Global J. Environ. Sci. Manage., 2023, 9(SI): 233-250

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

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SPECIAL ISSUE: Eco-friendly sustainable management
RORIGINAL RESEARCH PAPEER

Modeling of peatland fire risk early warning based on water dynamics

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ARTICLE INFO

Article History:
Received 13 June 2023
Revised 18 July 2023
Accepted 31 August 2023

Keywords:
Antecedent precipitation index
Early warning model
Ground water level
Peatland fire risk
Soil moisture

DOI: 10.22034/GJESM.2023.09.SI.14

ABSTRACT

BACKGROUND AND OBJECTIVES: To minimize the potential risk of land fires, climate monitoring and hydrology characterization are crucial factors in managing peatlands. Therefore, this study aimed to investigate the relation between climate variability and water dynamics to develop a peatland fire early warning model.

METHODS: This research was conducted in an oil palm plantation located in Pangkalan Pisang village, Koto Gasib subdistrict, Siak district, Riau province, Indonesia. Herein, the observed parameters were climate and dynamics of ground water level and soil moisture, which were monitored using data loggers installed on predefined representative locations and distributed over three blocks of 30 hectares in the palm oil plantation research site. Thus, the peat fire early warning model was developed based on the relation between peat water dynamics and the recorded history of peat fire events.

FINDINGS: Herein, a recession curve analysis of soil moisture and ground water level revealed the relation between soil water dynamics and local climate. Consequently, this study found that soil moisture was the suitable parameter to estimate peat fire risk owing to its predictability. Furthermore, this study has identified a threshold of low and high peat fire risk in the area with less than 104 percent and 129 percent dry weight of soil moisture content, respectively. Afterward, this soil moisture criterion was transferred into precipitation value to develop a peat fire early warning model for estimating the days left before a high peat fire risk status was attained based on the latest daily rainfall rates.

CONCLUSION: This study has developed a simple peat fire early warning model using daily precipitation data. The accurate estimation of countdown days to peat fire susceptibility status in an area would enhance fire mitigation strategies in peatlands.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
47	10	4

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Note: Discussion period for this manuscript open until April 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Indonesia's peatland of about 13,430,517 hectares (ha) is the fourth largest area after Canada, Russia, and the United States (Page *et al.,* 2002). This country's peatland area is distributed among its four main islands: Sumatera (5,850,561 ha), Kalimantan (4,543,362 ha), Papua (3,011,811 ha), and Sulawesi (24,783 ha) (Anda *et al.*, 2021). This peatland has long become an essential part of ongoing agriculture and economic development in Indonesia and its neighboring country, Malaysia (Evans *et al.,* 2019). However, since peatland cultivation poses high environmental risks, such as peat fire, global climate change, and land degradation, it must be closely monitored and regulated to eliminate its negative impacts (Page *et al.*, 2011; Turan and Turgut, 2021; Rodelo-Torrente *et al.*, 2022). From the 1990s, various scales of peat and forest fires have been recorded in Indonesia (Miettinen *et al.*, 2012). From 1997–2015, tropical peat fires in South East Asia were estimated to release about 0.8 to 9.43 Gigaton carbon dioxide (Gt CO_2) into the atmosphere, which was equivalent to ~30 percent (%) of the estimated global fossil fuel total emission in 2020 (Horton *et al.*, 2022). Therefore, increasing peatland cultivation could further raise the potential risk of peat fire because the drained peatland would expose the highly flammable carbon material. Additionally, peat fire would trigger an irreversible peatland degradation that contributes to large-scale anthropogenic ecosystem disruption, which in turn potentially leads to local and regional economic losses and health problems (Pribadi and Kurata, 2017; Herdiansyah and Frimawaty, 2021). Thus, to minimize the risk of peat fires, the Indonesian government has regulated the maximum depth of cultivated peatland ground water level (GWL) to 40 centimeter (cm.) However, determining the optimal GWL depth for cultivated peatlands with varying peat types is difficult because of its diverse peat soil physical properties (Taufik *et al.*, 2015). Moreover, actual peat water content depends on water level while soil capillarity influences peat moisture, especially during the dry season (Moyano *et al.*, 2013). Longer drought periods, such as El Niño period, increase the chance of peat fire occurrences. During the 2015 El Niño in Indonesia, fires occurred at about 8,500 km^2 of peatland in Sumatera and Kalimantan, including commercial plantations, small farmer lands, and degraded peatlands (Taufik *et al.*, 2019). Hence, the implementation of an early warning system (EWS) emerges as a pivotal strategy for effective mitigation of peat fire risk (Prasasti *et al.*, 2013). EWS helps identify high fire-risk locations so that earlier mitigation planning can be applied. Nugroho *et al.* (2019) proposed a peat fire EWS utilizing the wireless sensor network with three parameters, namely oxygen concentration, soil moisture, and ambient temperature. The system employed a web interface to display the spatially distributed predicted area that was vulnerable to fire risk to assist stakeholders in establishing a mitigation action plan for the targeted area. Meanwhile, Spessa *et al.* (2018) developed toward a fire early warning system for Indonesia (ToFEWSI), a peat fire EWS model based on climate and hydrology data to predict fire occurrences and mitigate their impact in the Riau province of Indonesia. Another peat fire EWS based on satellite imageries for sustainable palm oil plantations in Indonesia was developed by Yulianti *et al.* (2014). Other peat fire EWS, such as the probabilistic early fire warning system (ProbFire), was developed for Indonesia by Nikovonas *et al.* (2022) based on seasonal drought prediction analysis. The majority of the previously published EWS utilized satellite imageries as the main data input, and hence, focused on the identification of the spatial distribution of highly susceptible areas to peat fire. Depending on the satellite data used, these satellite-based EWS could have a very large identification scale that might reduce the efficiency and effectiveness of planned mitigation actions. Although exceptions should be made for the work by Nugroho *et al.* (2019), it should be noted that the use of specific hardware (sensors) and software systems could further complicate and increase the cost of EWS implementation and maintenance, especially for large-scale implementation. Therefore, this research offers a peat fire EWS model based on continuously monitored peat water dynamics. The detailed information on peat water dynamics at a field level would enhance the understanding of its influence on peatland biophysical characteristics and the effect of local climate variability on soil moisture and GWL dynamics, including its correlation to peat fire susceptibility. Moreover, this research specifically addressed a prevailing research question of the drought intensity level that will increase peat fire risk. Therefore, the current study aims to develop a EWS model to estimate drought period length in relation

