity. Only BR2 had water-table responses that were not strongly affected by Rising-vars.

Water-table drawdown

Figure 4 shows the distribution of standardised water-level drawdown speed (DSpeed) and hydraulic head difference (HHead) in the study sites. In brief, there were different patterns of water-table drawdown between seasons and between wells in the study sites. In periods without rain, the water tables decreased as a result of the on-site differences in hydraulic head, the high permeability of peat (Baird *et al.* 2017, Kurnianto *et al.* 2019) and the evapotranspirative demand (potential evapotranspiration data were presented by Putra *et al*. (2021)). Our results show that the distribution of water-level drawdown speed (DSpeed) and hydraulic head difference (HHead) varied with depth and depended on site conditions (Figure 4).

In Forested, drawdown speed varied slightly with depth, with deep peat having a lower variability of drawdown speed values than shallow peat. The variation of drawdown speed values was similar among wells. The mean drawdown speed values for deep peat were 0.038 (SD = 0.020) cm hour^{-1} at AL0, 0.039 (SD = 0.024) cm hour^{-1} at AL1, and 0.039 (SD = 0.026) cm hour^{-1} at AL5; while for shallow peat they were 0.045 (SD = 0.032) cm hour^{-1} at AL0, 0.047 (SD = 0.039) cm hour^{-1} at AL1, and 0.048 (SD = 0.057) cm hour^{-1} at AL5. In Forested, hydraulic head difference data were not calculated because water-level differences among wells were relatively small (less than 10 cm).

In Blocked, water-level drawdown speed (Dspeed) differed with depth and with distance to the main ditch outlet. Drawdown speed values for deeper peat were more variable than in Forested and Drained (Figure 4). Also, drawdown speed values at the well farthest from the main ditch outlet (CA2) were more variable (larger SD) than at the nearest well (BB1). The mean drawdown speed values for deep peat were 0.061 (SD = 0.037) cm hour^{-1} at well B1, 0.050 (SD = 0.035) cm hour^{-1} at BB2, and 0.065 (SD = 0.067) cm hour^{-1} at CA2; while for shallow peat they were 0.109 (SD = 0.085) cm hour^{-1} at BB1, 0.107 (SD = 0.125) cm hour^{-1} at BB2, and 0.087 (SD = 0.070) cm hour^{-1} at CA2.

Table 3. The contributions of storm variables to Principal Components 1 and 2 (PC1 and PC2) at individual wells, during the shallow water-table conditions. The codes are explained in Table 1. Column ns contains the number of storms considered. Column sum.pov contains the variances of the response to storms that are represented by PC1 and PC2. For each well, storm variables with the largest contributions are indicated by †.

Well	Location	ns	sum.pov (%)	Contribution to PC1 and PC2 (%)										
				------Initial-vars------					-----Rising-vars-----			------Peak-vars------		
				sRI	rR	dLS	dSR	dP2	dSP	dPP	dRP	30MP	1HP	pR
AA1	Drained	15	64.3	10.4	3.0	2.2	7.1	2.4	13.7†	12.9	11.3	11.4	12.8	13.0
AA2	Drained	15	72.0	9.0	7.7	7.4	9.1	8.2	7.6	10.8	11.2†	9.7	11.0	8.5
AA3	Drained	19	64.1	11.7	6.2	4.9	9.3	1.4	13.5†	13.3	2.4	11.7	12.9	12.7
BB1	Blocked	17	68.7	10.8	11.1	7.1	8.1	1.3	9.2	9.3	10.5	10.3	10.3	11.8†
BB2	Blocked	23	66.6	9.8	10.6	4.0	11.9†	7.1	7.3	7.6	9.1	10.2	11.0	11.4
BB3	Blocked	20	64.4	12.4	5.1	3.6	5.7	0.6	12.9	12.7	7.8	12.3	13.4	13.5†
CA2	Blocked	22	70.8	11.7	3.3	3.3	9.6	1.9	11.9	11.1	10.7	11.7	12.1	12.6†
AL0	Forested	19	72.9	5.0	9.7	4.3	6.9	5.0	12.2†	11.8	11.9	10.3	11.5	11.5
AL1	Forested	20	73.9	5.7	9.6	5.5	7.4	4.9	11.3	10.7	10.8	11.2	11.7†	11.2
AL5	Forested	17	67.6	8.1	8.4	7.0	6.6	4.3	11.7†	11.2	11.6	10.4	10.8	9.8
BL1	Forested	23	70.9	4.7	9.8	5.3	5.6	4.6	12.2†	11.7	11.5	11.0	12.1	11.4
BL5	Forested	23	69.2	2.1	9.5	5.4	5.1	4.8	12.9†	12.6	12.4	11.1	12.4	11.7
BR2	Forested	22	67.8	9.3	10.8	6.3	6.8	5.6	3.2	10.8	10.6	11.9	12.7†	11.9

