Disaster Prevention and Management: An International Journal

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Laxmi Kant Sharma Shruti Kanga Mahendra Singh Nathawat Suman Sinha Prem Chandra Pandey

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Laxmi Kant Sharma, Shruti Kanga, Mahendra Singh Nathawat,
Suman Sinha and Prem Chandra Pandey
*Department of Remote Sensing and Geoinformatics,
Birla Institute of Technology, Ranchi, India*

Abstract

Purpose – The purpose of study is linked to management and policy-making strategies, such as forest management, land use planning and sustainable management of natural resources. It aims to help prevent forest fire by taking precautions. It also aims to be helpful for authorities coping during the event of occurrence of fire.

Design/methodology/approach – The methodology paradigm applied here is based on knowledge-based and analytic hierarchy process (AHP) techniques. Knowledge-based criteria involve topographic and different themes for risk assessment. The assignment of value given to equation is significant due to its importance.

Findings – Results are in strong agreement with actual fire occurrences in the past years. The risk zones are identified according to past occurrence of fire. The gradients of low- to high-risk zones are according to fuel, topographic features and weather conditions. Direction and aspect value were taken accordingly.

Originality/value – The paper presents forest fire risk zones designed on knowledge-based information. Crisp and fuzzy AHP approaches were applied to improve the efficacy of the model. The mapping results were in accordance with actual fire occurrences in the past years.

Keywords Geographic information systems, MCDA, Index modelling, Cumulative Fire Risk Index, Forests, Fire, Risk management

Paper type Conceptual paper

Introduction

Wildland fires are those fires, which burn vegetative cover (Garner, 1989). As fire is a threat to the forest sector economy at a regional or even national level, the last step is the inclusion of fire risk in broad-scale scenario analysis (Gadow, 2000). Worldwide, specifically tropical areas, the loss of natural forests through forest fires has lead to destabilization of soil-water conservation and climatic regulation of the forest ecosystems (World Research Institute (WRI), 1997). Fire can be considered a natural element of the Mediterranean forest, determining its species composition and landscape structure (Trabaud, 1994). Olabarria (2006) applied fire occurrence model and fire damage model to study the forest fires of Catalonia which revealed their effect on the environmental, economical and social values. Numerous models for assessing fire risk have been developed throughout the world (Chuvieco and Congolton, 1999). While the earliest models were non-spatial, recent advances in geographic information systems (GIS) have allowed for the development of spatial fire risk models (Hirsch *et al.*, 2001; Loehle, 2004). According to a Forest Survey of India (2003) report, about

The authors express a deep sense of gratitude to the Vice Chancellor, BIT, Mesra for their encouragement. The authors are thankful to the forest authority of Himachal Pradesh for their co-operation during a field visit. The Ministry of Environment and Forests, Govt. of India, is acknowledged for their financial assistance to Ms Shruti Kanga as Research Associate.

Disaster Prevention and Management
Vol. 21 No. 2, 2012
pp. 160-171

0965-3562
DOI 10.1108/09653561211219964

50 percent of forest areas in the country are fire prone. Along with various factors, forest fires are a major cause of degradation of Indian forests (Roy, 2000). People studied forest fire risk zone (FFRZ) with a variety of mapping methods by directly using remote sensing and GIS that contain topography, vegetation, land use, population and settlement information (Chuvieco and Salas, 1994; Jaiswal *et al.*, 2002). India witnessed the most severe forest fires during the summer of 1995 in the hills of Uttaranchal and Himachal Pradesh.