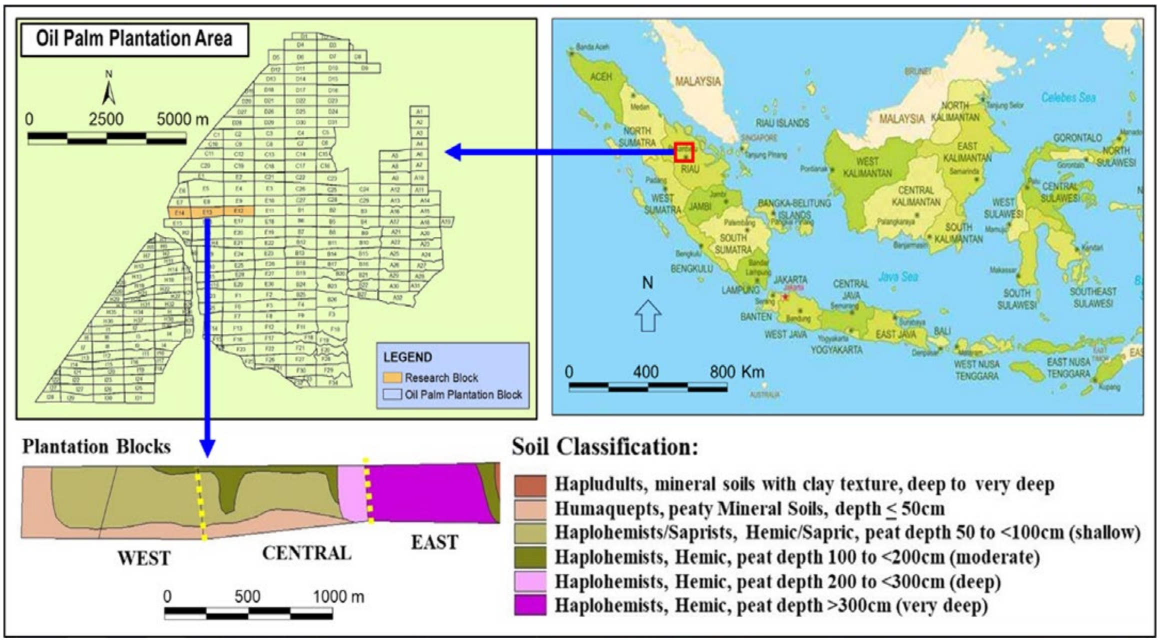

Fig. 1: Geographic location of the study area and the soil classification in Pangkalan Pisang village, Koto Gasib, Siak, Riau Province in Indonesia

to the increasing peatland fire susceptibility. This information could help decision makers to mitigate peat fire and its negative impacts on the surrounding environment. This study was conducted in a palm oil plantation in Pangkalan Pisang village, Koto Gasib subdistrict, Siak district, Riau province, Indonesia during 2021–2022.

MATERIALS AND METHODS

This study was conducted in a palm oil plantation in Pangkalan Pisang village, Koto Gasib subdistrict, Siak District, Riau Province, Indonesia during 2021–2022. The site is a freshwater topogenous peatland dominated by shallow (<3 m) peat depth located within the Gasib and Siak River peat hydrological area. Moreover, the Gasib-Siak peat hydrological area is a nonpeat dome region that covers about 3.487 hectares (ha) of peat area. The Gasib River, a tidal river with about 1.5 m magnitude, is located west of the study region and is the plantation drainage estuary. Three existing plantation blocks, each of about 30 ha (300 m x 1000 m), were selected as a water dynamic monitoring site. Fig. 1 presents the location of the three plantation blocks and the soil classification based on soil taxonomy (Soil Survey Staff, 2014). The peat soil depth in the study site varies between 50 cm and 300 cm (shallow to very deep) while the peat decomposition level is between Hemic and Sapric (moderate to highly decomposed peat soils).

From 2011 to 2019, the local average monthly precipitation data in the study area showed a wet climate with more than 2,500 mm in annual precipitation. Bimodal rainfall seasonal patterns with two distinct periods of high precipitation were identified throughout the year; one occurred during April while the other around November. Moreover, observed air temperatures were between 26.64 and 28.40˚C while relative air humidity were between 36.13% and 61.01%. The potential evapotranspiration (PET), calculated using the Penmann method, fluctuated relatively constant throughout the year with an average of about 82 mm (Penman, 1948). The highest PET value was recorded during March at 91 mm while the lowest was identified in December at 71 mm. Continuous water dynamics monitoring was performed using three water level loggers, one soil moisture logger, and one automatic weather station. The water level loggers were installed at the center of each block while the soil moisture logger was installed at the center of the East Block with the recording interval of each automatic data logger set to 30 minutes (min.). Soil Moisture Content (SMC) observation was exclusively conducted within the East Block because of several factors that include a deeper peat soil layer, a higher degree of peat decomposition, and the more distinctive presence of mineral soil compared to the other two research blocks. The weather station was located at 0.674929˚N and 101.733261˚E, about 3 km south of the research blocks, and was set to record data on a daily interval. The GWL and SMC recession rates were analyzed based on recorded data using the recession curve derived from Eq. 1 (Toebes *et al.,* 1969):

$$H_t = H_0 * exp^{(-k \cdot t)} \quad (1)$$

Where, H_t is the GWL or SMC at time *t*, H_o is the initial GWL or SMC, *k* is the recession constant, and *t* is the time interval.

The peat fire early warning of this study was modeled using two different methods: simple linear regression and the deterministic model based on the simulated SMC. Also, the simple linear regression model considered a correlation between precipitation that was represented by an antecedent precipitation index (API) and soil moisture recession rate during a no-rain days period. The API was calculated using Eq. 2 (Koehler and Linsey, 1951):

$$API = \sum_{t=-1}^{-d} R_t k^{-t} \quad (2)$$

Where, R_t is rainfall during period *t*, *k* is the decay constant, and *d* is the considered number of antecedent days. Meanwhile, the simulated SMC for deterministic modeling was calculated based on the equation that was developed by Georgakakos and Baumer (1996). SMC for each unit area was estimated based on the surface soil water balance at a certain soil depth D (i.e., a rainfall storage zone) that is later reduced by evapotranspiration and soil drainage processes over time. The SMC simulation formulas are presented in Eqs. 3, 4, 5, and 6 (Georgakakos and Baumer, 1996).

