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Paper:

Drought Index for Peatland Wildfire Management in Central Kalimantan, Indonesia During El Niño Phenomenon

Novitasari Novitasari*, **Joko Sujono***,†, **Sri Harto***, **Azwar Maas****, **and Rachmad Jayadi***

*Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada
Jl. Grafika No 2, Yogyakarta 55281, Indonesia
†Corresponding author, E-mail: jsujono@ugm.ac.id
**Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, Indonesia

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Peatland wildfires, especially in tropical ecosystems, are often caused by drought, and lead to smoke and other related problems in all aspects of community life in Indonesia, especially in Central Kalimantan. Drought is worsened by the number of dry days in the dry season, known as the El Niño phenomenon, and the drainage system in a peatland. Additionally, drought decreases the water table and increases the probability of occurrence of wildfires in peatland areas. This study aims to modify the numerical formula of the drought factor (DF_t) in the Keetch–Byram drought index (KBDI) based on tropical peatland wildfire conditions in Central Kalimantan during the El Niño phenomenon in 2015. Furthermore, it applies a revised peatland water table reference of 400 mm below the ground surface, based on previous research and the Government regulation on peatland ecosystem protection and management in Indonesia. These El Niño conditions caused a rain decline of approximately 35% in Block A, Ex-Mega Rice Project, Mantangai sub-District, Kapuas District, Central Kalimantan Province. The modified KBDI is compared with the Number of Fire Alerts (NFA) using NASA's Active Fire Data in 2015. The analysis results demonstrate that the modified DF_t under tropical peatland conditions leads to an increase in the drought index value, beginning on the driest days between July and November 2015. The value of the KBDI drought index increases from the high to the extreme index from September to November 2015, when as many as 61 extreme drought indices became indicators for peatland wildfire risk assessment. The extreme KBDI is directly proportional to the NFA recorded during 2015, and the highest number of fire alerts is observed for October 2015, with 1746 fire alerts within 31 days and extreme drought indices from 27 days. Hence, this modified formula is suitable for wildfire conditions on this peatland in Central Kalimantan. Overall, the modified DF_t can be successfully applied to the El Niño phenomenon in 2015.

Keywords: Keetch–Byram drought index (KBDI), number of fire alerts, El Niño, water table, peatland wildfire

1. Introduction

The forest wildfires of 2015 were the largest wildfires in Indonesia for the last ten years in terms of the amounts of trace gases and aerosols released, which have been monitored in several previous studies [1]. The severity of theses wildfires was similar to the disaster that occurred in 1997 [2]. Forest wildfires in Indonesia not only occur in upland environments but also in wetlands [3]. These forest wildfires mainly occur in tropical peatlands [4]. Wildfires in tropical peatlands occupy an area equivalent to 10.8% of Indonesia's land area [5]. Among tropical countries, Indonesia has the largest area of tropical peatland, which is approximately 14 million ha and is mainly found in Sumatra, Kalimantan, and Papua [6]. Indonesia's peatland is a part of the wider tropical peatland habitat in Southeast Asia [7]. Tropical peat comprises accumulated organic materials in a wetland ecosystem [8]. Tropical peat is formed in forests under wetland conditions with the production of large quantities of organic materials [9, 10].

Indonesia's peatland has been developed by the building drainage systems. Canals are intended to decrease the water table in the peatland. These canals are utilized to support the cultivation of crops, such as oil palm and acacia. The resulting decrease in the water table can cause the peat to become overdrained and thereby make it flammable, damaging the ecological balance and eliminating forest and peatland biodiversity [10]. Peatland is commonly burned to minimize production cost; however, this practice may cause uncontrolled peatland wildfires [11]. In addition to human-caused fires, peatland wildfires are caused by meteorological drought factors, such as a lack of rainfall and high evaporation rate [12]. Dry peatland, which is fundamentally unstable, loses water from the soil, allowing oxygen to penetrate the pores and oxidize the peat through biological and chemical processes [13]. Peatland wildfires not only cause rainforest degradation [14] and affect biodiversity [15], but also release smoke and carbon emissions to the atmosphere; fire harms nearby communities and leads to the loss of lives and property [16]. Peatland wildfires slowly spread through the surface, and those classified as smoldering fires are absorbed by the subsurface and organic layers [17]. This type of fire is difficult to detect [18]. Smoldering wildfire causes the lateral spread of flames under different moisture and wind conditions [19] and creates strong smoke that spreads over extensive areas [20]. Drought and fires are important components for the assessment of the dynamics of tropical peat forests [21].

