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Research article

Mapping potential forest and land fires around Tumbang Nusa Village area through integration of overlay methods and remote sensing technology

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Abstract

Importance of the work: Forest and land fires are disasters that occur every year in Indonesia. One of the areas prone to forest and land fires is the Tumbang Nusa Village area, Central Kalimantan, Indonesia.

Objectives: To map the potential for forest and land fires around Tumbang Nusa Village, Central Kalimantan, Indonesia.

Materials and Methods: The land fires were mapped around the Tumbang Nusa Village, Central Kalimantan using overlay method and remote sensing technology. Landsat 8 imagery, hotspot data from MODIS and other spatial data were analyzed using the normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), land surface temperature (LST) and Euclidean distance methods for roads and settlements, as well as overlays. A fire hazard map was produced.

Results: Based on the results, variables such as NDVI, NDMI and LST influenced the fire risk in the Tumbang Nusa Village area, Central Kalimantan, Indonesia. However, among these variables, the road access and residential access were the main causes of fire risk in the area.

Main finding: The main fire risk was associated with accessibility in the Tumbang Nusa Village area, Central Kalimantan, since access allowed individuals to carry out activities and burn land. Therefore, fire mitigation strategies in the Tumbang Nusa Village area should focus on managing and monitoring accessibility, which should reduce the potential for uncontrolled burning.

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Introduction

Forests make a major contribution to terrestrial biodiversity, as well as providing nutrition and protection for various species (Altuntaş and Barut, 2023). Unfortunately, there are serious challenged to the long-term existence of forest, such as forest fires, which cause major environmental disturbance and have attracted the attention of researchers, policy makers and the global community (van Wees et al., 2021; Zheng et al., 2021).

Forest fires can be caused naturally by geographical and climatic conditions (Papaspiliou et al., 2014). Forest fires can be a serious threat to sustainable development efforts because they have a large negative impact on various sectoral problems, such as ecosystem damage, causing increased carbon emissions, global public health, degrading water quality, disturbing natural habitats and as a major marker of environmental damage (Zhang et al., 2022).

However, there are also widespread cases of forest fires due to other problems such as the lack of law enforcement in the form of laws regarding forest fires and laws that regulate responsibility for poor fire management that damages forest ecosystems (Sanders et al., 2019). Cases of forest fires in peatland areas require appropriate handling considering that forest fire investigation activities are a long, expensive and complex process (Astuti and Fatimah, 2024).

In Indonesia, which is a tropical country, a substantial problem is related to land use in the form of deforestation, which is the main cause of increasing degradation of river basins (Wiwoho et al., 2024). Over time, the frequency of forest fires has increased, especially due to human-based causes (Abram et al., 2021; McMichael, 2021; Suhardono et al., 2024; Syaufina et al., 2016). Indonesian forests are dominated by swamp lands, which when subjected to fire produce a toxic haze that can cover much of the Southeast Asian region (Koplitz et al., 2016), as well as contributing to global warming (Kadir et al., 2022). Thus, forest fires are a problem that needs to be addressed immediately in Indonesia's forest areas, especially in Central Kalimantan, where peat is a dominant factor, with one such location being the Tumbang Nusa Village area.

The Tumbang Nusa Village area in Central Kalimantan, Indonesia functions as a forest for educational and research facilities, with characteristics that are different from other areas. This forest area is readily accessible by the local community and is almost entirely growing on peat. This area has been affected by canalization from the PLG (Peat Land Project) project, covering around 5,000 ha. The Tumbang Nusa forest area has experienced several fires, with those 1997 and 2015 burning 90% and 50%, respectively, of the total area. Forest fires are a serious problem, especially in the dry season (Wicaksono et al., 2022).

Based on these problems and considering the urgency in handling forest fires, especially in the Tumbang Nusa Village area, there is an urgent need to formulate appropriate preventative measures, one of which is carrying out mapping so that detailed information can be provided regarding the level of spatial-based risk in the Tumbang Nusa Village area that can be used to provide disaster mitigation recommendations.

