Water table variations on different land use units in a drained tropical peatland island of Indonesia

Ismail Ismail a,b,*, Ali Torabi Haghighi a, Hannu Marttila a, Uun Kurniawan b, Oka Karyanto b and Bjørn Kløve a

a Water, Energy, and Environmental Engineering Research Unit, Faculty of Technology, University of Oulu, P.O. Box 8000, Pentti Kaiteran Katu 1, Oulu 90014, Finland
b Faculty of Forestry, Universitas Gadjah Mada, Agro Street 1, Bulaksumur, Yogyakarta 55281, Indonesia

*Corresponding author. E-mail: ismail.ismail@oulu.fi

ABSTRACT

Restoration and water table control on peatlands to limit fire risk are national priorities in Indonesia. The present study was initiated at Padang Island, Sumatra, to increase understanding on peatland hydrology in the tropics. At the pilot site, water table and precipitation were monitored at different stations. The results show variation in water table depths (WTDs) over time and space due to spatial and temporal variability in rain intensity and drainage networks. In part of the island, large-scale drainage for plantations led to deep WTD (>1.8 m) and high WTD recession rates (up to 3.5 cm/day). Around villages, farm-scale drainages had a smaller impact with a lower recession rate (up to 1.8 cm/day) and shallow WTD, typically below ~0.4 m, the threshold for sustainable peatland management in Indonesia. The recession rates levelled off at 1.0 cm/day near the drained forest/plantation and at 0.5 cm/day near the farm. Deeper layers had much lower specific yield (Sy), 0.1 at >1.5 m depth, compared with top peat soils with Sy up to 0.3. Proximity to drainages extended discharge flow to deeper layers. The results highlighted the severity of peatland drainage impact on most coastal zones of Padang Island, which have intensive drainage networks.

Key words: fire risk, peat degradation, peat hydrology, peat swamp forest, restoration, water table

HIGHLIGHTS

• High spatial and temporal variability of water table was observed in Padang Island.
• The variability was partially driven by variation in land use and farm drainages.
• Recession rate near pulp plantations remained high (0.01 m/day) at ~1.5 m depth.

INTRODUCTION

Millions of hectares of peat swamp forest in Indonesia have been degraded and deforested within recent decades (Miettinen et al. 2016). Peatlands have been drained mainly for large-scale monoculture of palm oil and pulp plantations (Hooijer et al. 2012). Peatland drainage has led to major carbon emissions (Hirano et al. 2012; Hooijer et al. 2012; Jauhiainen et al. 2012; Wakhid et al. 2017; Marwanto et al. 2019), with an estimated increase of 900 g CO₂ m⁻² a⁻¹ for every 10 cm of drainage depth (Cowanberg et al. 2010), and thus exacerbating global climate change (Warren et al. 2017). Peatland drainage also poses a high risk of wildfire (Wösten et al. 2008; Cattau et al. 2016; Taufik et al. 2018). To reduce the disastrous impacts of peatland drainage, the Indonesian authorities have established the national Peatland Restoration Agency (Badan Restorasi Gambut/BRG) to manage the restoration of more than two million hectares of degraded peatlands (BRG 2016).

In natural conditions, the water table in peatlands lies close to the surface but may drop to ~0.3 m from the surface in the dry season (Hooijer 2005; Cobb & Harvey 2019) or even deeper during extreme conditions such as El Niño (Wösten et al. 2008). Lowering the water table results in carbon emissions (Cowanberg et al. 2010; Hooijer et al. 2012; Wakhid et al. 2017), with strong empirical evidence of a relationship between water table and carbon emissions (Hirano et al. 2012; Mezbahuddin et al. 2014; Carlson et al. 2015). Restoration of degraded peatlands aims to raise the water table to a level closer to that prevailing in natural conditions (Jauhiainen et al. 2008; Jaenicke 2010; Ritzema et al. 2014; Dohong et al. 2018; Urzainki et al. 2020). Peatland water table is commonly measured and used as an indicator in restoration program (Ritzema et al. 2014;
Dohong et al. 2018). In addition, water table is a good indicator of fire susceptibility and thus useful as an early warning in fire prevention on peatlands (Usup et al. 2004; Page et al. 2009; Jaenicke 2010).

Intact tropical peatlands, such as those in Indonesia, are typically ombrotrophic (Page et al. 2006), with water table primarily controlled by rainfall, evapotranspiration (ET), and discharge. Rainfall generally far exceeds ET during the rainy season (Hirano et al. 2015), while discharge mainly occurs in the top-soil layer or as overland flow when the water table is above the surface (Hooijer 2005; Wösten et al. 2006; Mezbahuddin et al. 2015). As the water table falls during the dry season, discharge rapidly declines and the recession is eventually driven solely by ET (Cobb & Harvey 2019). However, human interventions such as artificial drainage strongly influence water table dynamics (Hooijer et al. 2012; Ishii et al. 2016). Despite its critical role in tropical peatlands, few previous studies have measured water table dynamics at high temporal resolution in peat soils in Indonesia over longer periods, i.e., multiple seasons. Most of these studies have concentrated on the island of Borneo (Lampela et al. 2014), particularly around Sebangau National Park (Wösten et al. 2008; Jaenicke 2010; Hirano et al. 2012; Ishii et al. 2016; Takeuchi et al. 2016), and on the Kampar Peninsula in mainland Sumatra (Jauhiainen et al. 2012; Marwanto et al. 2019; Deshmukh et al. 2020). Since there are more than 20 million hectares of peatlands spread across the Indonesian archipelago (Hergoualc’h et al. 2018), these studies represent a very limited spatial distribution of peatlands, and hence more in situ measurements are needed. In general, hydrological monitoring to support restoration planning in Indonesia is still lacking (Graham et al. 2016).

