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Fire Susceptibility Mapping of Bhaktapur District, Nepal incorporating GIS-based AHP model

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Abstract

The average loss of property due to fire hazard is comparatively higher than other disasters like landslide, flood, earthquake, etc. in Nepal (). The haphazard and unplanned developmental trends in urban areas of Bhaktapur district in Kathmandu Valley is making those area highly susceptible to fire disasters. A fire susceptibility mapping of this district will help to get more clear view of the nature fire susceptibility in Bhaktapur District. This research applies analytic hierarchy process (AHP) a type of multi-criteria decision making (MCDM) tool to assess the fire susceptibility factors of Bhaktapur district using expert opinion, which is then integrated with GIS software to generate fire susceptibility map. Weights of seven anthropogenic factors including, population density, distance to fuel stations, distance to roads, distance to dense settlements, distance to high-voltage transmission lines, land use and building typology is assigned using AHP, depending on the influence of each contributing factors. The fire susceptibility map is derived using weighted sum of individual maps of each contributing factors. This map shows that 76.38 percent of area fall under low to very low susceptible zone, 12.75 percent area fall under moderate zone and 10.88 percent of area fall under high to very high zone. It is seen that major fire susceptible zones lie in densely populated areas, near fuel stations and dense settlement areas. The map is also validated with past fire incidences and it is concluded that past fire incidences are in good agreement with fire susceptibility map.

Keywords

Fire Susceptibility, Multi-Criteria Decision Making (MCDM), Analytic Hierarchy Process (AHP), Geographic Information System (GIS).

1. Introduction

Bhaktapur district is one of the fast-developing urban districts of Nepal. Fire is the one of the most recurrent disasters in Nepal [1] and that includes areas in urban settlements, forest land, agricultural land, dumping sites as well as industrial areas.

According to a review of disasters in Nepal from 1971 AD to 2022 AD, fire is the most common type of disaster, with 6004 events and 1386 deaths. Between 2021 and 2022, fires caused the most economic damage to the country, an estimated loss of nearly 2 billion in NRs. also killing around 102 people and injuring 364 more [2]. Around 5 percent of those who are victims of these fires suffer serious disability, making it Nepal's second most common cause of bodily injuries [3]. Fires are projected to become even more dominating disaster as a result of poorly planned urban settlements, highly inhabited areas, and greater usage of plastic products, as well as human irresponsibility[3].

The study of the integration of the Analytical Hierarchy Process in GIS has been broadly researched in different fields of scientific studies [4]. The acceptance of decision analysis and support systems by the science community, and the lower costs and user-friendly feature of AHP made this method bloom around the year 2000 (Carver, Jan 2015). The main advantage of AHP over other decision-making tools is its ease of applicability, flexibility and its ability to check for inconsistencies [5]. This paper incorporates the application of AHP method, developed by [6] for preparing fire susceptibility map of Bhaktapur district. This paper thus summarizes the outcome of fire susceptibility mapping study in Bhaktapur district.

2. Study Area

The smallest of Nepal's 75 districts, Bhaktapur or Khwopa, is known around the world for its magnificent art, fantastic culture, and traditional way of life. Bhaktapur district is located in the region between latitude and longitude of 27°36'-27°44' and 85°21'-85°32' respectively. It is bounded by Kathmandu and Lalitpur Districts in the west, Kavrepalanchwok in the east, Kathmandu and Kavrepalanchwok District in the north and Lalitpur District in the south. It covers about 119 km2 area and its length is 16 km. The altitude of Bhaktpaur ranges from 1,331 m to 2,191 m above the sea level [7]. Changunarayan Municipality, Suryabinayak Municipality, Bhaktapur Municipality, and Madhyapur Thimi Municipality are the four municipalities that comprise the district. The regional landscape of Bhaktapur district is changing rapidly. As such, there has been sharp increase in urban settlement areas and industrial areas. This rapid growth of development in Bhaktapur has led to increased fire incidents.