Materials and Methods

The focus was on mapping the risk of forest and land fires in the Tumbang Nusa Village area, Pulang Pisau Regency, Central Kalimantan, using satellite imagery and spatial data from September to November 2023. Tumbang Nusa Village is at an altitude of 30 m above mean sea level and has an average annual rainfall of 6 mm and an average air temperature of 23–30°C, with most of the area being lowland peat swamp. The topography and climate result in the hydrological system in the peatland tending to be horizontal, with extreme dryness if there is a long dry season, resulting in ground fires occurring throughout the year. The decline in the soil height in peatlands tends to occur continuously if rehabilitation measures are not taken on critical lands. Tidal changes from upstream in the rainy season result in increased surface water levels in the Tumbang Nusa Village area causing flooding where the waterflows from upstream and downstream meet.

The Tumbang Nusa Village area is administratively included in the Jabiren Raya District in the Pulang Pisau Regency. The location of Tumbang Nusa Village (2° 18' 7.11" LS - 2° 25' 34.30" LS and 114° 3' 56.71" BT - 114° 16' 37.47" BT) is very strategic, being on the Trans Kalimantan route (the main road across Kalimantan), and on the edge of the Kahayan watershed, facilitating public transportation to access the city as an economic and trade center.

The Tumbang Nusa Village area covers approximately 200 km^2, with a total of 286 family groups. The area has abundant natural resources, one of which is peat soil. A map of the research location is provided in Fig. 1.

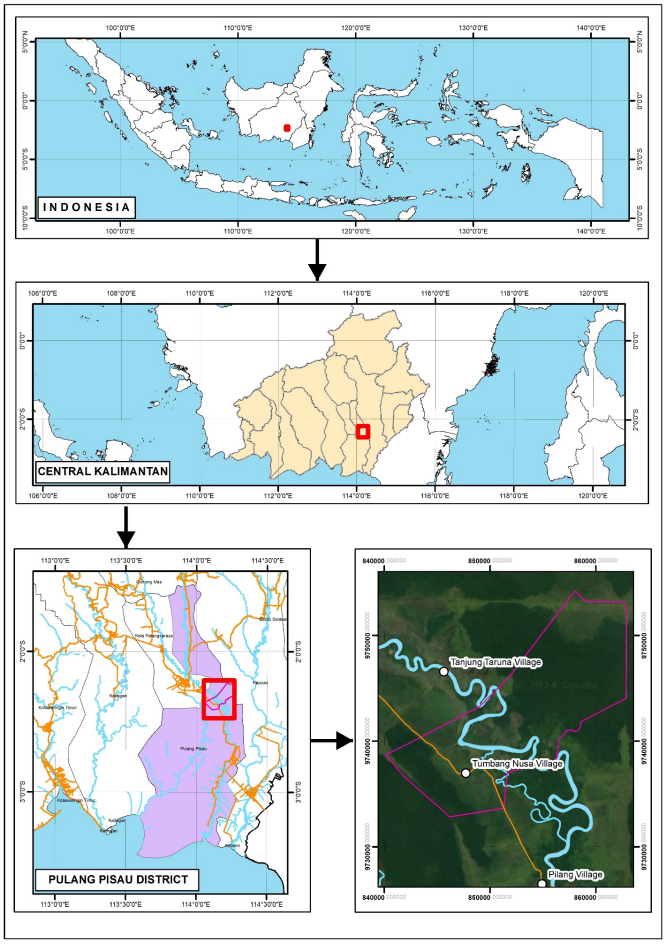

Fig. 1 Maps of research area, Indonesia

The landsat 8 satellite imagery used was from Path 118 Row 62, collected on 2 September 2023, in conjunction with hotspot data from the MODIS satellite imagery for the 2021–2023 period and other spatial data from maps of the road network, rivers and settlements of the Tumbang Nusa Village area, all of which were obtained as secondary data from public sources or via requests from the related institutions. The research flow chart is provided in Fig. 2.

