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Assessing rainfall pattern, groundwater level, and peat hydraulic conductivity for effective peat prevention measure

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Abstract. Severe drought and less precipitation during a prolonged dry season and El-Nino events has been observed as a main trigger of the decrease of groundwater level leads to the dryness of the degraded peat and exacerbates burning conditions. To get a better understanding of this issue, we studied fire conditions in a portion of the ex-Mega Rice Project (MRP) area, Central Kalimantan. Here, we examine fire season and hydrology factors affecting peat fires by using Terra/Aqua MODIS hotspots dataset and groundwater level data from 300 dipwells and 15 staff gauges established in the MRP area. We use the Interpolation Data Weighting (IDW) to explain the fire risk in the area based on its hydraulic conductivity. Our results clearly show that even the moderate to high rainfall intensity is not enough to rewet the dry-degraded peat and thus to leave them in dry condition. Here, we highlight the importance of considering the rainfall pattern of previous successive dry and rainy season for fire risk assessment. Most of the fires occurred in the area between 1.1×10^{-6} and 2.1×10^{-6} cm/s hydraulic conductivity and below -10 cm groundwater level, sharply pointing out the importance to keep degraded peat in wet condition for fire prevention.

1. Introduction

Peat fires in Indonesia have become a recurrent problem for the country, mainly in the peatland of Kalimantan and Sumatra. The severity of peat fire in Central Kalimantan was high and the burned area was enormous [1], leads the province as the largest tropical peat swamp forest where the peatlands were on fire [2].

All the peat deposits in Central Kalimantan were mainly covered with peat swamp forest but most of them falls to degraded condition. The degradation was started from economic development in 1996 when they have been conquered to intensive drainage and conversion to rice fields and transmigration through the Mega Rice Project (MRP). The MRP was the failed project but resulted to the severe dry peatland during dry season. This leads to enhanced the ease of peat to be burned during drought and long dry season. Drought and fire have always been a part of the natural environment in Kalimantan [3].

Drought and fire affects near-surface hydrological processes [4]. Water balance influence the hydrological processes. Precipitation and groundwater level (GWL) are among the factors determine the water balance. Recurrent fires in the Ex-MRP area may result to the decreasing of peatland capacity for retaining and absorbing water from precipitation, lowering groundwater level and thus exacerbates burning condition. Fire have been shown to reduce hydraulic conductivity and infiltration on forest soils [5,6].



The relationship between fire season and hydrology factors is becoming a key way of describing vulnerability of peat to be burned. The objective of this paper is to examine the situation by linking the fire season and hydrology factors affecting peat fires by using Terra/Aqua MODIS hotspots dataset and changing groundwater level data from 300 dipwells and 15 staff gauges established in the Ex-MRP area. This information will become very important for fire prevention, mainly in the high fire risk peatland area.

2. Research method

The study area is located in the northern part of block A and southern part of block E of the Ex-MRP area (figure 1). We used 18-years of daily precipitation data from TRMM satellite (2000–2017) to illustrate precipitation patterns in the study area. The study area covers four TRMM pixels, thus we have four different precipitation regions for the study area (figure 2). The 16-years daily MODIS hotspot data (2002–2017) was used to explain fire occurrences and tendency in the area. To understand the GWL patterns in the area, we analyze the 8-years changing groundwater level data (2010–2017) from 300 dipwells. Further, precipitation and groundwater level data were used to estimate the hydraulic conductivity by using ellipse model [7] from 2010–2012 dataset.