The risk of wildfires increases as the frequency and duration of drought increases [22]. Natural drought is a condition that cannot be managed [23] and has affected millions of square kilometers of land in many areas, such as North America, West Africa, and East Asia [24]. In Indonesia, drought in peatlands leads to sub-surface wildfires all around the ecosystem. These wildfires cause smoke to spread to other countries, such as Malaysia [25]. Fires occur almost every year in Indonesia during the dry season. Wildfires usually occur between June and September and intensify during El Niño [26]. El Niño is a natural phenomenon characterized by the warming of temperatures in the Pacific Ocean and causes drought in the Asian region [27]. El Niño decreases the amount of rainfall in Indonesia [16].

A situation with lower than average water availability due to climate variability may cause drought [28]. The limitations for drought have not yet been widely agreed upon, which indicates that drought is a region specific event. However, there are several types of drought that can be used as reference. A decreased amount of rainfall is also one of the causes of drought, namely, meteorological drought [29]. This type of drought appears in various components of the hydrological cycle [30]. Drought is not only caused by meteorological factors (lack of precipitation), but also by agricultural (lack of soil moisture), hydrological (lack of river discharge and dam inflows), and socio-economic (lack of water supply to meet water demand) factors [29, 31].

In Indonesia, meteorological drought is often accompanied by dry peatland caused by the decline in the water table and changes in the physical properties of peat due to the drainage system. Some fires are also caused by human activities, such as land clearing. The blocking of canals can reduce the degradation of peatlands to a larger extent [32]. Additionally, it can also help to maintain the water table [33] to prevent drought on peatlands.

The process by which drought leads to wildfires is a complex process, and a drought index cannot be easily specified. No index can fully explain the complexity of drought and its impacts [34]. A drought index can be used as an indicator to determine the classification of the drought level of a particular region or area [28]. Many drought indices have been expanded to appraise the scale, type, and impact of drought [35]. Many drought indices are easy to build and use, based on meteorology data, soil moisture, hydrology, and remote sensing [36]. One formula that uses meteorological data is the standardized precipitation index (SPI) [29] and the Keetch–Byram drought index (KBDI) [37].

Some drought indices are built for specific uses and environments. In forestry, many drought indices are designed for fire risk assessment [38]. The most widely used drought indices are the Nesterov index, Zhdanko index [39], Angstrom index [40], Baumgartner index [41], McArthur forest fire danger index [42], and KBDI [43]. KBDI is one of the most widely used indices for forest fire management under various climatic conditions [2, 34]. KBDI was first developed for forest fire management in the sub-tropical Florida region in USA [3]. KBDI was also developed to be suitable under Mediterranean conditions, providing accurate results for forestry and fire risk management in Thessaloniki, Northern Greece [44]. Therefore, this study aims to test the behavior of KBDI, modified for peatland wildfires in Central Kalimantan under tropical climate conditions affected by the El Niño disaster in 2015, when the El Niño conditions caused a significant rainfall decline in most parts of Indonesia.

2. KBDI Index Modification

2.1. KBDI and Wildfire Risk Assessment

KBDI was first introduced to manage forest fire control under a sub-tropical climate. This index represents the net effect of evapotranspiration and precipitation on cumulative moisture deficiency in deep duff or upper soil layers, and is related to the flammability of organic materials in the ground [43]. KBDI is applied to human activity-caused fire and sub-surface fire, and is determined using Eq. (1).

$$KBDI_t = KBDI_{t-1} + DF_t - RF_t, \quad \ldots \ldots \quad (1)$$

where DF_t is drought factor (mm), RF_t is rainfall factor (mm), and t is time (day).

The value of the rainfall factor (RF_t) is determined using meteorological data, in the form of annual rainfall and daily rainfall. An RF_t of more than 5.1 mm/day is considered a reduction in the drought index and is determined using the following equation [43].

$$RF_t = \begin{cases} (R_t - 5.1), & R_t \geq 5.1 \text{ mm/day, 1st rainy day}, \\ R_t, & R_{t-1} \geq 5.1 \text{ mm/day, 2nd and the next rainy day}, \\ 0, & R_t < 5.1 \text{ mm/day}, \end{cases} \quad (2)$$

where R_t is daily rainfall at t and R_{t-1} is daily rainfall at $t-1$.

The drought factor (DF_t) was determined based on the basic theory of soil moisture degradation in the forest area by assuming the following: (1) the field capacity of the organic layer is considered as 203 mm of water in excess of moisture held by the layer at the wilting point; (2) the organic soil layer obtains moisture from rainfall and loses moisture from evapotranspiration, and the lowest moisture level is detected at the wilting point; (3) the rate of evapotranspiration is a function of meteorological variables and vegetation density, and (4) the vegetation density is a function of the mean annual rainfall [43]. The basic formula of DF_t from Eq. (18) of [43] is modified

Table 1. Climate variables and the coefficient drought factor.