$$W_{(t)} = W_{(t-1)} + INF_{(t)} - PET_{(t)} - PER_{(t)} \qquad W_{(t)} < W_{max} \quad (3)$$

$$INF_{(t)} = R_{(t)} \left(1 - \frac{W_{(t)}}{W_{max}}\right)^m \quad (4)$$

$$PERC_{(t)} = K_S \left(\frac{W_{(t)}}{W_{max}}\right)^{3+\frac{2}{\lambda}} \quad (5)$$

$$W_{(t)} = \left[\theta_t - \theta_\tau\right] D \quad (6)$$

Where, $W_{(t)}$ is daily SMC (mm), $W_{(t-1)}$ is daily SMC before t (mm), $INF_{(t)}$ is daily infiltration (mm), $R_{(t)}$ is daily rainfall (mm), W_{max} is the maximum soil water holding capacity (mm), m is the infiltration constant, $PET_{(t)}$ is the daily evapotranspiration (mm), $PER_{(t)}$ is the daily percolation (mm), *Ks* is the hydraulic conductivity (m/s), *l* is the soil pore index based on the soil layer structure, qt is the saturated water content (m^3/m^3), qt is the water content (m^3/m^3), and D is the soil depth (m). This study specifically used SMC in the unit of percent dry weight to correlate the field data with peat fire risk which was calculated using Eq. 7 (Moorberg and Crouse, 2021):

$$SMC_{w/w} = \frac{SMC_{v/v}}{BD} * 100, \quad (7)$$

Where, $SMC_{w/w}$ is the soil moisture content based on dry weight (%), $SMC_{v/v}$ is the soil moisture content based on volume (%), and BD is the soil bulk density in dry weight per volume (gr/cm^3).

RESULTS AND DISCUSSION

Ground water level dynamic

Fig. 2 depicts the high temporal dynamics of GWL observations in the eastern, central, and western blocks from January to December 2021. Recorded data for the eastern block showed that the GWL reached a maximum of 107.9 cm/30 min on June 6, 2021, at 15:00 and a minimum of 28.2 cm/30 min on April 22, 2021, at 6:30. The average GWL in the eastern block during the observation period was 66.9 cm/30 min.

Recorded data for the central block indicated that the maximum GWL of 92.70 cm/30 min was reached on February 27, 2021, at 15:30 while the minimum of −3.10 cm/30 min was recorded on April 22, 2021, at 6:00. The average GWL for the central block during this period was 37.81 cm/day. Similarly, recorded data from the western block showed that the maximum GWL of 117.5 cm/30 min was detected on March 6, 2021, at 14:30 while the minimum GWL at 11.0 centimeter per minute (cm/min) was reached

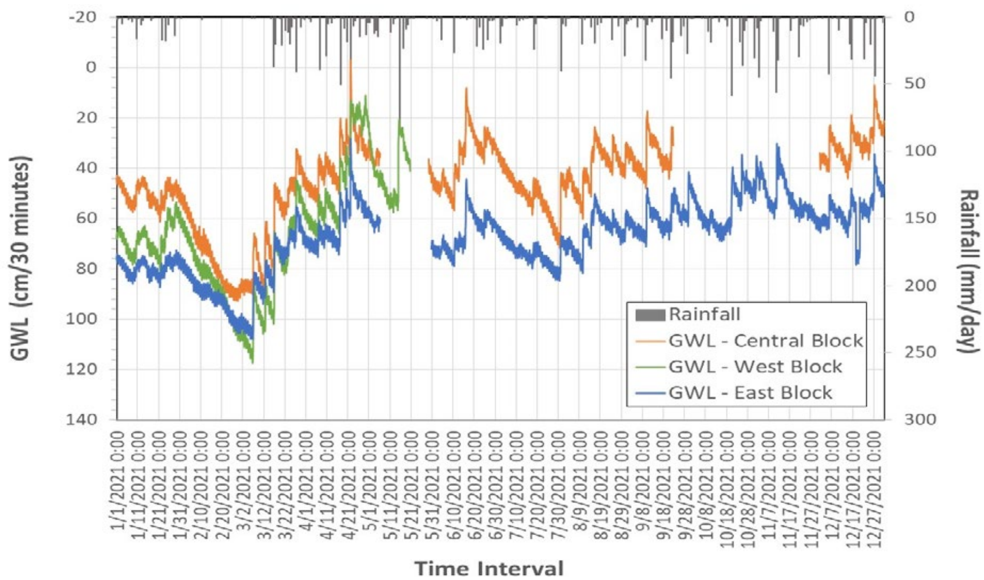

Fig. 2: Rainfall and ground water level dynamics in the eastern, central, and western Block recorded from January 1 to December 31, 2021

on April 29, 2021, at 9:30. The average GWL for the western block during this period was 65.7 cm/min. Recorded data from the three research blocks (Fig. 2) shows that GWL in the study area was highly fluctuated based on the rainfall pattern throughout the year. Kurniasari *et al.* (2021) stated that rainfall greatly influenced GWL in peatland areas through direct infiltration. Almost all of the precipitated water directly infiltrated into the peat soil because of its high hydraulic conductivity, specifically, at the peat soil surface (Wösten *et al.*, 2008). GWL in peat areas approaches the surface during the rainy season and decreases by approximately 30 cm during the dry season (Cobb and Harvey, 2019). Further decreases of over 150 cm soil depth could be reached under extreme conditions, such as during El Niño (Rossita *et al.*, 2018). Rainfall has been known to strongly influence the increasing GWLs at various locations in the Kampar Peninsula of Riau, Indonesia (Maryani *et al.*, 2020). The average GWL during the dry year of 2015 was −73 cm, with variations ranging from 1 cm to −171 cm (Wakhid *et al.*, 2019). Meanwhile, the GWL recession curve analysis of the longest no-rain day's period between January 28 and March 6, 2021, showed a substantial coefficient of determination for the eastern, central, and western blocks at 0.9428, 0.9486, and 0.9691, respectively. The curves tend to be relatively stable during the dry season possibly due to the absence of rainfall, previous water levels, and saturated aquifer thickness (Hussain *et al.*, 2022). Furthermore, the GWL recession curve data analysis for the eastern block, recorded from January 28 to March 6, 2021, indicated a recession rate of 6.99 mm/day with a total decline of 26 cm over 37 days and 4.5 hours. The maximum GWL was 175 cm while the minimum was 18.50 cm, with an average of 69.21 cm. Moreover, the central block GWL recession curve, recorded from 28 January to 27 February 2021, showed a recession rate of 14.32 mm/day with a total decline in GWL of about 44 cm over 30 days and 17.5 hours. The maximum GWL was 92.70 cm while the minimum was −12.80 cm, with an average of 37.81 cm. Similarly, the western block GWL recession curve, recorded from 28 January to 6 March 2021, showed a decline of 57.8 cm over 36 days and 23 hours with a recession rate of 15.64 mm/day. The maximum GWL was 117.50 cm while the minimum was 11.00 cm, with an average of 62.90 cm. Overall, GWL monitoring data showed that the recession rate for the central and western blocks was greater than for the eastern block. The rise and fall of the peat water table depend on the balance between rainfall, evapotranspiration, and groundwater flow. The water table gradient tends to be steeper near the dome boundary, where water flow is faster (Cobb *et al.*, 2017). Naturally, for tropical peatlands, the water table is always close to