First, the spatial data were processed using geometric correction, to correct image distortion due to sensor factors, sun position and earth surface relief (Wu et al., 2023). Geometric correction was carried out using reference ground control coordinate data from the 1:50,000 scale base map Rupabumi Indonesia (RBI). Next unsupervised image classification was carried out using the KMeans Clustering iteration technique to obtain land cover class information (Abdulnassar and Nair, 2023).

Further analysis involved: 1) calculating the normalized vegetation index (NDVI) to obtain information about the density and condition of vegetation; 2) calculating the normalized difference moisture index (NDMI) to evaluate soil moisture levels; and 3) calculating surface temperature using the land surface temperature algorithm from radiation values in the Landsat 8 image thermal band.

Fire risk was analyzed by combining several parameters (NDVI, NDMI, surface temperature, the distance to roads and the distance to settlements). The accuracy of the developed fire hazard map was carried out by comparing the results with hotspot point distribution data from MODIS using an error matrix to determine accuracy.

Results and Discussion

Normal difference vegetation index analysis

The NDVI is the most commonly used vegetation index used to describe the level of greenness in land vegetation cover. NDVI is calculated as the ratio between the spectral reflectance measurements acquired in the red (visible) and near-infrared regions. Interpretation of the absolute values of NDVI is very informative, as it allows a general assessment of vegetation conditions, providing information about the state of vegetation of a location, whether it is a forest area, agricultural zone, or other type of land cover. NDVI is an effective indicator of vegetation growth and density pattern and has been used to explore numerous ecological studies of vegetation dynamics and their major drivers (Xu et al., 2024; Yang et al., 2024). NDVI analysis is a key tool in managing fire risk, providing information to stakeholders to design strategies to maintain ecosystems and minimize fire risk.

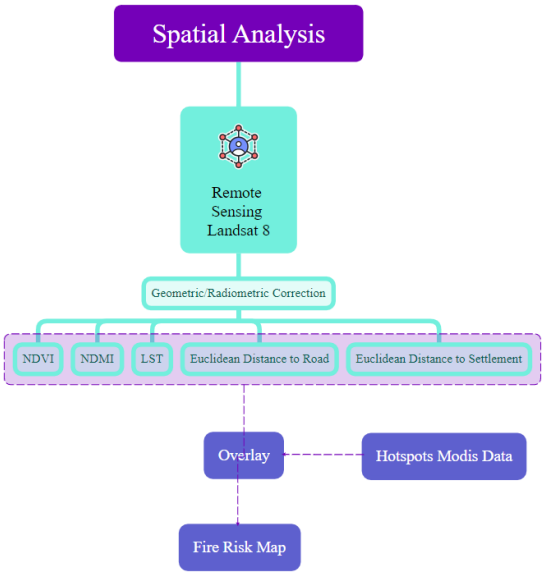

Fig. 2 Flow chart of analysis

The results of the imagery analysis and applying the to obtain land cover types based on the level of healthy vegetation density and potential fire risk in the area are in Table 1 and Fig. 3.

Table 1 Fire risk based on normalized difference vegetation index for Tumbang Nusa Village area, Indonesia

Risk level	Area (ha)
Very low	9,583.43
Low	8,943.83
Current	1,793.62
High	118.66
Very High	428.12
Total	20,867.67

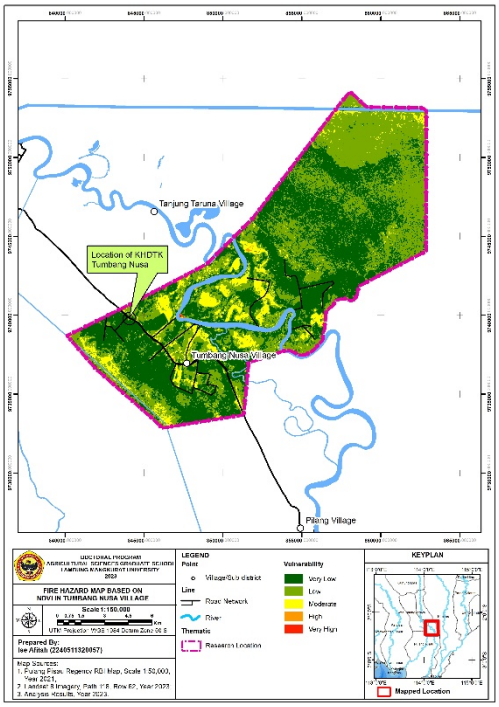

Fig. 3 Fire risk map based on normalized difference vegetation index for Tumbang Nusa Village area, Indonesia