A common practice was that FFRZs were delineated by assigning knowledge base weights to the classes of all the layers according to their sensitivity to fire or their fire-inducing capability. Analytic hierarchy process (AHP) (Saaty, 1980, 1988) is an useful technique in decision making that has been widely used as a efficient multi-criteria decision analysis (MCDA) tool or a weight estimation technique in different cases (Vaidya and Kumar, 2006). Researchers made the Saaty's AHP (crisp AHP (CAHP)) modified and fuzzified to formulate and control uncertainty. Hence, trapezoidal membership function for comparison ratios in AHP has been formulated (Buckley, 1985) and a new approach for triangular case has been developed (Chang and Wang, 2009). Triangular fuzzy number is a special class of fuzzy number whose membership is defined by three real numbers (Vahidniaa *et al.*, 2008). The mathematics of fuzzy set theory is described in Fuzzy Sets (Zadeh, 1965). Use of fuzzy AHP (FAHP) in GIS and its different methods and applications has been well defined (Vahidniaa *et al.*, 2008).

Many factors have been considered to explain the variation in the fire regime in recent decades in climate change (Piñol *et al.*, 1998), changes in landscape configuration (Badia *et al.*, 2002), other aspects related to the land uses (Vélez, 2002), changes in the ignition causes (Vazquez and Moreno, 1995) and even the success of the predominant fire suppression policy in Spain (Terradas *et al.*, 1998; Piñol *et al.*, 1998). A precise evaluation of forest fire problems and decisions on solutions can only be satisfactory when a forest risk zone mapping is available to the management authority (Jaiswal *et al.*, 2002).

Study area

Taradevi forest range of Shimla Forest Division (Himachal Pradesh) has been taken for the current study, having an area of 1564.90 ha and spatial extent lies between 76°59′12.66″E to 77°11′16.96″E and 31°01′15.59″N to 31°10′45.42″N (Figure 1). The area has hilly terrain with the elevation ranging between 900 and 2200 m. The area is covered with thick forest cover which constitutes mainly Chil (*Pinus roxburghii*), Blue pine (*Pinus wallichiana*), Ban oak (*Quercus leucotrichophora*) and Deodar (*Cerdus deodara*) with variety of broad-leaved trees along with shrubs and grasses. The relative humidity remains high around 80 percent. Temperature also falls between 15 and 22°C. The average total annual precipitation is 1520 mm.

Methodology

Satellite and ancillary data

IRS-P6 LISS-III imagery of November 2004, Shuttle RADAR Topographic Mission (SRTM) 90 m and SOI Toposheets on 1:50,000 scale were used for this research work along with Fire Management Plan of Shimla Forest Division which was procured from State Forest Department, Shimla. Satellite images were visually interpreted with ground truth validation to produce forest type and density map and land-use maps. The overall methodology applied in the study was categorized into three parts: pre-fieldwork, fieldwork and post-fieldwork (Figure 2). SRTM data are being used for the creation of slope, elevation, aspect and Digital Elevation Model.