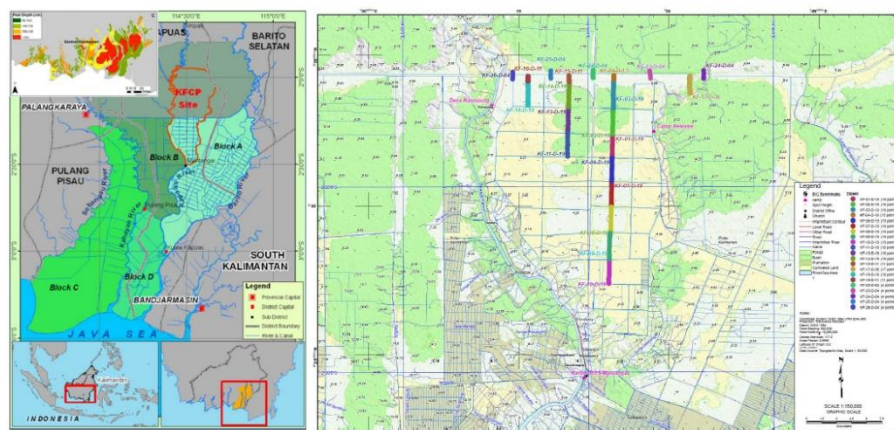


Figure 1. Map of study area (left) and location of 300 dipwells (right) [7].

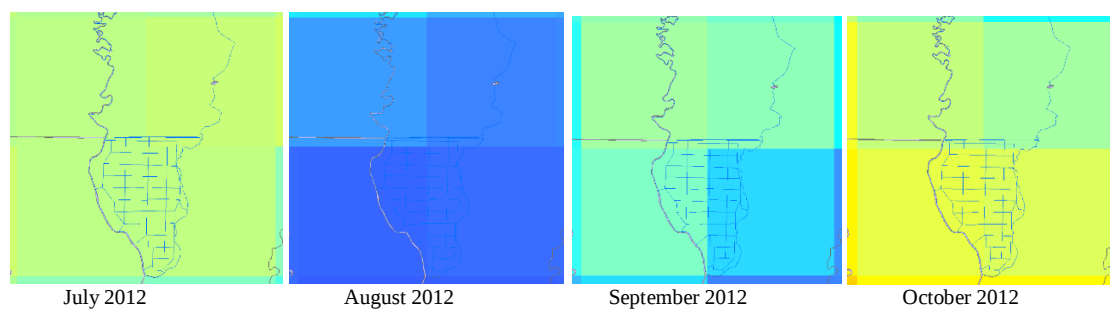


Figure 2. Monthly precipitation surrounding area, July–October 2012. The graduated color indicates precipitation rates; dark blue for lowest precipitation (0–10 mm), yellow for moderate rain (30–40 mm); light blue and green indicates precipitation rate between lowest and moderate.

We used the ellipse model [7] to estimate the hydraulic conductivity of the peat in the study area. The model is described in the following equation:

$$h^2(x) = h_{w}^2 + \frac{h_w}{s + \ell} \frac{R - ET}{K} (2sx - x^2)$$

Where:

$h(x)$	The groundwater level above the impermeable layer at a distance of x from the canal (m)
h_w	The water level in the canal above the impermeable layer (m)
R	Precipitation (mm day^{-1})
ET	Evapotranspiration (mm day^{-1})
K	Hydraulic conductivity (mm day^{-1})
x	Distance from canal (m)
$2s$	Distance between canal and canal (m)
ℓ	Canal width (m)

$h(x)$, h_w , x , $2s$, and ℓ were obtained by field observation data from the study area. R data from daily precipitation TRMM satellite and ET was calculated by Penman-Monteith method which available in RSNI T-01-2004 [8] as follow:

$$ET_0 = \frac{0.408\Delta R_n + \gamma \frac{900}{(T + 273)} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

Where:

ET_0	The standardized reference evapotranspiration (mm day^{-1})
Δ	Slope of the vapor pressure curve (kPa°C)
R_n	Net radiation flux ($\text{MJ m}^{-2} \text{day}^{-1}$)
γ	Psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$)
T	Daily mean temperature ($^\circ\text{C}$)
U_2	Wind speed at 2 m height (m s^{-1})
e_s	Saturation vapor pressure (kPa)
e_a	Actual vapor pressure (kPa)