Variable	Subtropical	Tropical
T_m [°C]	26.67	26.67
R_0 [mm]	1270	2540
a	0.9667	0.4982
b	0.0875	0.0875
c	8.30	4.27
w_c	203	203

with [37] for tropical condition, and [45] for the a, b, and c coefficients as follows:

$$DF_t = (w_c - KBDI_{t-1}) \frac{\left(ae^{(bTm+1.5552)} - c\right) 10^{-3}}{1 + 10.88e^{(-0.001736R_0)}}, \quad (3)$$

where DF_t is drought factor (mm), w_c is corresponding field capacity of available water in the layer (mm), $KBDI_{t-1}$ is moisture deficiency (KBDI at $t-1$), T_m is daily maximum air temperature (°C), t is time increment (day), R_0 is average annual rainfall (mm), a and c are coefficients influenced by the mean annual rainfall (R_0), and b is coefficient influenced by evapotranspiration.

In a sub-tropical climate, the average annual rainfall R_0 is 1270 mm, maximum temperature (T_m) is 26.67°C, and corresponding field capacity of available water in the layer (w_c) is 203 mm [43]. $t_{26.67;R_0}$ from Eq. (13) of [43] gives $t_{26.67;R_0} = 56.41$ days. If $R = \infty$ and $R_0 = 1270$ mm for a subtropical climate, $t_{26.67,\infty}$ from Eq. (16) of [43] gives $t_{26.67,\infty} = 0.4545\, t_{26.67;1270} = 25.64$ days.

[37] modifies the drought-factor formula (DF_t) affected by tropical annual rainfall (R_0) as 2540 mm, w_c, and the temperature used is the same as that in [43], which is 26.67°C. w_c is 203 mm. [37] adjusts the constants $t_{26.67,\infty}$ for a tropical condition from [37] as $t_{26.67,\infty} = 0.8831\, t_{26.67;2540} = 49.87$ days.

The coefficients a, b, and c for the sub-tropical condition [43] and tropical condition [37] are listed in **Table 1**.

2.2. KBDI Index Modification for the Tropical Climate

2.2.1. KBDI Index Modification for Tropical Wetland

[37] modified DF_t is affected by annual rainfall and evapotranspiration in a tropical climate through changing the values of the coefficients a and c. It was concluded that the loss of evapotranspiration in the tropical climate is 15% higher relative to that in the sub-tropical climate; thus, the coefficient b in **Table 2** become 0.0905 [37]. These coefficients are used as the modifications for the tropical wetland conditions in this paper.

2.2.2. KBDI Modified for Tropical Peatlands Followed by El Niño

The formula of DF_t (Eq. (3)) has been developed to represent the average rainfall conditions for wildfire risk control in tropical wetland ecosystems. However, wildfires in tropical forests, especially those in Indonesia's tropical forests, are also affected by the El Niño phenomenon, which causes extreme warming to the equatorial Pacific. El Niño causes severe droughts in Australia, Indonesia, India, and South Africa, as well a reduction in average rainfall [27]. In 2009, the Southern part of Kalimantan received low precipitation, which caused peatland drying and the easy spread of fires [46]. Analysis of rainfall from three stations in the study area indicates that when El Niño occurred in 2015, rainfall decreased by approximately 35% from the annual average rainfall. The annual rainfall in 2015 at the study area was 1650 mm. The evaporation time for the same temperature used by [43] was 26.67°C.

Table 2. Climate variables and the coefficient drought factor for tropical wetland and peatland condition.

Parameter	Tropical wetland	Tropical peatland due to El Niño
T_m [°C]	26.67	26.67
R_0 [mm]	2540	1650
a	0.4982	0.3614
b	0.0905	0.0905
c	4.27	3.10
w_c	203	400

In addition to the changes in the coefficients a and c on DF_t, w_c was also modified. In the initial equation of KBDI, the w_c value is assumed to be 203 mm of the soil water available for evapotranspiration [43]. The w_c value was on the scale from 0 to 203, where 0 denotes no moisture depletion, and 203 indicates the highest depletion [37]. The w_c value is influenced by the depth of the reference water table. This value was based on peatland research in the Netherlands that used a 400 mm depth for the reference water table to avoid peat subsidence [11]. Peat dryness correlated with wildfire frequency and the reduction of groundwater level [47]. The Government Regulation of the Republic of Indonesia No. 57 of 2016 on peat ecosystem protection and management, clause 23 point 3, states that peat ecosystems with a cultivation function could be damaged if the water table depth is more than 400 mm below the peat surface [48]. Thus, for the El Niño modifications in this paper, R_o is set as 1650 mm, T_m is 26.67, and w_c is 400. Based on the above concept, adjustment constants using Eqs. (13) and (16) of [43] in tropical peatland gives $t_{26.67;\,1650} = 111.17$ days and $t_{26.67,\infty} = 0.617\, t_{26.67;\,1650} = 68.6$ days.