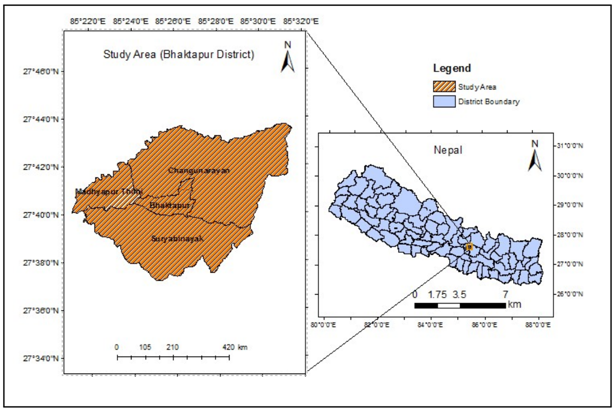

Figure 1: Location of Study Area.

3. Relevant Data and Parameters

3.1 Fire Inventory Mapping

Fire Susceptibility mapping fundamental requirement is the inventory mapping. Knowing the geographical relationship between incident locations and their predisposing factors requires mapping of fire incident events. In this study, 136 historical fire-related episodes were mapped using the Google Earth , past data, and a review of literature during a period of about seven years, from 2015 AD to 2022 AD. The inventory was double-checked using information from the Bhaktapur fire brigade station.

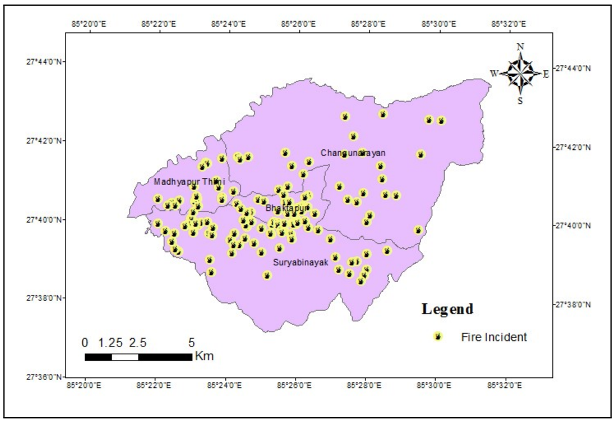

Figure 2: Map showing recent fire incidents in Bhaktapur district.

3.2 Influencing Factors in Fire Susceptibility

For the purpose of this study, anthropological factors are only considered as the contributing factors to fire susceptibility. Since large portion of area in Bhaktapur district is urban built-up area and agricultural lands and almost all past fire incidences dictate an anthropogenic cause, seven fire susceptibility factors are thus devised to justify the cause of incidences. Thus, the strategy used in this study is based on the correlation of historical fire occurrence from inventory maps with the spatial distribution of triggering anthropological elements.

Table 1: Table showing data types and sources.

Datasets	Source
Population Density	CBS office
Building Typology	NRA and Google Earth
Distance from Main Settlements	Field Survey and Google Earth
Distance for Fuel Stations	Field survey and Google earth
Distance from Road	Regional Database System, ICIMOD
Distance from Transmission Lines	Nepal Electricity Authority (NEA)
Land Use and Land Cover	Google Earth and Copernicus

The qualitative and quantitative data were employed in this study using both primary and secondary sources during study of fire susceptibility parameters. The derivation of fire susceptibility parameters like land use, distance from transmission lines, population density, building typology, dense settlement locations and road networks were obtained from relevant secondary sources such as satellite imagery, google earth, respective websites, offices, etc. Other data such as location of fuel stations and past fire incidents used primary as well as secondary data sources. Fire incidents related information was collected from official portal of Government of Nepal as well. The type and sources of data used in fire susceptibility mapping are presented in Table 1. Seven influencing parameters were selected for mapping based on available data.