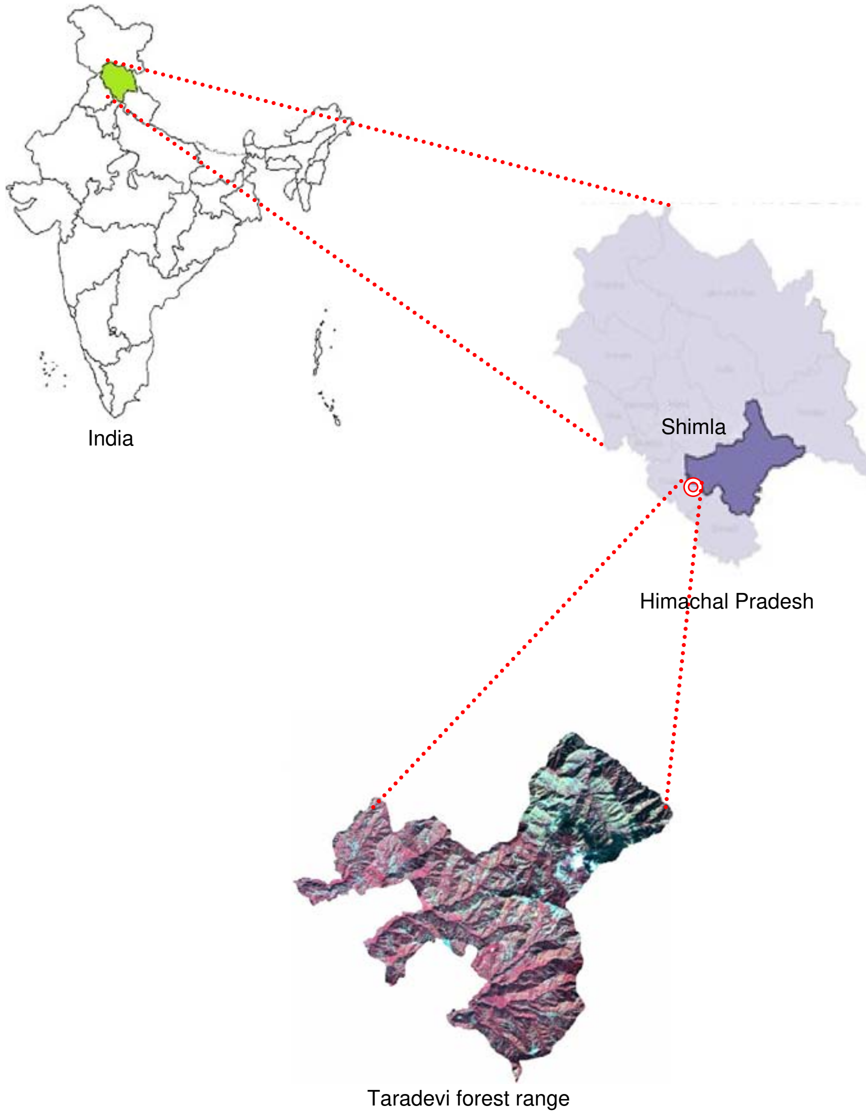

Figure 1.
Location map of study area

Criteria in GIS-MCDA

Spatial modeling to get combined effect of fuel-type index, elevation index, slope index, aspect index, road index and settlement index with weightage assigned on the basis of relative importance of variables was done on the basis of previous study in Corbett National Park, India (Sharma, 1995) and in Motichur range of Rajaji National Park (Porwal *et al.*, 1997). The factors influencing forest fire risk were analyzed in the following order of importance: fuel type, slope, aspect, elevation and distance from roads and settlements. These factors were classified according to their sensitivity to fire or their fire-inducing capability. First classes represent high-risk places and last classes represent the minor risk place. Each class has different values as shown in Table I.

