Assessing the severity of forest fire in Sungai Buluh Protected Peat Forest, Jambi

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Abstract. Jambi is one of the provinces that has a high level of forest fires in Indonesia. Sungai Buluh Peat Protected Forest is one of the protected peat forest areas in Jambi Province which experienced severe forest and land fires in 2019. Fire severity was estimated using the NBR Index from the Sentinel-2 satellite imagery data. The results showed that fire severity in the HLG Sungai Buluh in 2019 was dominated by high-class fire severity, covering an area of 207.9 ha. The NBR Index has a good ability to estimate the severity of forest fires with a D-value of 2.816 with an accuracy rate of 91.984%. The severity of the fires that occur is linked to the groundwater level dynamics which are strongly and significantly (p < 0.05) influenced by precipitation. Fires were detected in September when groundwater levels averaged -57.66 cm and very low amounts of precipitation (17.43 mm) occurred. It is important to maintain high groundwater levels, less than 40 cm below the surface, to reduce the risk of fire and prevent future peatland degradation.

1. Introduction
The incidence of forest and land fires, especially on peatlands, continues to degrade and reduce the number of peatlands in Indonesia. The 2019 forest and land fires were among the worst of the last two decades. Ministry of Environment and Forestry of the Republic of Indonesia stated 1,649,258 ha of forest and land in Indonesia had been burned in 2019, with 494,450 ha on peatland area [1]. One of the peatland areas affected by this incident is the Sungai Buluh Peat Protected Forest (HLG Sungai Buluh).

The HLG Sungai Buluh is located in Tanjung Jabung Timur Regency in Jambi Province. The land area of HLG Sungai Buluh is 12,766 ha on peatland which has the status of protected peat forest [2]. The HLG Sungai Buluh is included in the Peat Hydrological Unit (KHG) area of the Batanghari River - Mandahara River with the entire HLG area in the form of a peat dome. The HLG status shows that the area needs to be maintained and protected because the function of peatlands is very important.

Monitoring the severity of forest and land fires in the HLG Sungai Buluh must be carried out so that the effectiveness of peatland rehabilitation processes can be maximized. At present, HLG Sungai Buluh receives no information regarding the severity of fires that occur to determine the appropriate post-fire
treatment. Remote sensing can play an important role in estimating fire severity with utility as a rapid monitoring method [3].

This research describes and provides information regarding estimated severity of forest and land fires in 2019 at HLG Sungai Buluh. The implementation of remotely sensed severity estimation of forest and land fires was carried out using Sentinel-2 imagery and calculation of the Normalized Burn Ratio (NBR) index. Sentinel-2 imagery includes infrared bands and has good spatial and temporal resolution, comparable to LANDSAT. The imagery is open access and free of charge. Normalized Burn Ratio (NBR) index is a method of calculating image pixel values using Near Infrared (NIR) band values and Short-wave Infrared Imagery (SWIR) band values in a satellite image. The NBR index is best for estimating the severity of fires using satellite imagery.

2. Method

2.1. Materials

The material used in this research include hotspot data at HLG Sungai Buluh, obtained from the NASA FIRMS catalog (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms), monthly GPM precipitation data obtained from NASA (https://disc.gsfc.nasa.gov/), monthly peat Groundwater Level (GWL) data from HLG Sungai Buluh Jambi obtained from IPB/UMCES Tropical Peat Fire Research, HLG Sungai Buluh boundary data from the Ministry of Environment and Forestry (http://webgis.menlhk.go.id:8080/kemenhut/index.php/id/), Indonesia's administrative boundary data from the Indonesia Geospatial Portal (https://tanahair.indonesia.go.id/portal-web), and Sentinel-2 imagery with data products as shown in Table 1 obtained from the European Space Agency (https://scihub.copernicus.eu/).

| Table 1. Sentinel-2 products used in research |
|--------------------------------------------|
| Image               | Acquisition Date | Level | View Point | Fire Time   |
|---------------------|------------------|-------|------------|-------------|
| Sentinel-2 MSIL2A   | September 8, 2019 | 2.0   | Ascending | Before (pre)|
| Sentinel-2 MSIL2A   | November 7, 2019  | 2.0   | Ascending | After (post)|

2.2. Data Processing Procedure

Data processing begins by observing the relationship between monthly hotspot data and monthly precipitation in the Sungai Buluh HLG in 2019. Both data are visualized in the form of graphs to determine the period before the fire, the peak of the fire, and after the fire. This fire period information is used to determine the timescale of the Sentinel-2 imagery selected for the estimation of fire severity.