Based on the NDVI analysis, the study area could be divided into five fire risk categories. Areas with very high NDVI levels (9,583.4 ha) indicated healthy vegetation and a stable environment with a very low risk of fire, while areas with low NDVI levels (8,943.83 ha) were classified as having a low risk but still required monitoring and preventive measures. Medium areas (1,793.62 ha) had good NDVI levels but some areas might experience fire risk, requiring mitigation measures. Areas with high NDVI levels (118.66 ha) had lower vegetation or environmental stress, requiring intensive monitoring. Areas with very low NDVI levels (428.12 ha) indicated a major potential fire risk, requiring in-depth prevention and management measures.

Water index based on normalized difference vegetation index

NDMI can be used to calculate the water index (Taloor et al., 2021). The imagery and NDVI results for the current research area were applied to evaluate the level of soil moisture and potential fire risk in the area (Table 2 and Fig. 4).

Table 2 Fire risk based on normalized difference vegetation index for Tumbang Nusa Village area

Risk level	Area (ha)
Very low	10,012.74
Low	5,150.71
Current	3,090.13
High	1,905.73
Very High	708.37
Total	20,867.67

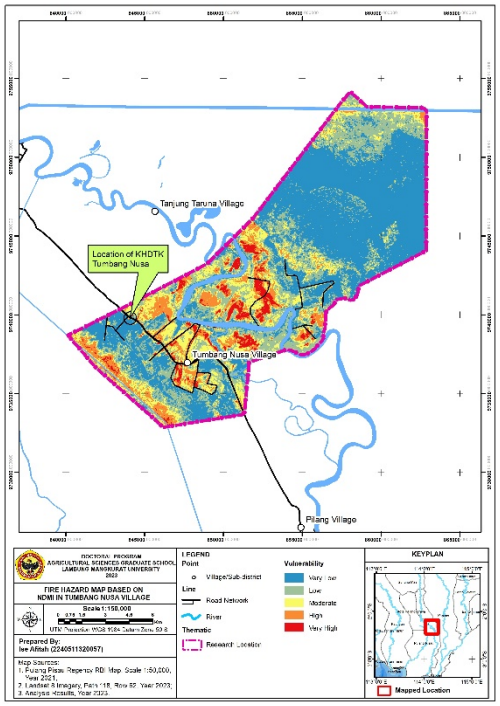

Fig. 4 Fire risk map based on normalized difference vegetation index for Tumbang Nusa Village area, Indonesia

Three categories of fire risk were identified. Areas with very low soil moisture levels (10,012.74 ha) had a good level of vegetation sustainability with very low fire risk. Areas with low soil moisture levels (5,150.71 ha) had stable vegetation conditions with a relatively low risk of fire but still required monitoring and preventive measures. Finally, areas with moderate soil moisture levels (3,090.13 ha) had moderate moisture levels, possibly indicating a moderate fire risk, and requiring mitigation measures. The NDMI analysis provided key information to understand soil moisture levels

and manage fire risk to maintain ecosystem sustainability in the Tumbang Nusa Village area.

Areas with high levels of soil moisture (1,905.73 ha) indicate vegetation conditions that may be less than optimal or experiencing environmental stress, requiring intensive monitoring and preventive measures to prevent greater fire risks. Although the relative area in this case may be small, areas with very low soil measures levels (708.37 ha) represent a lower fire risk. Therefore, in-depth prevention and management measures should be carried out in this region. These results of the NDMI analysis provided and important tool in identifying and managing fire risks in the Tumbang Nusa Village area, providing stakeholders with the information needed to design effective strategies for maintaining ecosystem sustainability and minimizing potential fire risks.

