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# Integrating Remote Sensing and GIS for Fire susceptibility Modeling in Suryabinayak Municipality: A Frequency Ratio Approach

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## Abstract

By integrating GIS-based and remote sensing analysis, fire hazard areas were identified and mapped with the aim of providing useful information about the regions most likely to be damaged by fire caused by natural as well as anthropogenic activities in the Suryabinayak Municipality. In the southeast of Suryabinayak Municipality, fires are one of the most devastating threats. While it is challenging to control fires, it is possible to map fire risk using geospatial technology, reducing the frequency of fires and the damage they cause. A probabilistic approach of Frequency Ratio model was implemented to develop the fire hazard assessment model used in this study. As factors influencing fire, vegetation, landuse, moisture, slope, aspect, elevation, distance from roads, and proximity to settlements were all taken into consideration. These indices were created by assigning weight values depending on the classes and layers' sensitivity to fire. To generate a final fire hazard map, spatial analysis was used to classify and overlay all the individual causative factor maps. The actual fire occurrence map and the fire inventory were compared to validate the model and verified using hotspot data from MODIS satellite sensor. The model can only be utilized in certain areas, and if it is used in other areas, additional criteria need to be taken into consideration. The findings demonstrate that the majority of actual fire spots are situated in the model's high and very high fire risk zones.

### Keywords

Fire Hazard, Remote Sensing, GIS, FR (Frequency Ratio) Method, Fire Susceptibility.

## 1. Introduction

Fires have serious environmental and ecological consequences that endanger human life and result in enormous losses in terms of both people's lives and property [1]. The use of geographic information systems (GIS) alongside other technological tools like remote sensing and computer modeling is growing across all regions to oversee fires [2]. In order to develop a successful fire management system, especially for managing and avoiding fires, investigation into modeling fire hazard assessment is crucial.

Based on the physiographic or environmental parameters that trigger fire, many researchers have created fire hazard models for a particular location [3]. Areas that have a high probability of fire needs to be defined as an important feature for fire management planning hence it was necessary to create a fire hazard model and map in order to identify, categorize, and identify fire hazard zones [4]. The study's output is a contribution to developing a fully functional GIS for managing fires, particularly fire prevention.

In this study, the fire susceptibility characteristics of Suryabinayak Municipality are evaluated using expert opinion and a frequency ratio (FR) model, a form of multi-criteria decision making (MCDM) tool. This model is then combined with GIS software to produce a fire susceptibility map [5].

Fire is the most frequent sort of disaster accounting for 6004 incidents and 1386 fatalities in Nepal between the years of 1971 and 2022, according to a survey of disasters. [6]. There are various research on the integration of the FR approach with GIS [7].

This paper incorporates the application of FR method [8] for preparing fire susceptibility map of Suryabinayak Municipality. Establishing fire hazard regions has been made possible by combining various variables using a GIS technique. The results of the fire susceptibility mapping study in Suryabinayak Municipality are thus summed up in this paper.

## 2. Study Area

Suryabinayak Municipality is one of the four municipalities in Bhaktapur, consisting of 10 wards. It is a loose soil deposit with relatively flat terrains, and mountains ranging from 1198 m to 2722 m above mean sea level (MSL) in the fringes. The

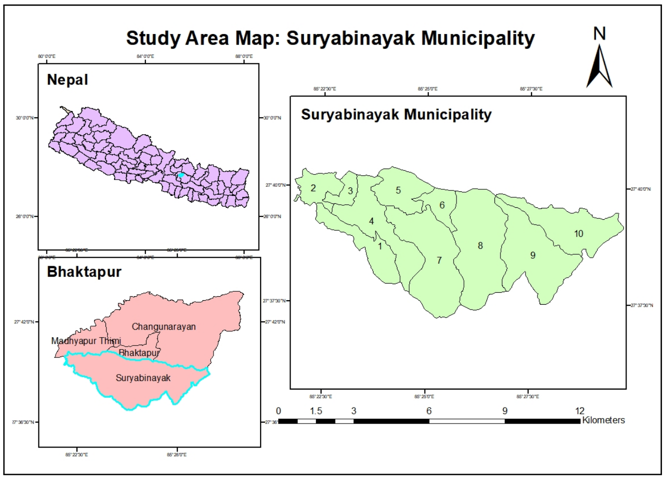

**Figure 1:** Location of Study Area.

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weather is influenced by the South Asian monsoon with hot and wet summers (March–August) and cold dry winters (September– February) hence subtropical. The average monthly rainfall varies widely with the lowest (4.2 mm) and the highest (402.1 mm) precipitation occurring in December and July, respectively [9]. The area is filled with soft sediments and organic clay [10]. The main river system of this municipality is Hanumante. Suryabinayak is traditionally an important city with a unique culture and norms.