The main objective of this study was to increase knowledge on hydrology of tropical peatlands by studying the spatial and temporal variability in peatland water table. We assessed how rainfall and drainage influence water table dynamics on a peat island off the mid-eastern Sumatra, where peatland drainage and deforestation go hand in hand. An in-depth understanding of peat hydrology is critical for implementation of hydrological restoration (BRG 2016) and improvement of our knowledge in ecohydrological processes in tropical peatland ecosystem (Mezbahuddin et al. 2015).

MATERIALS AND METHODS

Study area

The study site selected was Padang Island, off mid-eastern Sumatra (Figure 1). Padang Island is around 100,000 hectares in size and is mainly covered by a peat layer. The terrain is relatively flat, with maximum elevation to 10 m above sea level. The status of peatlands on Padang Island is similar to that of many other peatlands in Indonesia. The island is suffering various disturbances that are ravaging peatlands across the country, such as deforestation, logging, low-intensity to large-scale drainage, burning, and social conflict. Hence, Padang Island has been designed a pilot restoration site by BRG. There are two different layers of peat in the region: an upper deposit with slight to moderate humification and fibric to hemic texture, and a lower deposit with higher humification and sapric texture (Supardi et al. 1993).

Padang Island is drained along much of its coast (Figure 1(a)). It has a massive intensive open drainage network that occupies at least one-third of the island’s area, which was created in late 2011 to establish pulpwod plantations on the western side, and a less intensive drainage network that occupies roughly another one-third of the island’s area enabling small-scale agriculture in the rest of the coastal zone (Susanti et al. 2018). The plantation drainage vary in width from 1 m (tertiary drainage) to 10 m (primary drainage), and in depth to as much as 5 m with drain spacing of only 130 m. The smaller drainage systems serve local settlements, consist of drainage less than 1 m in width, usually surrounding agricultural land (mainly rubber and sago farms) and running along both sides of the road network. Only around 30% of the island is still occupied by forest (Figure 2). The region of Padang Island receives much precipitation (1,000–5,000 mm) distributed throughout the entire year, although February and May–July are considered dry seasons, while the air temperature is relatively constant within the range of 21–36 °C (Ardhitama & Sholihah 2014). ET in the region is around 1,300 mm/year.

Hydrological monitoring

The study on Padang Island was part of a national campaign by BRG to monitor peatlands in Indonesia in which hundreds of monitoring stations were installed in seven provinces (BRG 2019). The present study investigated peatland hydrology on the island to obtain information that could be used to explain the physiology of surface vegetations. In April 2017, five monitoring stations were installed across Padang Island (Figure 1(a)) and equipped with water table sensors and rainfall sensors (Figure 1(e)). The water table sensors were set inside perforated pipes that penetrate up to 2 m below the surface, as the stations were on a peat 7–9 m deep. The siting of the stations was primarily based on degradation level (i.e., position relative to a drainage network) and road access. The Tanjung Padang (Sd-TP) and Anak Kamal (Sd-AK) stations were classified as
representing ‘severely drained’ sites, as they were located less than 2 km from the plantation drainage system (Figure 2), while the Kudap (Ld-Ku), Selat Akar (Ld-SA), and Mengkirau (Ld-Me) stations were taken to represent ‘less drained’ sites.

An OEM HC-801 submersible pressure level transducer was used as a water table sensor and a tipping bucket rain gauge manufactured by Diwi (http://diwicontrol.com) was used to measure rainfall. The accuracy of the water table sensor is 1 cm, while calibration of the rain gauge suggested that one tip was equal to 0.3 mm. Both sensors were chosen for their affordable price and adequate accuracy. The measurement interval was set to 10 min. However, equipment at the stations was stolen or vandalized by late 2018 and the Ld-Ku station was destroyed only a few weeks after installation. Padang Island is a conflict zone between pulp plantation companies and local communities due to land disputes (Detiknews 2011), which are common in Indonesia (Uda et al. 2017). Parallel measurement of water table and rainfall enabled estimation of other variables such as specific yield and water table recession. Data on these parameters are rarely available from tropical peatlands in Indonesia.
but are important for hydrological restoration, e.g., for water table modelling to evaluate the effects of restoration. Some
periods of measurement were missed due to temporary insufficient power from the solar panel power sources.