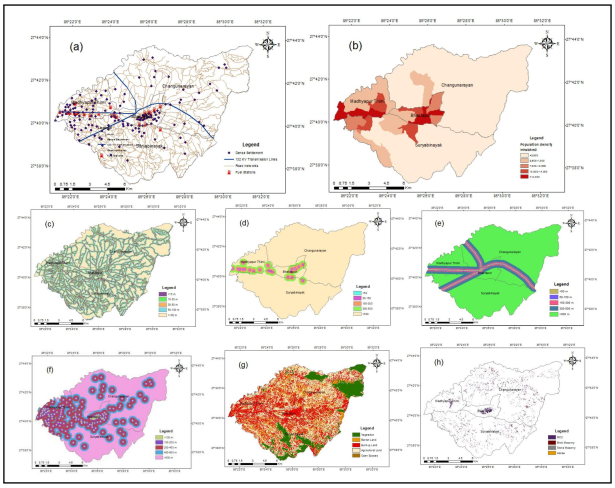

Figure 3: Thematic Map showing (a).major settlements, transmission lines, road networks and fuel station; and classes of factors :(b). population density; (c). distance from roads; (d). distance from fuel stations; (e). distance from transmission lines; (f). distance from dense settlements; (g). LULC; and (h). spatial distribution of building typology of Bhaktapur district.

Population Density The average population density of Bhaktapur district is 3,574 per sq.km. as per District Coordination Committee Office, Bhaktapur. Population density is one of the causative factors of fire. The likelihood fire related incidents are directly and positively correlated with population density. Response and evacuation during fire, landslide, and earthquake dangers are made more difficult by the high population density and congested towns [8].

Using data management tools and spatial analysis tool in ArcGIS, population data was distributed evenly over individual wards to obtain Population Density map and was classified as above mentioned. The population of Bhaktapur district was obtained from CBS and was interpolated to get ward-level population. The district is classified into five classes namely, (i) 0-3,500 inhab/sq.km., (ii) 3,500-7,000 inhab/sq.km., (iii) 7,000-10,500 inhab/sq.km. (iv) 10,500-14,000 inhab/sq.km. and (v) above 14,000 inhab/sq.km..

Building Typology Bhaktapur district consist of various types building with different material composite. For this study the building is classified into three broad classifications of building types to represent the nature of building composite. These elements can result in insufficient fire safety precautions inside a building and considerably raise the risk to people's lives, the building's structural integrity, and the safety of its contents in the event of a fire [9].

The spatial distribution of different building typology in this study was obtained by geo-referencing data of the survey conducted by National Reconstruction Authority (NRA). On this basis, with a sample of approximately 14,000 houses, the dominant building typology was classified as (i) RCC; (ii) Brick Masonry; (iii) Stone Masonry; and (iv) Adobe.

Distance from Main Settlements Dense settlements have higher chance of fire incidents. Core areas with archaeological importance, new settlement areas as a result of land pooling and areas with rich historical importance are destinations for day-to-day migrations and economic activities. In Bhaktapur district, such areas are resided on bazaars (market area), industrial areas, university premises, hospital premises and new establishments. Additionally, the old settlements of the Bhaktapur district are at risk for fire because of their congested streets, crowded housing stock, use of flammable building materials, lack of safety precautions, and predominance of vulnerable structures [8].

Active settlement hubs challenges firefighting, response, and evacuation operations in the case of a fire incidence. The settlements of Bhaktapur district have limited basic firefighting capacities and infrastructures, road networks, and supply of water during firefighting, etc. [8]. The distance from the center of the major settlements areas was classified into five classes (i) 0-100 m; (ii) 100–200 m; (iii) 200–400 m; (iv) 400–600 m and (v) above 600 m.

Distance from Fuel Stations The Nepal Oil Corporation (NOC) has defined all conceivable safety regulations in fuel pumps in order to prevent the chances of human life and property being damaged[10]. The fuel stations in Bhaktapur district are seen to have followed the NOC regulations. A fire incident on a 500 m blast radius due to sparks or ignition can have catastrophic consequences nearby the area [10]. NOC has recommended that the proximity of fuel stations be at minimum 500 m. A blast or fire in one fuel station due to any sparks could destroy a large number of structures within a 500 m radius distance approximately [10] .