Rapid change is occurring in the Municipality's regional environment. As a result, urban settlement areas and industrial regions have sharply increased. There have been more fire occurrences as a result of Suryabinayak's rapid development growth.

## 3. Data Collection and Methodology

### 3.1 Fire Inventory

The mapping of the inventory is an essential prerequisite for fire susceptibility modeling. Fire incident occurrences must be mapped in order to understand the spatial relationships between incident locations and their influencing variables. The data for the fire inventory was obtained from NASA FIRMS: MODIS Hotspot data, a 10-year period of point data was obtained and the point data was changed into the raster data using GIS.Google Earth, Historical data, and fire brigade data were used to verify and double-check the inventory.

The MODIS satellite uses thermal infrared and medium infrared bands to locate fires and identify thermal abnormalities, and it has comparatively superior precision [11]. Based on a review of the literature, a number of geological, topographic, and other significant elements that are connected both alone and in combination with the incidence of fire are chosen. The information relative to various factors is presented in this research.

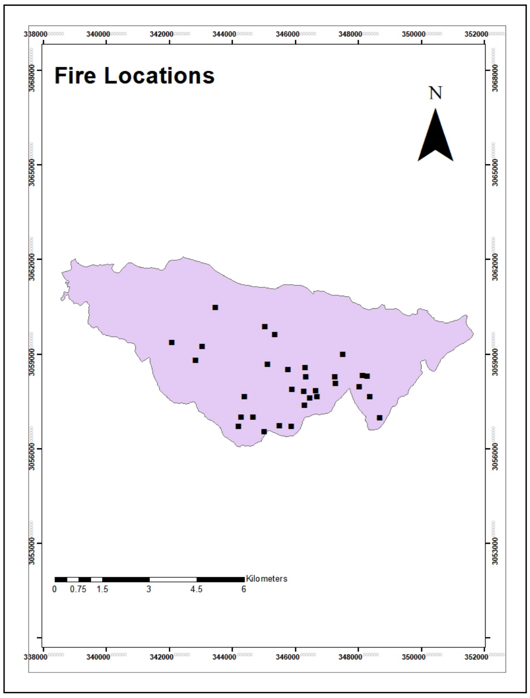

**Figure 2:** Map showing fire incidents in Suryabinayak Municipality.

### 3.2 Spatial Distribution of Thematic Layers

The spatial distribution of thematic layers gives light to the particular facts or phenomena that are dispersed throughout the terrain. For the study, the necessary data related to Digital Elevation Models (DEM) is sourced from ALOS Palsar, land cover information from ICIMOD, Copernicus, and Google Earth, as well as distances from main settlements using World Settlement Data. Fire data is obtained from NASA FIRMS, while Sentinel Data is accessed from the Earthdata Website. Geology information is sourced from ICIMOD, wind velocity data from the Global Wind Atlas, and distances from roads are obtained through QuickOSM and the Regional Database System by ICIMOD. Rainfall and discharge data is collected from DHM, and soil data is sourced from ICIMOD. Information on fire occurrences was also gathered from the official website of the government of Nepal. Table 1 showcases the diverse range of data sources (remotely sensed and inventory), which can be utilized for spatial analysis using GIS.

For the purpose of identifying the fire in the research region, a total of eleven thematic layers were examined, including aspect, slope, soil, Topographic wetness index (TWI), curvature, distance to road, distance to settlement, NDVI, NDMI, elevation, and wind speed. The eleven thematic layers used in the study are described and presented as map layers below.

**Aspect** The orientation of slopes, also known as aspect, plays a significant role in determining exposure to sunlight, wind patterns, and precipitation levels. Consequently, it has a direct impact on various factors that contribute fires, such as soil moisture, the density of vegetation cover, and the depth of the soil. [12]. The aspect map for the study area is derived from DEM data and it is divided into nine classes, namely Flat (-1°-0°), North (0°-22.5° and 337.5°-360°), North-East (22.5°-67.5°), East (67.5°-112.5°), South-East (112.5°-157.5°), South (157.5°-202.5°), South-West (202.5°-247.5°), West (247.5°-292.5°), and North-West (292.5°-337.5°).