3 Results and discussion

3.1 Precipitation and ground water level pattern

Central Kalimantan has two seasons namely a dry and a wet seasons. Previous studies [1, 9, 10, 11] have defined dry and wet season in Central Kalimantan by using the monthly precipitation. However, our analysis using 18-years daily precipitation suggests start of July to middle of November as a dry season in Central Kalimantan (figure 3). Dry season may bring the severe dry condition of fuel and peat in the area, and thus increasing its risk to be flamed. According to Hooijer *et al.* [12], the normal dry season in Central Kalimantan happens on July–October. However, recently the area has been suffering from longer lack of precipitation as daily precipitation drops below its mean value from the middle of May to the end of October. A wet season in Central Kalimantan usually still happens on May and June [13], but our study reveals that recently longer dry season may occurs in the study area.

The groundwater level (GWL) could be one of the key indicators assessing fire risk in peatlands because the dryness of peat and the moisture content of surface peat are directly influenced by GWL [10]. In its natural condition, peat always inundated with water [13]. However, our prolonged research observed the deficit of GWL in the area for the whole of the year [14], it was the unnatural phenomenon for the peat hydrology system. This study reveals the similar findings. The recent GWL in the area remains in negative value below peat surface for almost whole of the year. It may greatly explains the severe dry condition of the peat in the area and my indicates the peat has loss its ability to absorbing and storing water (hydrophobic condition). This condition exacerbates peat burning conditions in the area.

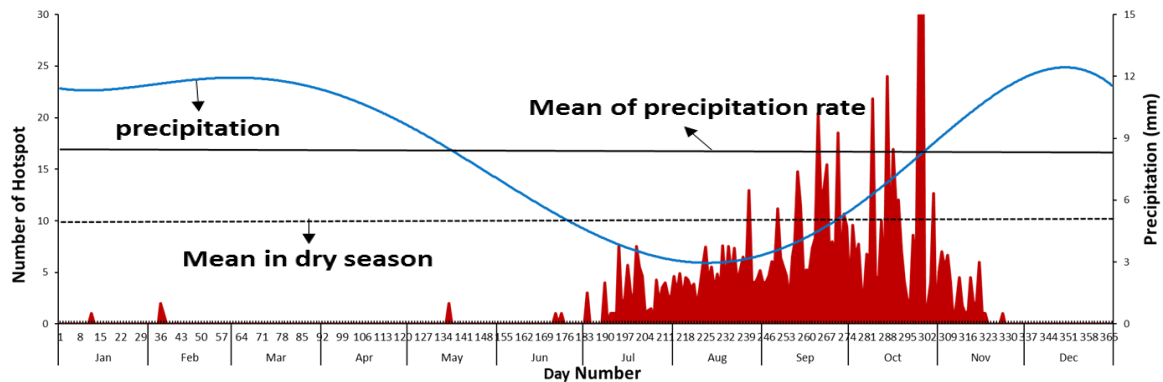


Figure 3. Hotspot and precipitation tendency in the study area.

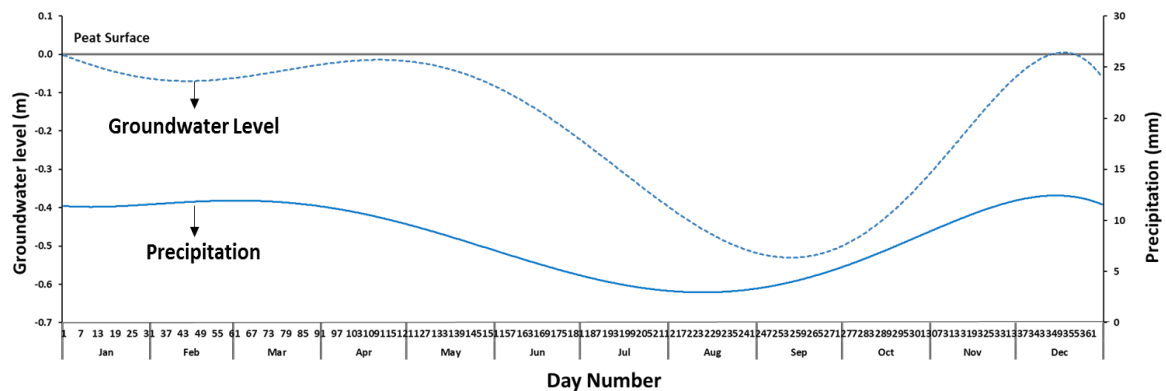


Figure 4. Precipitation and groundwater level tendency in the study area.