One-off manual measurements of water table were conducted along transects (T1–T8) around Sd-TP, Ld-Me, and Sd-AK
stations (Figure 2(b)–2(d)). The transect measurement was intended to compensate for the limited spatial distribution
of the stations by extending the measurements into various land cover types around the stations. The measurements were car-
ried out in early May 2018, at the beginning of the second dry period in the region as suggested by Ardhitama & Sholihah

Figure 2 | Maps from airborne images showing the major land cover (a) throughout Padang Island and around the monitoring stations
(b) Tanjung Padang (Sd-TP), (c) Mengkirau (Ld-Me), and (d) Anak Kamal (Sd-AK). Transects of manual measurements of water table depth
(WTD) around the stations are also shown.
Transects were designed primarily based on existing monitoring stations, variation in elevation and land cover, drainage network, and ground access (Figure 2). In order to get the maximum variation in elevation, the plan was to draw transects from riverbank or shoreline, where the elevation is lowest, across the peat dome, where the elevation is highest. However, limited ground access (road network, private property) restricted the possibility of completing full transects, and only two complete transects were possible (T3 and T4; Figure 2(c)). Instead, the approach used was to look for the closest road network to the monitoring station, and then identify any straight road path with maximum elevation gradient and land cover variation. Measurement points were distributed along the transect to represent different elevations, and thus, the interval varied according to the elevation gradient, i.e., it was shorter for steeper gradients.

Transects were established much later than the monitoring stations and, to maintain straight transects, the monitoring stations did not necessarily lie on any transect. Distance from the monitoring station generally varied from 0.1 km (T2) to 1.2 km (T3) except for T8, which was 3.1 km from Sd-AK station. It was impossible to extend T7 further north, and thus another transect (T8) was established in that location (Figure 2(d)). As a compromise between limited resources, wide distribution of transects and transport across the island, transects were set in three main areas, where Ld-SA station was considered to lie in the same area as Ld-Me station. Perforated tubes were installed at the measurement points along the transects, generally to 1 m below the ground, but to 2 m for measurement points less than 2 km from a plantation or large drainage. The tubes were installed a few weeks before measurements began. The depth of the water table was measured manually by inserting a measuring stick into tube. Each transect was finished within a single day, to minimize temporal variation along the transect.

Data analysis

A brief flowchart of data analysis is presented in Figure 3. Statistical analysis was used to examine water table dynamics and spatial variability, the contribution of rainfall to water table change, and recession curves. The recorded water table was presented as water table depth (WTD) in negative values, to represent depth below the ground surface. The statistical analysis included an unpaired t-test for time series of WTD between stations, regression analysis between rainfall intensity and pre-rain WTD and WTD rise, and time residence curve (Holden et al. 2011). Analyses were performed within and between stations to assess whether the results were site-specific, since the drainage severity level varied between the stations. Data on WTD were missing for a total of 21% of the whole duration of measurement. Missing data for rainfall were substituted by values obtained from Global Precipitation Measurement (GPM) version 6 (Huffman et al. 2019) and from gauge measurements by the

Figure 3 | Flowchart of data analysis.
Indonesian Meteorology and Climatology Agency (BMKG) in Pekanbaru city, the closest BMKG rainfall gauge to Padang Island (approximately 100 km away) (BMKG 2015). The city lies near to BMKG weather zone 14, which covers Padang Island (Ardhitama & Sholihah 2014). A previous study in the region found that monthly GPM rainfall data are sufficiently accurate to reflect the temporal variation in monthly rainfall (Tan & Duan 2017).

**Spatial and temporal variability**

The WTD dynamics within and between measurement stations were examined to determine the spatial and temporal variability. Monthly rainfall data derived from the GPM and BMKG networks were used to explain the seasonal variability in WTD, due to limited rainfall records at our monitoring stations. The variability between stations was also examined using time residence curve of WTD (WTD-TRC) adapted from Holden et al. (2011). The WTD-TRC was created from the cumulative distribution of WTD from the deepest to the shallowest depth, with intervals of 0.1 m, and used to illustrate the proportion of time for which WTD was below 0.4 m from the surface. This is the WTD threshold for healthy tropical peatlands (Usup et al. 2004; Wösten et al. 2008) as regulated by law in Indonesia (Kemenkunham 2016), and cumulative distribution of WTD below this threshold can be used to assess peat degradation severity. However, missing WTD records at some stations could have introduced bias when using WTD-TRC for comparison between stations, and thus WTD-TRC was created only from simultaneous WTD records.

**Rainfall–WTD relationship**

Rainfall–WTD relationship was analyzed by calculating WTD rise induced by rainfall events, using hourly aggregated time-series data that were originally recorded every 10 min. A single rainfall event was defined from further aggregation of multiple rainfall that occurred within less than a 2-h interval. For each rainfall event, the associated WTD rise was defined from the first inflection point of the hydrograph (Figure 4), at the beginning of the rising limb, until the second inflection point, when the water table was at its peak and began to drop. WTD rise was then calculated as the differences in 2-h average WTD before and after these inflection points. Any rainfall event with a total intensity less than 5 mm was removed, as this intensity did not induce a sufficient WTD rise or the response was inconsistent. Pearson correlation between total rainfall intensity and WTD rise was then calculated for all stations and each station separately. However, in some measurement periods, rainfall was underestimated due to insufficient power supply from the solar panels, which restricted rainfall measurement to daylight hours. These periods were excluded from the rainfall–WTD analysis. The rainfall–WTD relationship was used to estimate specific yield (Sy) as a function of pre-rain WTD, using the method adapted from Bourgault et al. (2016) and Cobb & Harvey (2019). Sy was defined as the rain-to-rise ratio, i.e., the amount of rainfall (mm) for each mm of WTD rise. It was assumed that the duration of rainfall events was too short for ET.