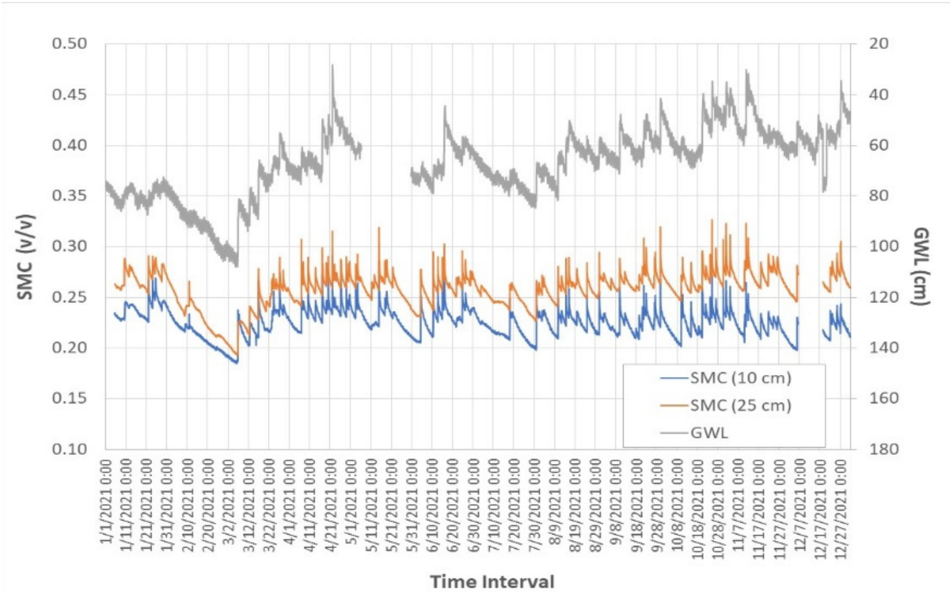

Fig. 3: Comparison between ground water level (GWL) and soil moisture content (SMC) dynamics in the eastern block during January 1–December 31, 2021

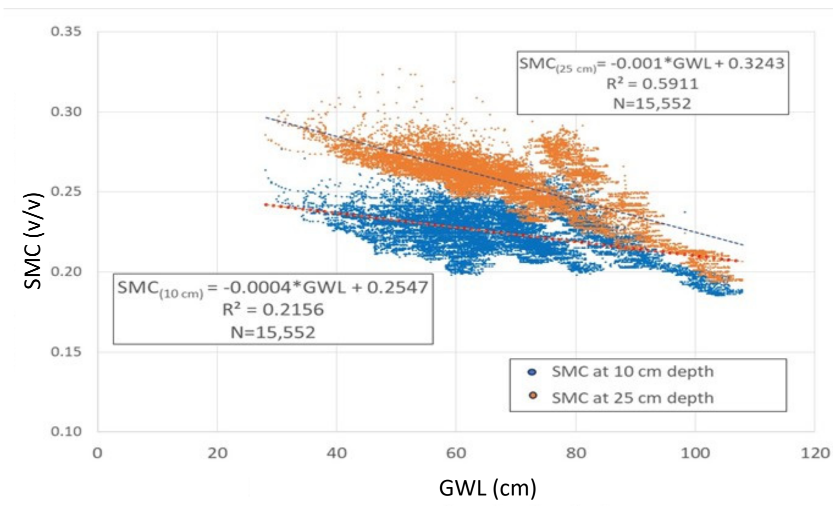

Fig. 4: Linear correlation between ground water level (GWL) and soil moisture content (SMC) data at 10 cm and 25 cm peat soil depth

the surface and its fluctuations in peat surfaces are found to be uniform (Cobb and Harvey, 2019).

Soil moisture dynamic

The GWL and soil moisture dynamics in peatland exhibited considerable fluctuations over time (Fig. 3). Analyzing the relation between GWL and SMC in the peatland surface layer revealed a relatively strong correlation between the two variables (R^2 = 0.59) at a depth of 25 cm. However, the correlation was weaker (R^2 = 0.22) at a depth of 10 cm (Fig. 4) compared to that at a depth of 25 cm. Previous studies noted that a shallow water table is commonly observed in peatlands during the rainy season

(Moyano *et al.*, 2013). Under these conditions, the actual SMC depends on the GWL, thus leading to a potentially strong correlation between GWL and SMC. The weaker correlation between GWL and SMC at a depth of 10 cm can be attributed to the reduced capillary potential of peat soil as it moves further away from the GWL. This finding aligns with the study conducted by Nugraha *et al.* (2016) in which they reported a decrease in capillary potential and consequently, a decrease in SMC with an increasing distance from the GWL. Furthermore, peat soil maturity positively influences capillary potential. At the research location, where peat maturity is sapric to hemic, water movement during no-rain day periods could be largely influenced by capillary potential. Additionally, capillary water plays a role in replacing the evaporated water at the upper layers (Yazaki *et al.*, 2006). Moreover, the weak correlation between GWL and SMC at the peat surface layer of 10 cm depth suggested that using GWL as an indicator to assess peatland fire potential could be less appropriate. Instead, a variable representing moisture conditions (i.e., SMC) could be more representative in capturing the peatland conditions related to fire risks (Prat *et al.*, 2013).

The measurements of peat surface SMC over one year from January to December 2021 ranged from 0.1848 to 0.2908 m^3m^{-3} or approximately 108.7% to 171.1% weight-to-weight ratio (w/w) at a depth of 10 cm and from 0.1928 to 0.3264 m^3m^{-3} or approximately 160.7% to 272.0% w/w at a depth of 25 cm. Meanwhile, the lowest average SMC occurred in February and March 2021, which were approximately 0.2154 m^3m^{-3} or 126.7% w/w at a depth of 10 cm, and 0.2342 m^3m^{-3} or 195.2% w/w at a depth of 25 cm. In this context, surface SMC was the primary determinant of peatland susceptibility to burning. Frandsen (1997) found that peat or organic soil will undergo continuous or sustained burning at an SMC range of 104%–129% w/w. In addition, Rein *et al.* (2008) explained that peat starts to ignite/burn at moisture levels >125% w/w. The critical SMC threshold for peatland fire risk is also determined by the degree of peat maturity, in which a higher maturity has a relatively low critical SMC. Azri (1999) stated that the critical SMC for peat fire ranged from 225.66% to 302.10% w/w for sapric, 216.89% to 290.38% w/w for hemic, and 311.24% to 417.76% w/w for fibric. The relation between the duration of no-rain days and SMC in peat soil surface layer was investigated through SMC data collected during periods of prolonged rainfall absence (>1 week without rain). Specifically, SMC dynamics were recorded from January 30 to February 9, 2021 (10 consecutive days without rain) and from February 11 to February 26, 2021 (16 consecutive days without rain). Linear regression analysis results showed a substantial negative linear relation between the duration of no-rain days and SMC at both the 10 cm (R^2 = 0.68) and 25 cm (R^2 = 0.80) soil depth. This result indicated that peat surface SMC was highly influenced by climate factors, particularly, rainfall; the longer the absence of rainfall, the lower the peat surface SMC, as described by the generated equations in Fig. 5. At the upper layer (10 cm depth), SMC decreased to >129% w/w after eight days without rain (Fig. 5), which is classified as susceptible-to-fire based on Frandsen's (1997) criteria.