We found the decreasing tendency of groundwater level during dry season and a-month time lag between lowest precipitation in the middle of August and lowest groundwater level in the middle of September (figure 4). Combination of early dry season and low GWL accelerate the ease of the peat to be ignited, resulted to the start of fire season in around 60 days after the start of the steep decrease of precipitation (figure 3).

Precipitation and groundwater level were associated each other. Normally, groundwater level will be increased after the peatland having high precipitation and will be decreased under low precipitation. Dry peat condition leads to the decreasing of GWL. Ludang *et al.* [15] remarked that precipitation and vegetation of peatland affect significantly surface temperature as well as groundwater table. However, the drop of groundwater level under ground surface in recent year may indicates that the decreasing of peatland capacity in the area to store water. This condition exacerbates peat burning conditions in the area.

A dry month is determinated by Mackinnon *et al.* [16] as month with less than 100 mm mean monthly precipitation, and a wet month when the mean monthly precipitation exceeds 200 mm. Figure 5 showed that number of hotspot reached its highest number in the dry season 2014 and 2015, when precipitation fell to less than 100 mm. However, high number of fires happened in dry season 2011 and 2012 when precipitation was occurred more than 100 mm but less than 200 mm, indicating that moderate rainfall in dry season still not enough to stop the fires in the degraded peatlands once it occurred.

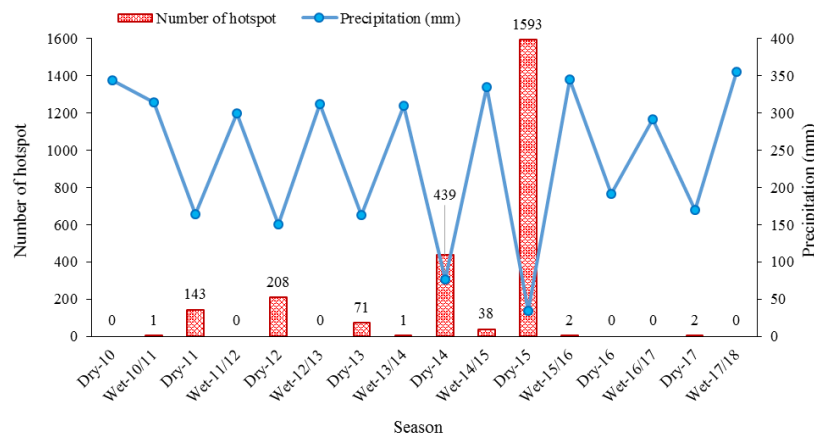


Figure 5. Precipitation and hotspot tendency beased on wet and dry season.

Figure 6 showed that a large number of hotspot occurred in 2012 and 2013 when the long dry season followed by the dry-rainy season (rainy season with lower precipitation than normal). In 2011, precipitation decreased gradually from May and reached the lowest point in August, creating the necessary dry conditions for fires to ignite. Equally, a large number of fires began to occur in July and became numerous during August and September. The end of fire season occurred during October in 2011, after having peak fire periods in September 2011. A large number of fires started again during August 2012, three months after the precipitation start to decrease in June 2012.