*Figure 4* | Time series of water table depth (WTD) and rainfall intensity at the Tanjung Padang (Sd-TP) station from 26 March to 5 April 2018. Vertical dotted line indicates ‘break point’, while vertical dashed lines indicate ‘inflection points’ representing the beginning and end of the WTD rise.
Recession curve analysis

A master recession curve (MRC) was created by the manual matching strip method adapted from Cobb & Harvey (2019). Initially, a recession curve was selected manually from the water table hydrograph, usually beginning when the rising limb was saturated (shallowest WTD) after a rain event and lasting at least 10 days. However, the recession curve was sometimes interrupted by another rising limb from the next rain event (Figure 4). The interrupted recession curve was still considered if the interrupting rising limb was insignificant, i.e., less than 10 cm or rainfall intensity less than 5 mm/day. A disconnected curve with missing values was only included if the gap was less than 1 day. All recession curves were then compiled into a single MRC by adjusting the timeline to set the curves to align or overlap one another. The shallowest WTD of the recession curves was set as day 1.

RESULTS

Spatial and temporal variability in WTD

There was apparent spatial and temporal variability in WTD on Padang Island (Figure 5). The mean WTD was much deeper at Sd-TP station (−1.2 m) close to the plantation than at other stations, and the range was considerably wider (−0.5 to −1.8 m). Other stations, located near the communities with small-scale farming, had shallower mean WTD, −0.61, −0.43, and −0.76 m for Sd-AK, Ld-Me, and Ld-SA, respectively. Their WTD ranges were very similar but narrower than the range of WTD at Sd-TP (Figure 5, right). Rainfall data from the BMKG station in Pekanbaru city showed high similarity to monthly rainfall estimated from GPM satellite data for mainland Sumatra (except for September 2017, when the sensor did not operate, Figure 6(a) and Padang Island (Figure 6(b)), demonstrating the potential of GPM monthly rainfall data. GPM rainfalls for Padang Island suggested that February 2018 and July–September 2018 were considerably drier, with monthly rainfall below the average (200 mm/month). There was a tendency for deeper WTD in all stations during the dry seasons such as in February 2018 (70 mm/month, Figure 6(b)). However, deeper WTD, in response to low monthly rainfall in July–September 2018 was only observed clearly at Sd-TP station. The discrepancy between deep WTD and dry season was prompted by lower temporal resolution of monthly rainfall (Figure 6) and some periods of missing WTD records for Sd-AK and Ld-Me stations.

The WTD was below the threshold of −0.4 m for most of the study period (Figure 7). However, WTD and the cumulative distribution varied between stations. Sd-TP station had the deepest WTD and for 20% of the time WTD dropped deeper than −1.5 m. The interquartile ranges also varied considerably, except for a slight overlap between Sd-AK and Ld-SA stations (Figure 7(b)). The overall mean WTD at the stations was significantly different (p-value <0.05) and was −1.17, −0.79, −0.60, and −0.44 m for station Sd-TP, Ld-SA, Sd-AK, and Ld-Me, respectively.

Actual WTD varied with land cover, but the difference was not significant (p-value from analysis of variance = 0.07). Despite lying under forest (T2, Figure 8(a)), WTD was deep (−1.1 m) to the east of Sd-TP due to the influence of a large drainage in a nearby plantation, which was less than 0.5 km away (Figure 2(b)). In contrast to measured values along T3 (Figure 8(b)), WTD in forest to the north of Ld-Me station was much shallower (−0.2 to −0.3 m), due to the absence of drainage. Drainage also caused variation in WTD on farms, with WTD on rubber-dominated farms to the south of Ld-Me station being deeper than that on sago-dominated farms along T8 (KM 1.0–2.5, Figure 8(c)). Sago is tolerant to shallow WTD and thus does not require intense drainage. The impact of elevation on WTD was negligible, as the correlation was very weak (R² = 0.03, p-value = 0.02). Note that the elevation scale is exaggerated in Figure 8 to visualize the variation, while the actual topography was mainly flat. For example, the elevation difference along T2 was only 6 m over a distance of 4 km. The uncertainty of WTD within a transect due to time lag measurement was assumed to be negligible as no nearby stations had a WTD drop that exceeded 0.02 m/day during measurement. Rain gauges recorded rainfall of 4.5 mm/day at Ld-Me station on 12 May, during measurements along T4, and 0.9 mm/day at Sd-AK station on 17 May, during measurements along T8. These rainfall events did not raise WTD by more than 0.01 m.