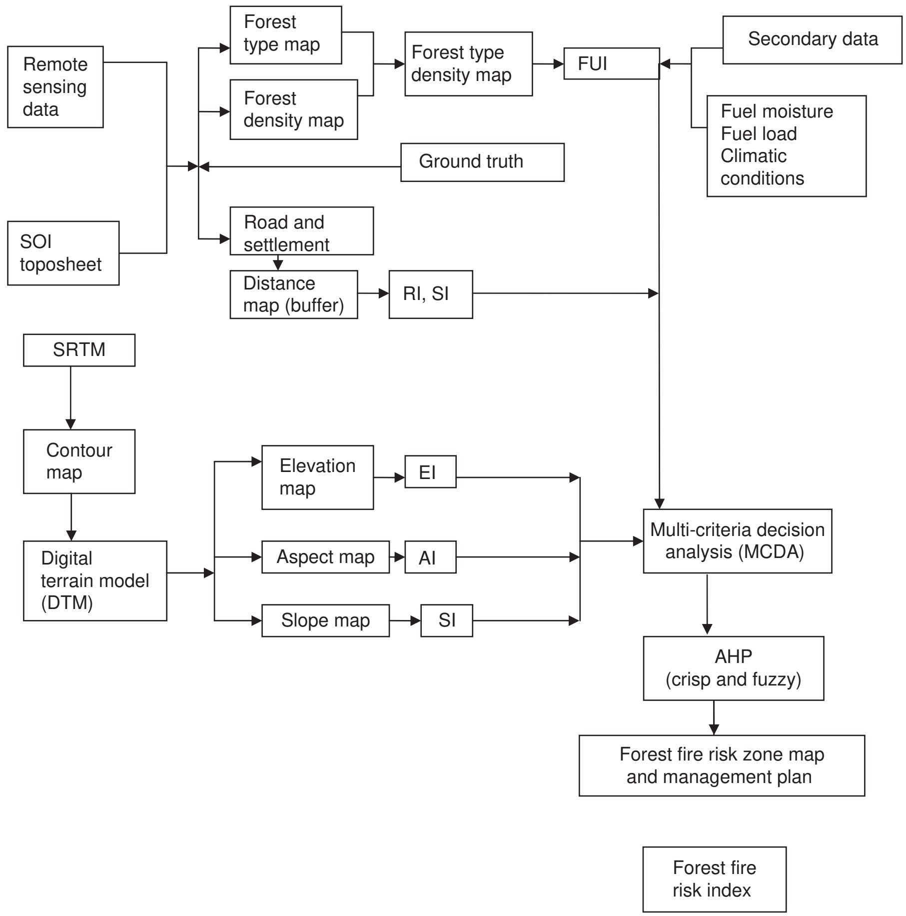

Figure 2.
Methodology adopted for forest fire risk assessment

Index modeling

Index modeling is especially important because variables can be evaluated by their relative importance against other variables (weight), and observed values can be scored or grouped into classes and scored (Pereira and Duckstein, 1993). In this model, different levels of uncertainty of analytical hierarchy process are used to assign weights to the parameters.

Knowledge-based approach

The fuel types were classified according to their flammability that has an influence on ignition and spread of forest fires. Steep gradient increases the chance of catching fire and the rate of fire spread because of easier loss of water and more efficient convective preheating. Aspect and elevation were assigned classes too. Since the sunlight is much more reflected on the slopes facing southward, fires break out easily and spread fast in the south sides and fire behavior trends to be less severe at higher elevation due to high rainfall. In the current study spatial modeling was been done to obtain the cumulative effect

Parameters	Weights	Classes	Index values	Fire rating class
Fuel type	4	Bluepine	5	High
		Chirpine	6	Very high
		Deodar	2	Low
		Oak	3	Moderate
		Mixed forest	2	Low
		Plantation Chirpine oak	4	Moderate high
		Plantation Chirpine	5	High
		Plantation Deodar	3	Moderate
		Plantation oak	4	Moderate high
		Scrub	1	Very low
		Agriculture	1	Very low
		Settlement	1	Very low
		Rocky waste	1	Very low
		Land with scrub	1	Very low
		Land without scrub	1	Very low
Elevation	1	950-1,250 m	6	Very high
		1,250-1,450 m	5	High
		1,450-1,650 m	4	Moderate high
		1,650-1,850 m	3	Moderate
		1,850-2,050 m	2	Low
		2,050-2,150 m	1	Very low
Slope	2	50°-60°	6	Very high
		40°-50°	5	High
		30°-40°	4	Moderate high
		20°-30°	3	Moderate
		10°-20°	2	Low
		0°-10°	1	Very low
Aspect	3	South	6	Very high
		Southwest	5	High
		Southeast	4	Moderate high
		East	3	Moderate
		West	2	Low
		Northwest	2	Low
		North	1	Very low
		Northeast	1	Low
Distance from road	1	0-200 m	6	Very high
		200-400 m	5	High
		400-600 m	4	Moderate high
		600-800 m	3	Moderate
		800-1,000 m	2	Low
		1,000-1,200 m	1	Very low
Distance from settlement	1	0-200 m	6	Very high
		200-400 m	5	High
		400-600 m	4	Moderate high
		600-800 m	3	Moderate
		800-1,000 m	2	Low
		1,000-1,200 m	1	Very low