Burned area estimation was done by visual interpretation and digital method. Estimation of burnt area by visual interpretation is done using an on-off layer delineation technique on the composite images before and after the fire. Composite RGB (12, 8, 4) images were created from the Sentinel-2 imagery. Composite image creation was carried out for each of the two Sentinel-2 imagery (the period before the fire and after the fire). Estimations of burnt area by digital method, using the NBR index with the formula [4][5]:

\[
\text{NBR} = \frac{B8 - B12}{B8 + B12}
\]

Where,

- NBR : Normalized Burn Ratio
- B8 : NIR band reflectance on band 8 Sentinel-2 (NIR band spectral wavelengths from 785 to 899 nm)
- B12 : The reflectance of the SWIR band on band 12 Sentinel-2 (SWIR band spectral wavelengths from 2100 to 2280 nm).
An image of the burnt area by using NBR index is built using the formula [6]:

\[ \Delta \text{NBR} = \text{NBR}_{\text{pre}} - \text{NBR}_{\text{post}} \]  

Where, for each pixel,
- \( \Delta \text{NBR} \): Change in NBR value
- \( \text{NBR}_{\text{pre}} \): NBR value before the fire
- \( \text{NBR}_{\text{post}} \): NBR value after a fire at a certain pixel

After the completion of visual interpretation of the burnt area, we created training data by using the NBR index. The training data creation aims to retrieve the pixel value of the NBR index calculated image based on the visual interpretation of the burnt area. We used the fishnet tool in ArcGIS to sample data pixel values, extracting multiple values for each point feature. The value of the training data is used to calculate the average value and standard deviation of the estimated burnt area pixels on \( \text{NBR}_{\text{pre}} \), \( \text{NBR}_{\text{post}} \), and \( \Delta \text{NBR} \). The average value and standard deviation become a reference for the threshold for the severity of forest and land fires.

2.3. Data Analysis Procedure

The burnt area of the NBR index image is determined by calculating the threshold. A pixel is declared as a burnt area if it meets the requirements as follows [6]:

\begin{align*}
\text{Condition 1} : & \text{if } \text{NBR}_{\text{post}}_{ij} \leq \alpha_{\text{NBR}} \\
\text{Condition 2} : & \text{if } \Delta \text{NBR}_{ij} \geq \beta_{\text{NBR}}
\end{align*}

where using the assumption of a normal distribution, the selected threshold value is:

\begin{align*}
\alpha_{\text{NBR}} &= \mu_{\text{NBR}}_{\text{post}} + 2\sigma_{\text{NBR}}_{\text{post}} \\
\beta_{\text{NBR}} &= \mu_{\text{NBR}} - 2\sigma_{\text{NBR}}
\end{align*}

Where,
- \( i \): Pixel line number
- \( j \): Pixel column number
- \( \text{NBR}_{\text{pre}}_{ij} \): NBR value before the fire at a certain pixel
- \( \text{NBR}_{\text{post}}_{ij} \): NBR value after a fire at a certain pixel
- \( \Delta \text{NBR}_{ij} \): Changes in the NBR value for that particular pixel
- \( \alpha_{\text{NBR}} \): Mark threshold for NBR after fire
- \( \beta_{\text{NBR}} \): Mark threshold for NBR change
- \( \mu_{\text{NBR}}_{\text{post}} \): Average value of \( \text{NBR}_{\text{post}} \) training data
- \( \sigma_{\text{NBR}}_{\text{post}} \): Standard deviation of \( \text{NBR}_{\text{post}} \) training data values
- \( \mu_{\text{NBR}} \): Average value of training data NBR
- \( \sigma_{\text{NBR}} \): Standard deviation of training data values NBR