**Slope** Slope refers to the steepness or incline of a surface. It is determined by assessing the highest rate of elevation change between a specific location and its immediate surroundings. Through slope, we can better understand how fire might spread across the landscape. Steeper slopes can

**Table 1:** Data Parameters and sources

| Data Parameters | Source |
|---|---|
| DEM 12.5 x 12.5<br>(Digital Elevation Model) | ALOS Palsar |
| Landcover | ICIMOD, Copernicus and Google Earth |
| Distance from Main Settlements | World Settlement Data (R26,C26) |
| Fire Data | NASA FIRMS, GON, Brigade Stations |
| Sentinel Data | Earthdata Website |
| Geology Map | ICIMOD |
| Wind Velocity | Global Wind Atlas |
| Distance from Road | QuickOSM and Regional Database System, ICIMOD |
| RAinfall/Discharge | DHM |
| Soil Data | ICIMOD |

hinder firefighting efforts, affect fire intensity, and alter the direction of fire propagation. Furthermore, slope influences factors like wind patterns, vegetation distribution, and soil moisture, all of which play a significant role in fire dynamics. Hence, incorporating slope data into fire analysis is crucial for effective fire management, prevention, and mitigation strategies [12]. The slope of the map of the study area is prepared from DEM data. It is classified into four classes; 0-15°, 15°-30°, 30°-50°, 50°-70°.

**Soil** Distributed extensively across the Earth's surface, various soil types possess different characteristics that separate them from one another. These soil types are demarcated as distinct mapping units, each comprising a cohesive collection of soil material. Over time, these soils interact with adjacent soil types, bedrock, or undisturbed sediment, shaping the landscape. Soil, a complex blend of organic matter and mineral-rich components, forms on the Earth's surface, nurturing and sustaining a multitude of life forms across our diverse ecosystems [10]. The soil data was obtained from the ICIMOD and the two types of soil was classified at the study area: CMe (Eutric Cambisols) and CMx (Chromic Cambisols) [10].

**TWI (Topographic Wetness Index)** The Topographic Wetness Index (TWI) is a commonly employed metric for assessing the impact of topography on hydrological processes. It is calculated by considering both the local upslope contributing area and the overall slope of a specific location. This index provides valuable insights into how topography influences the movement of water across a landscape. It effectively describes the spatial distribution of soil moisture, aiding in the understanding of areas prone to water accumulation or drainage. By utilizing TWI, researchers and environmental analysts can make informed decisions related to land management, watershed assessment, and the prediction of flood or drought-prone regions [13]. The TWI is expressed in equation 1.

$$\mathrm{TWI} = \ln\left(\frac{a}{\tan B}\right) \tag{1}$$

where,
$a$ = cumulative upslope area draining through a point (per unit contour length)
$\tan B$ = slope angle at the point

The topographic wetness map was created from DEM of the study area and it was classified into five classes:less than 5, 5–10,10–15,15–20 and greater than 20.

**Distance from Roads** The National Fire Protection Association (NFPA) mandates that access roads have enough space for setup and manual suppression operations, as well as enough access to the building. Fire department access routes must have a minimum of 20 feet (6.1 meters) of unobstructed width, 13.5 feet (4.1 meters) of unobstructed vertical clearance, and an acceptable radius for turns in the highways and dead ends in order for the mobile apparatus to turn around safely [4]. The road layer is extracted from OpenStreetMap using the QuickOSM plugin and the distance from the road is developed using the buffer tool at a different distance in GIS and classified as less than 300, 300-500 and greater than 500.

**Distance from Settlement** Settlements are usually formed around a key resource and have a history of people living together in a region. Understanding this spatial relationship helps evaluate the vulnerability of communities to fires. Urbanization is an ever-evolving phenomenon with profound impacts on our environment and societies. As more people migrate to cities, it is imperative to address the associated challenges. Settlement data also informs evacuation planning, firefighting resource allocation, and the development of fire prevention strategies in areas where human habitation interfaces with fire-prone landscapes [14]. The settlement data was obtained from the global human settlement layer (European Union) and the settlement was categorized into four classes: less than 1000,1000-2000,2000-3000 and greater than 3000.