Daily rainfall–WTD relationship

Daily rainfall clearly influenced fluctuations in WTD, as WTD rose in response to any rainfall event with intensity above 5 mm/day (Figure 9), except at Ld-SA where the rain sensor was inoperable. The time lag between an initial rain event and WT rise was as short as 2 h (Figure 9(b)). In the period shown in Figure 9(b), WTD rose at the rate of 0.4 m/h and then dropped at a rate of 0.008 m/h.
Figure 5 | Left: Time series of water table depth (WTD) for the monitoring stations (a) Tanjung Padang (Sd-TP), (b) Anak Kamal (Sd-AK), (c) Mengkirau (Ld-Me), and (d) Selat Akar (Ld-SA). Right: Range and mean WTD.
Larger rainfall led to higher WTD rise (Figure 10(a)) and the overall linear regression model delivered a good overall relationship ($R^2 = 0.76$, $p$-value < 0.05). The response of WTD to rain events with total intensity less than 5 mm was inconsistent and thus these events were excluded. In total, there were 14, 16, and 12 rain events at stations Sd-TP, Sd-AK, and Ld-Me, respectively. The rain intensities were mostly within the range 5–20 mm, with a few intensities higher than 20 mm at Sd-AK and Ld-Me stations. The correlation for Sd-TP station alone showed even better linearity ($R^2 = 0.93$, $p$-value < 0.05), while for Sd-AK ($R^2 = 0.82$, $p$-value < 0.05) and Ld-Me ($R^2 = 0.76$, $p$-value < 0.05) stations, the correlation was weaker, but still high. There was one anomaly at Sd-AK station, where WTD rise was small (0.3 m) despite very high rainfall (>50 mm), probably

**Figure 6** Monthly rainfall in the period May 2017–August 2018 in (a) mainland Sumatra based on Global Precipitation Measurement (GPM) data and measurements at an Indonesian Meteorology and Climatology Agency (BMKG) station in Pekanbaru city; and (b) Padang Island based solely on GPM data. The range and mean monthly rainfall (GPM) at both locations are shown in the right panel.

**Figure 7** Time residence curve of water table depth (WTD-TRC) with depth threshold = 0.4 m for (a) all stations and (b) the range, interquartile, and mean WTD (in bracket) for simultaneous measurement records, which lasted 325 days. WTD-TRC was created from the cumulative distribution of WTD below each 1 m depth interval.
Figure 8 | Spatial variability in water level along (a) transect T2, (b) T3, and (c) T8 across an elevation (elev) gradient (Figure 1(b)) and with different land covers (see Figure 2), visualized by coloured horizontal bar above the x-axis. The location and orientation of transects T2, T3, and T8 can be seen in Figure 2(b)–2(d), respectively. The stations were not necessarily on the transect and could be hundreds of metres away. Only three transects are presented, but all transect measurements are summarized in (d) water table depth (WTD) based on the major land cover. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.062.
Figure 9 | (a) Time series of daily rainfall and water table depth (WTD) at the (a and b) Tanjung Padang (Sd-TP), (c) Anak Kamal (Sd-AK), and (d) Mengkirau (Ld-Me) stations; (b) rainfall event and WTD rise on 7 March 2018 at Sd-TP station, illustrating the time lag between the starting point of rainfall and the beginning of WTD rise (left vertical dashed line), as well as the maximum WTD (right vertical dashed line) and the following recession.

Figure 10 | (a) Water table depth (WTD) rise for all rainfall events with total intensity greater than 5 mm and linear trendlines and (b) specific yield (Sy) from the rain-to-rise ratio versus pre-rain WTD with logarithmic trendline at all stations except Selat Akar (Ld-SA).
because the infiltration capacity was exceeded. However, $S_y$ varied from 0.05 to slightly above 0.30 (Figure 10(b)). The $S_y$ range for Sd-TP was narrower, with a maximum $S_y$ of only 0.15, which was generally lower than at Sd-AK or Ld-Me stations, where the $S_y$ ranges were much wider. The lower $S_y$ at Sd-TP station corresponded to deeper pre-rain WTD (below $-0.75$ m), while the higher $S_y$ at Sd-AK and Ld-Me stations corresponded to pre-rain WTD shallower than $-0.75$ m.

**Recession curve analysis**

Figure 11 shows the MRC and rate of WTD drop at Sd-TP and Sd-Ak stations. The recession curve was steeper at Sd-TP station, as WT dropped at a steeper and steady rate (Figure 5). The recession curve for other stations was less steep and shorter, as the recessions were interrupted by frequent WTD fluctuations. There were only a few apparent recession curves at Ld-Me station and even fewer at Ld-SA station, and thus both stations were excluded from the analysis. In total, 10 recession periods each for Sd-TP and Sd-AK stations were analyzed. Despite this small number, individual recession timelines lasted up to one month and the rates matched very well and were thus sufficient for analysis. The rate of recession was higher within stations at shallower WTD then decreased gradually to nearly constant rate at deeper WTD (Figure 11(a)). The WTD drops at Sd-TP station ranged from 3.5 to 1.0 cm/day for WTD from $-0.8$ to $-1.8$ m, while the WTD drops at Sd-AK station ranged from 1.8 to 0.5 cm/day for WTD from $-0.4$ to $-0.7$ m (Figure 11(b)). The constant rates of recession curve for Sd-TP and Sd-AK (dashed lines in Figure 11(a)) corresponded to a recession rate of 1.17 and 0.06 cm/day, respectively.