Land surface temperature analysis

LST is a key parameter for measuring the temperature of an area (Matias and Lopes, 2024; Patel et al., 2024). The results for the current study area relating LST to the potential for fire risk in the area are provided in Table 3 and Fig. 5.

Most of the Tumbang Nusa Village area presented land surface temperature levels that indicated good vegetation sustainability at very low levels (7,100.12 ha). Even though the risk of fire in these areas would very low, monitoring and preventive measures are still needed to maintain ecosystem stability. Areas with low but still good LST values (5,939.17 ha) indicate stable vegetation conditions, with a relatively low risk of fire, but preventive and monitoring measures are still needed for environmental sustainability. Although most of the area had good LST values (4,537.51 ha), some areas may experience moderate temperatures, an indicator of moderate fire risk, requiring mitigation measures. Areas with higher land surface temperatures (2,575.24 ha) indicated less than optimal vegetation conditions or environmental stress, requiring more intensive monitoring and preventive measures to prevent a greater risk of fire. Although the proportion was small, areas with very high land surface temperatures (715.64 ha) presented a major potential fire risk, requiring in-depth prevention and management measures. LST analysis was key to identifying and managing fire risks in the Tumbang Nusa Village area, providing information for stakeholders to design effective strategies in maintaining ecosystem sustainability and minimizing potential fire risks.

Table 3 Fire risk based on land surface temperature for Tumbang Nusa Village area, Indonesia

Risk	Area (ha)
Very low	7,100.12
Low	5,939.17
Currently	4,537.51
High	2,575.24
Very High	715.64
Total	20,867.67

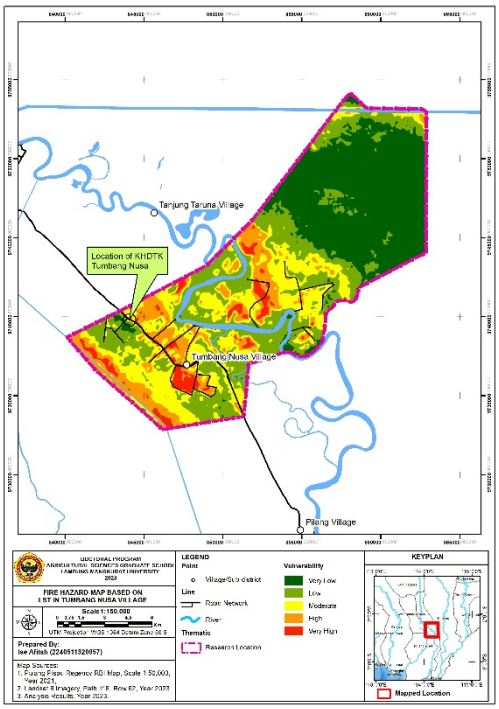

Fig. 5 Fire risk map based on land surface temperature for Tumbang Nusa Village area

Road Euclidean distance analysis

The analysis was carried out of the distance to the nearest road for its implications regarding potential fire risk, as a basis for determining remoteness. The broad Euclidean distance classification for roads in the study area is in Table 4 and Fig. 6.

Table 4 Fire risk based on Euclidean road distance for Tumbang Nusa Village area, Indonesia

Risk	Area (ha)
Very low	13,683.03
Low	1,450.49
Current	1,779.88
High	1,910.10
Very High	2,044.18
Total	20,867.67