In Drained, drawdown speed values (Dspeed) varied with depth and with distance to ditches, especially for shallower depths (see Figure 4). For both shallow and deep peat, the variation of drawdown speed data at AA2 (farther from ditches) was less than at AA1 and AA3 (closer to ditches). The mean DSpeed values for shallow peat were 0.200 (SD = 0.112) cm hour^{-1} at AA1, 0.187 (SD = 0.195) cm hour^{-1} at AA3, and 0.114 (SD = 0.061) cm hour^{-1} at AA2; while drawdown speed rates for deep peat

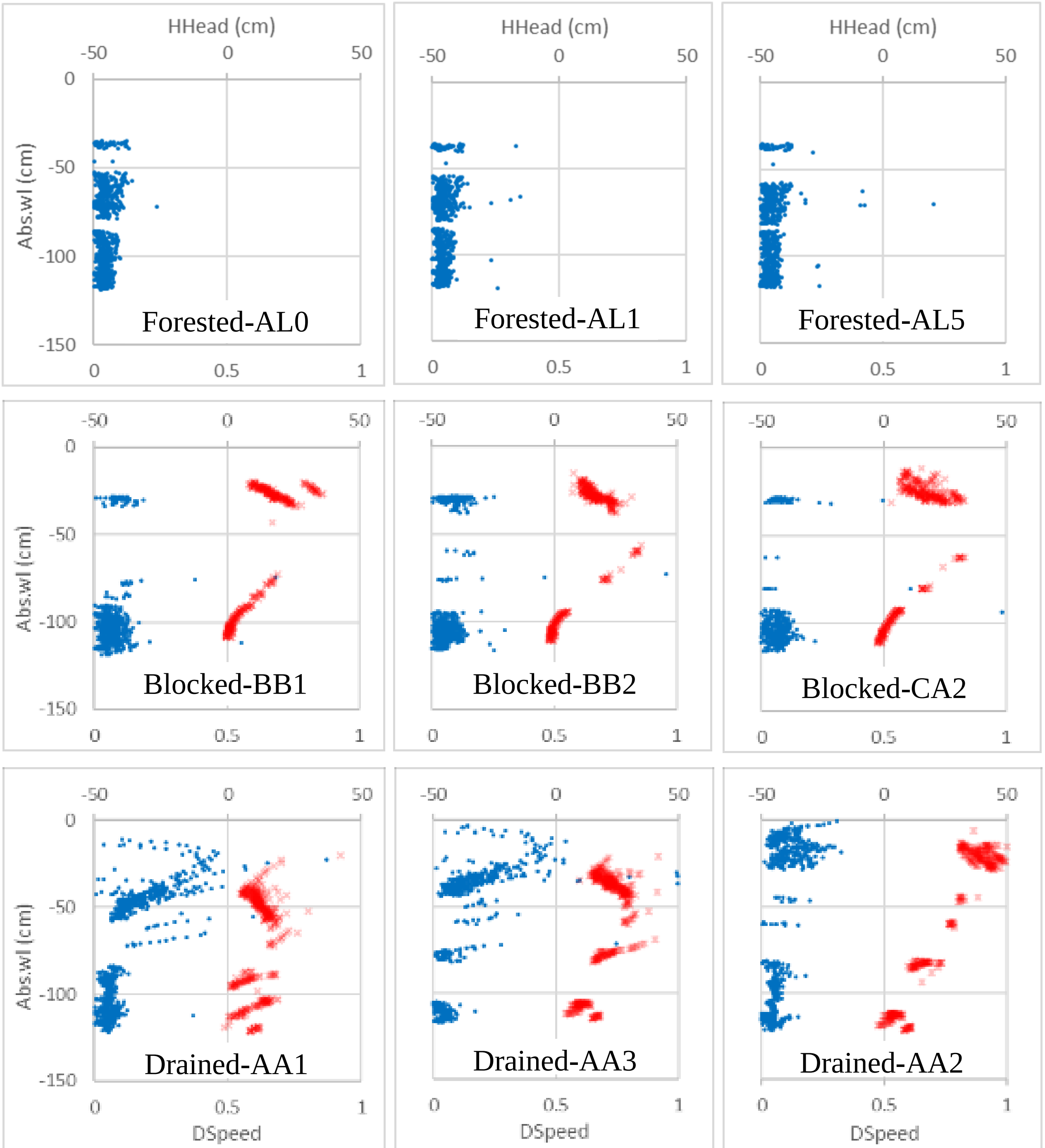

Figure 4. The distribution of standardised water-level drawdown speed (DSpeed) and hydraulic head (HHead) data in Forested, Blocked and Drained. The scattered blue-filled circles are the DSpeed data (left side in each graph). The scattered red crosses are the HHead data (right side in each graph). Negative HHead data indicate that the ditch water level was higher than the well water level at that time. No HHead data were available for Forested.

were similar to those in Forested and Blocked, with a mean of 0.052 (SD = 0.026) cm hour^{-1} at AA1, 0.035 (SD = 0.023) cm hour^{-1} at AA3, and 0.042 (SD = 0.024) cm hour^{-1} at AA2.

The hydraulic head difference (HHead) varied with depth, but differently between Blocked and Drained. In Blocked, HHead values were small (close to zero) for both the deepest and the shallowest water tables. In Drained, HHead data at AA2 had a different pattern from that at AA1 and AA3. HHead data at AA2 varied with depth, with HHead values being larger when the water table was deeper (mean = 37.3 cm, SD = 8.2 cm) than when it was shallow (mean = 4.4 cm, SD = 3.3 cm). In Drained, during deep water-table periods, the HHead data of AA1 and AA3 increased as the water level of the peatland increased. At several intervals, HHead data dropped close to zero, indicating that there were some rapid increases of the ditch water level during the intervals (see Figure 4). During shallow water-table periods, HHead data of well AA1 and AA3 decreased with reductions in water-table depth, due to gradual increases of the ditch water level.

Peat properties at well locations

Table 4 presents near-surface saturated hydraulic conductivity (*K*) data for the studied wells. Each value from the Drained site is accompanied by the mean distance of each well to nearest ditch and each value from the Blocked site by the distance of each

Table 4. Near-surface saturated hydraulic conductivity (*K*) for the studied wells.