The susceptibility of fire increases as the distance decreases toward the station. Therefore, the spatial map of Bhaktapur district consisting fuel station is classified into (i) 0- 50 m; (ii) 50–150 m; (iii) 150–300 m; (iv) 300–500 m and (v) above 500 m from the fuel station.

Distance from Roads According to the National Fire Protection Association (NFPA), access roads must provide sufficient access to the building as well as space to set up and undertake manual suppression operations. For the mobile apparatus to turn around, fire department access roads 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 adequate radius for turns in the roadways and dead ends [11]. Thus, the spatial data of road networks are analyzed using Euclidean method to produce distance from feature data. The distances have been classified into (i) 0- 15 m; (ii) 150–30 m; (iii) 30–50 m; (iv) 50–100 m and (v) above 100 m.

Distance from Transmission Lines Fire-related incidents and explosion in electric transmission lines occur due to many reasons. Chances of fire due to intentional or accidental short circuits and sparks leading to fire is still prevalent in Bhaktapur. Transmission lines make nearby fires and other types of damage, such as line tripping, more likely. The most important factors in fire incidents are probably vegetation, trees, and settlements close to the power lines. Due to factors like fuel kind, wetness, sporadic landowner disagreements, high costs for right-of-way clearing, weather, and human intervention, fire near transmission lines is always difficult to put out. Five classes of distance from high voltage transmission line was classified into (i) 0–50 m, (ii) 50–100 m, (iii) 100–200 m, (iv) 200–500 m, and (e) above 500m.

Land Use and Land Cover Land use change also affects fire regimes by altering the frequency of ignitions, the fuel loads, and management practices. The changing land use pattern in Bhaktapur including large encroachment of natural lands for human settlements have increased effect on fire-related incidences. The relationship between fuel loads and ignition and the likelihood of a fire can be complicated by a variety of factors, including fire suppression, fuel management, and many others [12]. This is due to the fact that most fires are started by humans in the majority of places. For preparing LULC raster image, Sentinel-2 satellite data of resolution 10m x 10m was extracted and processed using supervised classification in Arc-GIS 10.1. The LULC change parameter was classified into (i) forest, (ii) barren land, (iii) built-up area, (iv) agriculture land and (v) open spaces. The LULC data was then analyzed to get the area of each respective classes for Bhaktapur district.

4. Methodology

4.1 Analytic Hierarchy Process

AHP method is used in many related areas of decision-support in fire-related disaster management in Nepal such as fire protection zonation map [10], mullti-hazard risk assessment [8] and so on.

Saaty [6] has developed step-by-step procedure for applying AHP in any decision-making studies. The steps begin with (i) defining the problem and determining its goal and objective (ii) structuring the hierarchy from the objectives through the intermediate levels to the lowest level which usually contains the list of alternatives (iii) assignment of numerical values according to the relative importance of each factor (pairwise comparison), (iv) comparison matrix setting, and (v) normalized principal eigenvector calculation, giving the weight of each parameters. The importance levels are assigned by experts based on their judgements from 1-9, where 1 stands for equal importance and 9 stands for extreme importance of one domain over another.Each pair-wise comparison automatically assigns reciprocals. For each criterion, the maximal eigen value, consistency index, consistency ratio, and normalized primary eigen vectors are calculated. The consistency is calculated by using the maximum eigen value (λ_{max}) to determine the consistency index (CI) as given by the equation as:

$$CI = (\lambda_{max} - n)/(n-1) \quad (1)$$

where, n is the size of matrix.

Consistency ratio is checked using random index (RI) and consistency index (CI) which helps in determining the consistency of data [6]. A consistency value of 10 percent is acceptable for further calculation.

4.2 AHP application on Classes of Influencing Factors

After deriving suitable classes and intervals were based on data available and were rated from 1-5 using AHP where 1 being lowest to negligible influence and 5 being the highest kind. Further AHP was applied to influencing factors to derive weights of each factors and overlaid over one another to prepare susceptibility map.