Table I.
Weightages and parameters in determination of fire risk modeling

of fuel-type index, elevation index, slope index, aspect index, road index and settlement index. The equation used for forest fire zonation is shown in the following equation:

$$CFRISK = (1\times ELI) + (2\times SLI) + (3\times ASI) + (1\times SI) + (1\times RI) + (4\times FUI) \quad (1)$$

where CFRISK, cumulative fire risk index value of FFRZ map; ELI, elevation index; SLI, slope index; ASI, aspect index; RI, road index; SI, settlement index; and FUI, fuel-type index.

All factors have six classes where higher value represented as danger and the danger decreases as the value moves toward the lower value. Finally on the basis of these analyses, a fire risk zone map was created. Based on the statistics of different weight classes, the map was reclassified into five classes as very low, low, moderate, high and very high to generate fire risk map (Figure 3). The CFRISK was derived by assigning weights and the generated fire risk areas were validated using historical data of fire occurrence.

CAHP

AHP being a powerful tool in applying MCDA was developed by Saaty in 1980. Weights or priority vector for the alternatives or the criteria is required. For creating the pairwise comparison matrix (PCM), a system of numbers to indicate how much one criterion is more important than the other was designed by Saaty (1980). The value of $\lambda_{\max}$ is required in calculating the consistency ratio (CR) (Han and Tsay, 1998):

$$\text{Consistency index (CI)} = (\lambda_{\max} - n)/(n-1) \tag{2}$$

where n is the number of criteria and $\lambda_{\max}$ is the largest eigenvalue (Han and Tsay, 1998; Malczewski, 1999). The final CR is calculated by comparing the CI with the random index (Malczewski, 1999):

$$\text{CR} = \text{CI}/\text{RI} \tag{3}$$

where RI depicts random index and in this case RI = 1.24 (Saaty, 1980).

The CR is designed such a way that shows a reasonable level of consistency in the pairwise comparisons if CR < 0.10 and CR ⩾ 0.10 indicate inconsistent judgments. The final weightage values are documented in Table II.

Fuzzy weights

Fuzzy numbers denoted as $(\alpha, \beta, \gamma, \delta)$ where $0 < \alpha \leqslant \beta \leqslant \gamma \leqslant \delta$; α, β, γ and δ being four parts of the fuzzy number set. In a triangular membership function, $\beta_{ij} = \gamma_{ij}$. Geometric mean technique can be used in the process of fuzzifying the AHP (Buckley, 1985):

$$\begin{aligned}
\alpha_i &= [\Pi_{j=1}^{n} \alpha_{ij}]^{1/n} \text{ and } \alpha = \sum_{i=1}^{n} \alpha_i \\
\beta_i &= [\Pi_{j=1}^{n} \beta_{ij}]^{1/n} \text{ and } \beta = \sum_{i=1}^{n} \beta_i \\
\gamma_i &= [\Pi_{j=1}^{n} \gamma_{ij}]^{1/n} \text{ and } \gamma = \sum_{i=1}^{n} \gamma_i \\
\delta_i &= [\Pi_{j=1}^{n} \delta_{ij}]^{1/n} \text{ and } \delta = \sum_{i=1}^{n} \delta_i
\end{aligned} \tag{4}$$