**DISCUSSION**

Despite limitations in ground measurements and uncertainty in data from monitoring stations, the present analysis showed how variations in rainfall intensity and drainage conditions/land cover influence the spatial and temporal variability in WTD on Padang Island. This confirmed previous limited findings for other regions in Indonesia (Wösten et al. 2008; Ishii et al. 2016) and provided empirical evidence about the spatial extent of peatland draining in Indonesia.

**Rainfall–WT relationship**

The rise in WTD was strongly correlated with rainfall intensity, despite differences in the correlation strength between stations (Figure 10(a)). However, not all rainfall contributed directly to WTD rise, as shown by a time lag between the starting point of a rain event and WTD rise (Figure 9(b)). The time lag was assumed to be driven by ET losses, as the rain evaporates before infiltrating into the ground, with total annual ET rates of up to 1,636 mm/year in tropical peatlands (Hirano et al. 2015). This might also explain why rain events with intensity below 5 mm did not increase WTD. WTD at Sd-TP station fluctuated in deeper layers (below $-0.8$ m), while WTD fluctuations at Sd-AK and Ld-Me stations were in much shallower layers (Figure 9), resulting in the lower rain-to-rise ratio or $S_y$ for Sd-TP station (Figure 10(b)). Hence, WTD rise is also a function of pre-rain WTD. In general, $S_y$ in peatlands is controlled by degree of humification, which varies with depth as degree of decomposition and bulk density increase with depth (Lampela et al. 2014). However, measurements or estimates of $S_y$ in

![Figure 11](http://iwaponline.com/hr/article-pdf/52/6/1372/982018/nh0521372.pdf)

Figure 11 | (a) Recession curve for the Tanjung Padang (Sd-TP) and Anak Kamal (Sd-AK) stations, (b) and recession rate for different water table depths (WTD) at Sd-TP and Sd-AK stations. The dashed lines in panel (a) represent constant recession assumed by ET, while straight lines in panel (b) represent the average recession rate.
tropical peatlands are very rare in the literatures and thus there are few existing data for comparison. Previous studies in pristine tropical peatlands, also using rainfall–WTD analysis, estimated the $Sy$ range to be 0.05–0.30 for the peat layer down to $–0.3$ m depth (Hooijer 2005; Cobb & Harvey 2019), which was mainly within our estimates for the same depth. Our values were also within the $Sy$ range (0.2–0.4) used in a modelling study on tropical peatlands by Ishii et al. (2016).

**Impact of land drainage on WTD**

Drainage had a great impact on mean WTD. Sd-TP station, which was closest to the large plantation drainage system (Figure 2(b)), had the deepest overall mean WTD ($–1.17$ m), while Ld-Me station, which was surrounded by smaller and less intense drainage systems (Figure 2(c)), had the shallowest overall WTD ($–0.44$ m) (Figure 7(b)). The impact of drainage on WTD co-occurred with land cover, as some land cover types were associated with a certain drainage system. For example, the intensive networks of large drainages along the western coast of Padang Island (Figure 1(a)) were constructed for pulp plantations (Figure 2(a)), while small-scale farms, particularly rubber plantations, along other coasts have smaller drainage systems with a less dense network (Figure 1(a)). A combination of land cover and drainage intensity generally explained most of the spatial variability in WTD (Figure 8). The land cover alone was insufficient, as the ranges of WTD between different land covers mainly overlapped (Figure 8(d)). Forested peatlands can have deep WTD when they are close to drainage, while agricultural areas can have shallower WTD if drainage is not present, such as in sago plantations. Sd-TP station was situated less than $0.5$ km from the large-scale plantation drainage system and $100$ m from the system outlet (Figure 2(b)), resulting in very deep overall WTD and thus indicating severe degradation of peatlands in the area. Sd-AK station was also situated near the plantation drainage network (less than $1.5$ km) (Figure 2(d)), but the overall WTD was much shallower than at Sd-TP station (Figure 7(b)). Visual ground observations showed that nearby plantation drains had been blocked to maintain shallow water table, and thus, the impact on the surrounding area was minimal. Water table dynamics were affected not only by distance to plantation drainage, but also by drain functionality.

The overall WTD was shallowest at Ld-Me station (Figure 7(b)), which was situated at the edge of a large forest and relatively far from farmland and drainage (Figure 2(c)). However, peatlands at the site were still considered degraded, as more than $80\%$ of WTD-TRC was below the statutory $0.4$ m threshold (Figure 7(a)). At Sd-AK and Ld-SA stations, the range of interquartile WTD showed a wide overlap (Figure 7(b)), as conditions at these two stations were similar (surrounded by small-scale drainage) (Figure 1(a)). The interquartile WT was deeper at Ld-SA than at Sd-AK (Figure 7(b)), possibly also due to differences in drain functionality. Ld-SA station was located near a long-established rubber plantation, while Sd-AK station was situated around new small-scale agriculture established in a recent burn scar (Figure 2(d)), and thus drainage was not fully operational. Land cover and drainage status did not change significantly during the monitoring period and can thus be assumed to have had negligible impacts on the temporal variability in WT dynamics.