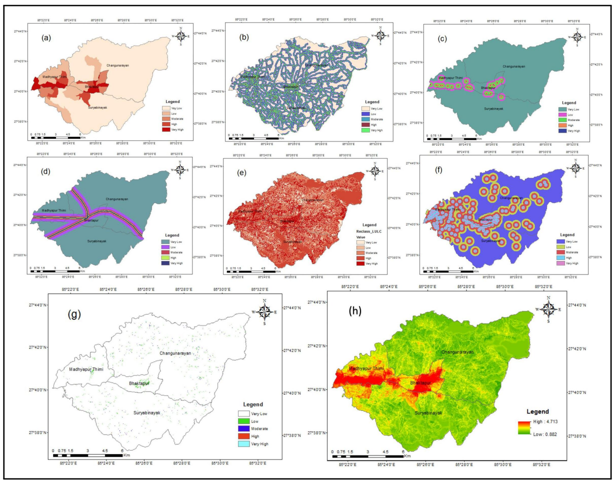

Figure 4: Thematic Map showing susceptibility ratings of influencing factors: (a). population density; (b). distance from roads; (c). distance from fuel stations; (d). distance from transmission lines; (e). distance from dense settlements; (f). LULC; (g). building typology; and (h). weighted combination of factors of Bhaktapur district.

For conducting AHP method in fire susceptibility mapping five experts were chosen from various governmental and non-governmental fields which include researchers in fire disaster, civil engineers and government officials from urban development division and fire brigade station. Two sets of questionnaires were prepared for AHP in five levels; first level on determining weights of contributing factors in fire susceptibility mapping (Table 5) and; second level in determining the susceptibility rating of classes of each contributing factors (Table 2).

A questionnaire from was developed and interviewed with experts for each class of different parameters and distributed to two experts working in the field of urban and building and as office chief of fire brigade station. The relative weights obtained from the experts were averaged to generate comparison matrix as shown in Table 3.

The calculation of normalized principal eigen vector for causative factors is shown in Table 4 consisting building typology, distance from fuel stations, transmission lines, dense settlements and roads; land use and population density for preparing fire susceptibility map. The consistency of results of pairwise comparison matrix is shown in Table 3. As all the parameters have consistency below 10 percent the calculation is acceptable for application in fire susceptibility mapping.

Table 2: Table showing sample question regarding classes of influencing factors

Parameter 1: Population Density				
Q1. How important is the sub-criterion 14,000 inhab/sq.km. with respect to the following sub-criteria in fire susceptibility mapping?				
Classes		Importance Value	Other domain is more important	
10,500-14,000 inhab/sq.km.				**Tick only
7,000-10,500 inhab/sq.km.				
3,500-7,000 inhab/sq.km.				
3,500 inhab/sq.km.				

Table 3: Table showing consistency of pairwise comparison.

S.No.	Causative Factors	n	λ_{max}	C.I.	R.I.	C.R.
a.	Population Density	5	5.2372	0.0593	1.12	0.0529
b.	Distance to Roads	5	5.2317	0.0579	1.12	0.0517
c.	Distance to Fuel Stations	5	5.1208	0.0302	1.12	0.0270
d.	Distance to Transmission Lines	5	5.1876	0.0469	1.12	0.0419
e.	Distance to Main Settlements	5	5.3259	0.0815	1.12	0.0727
f.	Land Use	5	5.2417	0.0604	1.12	0.0539
g.	Building Typology	4	4.1391	0.0464	0.90	0.0515

4.3 AHP application Influencing Factors

Using AHP tool, the pairwise comparison of a 7×7 matrix using the seven parameters namely population density, distance from roads, distance from transmission lines, distance from fuel stations, distance from dense settlement, land use and building typology was done. After averaging the weights of experts, distance from fuel station showed the maximum weight (0.3358) and distance from roads showed the lowest weight (0.0397). The CR was within acceptable limits for all parameters as shown in Table 6.