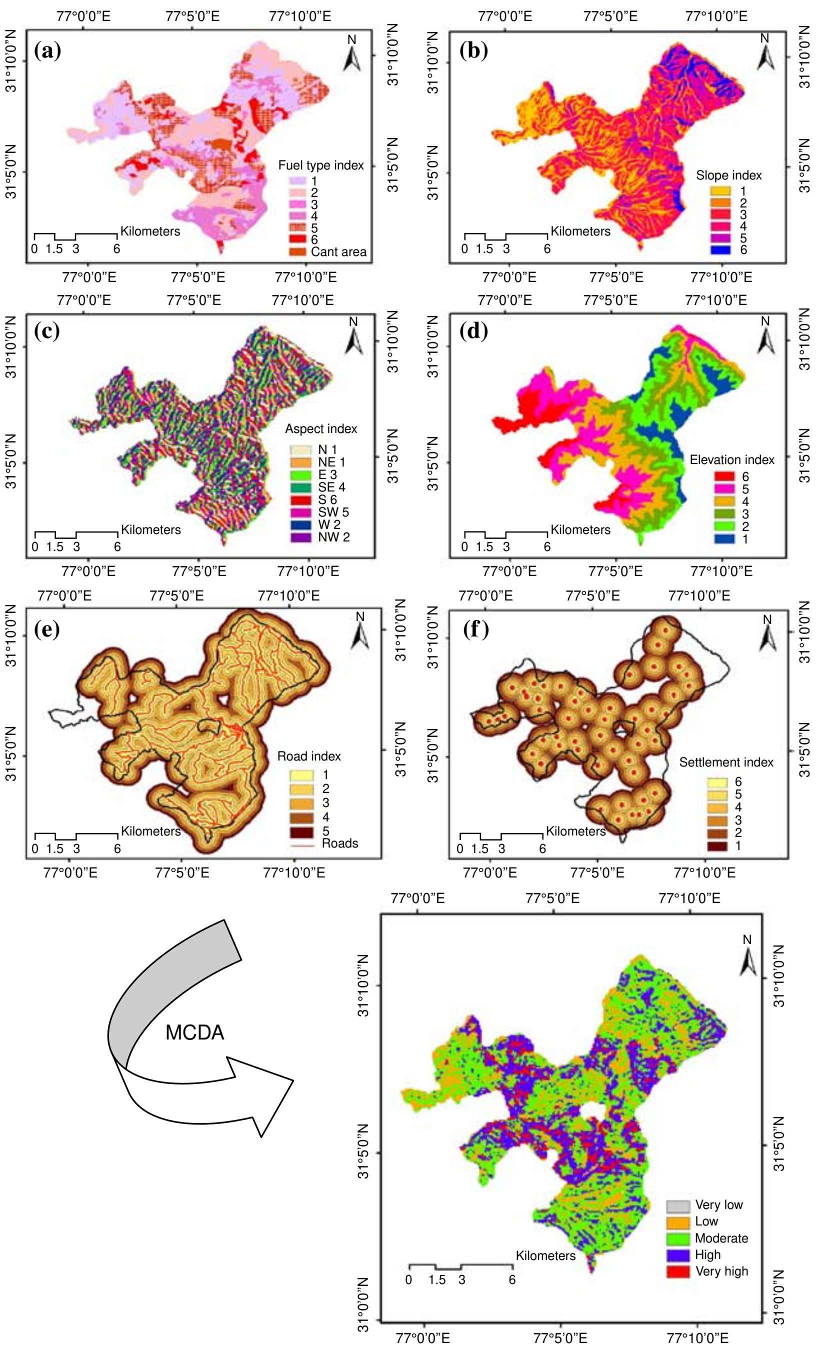

Figure 3.
Fire risk zonation map using knowledge-based approach in MCDA

Notes: Index maps: (a) fuel type index map; (b) slope index map; (b) aspect index map; (c) elevation index map; (e) road index map; (f) settlement index map

The final weights are given by:

$$w_i = [(\alpha_i/\delta), (\beta_i/\gamma), (\gamma_i/\beta), (\delta_i/\alpha)] \tag{5}$$

Defuzzification is done using the centroid method (Opricovic and Tzeng, 2003; Chang and Wang, 2009). The final weightage values are documented in Table III. The detailed methodology for forest fire risk assessment is depicted in Figure 2.