Well	Location	Mean distance to nearest ditch (m)	Distance to lowest ditch outlet (m)	*K* (m day^{-1})	
				Surface	20 cm depth
AL1	Forested	-	-	16.87	-
AL5	Forested	-	-	10.05	-
BB1	Blocked	-	21	4.71	-
CA3	Blocked	-	195	3.12	0.04
CA4	Blocked	-	222	10.10	0.23
CA2	Blocked	-	275	4.21	0.05
CA7	Blocked	-	387	9.84	-
CA1	Blocked	-	390	5.39	1.39
BB2	Blocked	-	424	6.07	-
BB3	Blocked	-	465	2.06	-
CA5	Blocked	-	469	5.07	-
CA6	Blocked	-	612	9.59	-
AA1	Drained	21	-	5.40	-
AA3	Drained	29	-	6.11	-
R5	Drained	112	-	10.70	-
R1	Drained	122	-	9.90	-
R7	Drained	129	-	3.41	-
R2	Drained	136	-	9.27	0.25
R3	Drained	168	-	15.38	0.81
AA2	Drained	173	-	10.52	-
R6	Drained	181	-	10.63	-
R4	Drained	249	-	11.03	-

well to lowest ditch outlet. The distances of AL1 and AL5 to the small trench at Forested are not presented. Table 5 contains simple statistical data of mean peat dry bulk density (DBD) and peat organic matter content (OM) at the study sites.

The highest surface K values were measured in Forested (Table 4). The surface K values in Drained (mean = 9.2 m day^{-1}, SD = 3.2 m day^{-1}) were generally higher than in Blocked (mean = 6.0 m day^{-1}, SD = 2.7 m day^{-1}). In Drained, the five points with shortest distances to ditches (AA1, AA3, R1, R2 and R7) had lower surface K values compared to other sampling points. In Blocked, the three points with shortest distances to the main outlet of the peat plot (BB1, CA3 and CA2) had lower surface K values compared to the three points at greater distances (BB2, CA5 and CA6). The sub-surface K values taken at a depth of 20 cm were consistently lower than the surface K values (Table 4).

In Drained and Forested, the dry bulk density of shallow peat (surface to 50 cm depth) tended to be lower than that of deep peat (Table 5). In Forested, the deep peat dry bulk density for AL0 was smaller than for AL1 and AL5, which may be because AL0 was located on the bed of a small trench (64 cm below the trench's bank). In Blocked, the dry bulk density of shallow peat was similar to that of deep peat (mean of 0.137 g cm^{-3} and 0.131 g cm^{-3} respectively). The organic matter content data were high with very little variability between wells or sites, which ranged between 98.6 % and 99.8 %. However, for each well, organic matter content data were greater in deep peat than in the upper 50 cm, except at point AL0 (at the small trench).

DISCUSSION

Storm variables that are influential to water-table variations

In the Results section we examined storm variables that are influential to water-table dynamics in tropical peatlands and provided evidence that the influence of each storm variable varied spatially and seasonally. In Forested, variables associated with the starting phase of the storm (Initial-vars) contributed little to water-table variation, perhaps because of forest interception in the initial phases of storms. Interception in tropical rainforests can be around 14.5–18 % of the annual rainfall (Dykes 1997, Manfroi *et al.* 2004, Moore *et al.* 2013). The raingauge in Forested was not below the forest canopy, so was not subjected to interception losses. In Blocked, Initial-vars did not strongly contribute to water-table variation during the deep water-table condition because ditch water levels were low and some rainfall would have been lost via seepage to the ditch (hydraulic head differences were increasing, see Figure 4). In contrast, during shallow water-table conditions in Blocked, the Initial-vars contributed strongly because drainage effects were minimal. Both Rising-vars and Peak-vars contributed significantly to water-table variations in Forested and Blocked (Figure 3), suggesting that those sites had the capacity for a rapid rise of the water table. In Drained, the responses to storms when water tables resided in shallow layers had less contribution from Peak-vars (high rainfall depth) than when water tables resided in peat more than 50 cm deep (see Figure 3).

Table 5. Mean dry bulk density (DBD) and organic matter content (OM) of peat at the study sites. Standard deviation values are in brackets. The ground surface at AL0 (†) was on the bed of a small trench, 64 cm below the surrounding peat surface.