After the burnt area is identified, the severity of the fire can then be estimated. We determined fire severity by calculating the class interval on the NBR index. The class interval calculation formula used is [6]:

\begin{align*}
\text{Low} : & \mu_{\text{ANBR}} - 2\sigma_{\text{ANBR}} \leq \Delta \text{NBR} \leq \mu_{\text{ANBR}} - \sigma_{\text{ANBR}} \\
\text{Moderate} : & \mu_{\text{ANBR}} - \sigma_{\text{ANBR}} \leq \Delta \text{NBR} \leq \mu_{\text{ANBR}} \\
\text{High} : & \Delta \text{NBR} \geq \mu_{\text{ANBR}}
\end{align*}

Where,
- \( \Delta \text{NBR} \): The NBR difference index
μΔNBR : Average value of training data NBR
σΔNBR : Standard deviation value of training data NBR

Furthermore, to test the ability of the NBR index in estimating the severity of forest and land fires, the distance value measurement (D-value) and accuracy tests were carried out. The D-value is calculated based on the formula [7]:

$$D = \frac{|\mu_2-\mu_1|}{\sigma_2+\sigma_1}$$

Where,
D : Distance
μ1 : Average value of training data before the fire
μ2 : Average value of training data after the fire
σ1 : Standard deviation of training data values before the fire
σ2 : Standard deviation of training data values after the fire

The indexability level based on the D-value is interpreted in the class in Table 2 [7]:

| D-value Range | Index Ability Level |
|---------------|---------------------|
| D-value > 1   | The index has a good ability to measure fire severity |
| D-value < 1   | The index has a poor ability to measure fire severity |

The calculation of the accuracy of fire severity is done by calculating the Individual Classification Success Index (ICSI) [8]:

$$ICSI = [1 - (Omission + Commission)] \times 100\%$$

Where,
ICSI : Individual Classification Success Index
Omission : Reference burnt area data not found in Index burnt area data.
   Omission = (area of omission / total area of the polygon)
Commission : The index burnt area data is not found in the reference burnt area data.
   Commission = (area of commission / total area of the polygon).

3. Results and Discussion

3.1. Hotspot and Precipitation

The 2019 monthly precipitation and September hotspots at HLG Sungai Buluh are shown in Figure 1. The daily distributions of hotspots and precipitation in September (Figure 2) show a strong negative correlation between them, where the number of hotspots increase in the absence of rain but are reduced or eliminated after measurable precipitation. Previous research has shown that the higher the monthly precipitation, the lower the number of monthly hotspots and vice versa [9]. Based on this analysis, it is assumed that the occurrence of forest and land fires in the HLG Sungai Buluh is mainly due to drought during the dry season, which is indicated by the low frequency and quantity of rainfall. All hotspots (Figure 2) occurred between 10 - 26 September 2019 indicating the period when most forest and land fires are suspected to have occurred. This time period was used to structure acquisition of the Sentinel-2 imagery used for the 2019 fire severity analysis in HLG Sungai Buluh.
RGB composite images were used to detect burnt areas, which appear reddish-brown, darker than the surrounding landscape, and often in the form of rectangular polygons [10]. Figure 3 provides examples of these features. Figure 4 shows the classification results of the visual interpretation method, having detected 366 ha of burnt area. The visually detected burnt area data was used as training data or reference data for testing the accuracy of the Normalized Burn Ratio (NBR) index. Differences between pre- and post-fire NBR (ΔNBR) were used to identify additional burnt areas and estimate fire severity.
3.3. Burnt Area Assessment from Digital Method

![Figure 5. Image extraction with NBR index at HLG Sungai Buluh in 2019: (a) NBR\textit{pre} image, (b) NBR\textit{post} image](image)

![Figure 6. The NBR difference index (ΔNBR) image](image)
Here, we found the NBR index decreased after fires, especially in the two locations where fires were suspected to have occurred (Figure 5(b), marked with red circles). In these two locations, the NBR\textsubscript{pre} value was close to number 1 and the NBR\textsubscript{post} value was close to the number -1. Large decreases in NBR\textsubscript{post} values indicate likely fires at that location. This is because, after burning, the vegetated area has low reflectance in the NIR band and high reflectance in the SWIR band. The SWIR band, which is very sensitive to the water content of land or vegetation, will have increased reflectance as water content decreases [11].