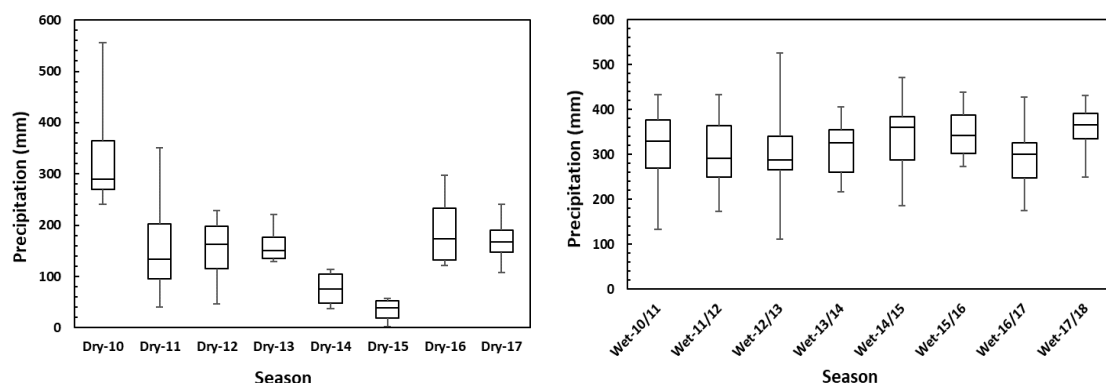


Figure 6. Box and whisker plots showing precipitation in the dry season (July–October) and wet season (November–June), respectively.

The same condition observed in 2013 when fires started to occurred in July 2013 after having gradual decrease of precipitation from May 2013. That conditions will drive a high intensity of peat fires. This peat fire occurrence tendencies may indicate that peat in the study area is still quite dry into the beginning of wet period, after suffering from severe dry conditions for prolonged dry periods. The rainfall intensity in the wet season 201/2012 and 2012/2013 were fell less than 300 mm and thus we categorized them as the dry-rainy season.

The severe dry season occurred in 2014 when the study area suffered from long dry season of less than 100 mm precipitation. This condition may result to the most severe dry condition of the peat during dry season and the coming moderate rainfall was not enough to rewet the peat there. Wet season 2014/2015 was having moderate rainfall between 300–400 mm, but huge number of fires was occurred in the dry season 2015 of more than 1500 fires. These findings, therefore, strongly recommends the use of precipitation pattern analysis in the previous successive dry and wet (rainy) seasons for better assessment of the fire risk in the upcoming dry season.

3.2 Hydraulic conductivity after fire

Hydraulic conductivity is an essential parameter to understanding the movement of groundwater [17]. Hydraulic conductivity is related to the peat's water holding capacity and rate of consolidation. During dry season 2010–2012, the highest mean hydraulic conductivity in the study area was 4.4×10^{-6} cm/s and the lowest was 1.4×10^{-6} cm/s. Whereas, during wet season 2010–2012, we record the highest mean hydraulic conductivity was 4.0×10^{-6} cm/s and the lowest was 3.4×10^{-6} cm/s. Mean of hydraulic conductivity tends to decreasing in the dry season and increasing in the wet season.

Figure 7 clearly shows that hydraulic conductivity and fire occurrences tendency are associated each other. Hydraulic conductivity decreases after the peatland having fire and increases gradually but still in a low value. The impact of fire on macropore flow may be related to the collapse of pores due to consolidation of bare peat subject to drying [18, 19]. The reduction of macropore leads to the decrease of hydraulic conductivity.