**NDVI (Normalized Difference Vegetation Index)** The vegetation cover often has a great influence on fire occurrence as they are related to anthropogenic interference on the hill slopes [15]. NDVI is generated from a Landsat-8 (30m resolution) satellite image which is acquired on 5, Sep 2022 and computed using equation 2;

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - R}{\mathrm{NIR} + R} \tag{2}$$

Where, NIR-spectral reflectance of near-infrared bands and R-spectral reflectance of red bands. NDVI range from -1 to 1 and a higher value implies denser green vegetation whereas lower values indicate less dense vegetation. The NDVI was classified into six class; less than 0.14, 0.14-0.22, 0.22-0.27, 0.27-0.31, 0.31-0.36, and greater than 0.36.

**Curvature** The Curvature map of the study area was generated from DEM data using spatial analysis tools and it was classified into three classes; concave, flat, and convex surface [5]. In the context of fire assessment, these curvature classes hold critical implications. Concave areas, characterized by negative curvature, often accumulate moisture and are potentially less susceptible to rapid fire spread. Conversely, convex regions with positive curvature may facilitate the quick propagation of fires due to their drier nature. Flat areas represent a middle ground. The positive, zero, and negative curvature are represented by convex, flat, and concave classification.

**NDMI (Normalized Difference Moisture Index)** NDMI (Normalized Difference Moisture Index) is a vegetation index commonly used to detect moisture content in vegetation. It is computed by the difference between the near-infrared (NIR) and mid-infrared (MIR) bands of satellite imagery, and then normalizing it by their sum as shown in equation 3. NDMI values range from -1 to 1, where values closer to 1 indicate a higher level of moisture in vegetation, while values closer to -1 indicate a lower level of moisture. This index is particularly useful in agricultural and environmental applications, as it can help to identify areas of drought stress, monitor crop health, and assess the impact of climate change on vegetation.

$$\mathrm{NDMI} = \frac{\mathrm{NIR} - \mathrm{MIR}}{\mathrm{NIR} + \mathrm{MIR}} \tag{3}$$

Where NIR is the reflectance value in the near-infrared band (Band 8A), and MIR is the reflectance value in the mid-infrared band (Band 11). Higher NDMI values indicates higher moisture content, and lower NDMI values indicating lower moisture content. The index can be used for a variety of applications, such as monitoring drought stress, assessing crop health, and studying the impact of climate change on vegetation. The NDMI was classified into four classes for the study area: less than 0.1, 0.1-0.2, 0.2-0.3, and greater than 0.3.

**Elevation** Elevation, within the context of geographic and environmental analysis, plays a multifaceted role in influencing various natural processes and landscape characteristics. It affects precipitation, degree of weathering, type of lithology present on slopes, slope gradient variation, soil thickness, land use, etc [2]. The elevation map of this study is derived from ALOS PALSAR (12.5m resolution) DEM, after resampling and using GIS analysis was classified into 3 classes as less 700, 1400-1800 and greater than 1800.

**Windspeed** Global Wind Atlas provides free access to high-resolution wind resource data for more than 200 countries and regions around the world. The data is based on a combination of mesoscale modeling and satellite observations and is validated using ground-based measurements. The Global Wind Atlas also provides a range of tools and resources for wind energy developers, planners, and policymakers to assess the wind resource potential and feasibility of wind energy projects. The data of the wind speed was obtained from global wind atlas website and was classified into five classes for the study area: less than 1,1-1.6,1.6-2.4,2.4-3.2 and greater than 3.2.