Peat chemical characteristics are strong but indirectly influence the risk of peat fire. Irreversible peat soil drying happens as the peat hydrophilic functional groups decrease along with a decrease in peat SMC. Consequently, a longer drought season could shift dominant groups in the peat material to become hydrophobic (Winarna *et al.*, 2016). Valat *et al.* (1991) explained that the peat drying process occurs because the flexibility of humic polymer fractions drives polar functional groups to associate and interact through hydrogen bonding under extremely low moisture conditions. This molecular shift results in reoriented nonpolar groups on the outer part of the molecule, causing the organic colloid surface to have a low affinity for water (hydrophobic). Besides, Winarna *et al.* (2016) reported a positive correlation between peat SMC and the content of–COOH functional groups in which a higher–COOH content leads to increased water retention. Szajdak *et al.* (2010) stated that the most hydrophobic fractions of peat soil contain many hydrocarbon chains. This study's results suggested that the transformation of peat properties from hydrophilic (water-loving) to hydrophobic (water-repellent) should be avoided for sustainable peatland utilization and management. Hydrophobic properties occur after the peat SMC decreases beyond the irreversible drying critical limit. Dekker *et al.* (2001) explained that the critical SMC level of peat hydrophobic properties represents a transition zone in which the upper limit

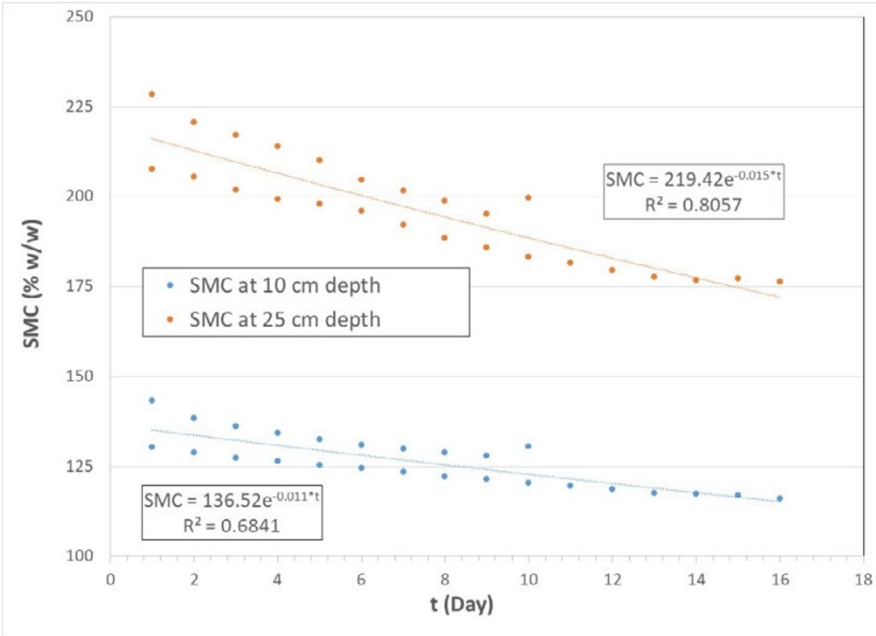

Fig. 5: Relation between the length of no-rain day with soil moisture content (SMC) at 10 cm and 25 cm peat soil depth

soil can be wetted, but the lower limit peat soil will still endure irreversible drying. Azri (1999) stated that a decrease in total acidity,–COOH functional groups, and phenolate–OH groups are signs of the irreversible drying process. Furthermore, the –COOH and phenolate–OH functional groups become nonfunctional if peat soil undergoes drought.

Peat fire risk threshold

Frandsen (1997) stated that peat will experience continuous burning under conditions of water content ranging from 104% to 129% w/w. Therefore, for this research, these values were used as the peat fire risk threshold. The lower limit (104% w/w) was set as the high fire risk threshold while the upper limit (129% w/w) was designated as the low risk threshold. Considering that the upper peat soil layer is highly susceptible to ignition compared to the underlying layers, the calibration of the peatland fire risk threshold was then applied to a series of soil moisture dynamics data at a depth of 10 cm in the eastern block as shown in Fig. 6. The graph illustrates soil moisture observations in the eastern block from January 1 to December 31, 2021, that did not exceed the high-risk threshold. Meanwhile, the lowest soil moisture value which measured 109.8% w/w, remains above the high-risk threshold of 104% w/w and occurred on March 5, 2021, due to a 40-day absence of rainfall prior to that date. Furthermore, there were approximately 25 instances throughout this period where the soil moisture exceeded the low risk threshold at 129% w/w.

Peatland fire risk early warning based on soil moisture recession curve

An SMC recession curve is one approach for predicting the peatland fire risk level by estimating the lowest SMC level that will be reached at the end of a no-rain day period. In particular, this research study used a constant declining rate to predict the SMC level. This method has been widely employed by previous studies including Romero *et al.* (2017) who analyzed the estimation of soil moisture decline rates to facilitate soil and water management. The estimation of the lowest SMC is highly dependent on the initial SMC (SMC_0) on the first day after the last rainfall event. This estimation also depends on the SMC declining rate which is greatly influenced by soil physical characteristics. The SMC_0 was determined based on the linear regression analysis between SMC and rainfall as well as the 1-day API (API_1). In this research, API_1 was selected because of its highest