Table 4: Table showing pairwise comparison of class of influencing factors.

S.No.	Causative Factors and Classes within each Factor	Normalized Principal Eigen Vector
a.	**Population Density**	
	[1] >14,000 inhab/sq.km.	0.5100
	[2] 10,500-14,000 inhab/sq.km.	0.2638
	[3] 7,000-10,500 inhab/sq.km.	0.1296
	[4] 3,500-7,000 inhab/sq.km.	0.0636
	[5] <3,500 inhab/sq.km.	0.0329
b.	**Distance to Roads**	
	[1] >100 m	0.0309
	[2] 50-100 m	0.0629
	[3] 30-50 m	0.1280
	[4] 15-30 m	0.2741
	[5] <15 m	0.5040
c.	**Distance to Fuel Station**	
	[1] <50 m	0.5511
	[2] 50-150 m	0.2535
	[3] 150-300 m	0.1051
	[4] 300-500 m	0.0467
	[5] >500 m	0.0436
d.	**Distance to Transmission Lines**	
	[1] <50 m	0.5123
	[2] 50-100 m	0.2650
	[3] 100-200 m	0.1302
	[4] 200-500 m	0.0513
	[5] >500 m	0.0412
e.	**Distance to Dense settlements**	
	[1] <100 m	0.5863
	[2] 100-200 m	0.2435
	[3] 200-400 m	0.0732
	[4] 400-600 m	0.0448
	[5] >600 m	0.0522
f.	**Land Use**	
	[1] Built-up Land	0.3691
	[2] Agricultural Land	0.2419
	[3] Open Spaces	0.0614
	[4] Barren Land	0.0313
	[5] Forests	0.2963
g.	**Building Typology**	
	[1] RCC	0.0529
	[2] Brick Masonry	0.1041
	[3] Stone Masonry	0.2533
	[4] Adobe	0.5897

Table 5: Table showing sample question regarding influencing factors.

Q1. How important is the criterion Population Density with respect to the following criteria in fire susceptibility mapping?			
Classes	Importance Value	Other domain is more important.	
Distance from Roads			**Tick only.
Distance from Fuel Station			
Distance from Transmission Lines			
Distance from Main settlements			
Land Cover and Land Use			
Building Typology			

Table 6: Table showing pairwise comparison of influencing factors.

S. No.	Causative Factors	Pair wise comparison matrix							Normalized Principal Eigen Vector
		[1]	[2]	[3]	[4]	[5]	[6]	[7]	
1	Population Density	1	4	1	3	1	3	1	0.2298
2	Distance from Roads	1/4	1	1/5	1	1/3	1	1/3	0.0397
3	Distance from Fuel Station	1	5	1	4	2	3	2	0.3358
4	Distance from Transmission Lines	1/3	1	1/4	1	1	2	1	0.0784
5	Distance from Main settlements	1	3	1/2	1	1	2	1	0.1398
6	Building Typology	1/3	1	1/3	1/2	1/2	1	1	0.0548
7	Land Cover and Land Use	1	3	1/2	1	1	1	1	0.1217

Table 7: Table showing consistency of pairwise comparison.

Causative Factors	n	λ_{max}	CI	RI	CR
	7	7.5769	0.0962	1.11	0.0866

The weights of each susceptibility parameters are derived directly from normalized principal eigenvector from Table 6. The value is multiplied with individual raster map to generate fire susceptibility map of the Bhaktapur district.