The deep mean WTD in areas near the large drainage system, such as Sd-TP station, was driven by higher recession rate after rain events (Figure 11), prompted by typically high permeability and/or hydraulic conductivity of top layers (Wösten et al. 2006; Baird et al. 2017; Kurnianto et al. 2019). Even though the recession rate decreased exponentially, the rate remained high even in deeper layers. Drainage extends discharge flow to deeper layers, in contrast to WTD dynamics reported for pristine tropical peatlands (Hooijer 2005; Cobb & Harvey 2019), where fluctuations in water table and discharge flow occur mainly near the surface. WTD in pristine peatlands can drop to $–0.3$ m in drier seasons (Hooijer 2005; Cobb & Harvey 2019) or further, below the threshold of $–0.4$ m, during weather anomalies such as El Niño (Wösten et al. 2008; Hirano et al. 2012). The recession rate in pristine tropical peatlands is much smaller, with shorter duration (25 days) from the shallowest to the deepest WTD (Cobb & Harvey 2019). In stark contrast, the mean WTD in pulp plantations in mainland Sumatra is reported to be $–0.7$ m (Hooijer et al. 2012). Monitoring in drained peatlands in central Kalimantan reported that WTD dropped to $–1.6$ m in the dry season in 2004 (Mezbahuddin et al. 2015). In the nearby peatlands that was also intensively drained, WTD dropped below $–2.0$ m in the dry season in 2011 (Ishii et al. 2016). The latter area has been ravaged by multiple severe fires in the recent decades (Atwood et al. 2016). Deep WTD induced by artificial drainage from plantations and agriculture exposes the peatlands on Padang Island to a very high risk of fire, with only the centre of the island spared from drainage (Figure 1(a)). Deep WTD has been linked to frequent fire (Takeuchi et al. 2016) and many burn areas on Padang Island, re-vegetated by shrubs/ferns, lie in close proximity to drainage systems (Figure 2(a)). Without interventions such as drainage blocking, rise of water table can only be achieved by rainfall, urging the implementation of restoration with priority should be given to areas near drainage. This could also reduce the fire risk across millions of hectares of drained peatlands in Indonesia.
Uncertainties and impact of other factors on WTD

Impacts of rainfall and drainage/land cover on water table dynamics on Padang Island were demonstrated, but there was high uncertainty in the results due to limited ground measurement. Non-significant differences on mean WTD between different land covers (Figure 8(d)) were caused by the underrepresentation of forest area ($N = 17$) in measurements, with half measurements being made at the forest edge, near drainage systems (Figure 2). The drainage impact can extend up to a few kilometres into neighbouring peatlands (Hooijer et al. 2012). Hence, the mean WTD in the forest could have been much shallower if more measurements had been made in the inland forest. However, limited ground access prevented this, and hampered the regular sensor maintenance to repair sensor failure, vandalism, and missing measurement records. Consequently, the time residence curve, i.e., the percentage of WTD below a certain depth (Figure 7(a)) might differ by 21% based on missing WTD records. The mean WTD (Figure 7(b)) might also be slightly deeper or shallower, as some WTD values recorded at certain stations were removed to fit the simultaneous timeline for direct comparison between stations. For example, the mean WTD at Sd-TP using trimmed WTD records was $-1.17$ m (Figure 7(b)), while the mean WTD using all WTD records was $-1.20$ m (Figure 5(a), right). Increasing the frequency of ground measurements and sensor maintenance would obviously reduce the uncertainty but might not be cost-efficient for Padang Island and many peatlands in remote areas across Indonesia.

Involvement of the local community in ground measurements could be an alternative, although the temporal resolution of such manual measurements (weekly or monthly basis) is inferior to that in sensor-based monitoring. Cobb & Harvey (2019) reported high similarity of temporal variability between nearby stations, indicating that installing monitoring stations within a short distance is unnecessary. Ultimately, uncertainty and/or accuracy is always a compromise between cost and goal of the measurement. For instance, the accuracy for evaluation of hydrological restoration should at least be able to distinguish whether WTD is shallower or deeper than the threshold of $-0.4$ m, particularly for implementation at a larger scale such as the national level. Rigorous analysis in future studies to determine the accuracy will require sufficient data.

The water table in tropical peatlands can also be controlled by other variables that were not measured in this study, e.g., sea tides, creating additional uncertainty. The nearest observations by the Geospatial Information Agency of Indonesia (BIG) show up to 2 m fluctuation, with a regular diurnal pattern of two peak tides (BIG 2019). However, the mean water level at Sd-TP station (mean WTD = $-1.17$ m, surface elevation = 5.6 m) and Ld-SA station (mean WTD = $-0.79$ m, surface elevation = 6.5 m), which were the two stations closest to the coastline or riverbank (Figure 1(a)), was 4.43 and 5.71 m asl, respectively, much higher than the maximum sea level (2 m). The detailed hydrograph (Figure 9(b)) did not show any diurnal variation, and our data analysis for the recession curve was performed from average daily WTD.