The decrease in rainfall affects the values of the coefficients a and c on DF_t in Eq. (3). The coefficient b used is 0.0905 [37]. **Table 2** shown climate variables for modification 1 (tropical wetland conditions [37]) and modification 2 (tropical peatland conditions due to El Niño) in 2015.

In the previous study, four fire danger classes were used, from 0 to 203 mm [37]. In the present study, the

Table 3. Drought index classes of KBDI modified for tropical peatland conditions.

Classes	KBDI index	KBDI index in tropical peatland
low	0–100	0–200
moderate	101–150	201–300
high	151–175	301–350
extreme	> 175	> 350

new value of w_c causes a change in the KBDI classes. The water table ranges from 0 to 400 mm. The water table at 400 mm below the surface is considered to cause the maximum drought index and a potential fire risk in the peat ecosystem. A water table of 0 mm, where water is on the surface of the land, is expressed as an ideal peat condition that is always inundated. Based on the new w_c value for the peatland condition, the value of the KBDI classes is corrected. Drought index classes are classified into four levels, as presented in **Table 3**.

3. Study Area and Methods

3.1. Study Area

The Mega Rice Project consists of one million hectares of peatland in Central Kalimantan and caused damage to the tropical peat forest [49]. It caused the large wildfire in 2015. The highest number of fire alerts (NFA) was recorded on October 19, 2015. The conditions of peatland wildfires in Kalimantan captured by the Moderate Resolution Imaging SpectroRadiometer (MODIS) from the NASA Aqua satellite are illustrated in **Fig. 1**. This image was taken on October 19, 2015; the red line indicates a hot spot where the sensors detected unusually warm surface temperatures associated with fires, and gray smoke signals the conditions [50].

The present study was conducted in Block A, the Ex-Mega Rice Project (EMRP) located in Mantangai sub-District, Kapuas District, Central Kalimantan Province, which is illustrated in **Fig. 2(a)** [51]. **Fig. 2(b)** depicts some post-wildfire conditions in the peatland around Block A in November 2015. This area underwent land clearing, which caused the peatland to become dry and flammable. A drought index for peat wildfire risk assessment was evaluated under peat wildfire conditions in 2015.

The largest wildfires occur in tropical peatlands, including the tropical peatland in Indonesia. Peat wildfires have previously occurred in the EMRP area in Central Kalimantan [52]. The Mega Rice Project was started legally on a Presidential decree 82/1995. The project caused 400 thousand ha of tropical rainforest cutting. EMRP was a program that failed considerably to conserve the peatlands in Indonesia [49]. The exploitation of forest and peatland in EMRP land occurred due to the construction of drainage network systems [49]. The drainage network systems divide peat domes, causing massive damage and resulting in the loss of function as field reservoirs, land subsidence, and a decreased water table [53]. This phenomenon causes irreversible peat drying, which triggers forest and peatland wildfires [54]. In addition to the decreased water table, peatland wildfires are caused by the rainfall reduction (the number of dry days), known as the El Niño phenomenon, which usually occurs from September to October.

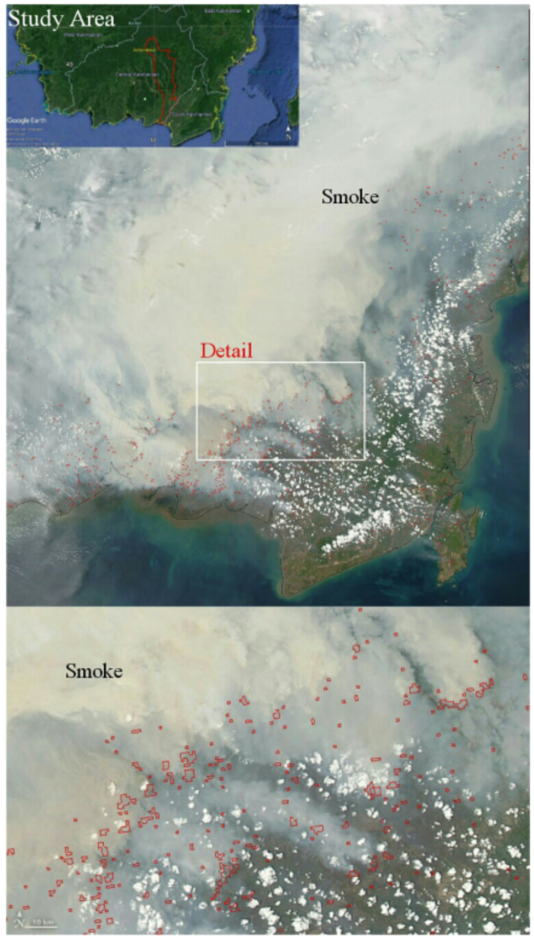

Fig. 1. Wildfires hazard was found on October 19, 2015.