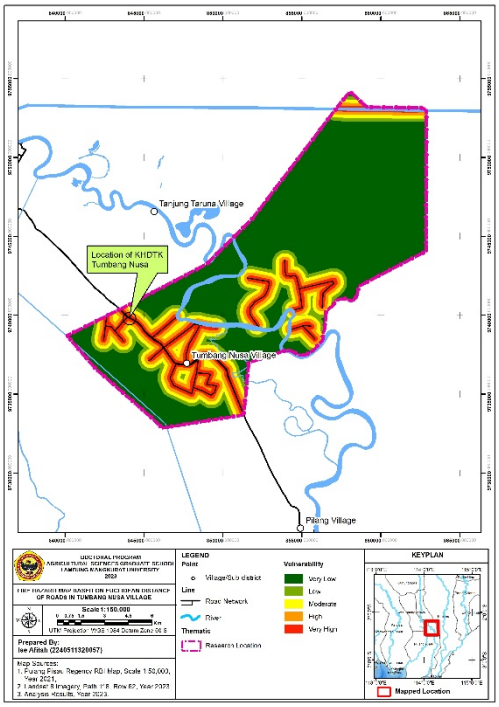

Fig. 6 Fire hazard map based on Euclidean road distance for Tumbang Nusa Village area, Indonesia

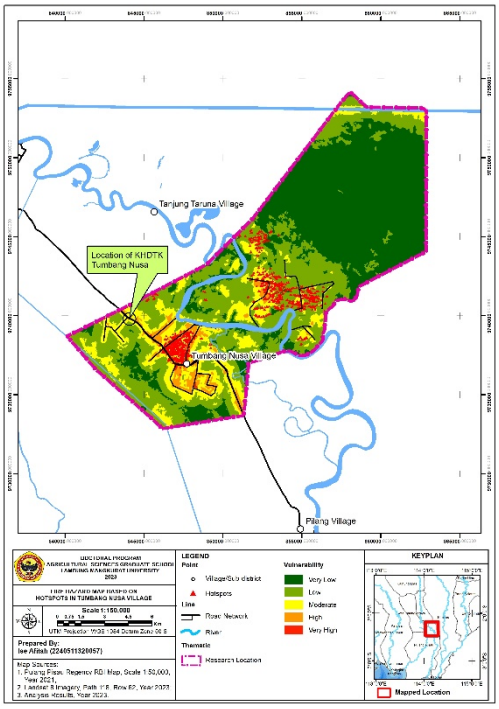

Fig. 7 Fire risk map based on hotspots for Tumbang Nusa Village area, Indonesia

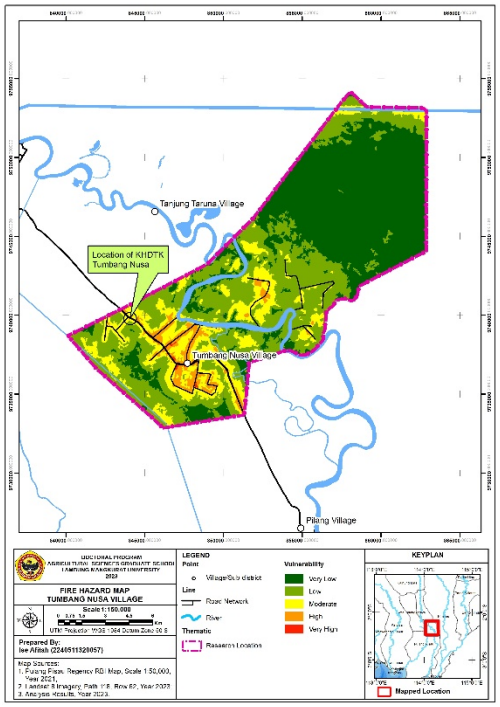

Fig. 8 Overlay map of fire risk for Tumbang Nusa Village area, Indonesia

The Tumbang Nusa Village area could be classified into three levels of risk based on distance to a road. First, at the very low level (13,683.03 ha), areas with very long distance to roads have minimal accessibility, which effectively reduces the risk of human-caused fires. The lack of accessibility is an advantage in preventing human activities that can trigger fires, so the level of risk is very low. Second, at the low level (1,450.49 ha), areas with a low distance to roads still have a fairly good level of accessibility. However, uncontrolled human activity could increase the risk of fire. Therefore, more intensive monitoring and preventive measures would be needed in this area to reduce the risk of human-caused fires. Third, at the medium level (1,779.88 ha), areas with a moderate distance to roads indicated that accessibility might have an impact on fire risk, especially if human activity were uncontrolled. Further analysis is needed to identify and address potential causes of human-caused fires in this area, although the level of risk is still placed at a moderate level.