Results

Criteria in GIS-MCDA for forest fire risk modeling

Five rating classes were used for the generation of FFRZ map. These five fire rating classes were based on the criteria using fuel type, slope, aspect, elevation, road and settlements (Figure 3). The main objective of the current study was to generate the forest fire risk map on the basis of weightage assignments followed by indexing to layers that are important input to FFRZ. Multi-criteria analysis and weighted sum (knowledge-based) method was used to model forest fire risk. The maps were generated and index maps were derived followed by the derivation of fire risk model (Figures 3 and 4).

Forest fire risk modeling

Model provides a clue for estimating the loss of forest resource, if wild fire occurs unexpectedly. As per our results reveals that remote sensing, GIS and GPS collectively play an important role in forest fire risk assessment and management. A method incorporating remote sensing and GIS with knowledge-based concepts are incorporated in this paper. Satellite images and topographic data were analyzed and the results showed that the methods are suitable for forest fire risk modeling. It can be applied successfully for managing forest fires for forest departments. As the study area is hilly and due to hard topographical conditions forest fire managers can find

Sl. no.	Parameters	CAHP (λ_{max})
1	Fuel type	0.452152
2	Slope	0.149059
3	Aspect	0.263077
4	Road	0.065369
5	Settlement	0.042108
6	Elevation	0.028236

Table II. Weightage assigned using AHP (λ_{max})

Sl. no.	Parameters	FAHP
1	Fuel type	0.454032
2	Slope	0.143654
3	Aspect	0.269224
4	Road	0.064039
5	Settlement	0.041103
6	Elevation	0.027948

Table III. Weightage assigned using FAHP (λ_{max})

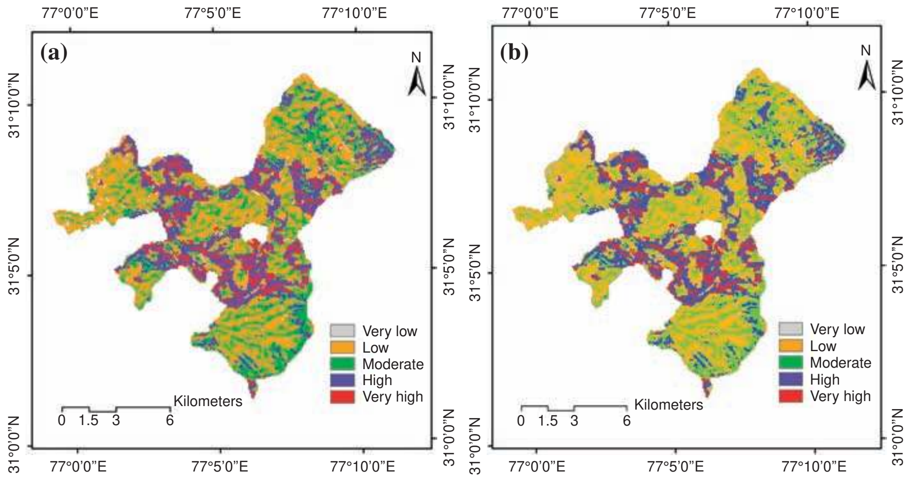

Figure 4.
Fire risk zonation map using AHP approach in MCDA

Notes: (a) Crisp; (b) fuzzy approach in MCDA

high-risk places easily and take proper actions to minimize frequency of forest fires and avoid damage.

In the study area 6.89 percent area of total area falls under very high-risk prone area, 28.71 percent area is under high-risk prone, 42.91 percent area is under moderate risk, 21.04 percent under low risk and 0.45 percent under very low risk (Figure 3).

AHP

The idea of multi-criteria techniques has been implemented with different uncertainty levels of AHP. Forest fire risk zonation map by weighted mean overlay analysis using AHP is thus obtained in GIS mode using MCDA. The CAHP λ_{max} method results in the weights (Table II) for each factor. Normalized and defuzzified weights are obtained from FAHP (Table III). The resulting weights from CAHP and FAHP are applied in the model. The output in the form of map after applying CAHP and FAHP is shown in Figures 4a and b, respectively.