The burnt area image is generated using the difference of NBR (\Delta NBR) between the image before and after the fire. Burnt area values are closer to 1, while unburnt areas have values close to 0. Area of substantial vegetation growth have values near -1. Figure 6 highlights the two main areas burnt areas in HLG Sungai Buluh.

### 3.4. Training Data

#### Table 3. The average value and standard deviation of the NBR index training data

| Mark          | NBR\textsubscript{pre} | NBR\textsubscript{post} | \Delta NBR |
|---------------|--------------------------|--------------------------|------------|
| Average       | 0.594                    | -0.032                   | 0.626      |
| Standard deviation | 0.093                    | 0.129                   | 0.144      |

Table 3 shows the average decrease in NBR pixel values after a fire occurs. After fire, the NBR index of the average pixel decreased by 0.626. This decrease occurred due to damage or loss of vegetation in the fire area, as indicated by increased reflectance values in the SWIR band.

### 3.5. Fire Severity Assessment

#### Table 4. Threshold value (threshold) detection of burnt area NBR index

| Index | \(\alpha\) Post Fire | \(\beta\) Change |
|-------|----------------------|------------------|
| NBR   | 0.226                | 0.338            |

Based on calculated threshold values (Table 4), a pixel is categorized as burnt area if it meets the following criteria:

Condition 1: if NBR\textsubscript{post} \(ij \leq 0.226\)
Condition 2: if \(\Delta\)NBR \(ij \geq 0.338\)

Figure 7 shows at total burnt area of 351 ha, with most concentrated in two large locations. Subsequently, \(\Delta\)NBR was used to estimate fire severity with thresholds calculated for three severity classes, namely low, moderate, and high (Table 5).

#### Table 5. Fire severity threshold value

| Severity    | \(\Delta\)NBR Value                         |
|-------------|--------------------------------------------|
| Low         | \(0.338 \leq \Delta\)NBR < 0.482           |
| Moderate    | \(0.482 \leq \Delta\)NBR < 0.626           |
| High        | \(\Delta\)NBR \(\geq 0.626\)               |

Based on the threshold values in Table 5, we created a spatial visualization of fire severity from the \(\Delta\)NBR index, as shown in Figure 8. The 2019 fire severity in HLG Sungai Buluh (Table 6) is dominated by high severity fire, covering approximately 207.9 ha (~59\%) of the total burnt area. The moderate fire
Severity class covered 108.629 ha (~31%) while the low severity class was 34.54 ha (~10%) of the total burnt area.

**Figure 7.** Map of burnt area in HLG Sungai Buluh in 2019 using the NBR index

**Figure 8.** Map of fire severity in HLG Sungai Buluh in 2019 using the NBR index

**Table 6.** Area and percentage of fire severity in HLG Sungai Buluh in 2019

| Severity Class | Area (ha)  | Percentage of Severity (%) |
|----------------|-----------|---------------------------|
| Low            | 34.540    | 9.839                     |
| Moderate       | 108.620   | 30.941                    |
| High           | 207.900   | 59.221                    |
| Total          | 351.060   | 100                       |

3.6. Test of Ability of NBR Index to Estimate Fire Severity

**Table 7.** Test of the ability of the NBR index to estimate fire severity

| Ability Test Index | Value     |
|--------------------|-----------|
| D-value            | 2.816     |
| Accuracy           | 91.984 %  |

The NBR index has a good ability to measure fire severity. The D-value of the NBR index is 2.816 (Table 7), which is well above 1, signifying that the index has a good ability to estimate fire severity [7]. In addition, the Individual Classification Success Index (ICSI), indicates that the estimated burnt area has an accuracy of 91.984%, when compared with the visually interpreted reference burnt area.