Settlement Euclidean distance analysis

A distance analysis of settlements was carried out to evaluate their impact on potential fire risk. The broad classification of fire risk based on the Euclidean distance of settlements

in the Tumbang Nusa Village area are presented in Table 5, with five levels of risk. At the very low level (16,908.22 ha), areas were far from settlements, reducing the risk of fires caused by human activities. The low level (669.31 ha) indicated areas quite remote from settlements, requiring monitoring to maintain conditions and reduce potential fire risks, whereas the medium level (906.92 ha) indicated areas closer to settlements, requiring further analysis to identify potential fire risks. At the high level (1,128.21 ha), there was increased risk because these areas we close to settlements, requiring intensive prevention and monitoring strategies. At the very high level (1,255.02 ha), even though the area was small, there would be a major risk because these were near residential areas, requiring in-depth management measures. Distance analysis to settlements provides an overview of important factors that influence fire risk, helping stakeholders design appropriate mitigation strategies to maintain sustainability and prevent fires in the Tumbang Nusa Village area.

Table 5 Fire risk based on Euclidean settlement distance for Tumbang Nusa Village area, Indonesia

Risk	Area (ha)
Very low	16,908.22
Low	669.31
Current	906.92
High	1,128.21
Very High	1,255.02
Total	20,867.67

Overlay analysis

Overlay (intersection) analysis was carried out using the NDVI, NDMI, LST, distance to roads, and distance to settlements data, as well as a comparative analysis with the distribution of hotspot locations for the last three years (from 2021 to 2023), to evaluate the level of fire risk. The resultant fire risk levels are presented in Table 6.

The overlay analysis between the level of fire risk and hotspot data provided a comprehensive picture of the extent to which the level of risk was correlated with the distribution of hotspots.

Table 6 Fire risk level for Tumbang Nusa Village area, Indonesia

Risk	Area (ha)	Number of hotspots
Very low	8,747.62	14
Low	8,090.45	345
Current	3,117.26	371
High	882.45	241
Very High	29.90	14
Total	20,867.67	985

Areas with a very low level of risk (8,747.62 ha; hotspots = 14) indicated that even though there were some hotspots, the general level of risk could still be considered low. Possible causes included healthy vegetation and other mitigation factors that were effective in controlling fire risk. Areas with a low level of risk (8,090.45 ha; hotspots = 345) had high correlation with hotspots. Even though the level of risk was still under control, the high number of hotspots may indicate potential risks that need further attention. Areas with a medium level of risk (3,117.26 ha; hotspots = 371) showed a strong correlation with hotspots, reflecting a higher potential fire risk. Therefore, intensive mitigation and monitoring measures may be required. Areas with a high level of risk (882.45 ha; hotspots = 241) show a strong correlation with the number of hotspots, indicating a high potential fire risk. This category would require stricter prevention and risk management measures. Areas with a very high level of risk (29.90 ha; hotspots = 14) indicated the presence of hotspots and a major level of risk, requiring special attention and in-depth mitigation strategies. The results of this analysis should provide a basis for government officials and stakeholders in designing appropriate response strategies to overcome the risk of forest and land fires in the Tumbang Nusa Village area, using hotspot monitoring as a basis for implementing effective prevention and mitigation measures.

Conclusion

Based on spatial analysis related to fire risk and hotspot mapping in the Tumbang Nusa Village area, the level of fire risk was heavily influenced by the road access and residential access. Although variables such as NDVI, NDMI and LST levels were also influential, the dominance of hotspots could be attributed to access, as the main trigger for human activity to result in burnt land. These findings highlighted the central role of accessibility in determining the level of fire risk in the region. Access that makes it easier for individuals to carry out activities and burn land was the main cause of increased fire risk. Therefore, fire mitigation strategies in the Tumbang Nusa Village area should focus on managing and monitoring accessibility which should reduce the potential for uncontrolled burning. A key point is effective coordination among the managing authorities, local communities and other related parties in managing and monitoring access to create sustainable solutions for overcoming fire risk caused by human activities in the area.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

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