Well	Location	Number of samples	Shallow peat		Deep peat	
			DBD (g cm^{-3})	OM (%)	DBD (g cm^{-3})	OM (%)
AA1	Drained	22	0.142[0.05]	98.8	0.128[0.03]	99.1
AA2	Drained	26	0.132[0.03]	99.3	0.175[0.05]	99.8
AA3	Drained	24	0.106[0.07]	99.4	0.142[0.03]	99.8
BB1	Blocked	22	0.140[0.04]	99.0	0.139[0.03]	99.5
BB2	Blocked	24	0.118[0.04]	99.3	0.116[0.03]	99.5
BB3	Blocked	23	0.154[0.05]	99.0	0.137[0.05]	99.6
AL0†	Forested	23	0.093[0.04]	99.2	0.095[0.03]	98.6
AL1	Forested	19	0.093[0.03]	98.6	0.112[0.03]	98.8
AL5	Forested	23	0.055[0.02]	99.1	0.121[0.03]	98.9

Effect of ditches and ditch dams on the responses to storms

Our findings provide evidence that ditches significantly altered the responses of water table to storms in the Drained compared to the Forested site. Drainage reduced the peatland's capacity to retain water provided by rainfall. We found that in Drained, less rainwater can be stored by shallow peat when the water table is near to the surface (little extra room for rainwater), with excess rainwater draining to the ditches via overland flow. The finding that water-table responses to storms vary with restoration state is in line with studies of water table and river flow responses to storms in temperate peatlands (Grayson *et al.* 2010, Holden *et al.* 2011, Holden *et al.* 2018, Shuttleworth *et al.* 2019).

The construction of ditch dams may have been responsible for the responses to storms in Blocked being more like those in Forested than those in Drained. In Blocked, in the wet period, the ditch dams could not fully minimise the hydraulic head difference (Figure 4), given that water was still being drained to the lowest outlet of the peat plot (Putra *et al.* 2021). To reduce water loss further the water level at the outlet needs to be raised whenever possible, and further restoration measures are needed to supplement the functioning of the ditch dams. Up to the time when this study was conducted (around five years after the ditch dams were built), the rewetting efforts did not result in fully recovered responses to storms in Blocked, assuming that Forested was close to natural benchmark. Several studies from temperate peatlands have come to similar conclusions, affirming that the recovery of the hydrological dynamics of drained peatlands cannot be achieved in a short period after the start of restoration (Holden *et al.* 2011, Kreyling *et al.* 2021, Williamson *et al.* 2017).

Possible effect of peat properties on the responses to storms

Our study provided dry bulk density data from tropical peatlands and such data are sparse in the tropical peatland literature. The dry bulk density of the peat in Drained (Table 5) is comparable to values reported from another highly degraded and non-forested peatland in Sebangau (Könönen *et al.* 2015) and at locations near to a canal in Mawas peatland (Block A of MRP; see Sinclair *et al*. 2020), but is higher than in the drained peatland in Selangor, Malaysia (Tonks *et al*. 2017). The dry bulk density of peat in Forested was comparable to that measured in the western side of Sebangau (Lampela *et al.* 2014), and also in the Amazon basin (Lähteenoja *et al.* 2013) and Sumatra (Shimamura & Momose 2005), but lower than values reported for Congo peatlands (Dargie *et al.* 2017). As far as we are aware, there are no comparable dry bulk density data from tropical peat plots where dams have been installed in the surrounding ditches. We also provided some surface hydraulic conductivity data (2.1–16.9 m day^{-1}) for Indonesian peatland, which may enrich the sub-surface hydraulic conductivity data (0.001–13.9 m day^{-1}) collected by Kurnianto *et al*. (2019).