The equation used for forest fire zonation applying CAHP is shown in the following equation:

$$\begin{aligned} \text{CFRISK} = {} & (0.028236\times\text{ELI}) + (0.149059\times\text{SLI}) + (0.263077\times\text{ASI}) \\ & + (0.042108\times\text{SI}) + (0.065369\times\text{RI}) + (0.452152\times\text{FUI}) \end{aligned} \tag{6}$$

The equation used for forest fire zonation applying defuzzified AHP values is shown in the following equation:

$$\begin{aligned} \text{CFRISK} = {} & (0.027948\times\text{ELI}) + (0.143654\times\text{SLI}) + (0.269224\times\text{ASI}) \\ & + (0.041103\times\text{SI}) + (0.064039\times\text{RI}) + (0.454032\times\text{FUI}) \end{aligned} \tag{7}$$

In the study area applying CAHP, 8.74 percent area of total area is classified under very high-risk prone area, 22.68 percent area under high-risk prone, 30.97 percent area under moderate risk, 35.90 percent under low risk while 1.71 percent under very low risk. However, when FAHP is applied, it is found that for very high-risk prone, area covered is 8.72 percent of total area, for high-risk prone it is 22.61 percent, moderate risk is 30.87 percent, low risk area is 35.98 percent while 1.82 percent under very low risk. Hence, applying different methods for assigning weights, difference in the form of area covered under each risk zone is obtained. The relative difference of the three methods used is graphically represented in Figure 5.

Discussions

Geospatial data and expert knowledge in GIS domain can be effectively integrated in MCDA to be implemented in FFRZ modeling. AHP provides an efficient method for determining the importance of the factors responsible for the forest fire active at site and weights thus generated through CAHP and FAHP are integrated in GIS. The results pointed out that 6.89 percent of the area is under very high-risk zone; however, AHP method suggest the value to be around 9 percent. The increased level of uncertainty in the study is implemented solely to use greater degrees of fuzziness or uncertainty in real-world applications. This seems to provide much more specific results though further increase in fuzziness might give rise to erroneous output; which is kept beyond the scope of the study. The information generated in this study would be of immense use if linked to other management and policy-making strategies, such as forest management, land-use planning and sustainable management of natural resources. Emergency managers play important role in prevention, control and management of disasters with in a quick time period. They have to be prepared for fighting the forest fire in case it happens. The study result shows the regions with high, moderate and low susceptible to forest fire with AHP and knowledge-based factors.

In the hilly regions, topographical and other features add favorable conditions to forest fire occurrence, where these findings can help emergency managers to find high-risk places easily and take proper actions to take preventive measures, minimize or cope with frequency of forest fires and avoid damage. Thus, emergency managers will save human life, natural resources and properties.

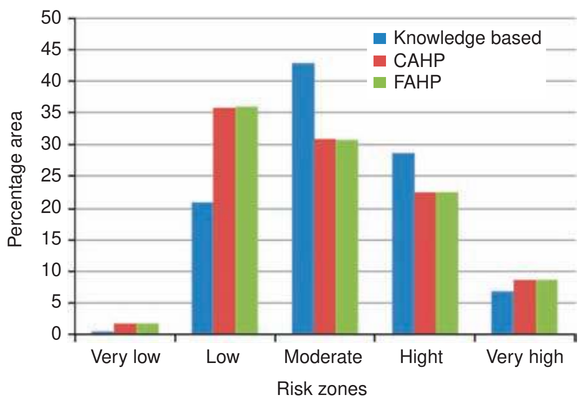

Figure 5.
Relative difference of the three methods applied

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Corresponding author
Laxmi Kant Sharma can be contacted at: lksharma@bitmesra.ac.in

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