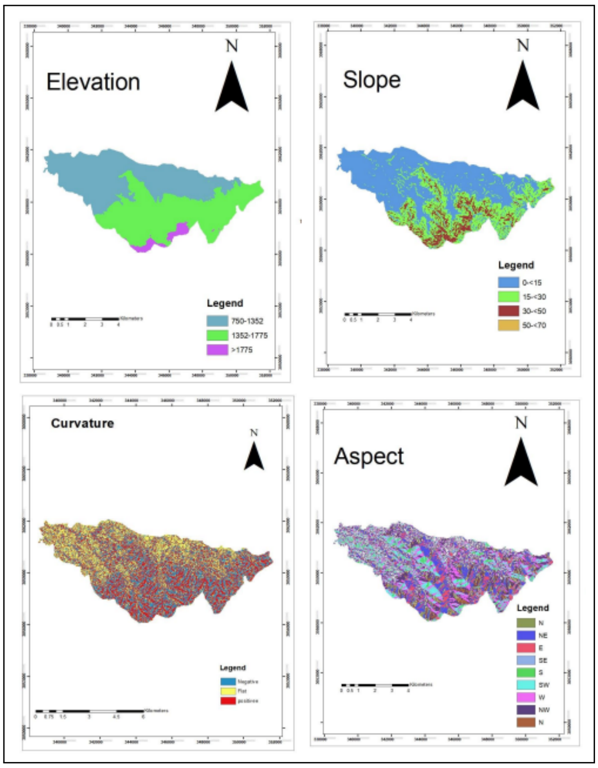

**Figure 3:** Thematic Map showing slope map, aspect map, curvature map and elevation map of Suryabinayak municipality.

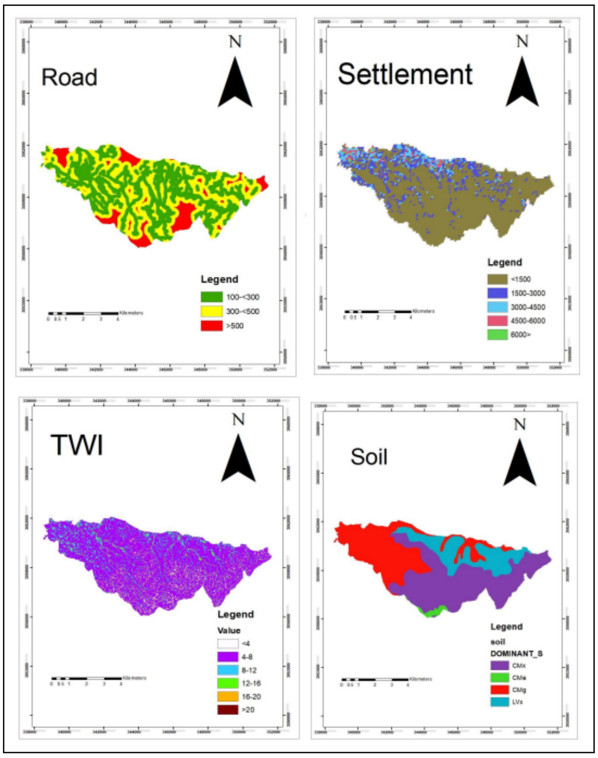

**Figure 4:** Thematic Map showing road distance, settlement, TWI and soil of Suryabinayak municipality.

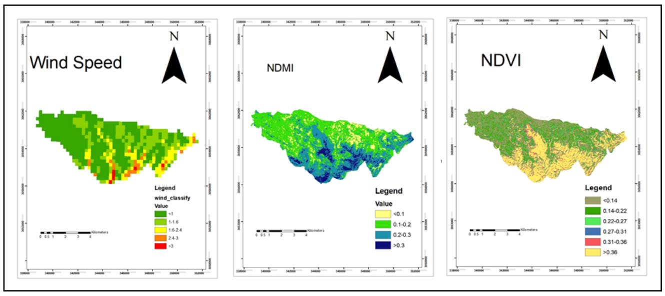

**Figure 5:** Thematic Map showing wind velocity, NDVI and NDMI of Suryabinayak municipality.

## 4. Methodology

### 4.1 Frequency Ratio Method

The Frequency Ratio Method is a commonly used technique in fire hazard mapping and is employed to assess and quantify the spatial distribution of fire occurrences based on various environmental and topographic factors. FR allows for the assessment of how specific attributes (subclasses) of a causative factor, like slope, lithology, or curvature, influence the occurrence of a particular phenomenon, such as floods or landslides. In essence, FR represents the ratio of the likelihood of a phenomenon happening in relation to the likelihood of it not happening, based on a given attribute [16]. This method aids in understanding the impact of factors on various natural events. This method involves a statistical analysis of historical fire data and associated factors to identify patterns and relationships that can help predict fire hazard areas [16]. Frequency ratio approaches rely on the observed connections between the distribution of hotspots and various hotspot-related factors to unveil the correlation between hotspot locations and these factors within the study area [17]. The frequency ratio model is employed to establish the spatial relationships between the occurrence of hotspots and each contributing factor. It involves calculating the frequency based on an analysis of how the factors relate to hotspot events [16].