In Blocked, the dry bulk density of the shallow peat was comparable to that of the deep peat (mean of 0.137 g cm^{-3} compared to 0.131 g cm^{-3}) but the contribution from Peak-vars (high rainfall depth) differed between the shallow and deep layers, which may indicate that differences in responses to storms in Blocked were not closely related to dry bulk density. Therefore, we think that the pre-storm water storage in the peat profile, approximately reflected by the initial water-table condition, might be important in determining the response of water tables to rainfall in Blocked. The water-table retention time profiles presented by Putra *et al*. (2021) and the typical seepage pattern in the area near to ditches with ditch dams presented by Putra *et al*. (2022) showed that the upstream area of the ditch dam was wetter than around the outlet, which may be caused by the dilation of peat (see an example from northern peatlands in Dise 2009) and may result in the high surface *K* and low dry bulk density conditions of peat upslope of the dam.

In Forested, the dry bulk density of shallow peat was comparable to that of deep peat (Table 5), yet those values were far lower than those in Drained and Blocked, suggesting more storm water was potentially stored by the peat layers in Forested than in the other sites. However, this presumption needs to be supported by more data on total porosity and drainable porosity. Putra *et al*. (2021) reported that the water-table differences among wells in Forested were less than 10 cm, indicating that rapid drawdowns of the water table after storms might be part of natural functioning. The only two measured *K* values in Forested are similar to the *K* values at points farther from ditches in Drained (e.g., at AA2 and R3, see Table 4). In accordance with other tropical peatland studies (see Baird *et al*. 2017, Kurnianto *et al*. 2019), it is possible that *K* at Forested may actually be higher than the measured *K* values in Table 4. The high *K* values at Forested could be the reason for the small differences in water tables between wells at Forested. Therefore, we think that subsurface flows in Forested could be greater than in Drained.

Applications and future improvements

The findings suggest that ditch dams only partially restore the water-table responses to storms in a drained tropical peatland, compared with a near-natural forested peatland. Water tables are controlled by input rainfall (after interception losses), inflow from other parts of the peatland, outflow drainage and evapotranspiration. In the future, our mechanistic understanding of peatland water-table responses to storms can be improved by closing the water budget for each of these components.

The differences in the number of storm events between sites is to be expected because storm selection for the PCA was based on the rise of water tables, and such rises were different at each site. More representative samples of storm events would be preferable, but we are confident that our data, incorporating more than 80 storm events at each site, provide a range of typical water-table responses to storms at the study sites.

Our dipwells were not anchored to the substrate underlying the peat, which may have added some errors to water-level values. However, we note that peat subsidence or expansion during the period of the study is likely to be small (perhaps a few cm) in comparison to the range of water-level changes we detected (~150 cm). We also recognise that we studied only one site representing each condition of Drained, Blocked and Forested. Further studies of storm response across more sites would be useful, for example to build a data driven model of the water-table responses to storms in tropical peatlands or to parameterise the hydrological variables extracted from the storm profiles into a model. Moreover, the rainfall and water-table data in this study only covered the second half of 2019, which was a typical ENSO (El Niño–Southern Oscillation) year in a neutral condition (WMO 2019, Becker 2020). Further work on storm responses to different depth-duration patterns of rainfall during El Niño and La Niña years may reveal additional components of hydrological functioning that we were unable to ascertain.

CONCLUSIONS

Understanding responses of water tables to storms is important for evaluating the hydrological condition of tropical peatlands. This study showed that responses of water table to storms were different between the studied intact, drained and ditch-dammed tropical peatlands. This article also provides evidence that several elements of hydrological functioning were seemingly not restored in the blocked site, at least when compared to the forested site. We also show that the responses to storms are spatially and seasonally variable, meaning that these factors need to be considered in tropical peatland hydrological modelling studies to better represent water-level dynamics rather than using constant seasonal boundary conditions or assuming spatially invariable responses. The simple measure of mean water-table depth may hide more detailed differences in hydrological functioning between sites under different types of management.

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AUTHOR CONTRIBUTIONS

In this publication, SP was responsible for designing the research, conducting fieldwork, collecting and analysing data, and also composing the manuscript. JH and AB were supervisors, providing advice and critical comments during the research, as well as improving the manuscript.

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