Rainfall data was recorded near the study area, such as in Tjilik Riwut, Beringin, and Sanggu Rain Station [55]. Rainfall data was analyzed from 01 January 2015 to 31 December 2015, and there were a total of 263 dry days, which is more than 70% of the total in 2015. The NFA in the form of hotspots were obtained by using NASA's Active Fire Data to determine the possible location of fires. The system uses NASA MODIS satellites, which survey the entire earth every 1–2 days. The sensors on these satellites detect hot marks in infrared spectral waves. Dur-

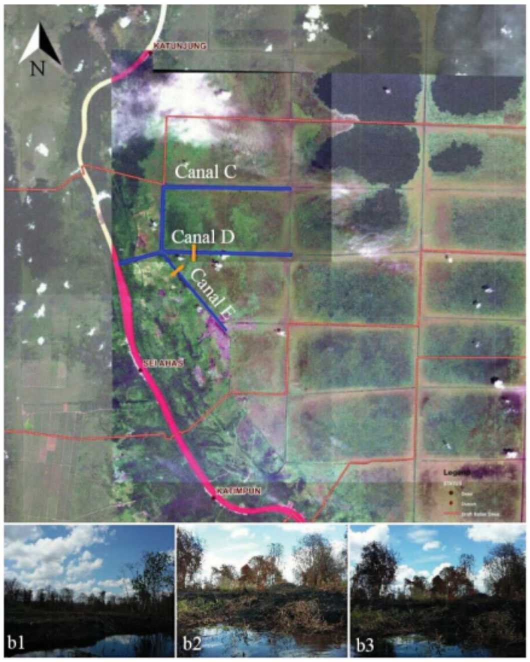

Fig. 2. (a) Study area on Block A of Ex-Mega Rice Project and (b) post-wildfire conditions in peatlands around canal C (b1), Canal D post-wildfire (b2), and Canal E post-wildfire (b3) in November 2015.

ing the processing of the satellite imagery, the algorithm looks for a heat sign and detects it as a fire sign. The system can indicate where a fire occurred and can provide a warning of high risk areas [56].

3.2. Methods

In this study, a modified KBDI was developed for wildfire risk assessment under tropical peatland conditions influenced by El Niño, with modification to the baseline groundwater conditions for peatland affecting the w_c value. The modified index was compared with KBDI under tropical wetland conditions [37]. The results of the two index modifications were compared against NFA recorded in the peat forest, Block A, Mantangai Subdistrict, Central Kalimantan Province, in 2015.

4. Results and Discussion

4.1. Rainfall Data

Based on the observations, rainfall from the three rain stations was almost uniform, with an average annual rainfall of 1650 mm in 2015. This rainfall value was below the average annual rainfall of areas with a tropical climate. The mean annual rainfall for areas with a tropical climate ranged from 2000 to 3000 mm [37]. This decrease in rainfall was caused by the El Niño in Indonesia. The average monthly rainfall at the three stations in the study site was the highest (134 mm) in November 2015. The net rainfall or rainfall factor (RF_t) was calculated using Eq. (2) to determine the number of dry days (**Table 4**). Dry day conditions were found on 29 days in July, 28 days in August, 30 days in September and 27 days in October 2015.

Table 4. Number of dry day and fire alerts.

	Number of the dry day	Number of fire alerts
Jan	9	1
Feb	26	0
Mar	17	0
Apr	17	3
May	23	1
Jun	21	1
Jul	29	19
Aug	28	488
Sep	30	1272
Oct	27	1746
Nov	18	10
Dec	16	3

4.2. Number of Fire Alerts Data

In 2015, there were 30,121 NFA events in the Central Kalimantan Province and 3,544 events in the Mantangai Sub-district. There were 3525 NFA events in Mantangai from July to November 2015, as much as 12.1% from the 29,171 events in Central Kalimantan. NFA increased from July to November 2015, and the largest number of NFA was observed in October 2015, with 1,741 events. This data indicates that the number of fire alerts in October represents half of the NFA for the year 2015, as presented in **Table 4**.