To compute the Fire Susceptibility Index (FFSI), the frequency ratio values of each factor are summed within the training area [16], as shown in equation. The FFSI value reflects the relative susceptibility to fire occurrence, with higher values indicating a greater susceptibility and lower values indicating a lower susceptibility to fire occurrence [16], equation 4 is used.

$$FFSI = Fr1 + Fr2 + Fr3 + ..... + Frn \tag{4}$$

FFSI: Fire Susceptibility Index; Fr: Rating of each factors' type or range

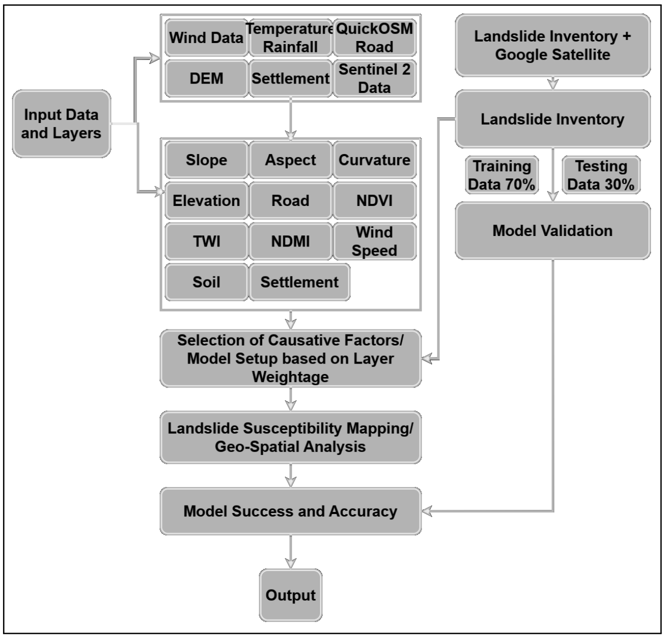

**Figure 6:** Methodology for Fire Susceptibility Assessment

### 4.2 Spatial Distribution according to FR method

The study encompassed eleven thematic layers, including aspects like aspect, slope, soil type, Topographic Wetness Index (TWI), curvature, distance to roads, distance to settlements, NDVI, NDMI, elevation, and wind speed, in the study area to assess fire risk. Notable findings include a high FR value of 4.35 for north-facing aspects, covering 7 percent of the area, and CMe (Eutric Cambisols) soil being most susceptible with an FR of 4.78. Areas with a TWI class of 4 - 8 exhibited an FR of 1.20, encompassing 78 percent of the total area. Negative curvature areas, constituting 37 percent of the total curvature area, had an FR of 1.43, indicating vulnerability. Furthermore, areas located more than 500 meters from roads posed a significant risk with an FR of 2.89. Areas within 1500 meters of settlements had an FR of 1.33, covering 75 percent of the total area, suggesting increased susceptibility. The analysis also revealed that areas with NDVI greater than 0.36 had a heightened FR of 2.26, while wind speeds in the range of 1.6 - 2.4 m/s were associated with a significant fire risk, boasting an FR of 4.04, and covering 12 percent of the total area. These findings provide crucial insights for targeted fire prevention and management strategies to safeguard both ecosystems and local communities in the study area.

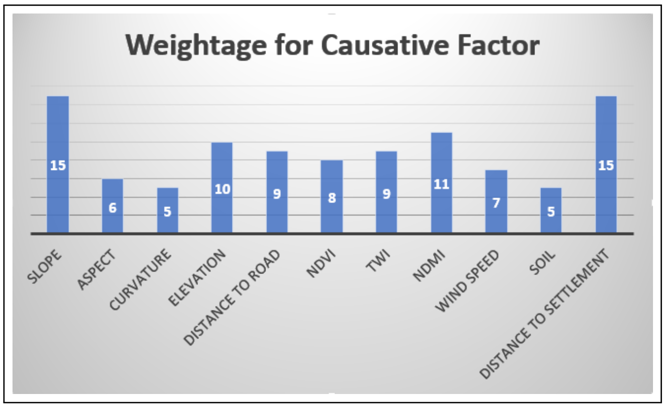

**Figure 7:** Weightage for Various Causative factors of fire

Based on the data depicted in the graph, it is evident that settlements and the slope were the primary contributing factor to fires in the study area, accounting for 15 percentage of the total incidents. Conversely, soil and curvature had the smallest influence on fires, representing only 5 percent of the total occurrences within the area.