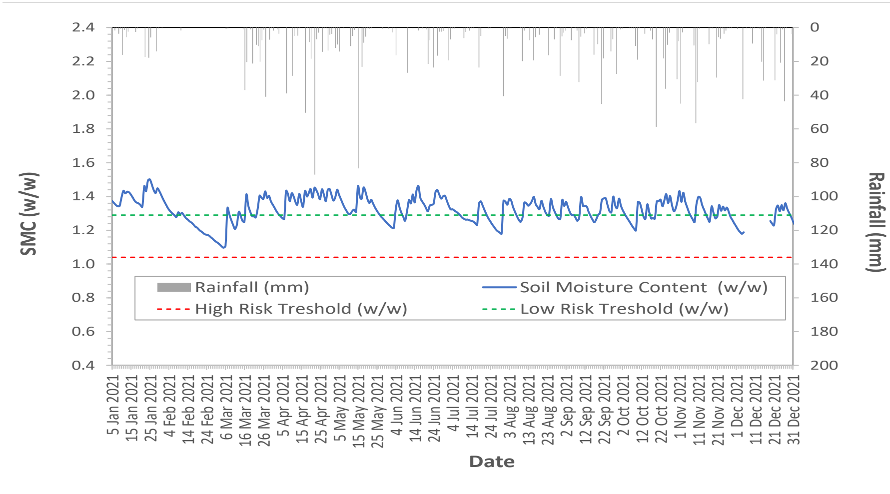

Fig. 6: Peat fire risk threshold compared to soil moisture content (SMC) dynamic in the eastern block recorded from January 1 to December 31, 2021

Table 1. Correlation between initial soil moisture content (SMC_o) and climate variables on nine different data recording episodes

Date	SMC_o (w/w)	R_i (mm)	$R_i + R_{(i-1)}$ (mm)	$R_i + R_{(i-1)} + R_{(i-2)}$ (mm)	API_1 (m)	API_2 (mm)	API_3 (mm)	PET_i (mm)	W_i (m/s)	T_i (°C)
July 03, 2021	1.324	7.00	7.20	12.60	11.80	11.80	11.80	2.20	0.46	28.40
July 19, 2021	1.371	5.00	28.60	28.60	14.30	14.30	14.30	1.80	0.36	27.80
January 04, 2022	1.231	5.00	5.00	8.60	0.00	2.70	2.90	1.70	0.29	27.00
April 12, 2022	1.371	0.20	23.40	23.40	14.10	19.00	22.00	2.10	0.17	27.80
April 22, 2022	1.382	0.40	14.60	14.60	8.60	8.60	8.60	2.10	0.19	29.10
April 26, 2022	1.402	0.00	16.80	16.80	10.20	10.20	10.20	2.00	0.12	29.30
May 05, 2022	1.435	2.00	26.00	26.40	14.60	15.70	19.10	2.00	0.31	28.40
May 17, 2022	1.398	0.20	26.60	26.60	16.00	16.00	16.00	2.20	0.13	28.50
May 29, 2022	1.371	0.20	16.00	16.00	9.60	9.60	9.60	2.20	0.41	28.50
Correlation (r)		−0.61	0.75	0.70	0.80	0.68	0.66	0.51	−0.30	0.69

correlation with SMC compared to other climate variables (Table 1). Linear regression analysis results showed a significant relation between SMC_0 and API_1 with a coefficient of determination of about 66% (Fig. 7 and Table 2). Van Liew *et al*. (2003) stated that an R^2 value greater than 0.5 is considered acceptable (Samimi *et al.*, 2023).

SMC's declining rate on a daily time interval was determined based on a regression analysis between SMC and the daily time interval during the period from January 29 to March 6, 2021. The SMC declining period was 37 days, following a rainfall event at 14 mm that occurred on January 28, 2021. The exponential equation showed the highest R^2 at 0.9718 (Fig. 8).

The formula resulted from the integration of the initial SMC_0 equation (Fig. 7) into the $SMC_{dec(t)}$ recession rate equation (Fig. 8) which was then utilized to simulate the SMC decreasing rate during the no-rain days period. Fig. 9 shows the simulated SMC validation result compared with the corresponding SMC field data measured by the Nash–Sutcliffe Coefficient of Efficiency (CE) of 0.65 (Nash and Sutcliffe, 1970).

Table 3 presents the estimated number of days required to achieve soil moisture equilibrium under low and high peatland fire risk conditions based on the previous day's rainfall scenarios. In the episode of May 17, 2022, with a precipitation of 26.40 mm or equivalent to an API_1 of 16.01 mm, the resulting initial moisture content was 1.401 w/w. Therefore, the low peatland fire risk would occur within 13 days, whereas the high peatland fire risk would occur within 43 days. Table 4 presents the data series of the previous day's rainfall interval classes that can be

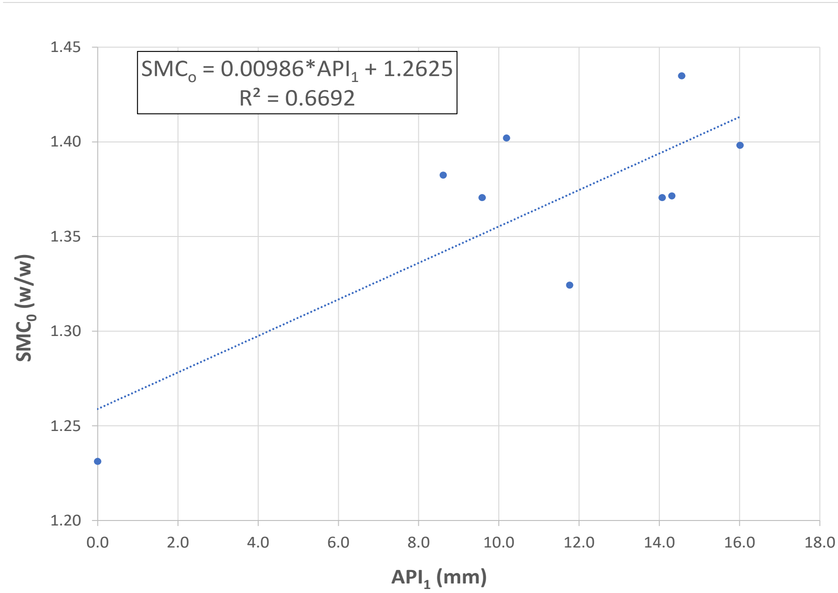

Fig. 7: Linear correlation between initial soil moisture content (SMC) and antecedent precipitation index API_1

Table 2. Regression statistics and analysis of the correlation analysis variance between initial soil moisture content (SMC_o) and 1-day antecedent precipitation index API_1

Regression Statistics								
Multiple R	0.8465							
R Square	0.7165							
Adjusted R Square	0.6692							
Standard Error	0.0347							
Observations	8							
Analysis of Variance								
	df	*SS*	*MS*	*F*	*Significance*			
Regression	1	0.0182322	0.0182322	15.16286609	0.008039927			
Residual	6	0.0072145	0.00120242					
Total	7	0.0254468						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1.2625	0.0302	41.7451	0.00000001	1.1885	1.3365	1.1885	1.3365
11.76669	0.00986	0.0025	3.8940	0.00803993	0.0037	0.0161	0.0037	0.0161

utilized as criteria for estimating the time needed for soil moisture to reach low and high peatland fire risk conditions. Thus, in this study, the resulting peat fire early warning model is considered simpler than other previously developed models. Mezbahuddin *et al.* (2023) used a surface water table parameter together with SMC to predict peatland fire risk status within a 2-week timeframe.