The high D-value and burnt area accuracy of the NBR index are related to the SWIR band, which has higher sensitivity to environmental water content than other bands in multispectral images.
Estimates of fire severity using the NBR index presume that burned areas experience large changes in vegetation water content that scale with the amount of vegetation loss. Use of the SWIR band makes the NBR index very sensitive to changes in water content, making burnt areas detectable [11] estimates of relative fire severity possible [12].

3.7. Relationship of Fire Severity and Groundwater Level
Peat fires are influenced by several factors, both peat characteristics and weather, namely peat water content, peat decomposition rate, groundwater level (GWL), and precipitation [13]. GWL has been used as a key indicator to predict fire incidence in degraded peatlands of Central Kalimantan and more than 99% of fires occur when the GWL is below ground surface[14]. Furthermore, repeated fires in an area can result in a decrease in the capacity of peatlands to retain and absorb water from precipitation, further lowering groundwater levels and making the area more susceptible to fire, especially in the dry season.

Groundwater Level (GWL) data for HLG Sungai Buluh was measured by installing dipwells and subsidence measuring devices at 28 locations. Interpolated GWL data are as shown in Figure 10. In April 2019, GWL measurements were not carried out because the research location was flooded due to high precipitation that month. July to December shows different GWL patterns compared to January to June (Figure 9). This is presumably due to the extremely dry months of July, August, and September 2019 (Figure 1), when the region experienced severe drought and GWL depths reached -105 cm.

Monthly precipitation greatly affects GWL levels in peatlands. Linear regression analysis (Table 8), showed that precipitation at HLG Sungai Buluh significantly influenced GWLs (Sig. F 0.038 (p < 0.05)). Throughout the year, GWLs of peatlands vary in close relation to precipitation [15], but a one-month time lag exists between the lowest precipitation in August (8.49 mm) and the lowest average GWL in September (-57.66 cm) (Figure 10). This time lag may reflect the decreased capacity of peat to absorb and retain water from rainfall, suggesting that groundwater levels in the area will recover only after having a large supply of water from continuous precipitation [16].

Figure 9. Comparison of monthly GWL interpolation on the HLG Sungai Buluh in 2019; (a) January; (b) February; (c) March; (d) May; (e) June; (f) July; (g) August; (h) September; (i) October; (j) November; (k) December
Table 8. Regression test results between precipitation and GWL

|                | df | SS      | MS  | F table | Significance F |
|----------------|----|---------|-----|---------|----------------|
| Regression     | 1  | 34993.91| 34993.910| 5.102249333 | 0.038209597    |
| Residual       | 16 | 109736.40 | 6858.526 |          |                |
| Total          | 17 | 144730.30 |       |         |                |

Figure 10. Distribution of monthly precipitation and GWL in HLG Sungai Buluh in 2019

Fires in the HLG Sungai Buluh occurred in dry peatlands during the drought. Ground water levels >40 cm have been cited as a critical level for when fires become increasingly probably in Indonesia peatlands [15]. Figure 11 clearly shows that the number of hotspots (190) in September 2019 corresponded to the lowest average GWL (-57.66 cm), well below the critical 40 cm threshold. HLG Sungai Buluh needs to be cognizant of the annual precipitation patterns and GWL responses and should manage GWLs to remain less than 40 cm from the surface to reduce the risk of fire.
4. Conclusion

Our estimation of the severity of forest and land fires in Sungai Buluh HLG show that burned areas are dominated by the highest fire severity class (207.9 ha). The ΔNBR index has a good ability for estimating fire severity, as indicated by a D-value of 2.816 and an accuracy rate of 91.984%. The occurrence and high severity of fires that occur are related to groundwater level dynamics which are strongly influenced by precipitation (p < 0.05), but with a lagged response. Fires occurred in September 2019 when the average groundwater level was at its lowest (-57.66 cm). Monthly precipitation was not the lowest in September but the amount was still very low (17.43 mm). Our findings support recommendations to keep the groundwater levels less than 40 cm below the surface to reduce the risk of fire and prevent peatland degradation in the future.

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