The Fire Susceptibility Map was generated with the help of GIS software by weighted linear combination of all causative factors. Fire Susceptibility Index Map = Weighted map of (Population Density + Land Use and Land Cover + Distance from Fuel + Distance from Roads+ Distance from Transmission Lines + Distance from Main Settlement + Building Typology)

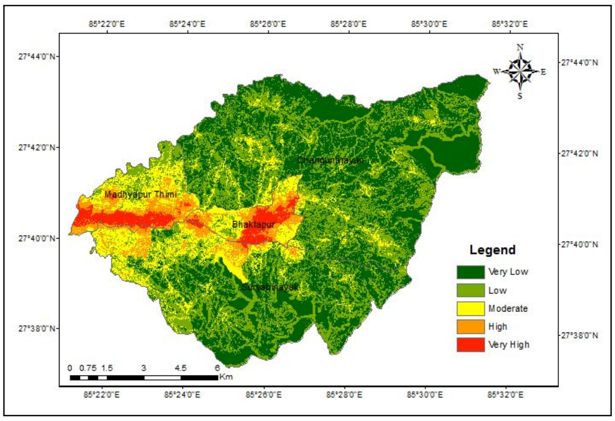

Figure 5: Fire Susceptibility Map of Bhaktapur District.

Table 8: Table showing area distribution of fire susceptibility zones.

S. No.	Fire Susceptibility Zone	Area	
		sq.km.	percent
1	Very Low	51.79	42.11%
2	Low	42.15	34.27%
3	Moderate	15.68	12.75%
4	High	7.43	6.04%
5	Very High	5.95	4.84%

Among the past 136 fire incidents recorded, the spatial location of these incidents with respect to susceptibility zones show valid results.

Table 9: Validation of different historical events with susceptibility maps.

S. No.	Fire Susceptibility Zone	Past Occurrences	
		Number	%
1	Very Low	8	5.88%
2	Low	9	6.62%
3	Moderate	22	16.18%
4	High	45	33.09%
5	Very High	52	38.24%

5. Discussion

Almost 85 percent of land in Bhaktapur district is used for settlements, agriculture, commercial, and industrial purposes. Since majority of forests areas lie in the periphery of the Bhaktapur district, those areas are less influenced by fire incidences. Areas around critical infrastructures, high population and main settlements can be seen as high susceptibility zones. Thus, only a tenth of the area in Bhaktapur district lie in high susceptibility zones and fire incidences in that zones are frequent and recurrent.

Among the past 136 fire incidents recorded between 2015 and 2022, the spatial location of these incidents with respect to susceptibility zones shows valid results. The incident records have shown that major fire incidences are caused during harvesting seasons in agricultural lands. Electric sparks and heat ignition sources are the next leading causes in buildings, stores and industries. Moreover, electrical short circuits in distribution lines and other bundled wires have caused fires in recent years and are increasing. Spatially the sources of fire leading to their cause have been incorporated in all the parameters considered in this study. The frequent and recurrent fire incidences due to anthropogenic factors are seen to lie spatially in the high to very high susceptible zones.

6. Conclusion

The AHP method is widely used as a multi-criteria decision analysis technique, based on expert opinions that are within the consistency rating. In this study, seven causative anthropogenic factors were considered namely, distance from fuel stations, distance from roads, distance from the transmission line, distance from dense settlement, building typology, land use, and population density. The factors considered in this study were devised to represent the causes and sources of fire incidences prevalent in Bhaktapur district. The weightage of these factors was calculated using the AHP tool via expert opinion.

The state of fire susceptibility of Bhaktapur district was analyzed with primary focus on human induced fire-related incidences. The results show that the high to very-high fire susceptible zone covers 10.88 percent of the study area, while the low to very low fire susceptibility zone covers 76.38 percent of the study area. The fire susceptibility area in high to very high zones is comparatively less in low, moderate and very low zones. The major area of fire susceptibility zones of Bhaktapur district lies in cultivation, built-up areas, and around the radius of fuel stations in the majority. The area in barren lands, open spaces, and forest land have shown low and very low susceptibility.

A formal check on recent incidents of fire cases shows that more incidences have occurred near the highly susceptible zones shown by the Fire Susceptibility Map. Thus, it can be concluded that the anthropogenic factors used in this study, population density, distance to fuel stations, distance to roads, distance to dense settlements, distance to high-voltage transmission lines, land use, and building typology all give a valid input in preparing fire susceptibility mapping, which is an important part of fire management.

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