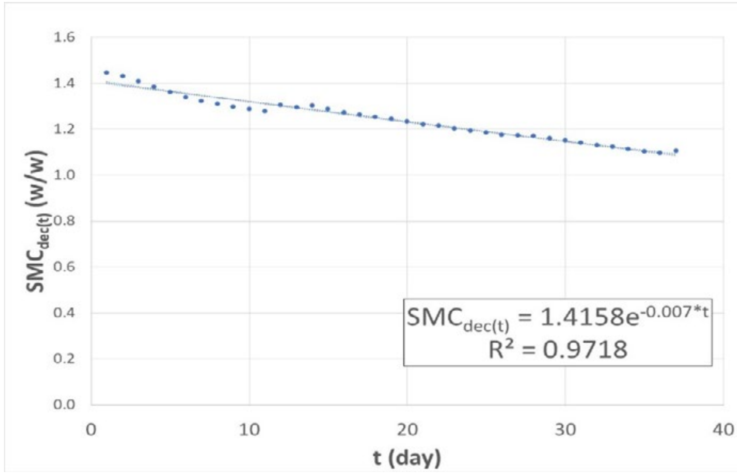

Fig. 8: Recession curve of soil moisture content (SMC) in a daily time interval

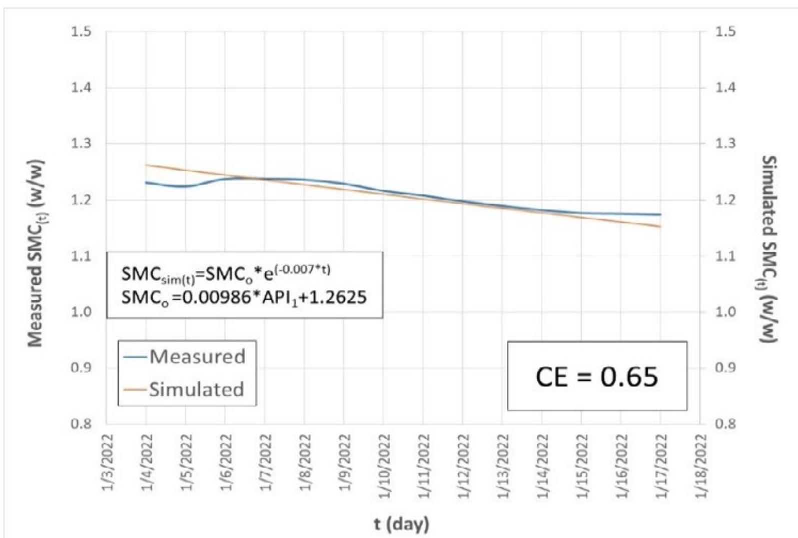

Fig. 9: Comparison between measured and simulated soil moisture content (SMC) during the no-rain period of January 4–17, 2022

Table 3: Estimation of time to low and high-risk threshold of peat fire risk based on rainfall events and the previous day's antecedent precipitation index API_1

Date	$R_{(i-1)}$	API_1	SMC_0	Time to low risk threshold (Day)	Time to high-risk threshold (Day)
May 17, 2022	26.40	16.01	1.410	13	43
May 05, 2022	24.00	14.56	1.396	11	42
July 19, 2021	23.60	14.31	1.394	11	42
April 12, 2022	23.20	14.07	1.391	11	42
July 03, 2021	19.40	11.77	1.370	9	39
April 26, 2022	16.80	10.19	1.355	7	38
May 29, 2022	15.80	9.58	1.349	6	37
April 22, 2022	14.20	8.61	1.340	5	36
January 04, 2022	5.00	0.00	1.259	1	27

Table 4: Previous day rainfall rate interval to estimate time to low and high peat fire risk

R_{i-1} (mm)	Time to Peat Fire Risk (Day)	
	Low risk	High risk
>20	11	42
10–20	3	34
<10	1	27

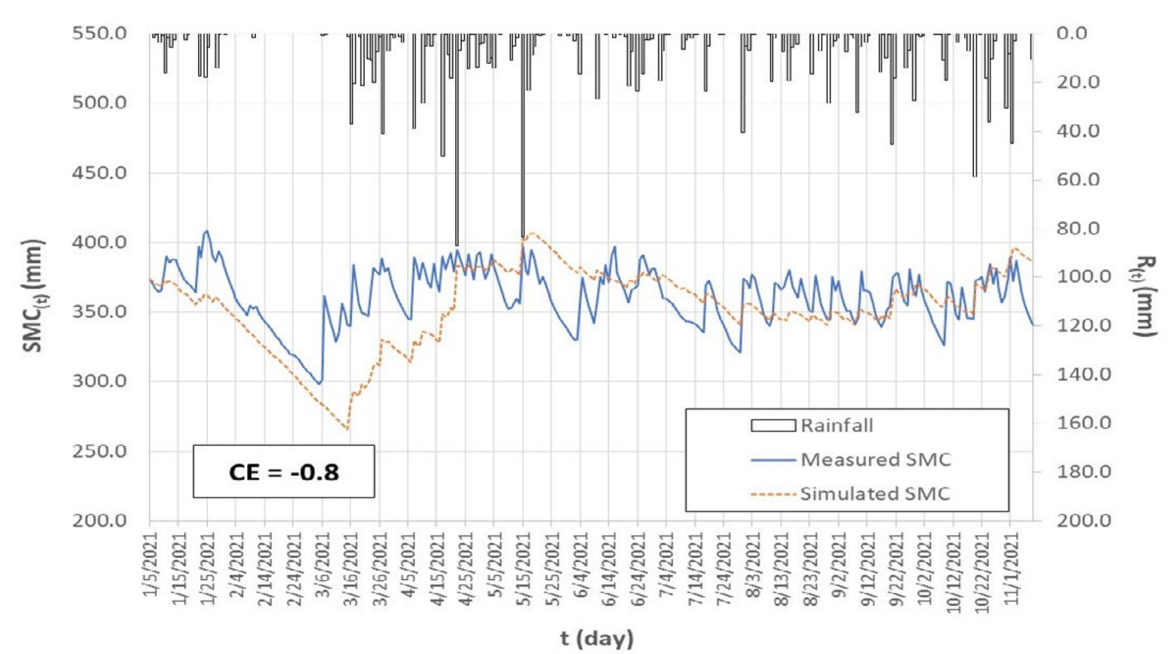

Fig. 10: Peat soil moisture content (SMC) simulation result based on rainfall data recorded from January 5 to November 1, 2021

Peatland fire risk early warning based on soil moisture content modeling

Furthermore, this research considered another SMC prediction model based on rainfall data developed by Georgakakos and Baumer (1996) to model peatland fire early warning. Fig. 10 presents the SMC simulation result using this model. Overall, the simulation results showed a tendency to underestimate SMC during the period of early January–late April but overestimate SMC between early May and late July. The Nash–Sutcliffe similarity analysis between the measured and simulated SMC showed a very low level of similarity with a CE value of −0.8. This indicates that a simple SMC prediction model based on rainfall data can still be explored to predict peatland risk to fire; however, adjustment from local SMC measurements is required to achieve better prediction precision. Moreover, this simple method is particularly useful in the area where SMC data is rare as rainfall data is commonly available.