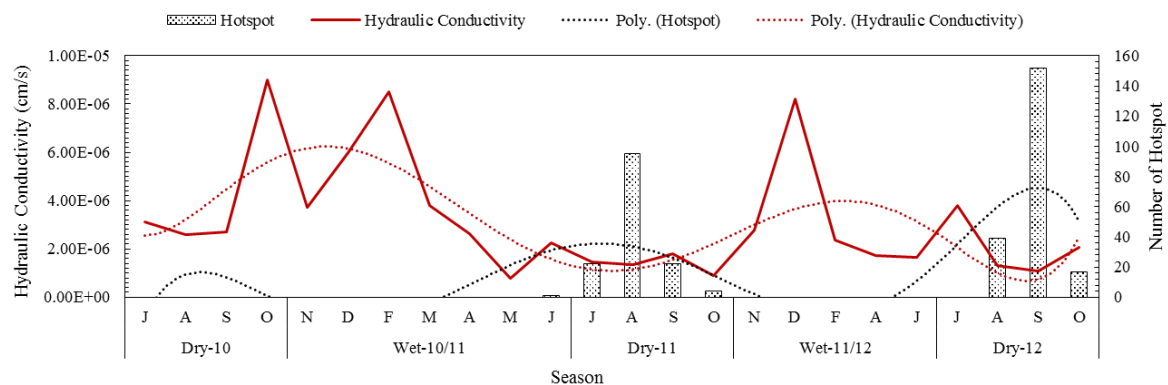


Figure 7. Hydraulic conductivity and hotspot tendency in the dry season (July–October) and wet season (November–June), 2011–2012.

Most of the fires in the study occurred under hydraulic conductivity between 1.1×10^{-6} and 2.1×10^{-6} cm/s (figure 8). Our previous research [20] showed that surface fires may occurred under GWL of less than 10 cm below peat surface. These findings strongly suggest that degraded peatlands are very vulnerable to fires even under relatively moist conditions. Therefore, we sharply pointing out the importance to keep degraded peat in wet condition for fire prevention. Here, we support the application of canals blocking as the best approach to maintain degraded peat in wet conditions for both of rainy and dry seasons.

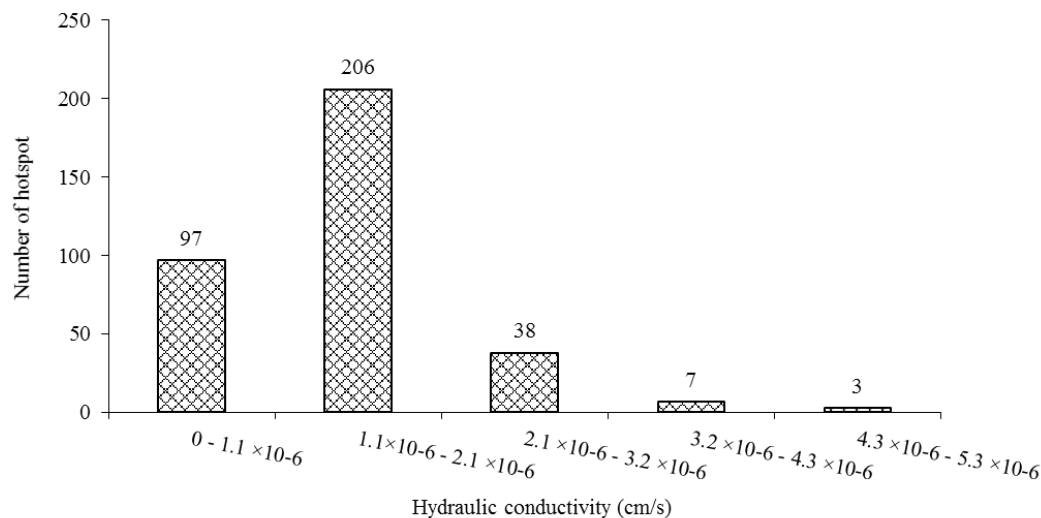


Figure 8. Hydraulic conductivity and number of hotspot in 2011 and 2012.

4 Conclusions

Most of the hydraulic conductivity of the peat in the area falls to a very low values, illustrating the loose of peat capability in the area to retain water. This condition leads to the high fire risk in the area when even the moderate to high rainfall intensity is not enough to rewet the dry-degraded peat and thus to leave the degraded peat in dry condition. Here we clearly show the great effect of the rainfall pattern of previous successive dry and rainy season to the fire occurrences in the upcoming dry season. Most of the fires occurred in the area between 1.1×10^{-6} and 2.1×10^{-6} cm/s hydraulic conductivity and below -10 cm groundwater level, sharply pointing out the importance to keep degraded peat in wet condition for fire prevention. Canals blocking, therefore, should be applied as the best approach to maintain degraded peat in wet conditions for both of rainy and dry seasons.

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