ET is another major determinant of WTD in tropical peatlands that varies over space and time, within the range 1–6 mm/day at their study sites (Takahashi 1999; Hooijer 2005; Hirano et al. 2015; Takeuchi et al. 2016; Cobb & Harvey 2019). The seasonal variation in ET is mainly controlled by net radiation, which shows little change, unless a major fire or weather anomaly occurs (Takahashi 1999; Hirano et al. 2015). In other studies, the seasonal variation in ET is considered minimal as the ET rate is assumed to be fairly constant (Jauhiainen et al. 2008; Ishii et al. 2016; Takeuchi et al. 2016), particularly in pristine tropical peatlands where the range of WTD is much narrower (Hooijer 2005; Cobb & Harvey 2019). However, Hirano et al. (2015) argued that significant WTD drawdown could reduce the ET rate, due to plant water stress. Meanwhile, simulations by Mezbahuddin et al. (2015) demonstrated that surface vegetation could adapt to deep WTD with deeper root growth. However, the feedback mechanism between WTD and transpiration in tropical peatlands is not fully understood (Mezbahuddin et al. 2015) and species respond differently to hydrological status (Hardanto et al. 2017). Despite much deeper mean WTD at Sd-TP station (Figure 7(b)), the recession curve (Figure 11) suggested that ET rate at Sd-TP was higher than at Sd-AK, as the recession rate levelled off at 1.0 and 0.5 cm/day at Sd-TP and Sd-AK, respectively. The higher minimum recession rate at Sd-TP was presumably induced by higher water uptake from the nearby forest (Figure 2). Hence, more in situ studies are needed to improve understanding of ecohydrological processes in tropical peatlands. Variation in elevation gradient (Figures 1(b) and 8) might also contribute to variation in recession rates between stations (Figure 11), as steeper slope increases lateral discharge. Deeper mean WTD might also be prompted by steeper gradient, in addition to recession driven by drainage discharge. However, lateral flow driven by elevation gradient occurs mainly in the top layer, while water table dynamics at stations in this study occurred in deeper layers (Figure 7).

Peatland management and restoration planning

Understanding water table dynamics is crucial for improved peatland management and hydrological restoration, but obtaining water table data for many remote tropical peatlands is very challenging. Hydrological models have been used for
simulation of water table dynamics (Hooijer 2005; Wösten et al. 2006; Mezbahuddin et al. 2015; Ishii et al. 2016; Takeuchi et al. 2016; Cobb & Harvey 2019), but they require numerous inputs (e.g., peat properties, hydraulic parameters, and boundary condition), some of which are even more difficult to measure than WTD. Consequently, the use of such models is usually restricted to areas where measurement systems have been established. Our results provide evidence of the empirical relationship between WTD and rainfall and drainage network/land cover (Figures 1(a) and 2), information that is relatively easier to obtain, for example from remote sensing (Miettinen et al. 2016; Huffman et al. 2019). Despite higher uncertainty, estimation of WTD at a large scale by remote sensing can be used in fire forecasting systems for peatlands (Wösten et al. 2008). Hence, more studies of satellite-based remote sensing for peatland hydrology are needed.

Our WTD measurements contribute estimation of Sy for depth at –1.7 m, much deeper than achieved in similar studies in pristine tropical peatlands (Hooijer 2005; Cobb & Harvey 2019). Sy is essential for hydrological modelling and can be used for restoration planning (Ishii et al. 2016), i.e., simulating the impact of drainage blocking on water table dynamics (Urzaíñki et al. 2020). However, restoration by raising the water table poses several issues in Padang Island, particularly for the agricultural sector. The dominant crops/plantations on Padang Island are non-native species such as pulp and rubber, which cannot tolerate inundated soil. Crops that are tolerant to shallow WTD, such as sago (Bintoro et al. 2018), are a better alternative for local communities. Other issues are increasing methane emission (Deshmukh et al. 2020) and slow recovery of vegetation (Dohong et al. 2018) and peat properties (Könönen et al. 2018). Overall, therefore, more research is needed to devise better strategies for the restoration of degraded tropical peatlands. Priority should be given to studies on (1) trade-offs between accuracy and detail of measurement, to develop cost-efficient hydrological monitoring at the landscape level, (2) ecohydrological processes such as vegetation response and tolerance to highly dynamic water tables, and (3) linking ground measurements to remote sensing data.

CONCLUSION

This study demonstrated the potential of using rainfall and drainage/land cover data to assess water table dynamics in tropical peatlands at a larger scale. A strong influence of rainfall and drainage/land cover was observed on water table dynamics on Padang Island, with WTD varying widely over time and space. At most measuring stations and transects studied, WTD was below the threshold of –0.4 m depth except in near-pristine forest and sago plantations, where WTD remained shallow. Rainfall–WTD analysis revealed a much lower rain-to-rise ratio in deeper layers, while recession curve analysis showed a high recession rate as nearby drainage systems extended the discharge to deeper layers. These distinct processes in water table dynamics compared with pristine tropical peatlands indicate that many areas on the island are susceptible to fire, urging improvements in water management. However, our results suffered high uncertainty due to difficulties in ground measurement and monitoring in remote tropical peatlands, expressing the need for further studies with in situ measurements.

ACKNOWLEDGEMENTS

This study on Padang Island was a collaborative project by the Indonesian restoration agency (BRG) and Universitas Gadjah Mada (UGM), supported by the United Nations Development Program (UNDP), while this article was prepared together with the University of Oulu through WaterPeat project funded by EU WaterJPI program and KONE Foundation, Finland.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

REFERENCES


First received 15 April 2021; accepted in revised form 11 October 2021. Available online 28 October 2021.