CONCLUSION

This research has collected evidence on the influence of climate and peat soil characteristics on peatland soil water dynamics. The continuous 30-min recording interval of GWL and SMC data observation showed a consistent declining trend for both parameters within the identified no-rain day episodes in the study area. However, this study could not identify a substantial correlation between GWL and SMC, mostly, due to a higher fluctuation of GWL dynamic compared to SMC. In an agricultural peatland with artificial drainage networks, the highly fluctuated GWL dynamic was largely influenced by water loss due to seepage and groundwater flow rather than evapotranspiration. The study area observation data showed that the rate of water loss was three times higher than evapotranspiration. In addition, this study found that the SMC dynamic was more suitable for estimating peatland fire risk due to its predictability compared to that of GWL. Moreover, the recession curve method successfully modeled the daily SMC declining rate during the successive no-rain day period that represented the natural characteristic of peat soil water dynamics and the influence of the local climate in the study area. Besides, this analysis enabled the peat fire threshold identification based on the estimated daily SMC on the recorded day of peat fire events in the observation area. Furthermore, this study has identified that an area with an SMC >104% of dryweight is considered to be a high peat fire risk. Using this criterion, this study has successfully developed a peat fire early warning model to estimate the days left before the peat fire high-risk status is achieved based on the last rain-day precipitation in a dry period. The use of rainfall data to estimate days to achieve high peat fire risk could simplify the implementation of this peat fire early warning because rainfall data is commonly available compared to SMC data. While the study area might represent the general environmental conditions of tropical peatland, implementation of this model in other peatland areas would require a further validation process to accommodate differences in climate and peat soil characteristics. Particularly in Indonesia, an official directive to incorporate this validated peat fire early warning model into the already established compulsory requirement to monitor daily rainfall in a private palm oil plantation would enhance peat fire mitigation at the national level.

AUTHOR CONTRIBUTIONS

B. Kartiwa executed the experimental design, analyzed and interpreted the data, engaged in modeling, drafted the manuscript text, and participated in reviewing and finalizing the manuscript. A. Dariah performed the literature review, compiled and interpreted the data, manuscript preparation, review and finalization. Suratman compiled and interpreted the data, drafted the manuscript text, participated in reviewing and finalizing the manuscript. Maswar performed the literature review, compiled and interpreted the data, review and finishing the manuscript. S Nurzakiah involved in the field experiments, compiled the original data preparation. N. Heryani prepared the literature review, interpreted the data, original draft preparation, review and finishing the manuscript. S.H. Adi performed data analysis, involved in manuscript review, and contributed to the finalization of the manuscript. H. Sosiawan conducted the literature review, drafted the initial manuscript, interpreted the data, engaged in manuscript review, and played a role in the finalization of the manuscript. P. Rejekiningrum participated in the literature review, interpreted the data, contributed to the preparation of the original draft, took part in manuscript review, and assisted in finalizing the manuscript. N.L. Nuraida conducted the literature review, interpreted the data, participated in manuscript preparation, contributed to manuscript review, and played a role in finalizing the manuscript. I. Lenin helped in the literature review, preparation and review of the manuscript. C. Tafakresnanto participated in the preparation, review and finalization of the manuscript.

ACKNOWLEDGEMENT

The authors extend their sincere gratitude to the esteemed members of the editorial board of Global Journal of Environmental Science and Management (GJESM) for their invaluable comments and constructive suggestions, which significantly contributed to the preparation of this paper for publication. The authors would also like to express their heartfelt appreciation to the Indonesian Agency for Agricultural Research and Development (IAARD) for providing crucial support throughout the project. Furthermore, the authors acknowledge and extend their thanks to all the individuals and organizations who have played a vital role in making this research possible, enhancing its quality, and supporting its dissemination. Their collaborative efforts and contributions have been instrumental in the successful execution of this study.

CONFLICT OF INTEREST

The authors declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percent
API	Antecedent Precipitation Index
BD	Bulk Density
CE	Coefficient of Efficiency
cm^3	Square centimeter
Cm	Centimeter
COOH	Carboxyl group
D	Soil depth
E	East
Eq	Equation
EWS	Early Warning System
G	Gram
GWL	Groundwater Level
$Gt\ CO_2$	Gigaton Carbon Dioxide
Ha	Hectare
INF	Infiltration
K	Recession constant
Ks	Hydraulic conductivity
Km	Kilometer
M	The infiltration constant
m^3	Cubic meter
Min	Minute
Mm	Millimeter
N	North
OH	Hydroxide group
PER	Percolation
PET	Potential Evapotranspiration
ProbFire	Probabilistic fire early warning system
R	Correlation
R	Rainfall
R^2	Coefficient of determination
SMC	Soil Moisture Content
SMC_o	Soil Moisture Content Initial
SMC_{dec}	Soil Moisture Content declining
S	second
T	time
T_i	Temperature
ToFEWSI	Towards a Fire Early Warning System for Indonesia
v/v	volume-to-volume ratio
w/w	weight-to-weight ratio
W_i	Wind speed
W_{max}	maximum soil water holding capacity
θt	saturated water content
$\theta\tau$	water content
Λ	soil pore index based on the soil layer structure

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HOW TO CITE THIS ARTICLE

Kartiwa, B.; Maswar; Dariah, A.; Suratman; Nurida, N.L.; Heryani, N.; Rejekiningrum, P.; Sosiawan, H.; Adi, S.H.; Lenin, I.; Nurzakiah, S.; Tafakresnanto, C., (2023). Modeling peatland fire risk early warning based on water dynamics. Global J. Environ. Sci. Manage., 9(SI): 233-250.

DOI: 10.22034/GJESM.2023.09.SI.14

URL: https://www.gjesm.net/article_707314.html