4.3. Keetch-Byram Drought Index (KBDI) Analysis

The results of the analysis using DF_t, under tropical wetland conditions [37] and under tropical peatland conditions influenced by the El Niño phenomenon are depicted in **Fig. 3**.

Figure 3 depicts an added line for the beginning of the extreme index, at 175 mm for KBDI modified for the tropical wetland condition, and at 350 mm for KBDI modified for tropical peatland conditions. The KBDI level, with DF_t formula for tropical wetland conditions, for a low index level from 0–100 was 218 values, the moderate index from 101–150 was 42 values, the high drought index from 151–175 was as much as 56 values, and the extreme drought index of more than 175 was 49 values. In the calculation of KBDI, with the modified DF_t formula for tropical peatland conditions including El Niño phenomenon, there were 59 values from the high level,

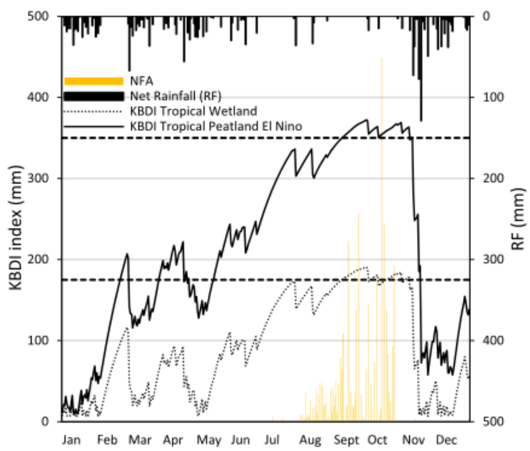

Fig. 3. Comparison of KBDI for tropical wetland and the modified KBDI for tropical peatland with the El Niño phenomenon.

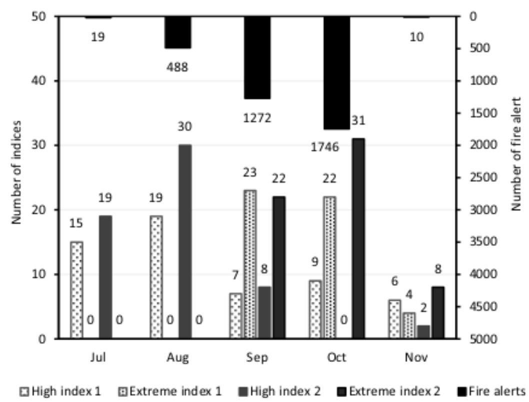

Fig. 4. Correlation between Keetch-Byram drought index (KBDI) values and number of fire alerts (NFA).

Table 5. Drought level conditions.

	Wetland conditions				Peatland conditions due to El Niño			
	Low	Mod	High	Extreme	Low	Mod	High	Extreme
Jan	31	0	0	0	31	0	0	0
Feb	23	5	0	0	26	2	0	0
Mar	30	1	0	0	30	1	0	0
Apr	30	0	0	0	21	9	0	0
May	28	3	0	0	20	11	0	0
Jun	25	5	0	0	0	30	0	0
Jul	0	16	15	0	0	12	19	0
Aug	0	12	19	0	0	1	30	0
Sep	0	0	7	23	0	0	8	22
Oct	0	0	9	22	0	0	0	31
Nov	20	0	6	4	15	5	2	8
Dec	31	0	0	0	31	0	0	0

and the extreme drought conditions increased to 61 occurrences, from July until November 2015. The class index is presented in **Table 5**.

Owing to the 35% reduction in rainfall occurring in the study area in 2015 due to El Niño, and the change in w_c caused by groundwater table change, the extreme drought index increased. High and extreme class results started at the beginning of the dry season from July. In calculating KBDI, with DF_t formula under tropical wetland conditions and tropical peatland conditions, high drought levels began to occur in early July 2015. Extreme drought levels began to occur in September 2015.**Fig. 4** shows the high and extreme classes in KBDI response (with the formula for tropical wetland conditions shown as modification 1, and KBDI with DF_t under tropical peatland conditions including El Niño as modification 2) against fire risk assessment represented by the number of fire alerts.

Figure 4 shows the high and extreme drought index results from the beginning of July to November 2015, representing the occurrence of fires beginning in July 2015, from KBDI modification for tropical wetland conditions and tropical peatland conditions. Two important findings are:

1. Index response with the DF_t formula for tropical wetland conditions

   Based on the analysis of KBDI with the DF_t formula for tropical wetland conditions, no extreme drought occurred at the beginning of July and August. Extreme drought indices occurred in September 2015 in 23 events, October 2015 in 22 events, and November 2015 in four events. Based on NFA data recorded in July, the study site had 19 fire alerts, followed by 488 fire alerts in August, 1272 fire alerts in September, and 1746 fire alerts in October. The highest level of extreme index results occurred in September 2015.