The fire hazard was categorized into the four classes: low, moderate, high and very high using the natural break classification method in GIS. The classification of fire are 32 percent, 33 percent, 29 percent and 6 percent for low, moderate, high and very high classification respectively. The fire susceptibility map of the Suryabinayak Municipality is shown in figure 8:

From the fire incidents documented by Suryabinayak Municipality and the fire brigade station, it is noteworthy to emphasize the meaningful relationship observed between the spatial distribution of these incidents and the zones indicated on the map.

**Table 2:** Historical events with respect to susceptibility map.

| S. No. | Classification | Past Occurrences | |
|---|---|---|---|
| | | Number | % |
| 1 | Low | 2 | 6.45% |
| 2 | Moderate | 6 | 19.35% |
| 3 | High | 10 | 32.25% |
| 4 | Very High | 13 | 41.95% |

The relation serves as compelling evidence of the accuracy and reliability of the susceptibility zone delineations. It reinforces the credibility of the methodology in assessing and predicting areas prone to fire occurrences, underlining the practical utility of susceptibility mapping in fire risk management. The credibility of the model has been consistently reinforced by prior articles and research findings. These preceding studies have consistently affirmed the validity and effectiveness of the model.

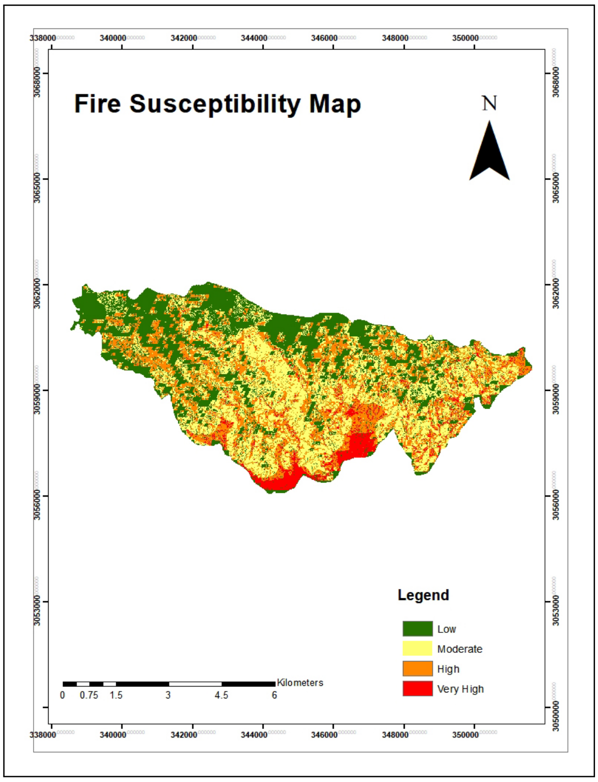

**Figure 8:** Fire Susceptibility Map of Suryabinayak Municipality.

## 5. Discussion

A noteworthy observation emerges while considering the documented fire incidents reported by Suryabinayak Municipality and the local fire brigade station. This observation highlights a significant relation between the spatial distribution of these fire incidents and the susceptibility zones outlined on the map. However, it is essential to recognize certain limitations and potential shortcomings in the study. Firstly, the accuracy of the results is contingent on the quality and reliability of the data sources, specifically the fire incident records. Moreover, the study relies on the natural break classification method in GIS, which, while widely used, is not without its limitations. Alternative classification methods might yield slightly different results, and the choice of classification method could impact the distribution of fire susceptibility categories.

Additionally, having identified spatial correlations between fire incidents and susceptibility zones, causality is not established within this study. Further research is needed to investigate the specific factors or variables that contribute to fire incidents within these susceptibility zones.

## 6. Conclusion

In conclusion, the study's results indicate that 35 percent of the surveyed region falls within the high to very-high fire susceptibility category, while the remaining 65 percent is classified as having low to moderate fire susceptibility. Notably, the primary areas in the Suryabinayak Municipality that exhibit high fire susceptibility encompass residential areas, road networks, and higher elevated regions. Conversely, areas characterized by barren lands and open spaces exhibit considerably lower susceptibility to fires.

After a review of recent fire incidents, it is evident that a significant number of these occurrences have taken place in close proximity to the areas identified as highly susceptible on the Fire Susceptibility Map. These maps, as demonstrated, play a pivotal role in effective fire management strategies. In light of this, it is imperative to underscore the vital importance of considering these factors when developing comprehensive fire susceptibility assessments for enhanced fire risk mitigation and management.[18]

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