2. KBDI response to a corrected DF_t for tropical peatland conditions

   In the corrected DF_t formula for tropical peatland conditions affected by El Niño, with a rainfall reduction of 35% with $R_0 = 1650$ mm and groundwater level 400 mm, high to extreme drought levels were observed from September to November 2015, with 61 indices. The results for the extreme drought index were 22 events in September, 31 events in October, and eight events in November 2015. This finding is consistent with the NFA data, where the starting point of fire is in July and the highest number of fire alerts are in October, with 1746 fire alerts. These fire alerts conditions in October 2015 are predicted by extreme drought conditions that cover the whole 31 days of the month.

4.4. Discussion

This study was conducted on a peat fire situation in 2015 in Central Kalimantan. This study conducted analysis on KBDI results for data collected in 2015, comparing corrected DF_t modifications for tropical wetland conditions and tropical peatland conditions and the number of fire alerts in Mantangai Sub-district, with the results demonstrating that:

1. The modifications of the KBDI index for tropical peatland conditions adequately represents the real fire risk assessment data recorded in 2015. KBDI modification for tropical peatland conditions increases from the high index level to the extreme index level to the value of 350 and continues to rise to the maximum value of 400 starting on September 9, 2015, representing 109 NFA events that day. KBDI modification for tropical wetland conditions increased from the high index level to the extreme index level on September 9, 2015, represented by 65 fire alerts. These modifications of the KBDI for the conditions of tropical peatlands can demonstrate the potential for fire disasters in the study area.
2. In October 2015, there were 1746 NFA events in Mantangai, with the KBDI modification for tropical peatland conditions resulting in 31 days of extreme indices, while the KBDI wetland modification only resulted in 22 days with extreme indices. According to the modified DF_t for tropical peatland conditions, the extreme class is 12 points higher than KBDI modified for tropical wetland conditions. It rises from September to November 2015 in the study area, with the corrected water table of 400 mm.
3. The highest number of NFA was on October 14, 2015, with 449 fire alerts events represented by the extreme value in KBDI modified for tropical peatland conditions, while the KBDI modified for wetland conditions only resulted in high index results, as shown in **Fig. 3**.
4. The statistical parameter for extreme classes compared against the number of fires from July to November using linear regression for modification 1 gave R^2 as 0.828 with p-value 0.03. Modification 2 for tropical peatlands gave R^2 as 0.829 with p-value 0.03. It has been shown that both modifications give a good statistical result.

The modified KBDI for tropical peatland conditions seems to perform better in wildfire risk assessment in the Central Kalimantan during El Niño in 2015 compared with other KBDI formulas. The results follow those of previous Kalimantan Forests and Climate Partnership (KFCP) observations. A study by KFCP from 2004 to 2013 in the same study area showed daily wildfire patterns indicating fires at the same locations and in the same months. Fires occurred from late July to early November. The peak of the fires occurred in September [51]. Previous research from 2001 to 2010 found large-scale land management practices using fire, which caused smoke hazards from mid-August to late October [52]. We can consider the use of the empirical drought index formula for tropical peatland conditions to have several general principles, which are as follows:

1. The KBDI formula must be based on the net rainfall factor set by the R threshold. This threshold for tropical conditions still uses the same threshold as in the previous KBDI formula defined under sub-tropical conditions.
2. Peatland wildfires are not just caused by meteorological conditions but also by many internal factors in the soil, such as peat decomposition, physical properties, water holding capacity [52], and capillarity rise.
3. Peatland wildfires are also affected by unwise peatland management, such as building drainage canals in the peat dome, which results in a change in the water table.

Evaluation of the performance of KBDI under a range of climatic conditions, including a sub-tropical climate, Mediterranean climate, and tropical climate, reports that KBDI is a flexible drought index for almost all climatic conditions and may represent an important tool for forest fire control.

5. Conclusion

KBDI modification, by correcting the DF_t formula for the referenced water table level for peatland and with the influence of rainfall reduction due to the El Niño phenomenon, can accurately represent NFA in peatland. The analysis shows the results of the KBDI; drought factor (DF_t) correction for tropical peatland conditions, gave an extreme index (375 to 400 mm) occurring from September 9, 2015. Twenty-seven dry days caused 31 days of extreme index, represented by 1746 fire alerts in October 2015. The highest NFA number was on October 14, 2015 with 449 fire alerts events represented with this formula as an extreme value. Therefore, this formula provided satisfactory results in the El Niño conditions of 2015. Further testing is still needed to prove the formula for other El Niño events. In addition to the meteorological and water table factors in the KBDI formula, which affect drought management in peatland, several supporting factors must be considered, such as peat decomposition, physical characteristics, water holding capacity, and capillarity rise. The degraded physical properties of peatlands also lead to larger wildfires with the same number of dry days.

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Name:
Novitasari Novitasari

Affiliation:
Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada
Department of Civil Engineering, Faculty of Engineering, Universitas Lambung Mangkurat

Address:
Jl. Grafika 2, Yogyakarta 55281, Indonesia

Brief Career:
2005- Lecturer, Department of Civil Engineering, Faculty of Engineering, Universitas Lambung Mangkurat
2015- Student, Civil Engineering Doctoral Program, Universitas Gadjah Mada

Selected Publications:
• "Restoration of Peat Dome in Ex-Mega Rice Project Area in Central Kalimantan," American Institute of Physics Conf. Proc., 1977, 040008 (2018), DOI: https://doi.org/10.1063/1.5042978, 2018.

Academic Societies & Scientific Organizations:
• Indonesian Association of Hydraulic Engineers (HATHI)
• Indonesia Water Resources Association (JSDA-Indonesia)

Name:
Joko Sujono

Affiliation:
Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada

Address:
Jl. Grafika 2, Yogyakarta 55281, Indonesia

Brief Career:
1989- Lecturer, Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada
2016- Head, Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada

Selected Publications:
• "A comparison of techniques for hydrograph recession analysis," Hydrological Processes, Vol.18, No.3, pp. 403-413, 2004.
• "Improving the water productivity of paddy rice (Oryza sativa L.) cultivation through water saving irrigation treatments," Agricultural Sciences, Vol.2, No.4, pp. 511-517, 2011.

Academic Societies & Scientific Organizations:
• International Association of Hydrological Sciences (IAHS)
• Indonesian Association of Hydraulic Engineers (HATHI)

Name:
Sri Harto

Affiliation:
Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada

Address:
Jl. Grafika 2, Yogyakarta 55281, Indonesia

Brief Career:
1994-1997 Dean, Faculty of Engineering, Universitas Gadjah Mada

Selected Publications:
• "The characteristics of Unit Hydrographs with different scale of antecedent Soil Moisture Condition," J. of Engineering and Applied Sciences, Vol.11, Issue 12, pp. 2594-2601, 2016.

Academic Societies & Scientific Organizations:
• International Association of Hydrological Science (IAHS)
• International Association of Hydro-Environment Engineering and Research (IAHR)
• Indonesian Association of Hydraulic Engineers (HATHI)

Name:
Azwar Maas

Affiliation:
Department of Soil Science, Faculty of Agriculture, Universitas Gadjah Mada

Address:
Jl. Flora, Bulak Sumur, Yogyakarta 55281, Indonesia

Brief Career:
2012-2016 Head of Soil Science Study Program, Faculty of Agriculture, Universitas Gadjah Mada
2016- Chairman of Expert for Peatland Restoration Agency (BRG)

Selected Publications:
- "The tolerance of photosynthesis of some maize cultivars (Zea mays L.) to waterlogging at different stages of growth," Int. J. on Advanced Science, Engineering and Information Technology, Vol.7, Issue 4, pp. 1296-1301, 2017.
- "Characteristics of three biochar types with different pyrolysis time as ameliorant of peat soil," Indian J. of Agricultural Research. Vol.51, Issue 5, pp. 458-462, 2017.

Academic Societies & Scientific Organizations:
- Soil Science Sociaty (HIT)
- Indonesian Wild and Land Fires Associate (Karhutra)
- Indonesia Disaster Expert (IABI)

Name:
Rachmad Jayadi

Affiliation:
Associate Professor, Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada

Address:
Jl. Grafika 2, Yogyakarta 55281, Indonesia

Brief Career:
2009-2012 Head of Master Program in Natural Disaster Management, Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada
2016- Head of Undergraduate Program in Civil Engineering, Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada

Selected Publications:
- "Impact of Sedimentation Counter Measure on the Performance of Flood Control: A Case Study of Wonogiri Reservoir," Int. J. of Applied Mechanics and Materials, Vol.881, pp. 78-85, DOI: 10.4028/www.scientific.net/AMM.881.78, 2018.
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Academic Societies & Scientific Organizations:
- Indonesian Association of Hydraulic Engineers (HATHI)
- Indonesian National Committee of ICID (INACID)

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