International Journal of Applied Earth Observation and Geoinformation 4 (2002) 1–10

INTERNATIONAL JOURNAL OF APPLIED EARTH OBSERVATION AND GEOINFORMATION

www.elsevier.com/locate/jag

Forest fire risk zone mapping from satellite imagery and GIS

Rajeev Kumar Jaiswal [a,*], Saumitra Mukherjee [b], Kumaran D. Raju [c], Rajesh Saxena [d]

[a] Department of Space, NNRMS, ISRO Headquarters, Antariksh Bhavan, New BEL Road, Bangalore 560 094, India
[b] School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110067, India
[c] Asian Elephant Research and Conservation Centre, Centre for Ecological Sciences, Indian Institute of Science, Bangalore 560 012, India
[d] Remote Sensing Application Centre, M.P. Council of Science and Technology, Arera Hills, Bhopal 462004, India

Accepted 24 September 2001

Abstract

A forest fire can be a real ecological disaster, regardless of whether it is caused by natural forces or human activity. It is impossible to control nature, but it is possible to map forest fire risk zones and thereby minimise the frequency of fire, avert damage, etc. Forest fire risk zones are locations where a fire is likely to start, and from where it can easily spread to other areas. Anticipation of factors influencing the occurrence of fire and understanding the dynamic behaviour of fire are critical aspects of fire management. A precise evaluation of forest fire problems and decisions on solution methods can only be satisfactorily made when a fire risk zone map is available. Satellite data plays a vital role in identifying and mapping forest fires and in recording the frequency at which different vegetation types/zones are affected. A geographic information system (GIS) can be used effectively to combine different forest-fire-causing factors for demarcating the forest fire risk zone map. Gorna Subwatershed, located in Madhya Pradesh, India, was selected for this study because it continually faces a forest fire problem. A colour composite image from the Indian Remote Sensing Satellite (IRS) 1D LISS III was used for vegetation mapping. Slope and other coverages (roads and settlements) were derived from topographic maps and field information. The thematic and topographic information was digitised and ARC/INFO GIS software was used for analysis. Forest fire risk zones were delineated by assigning subjective weights to the classes of all the layers according to their sensitivity to fire or their fire-inducing capability. Four categories of forest fire risk ranging from very high to low were derived automatically. Almost 30% of the study area was predicted to be under very high and high-risk zones. The evolved GIS-based forest fire risk model of the study area was found to be in strong agreement with actual fire-affected sites.

Keywords: Corridor map; Criterion-based analysis; Fire sensitivity; IRS 1D LISS III; Remote sensing; Subjective weights

1. Introduction

Forests are a major natural resource and they play an important role in maintaining environmental balance. The health of a forest in any given area is a true indicator of the ecological conditions prevailing in that area. Frequent occurrence of fire is one of the reasons for the degradation of forests in India. Fire is the greatest enemy of standing vegetation and wild animals. Small trees and regeneration are often affected very adversely. Even big trees are not spared if the fire is severe. Ground fire destroys the organic matter, which is needed to maintain an optimum level of humus in the soil. Annual fires may decrease the growth of the grasses, herbs and shrubs, which may result in increased soil erosion (Kandya et al., 1998).

* Corresponding author. Tel.: +91-80-3072446; fax: +91-80-3417455.
E-mail address: rajeev_jnu@hotmail.com (R.K. Jaiswal).

0303-2434/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0303-2434(02)00006-5

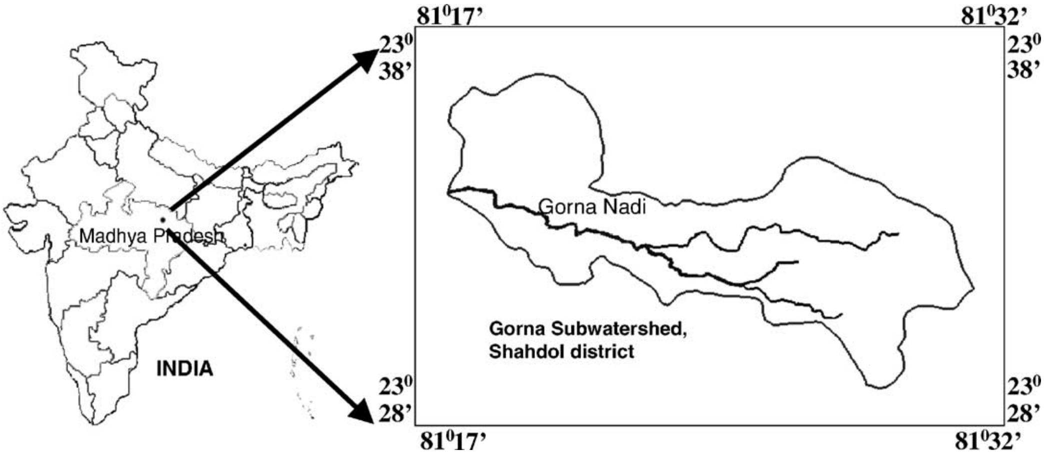


Fig. 1. Location of the study area.

Forest fires are considered to be a potential hazard with physical, biological, ecological and environmental consequences.

In India, forest fires are the most significant, and a steadily increasing, factor in the degradation process, although the extent of total damage is widely disputed. According to a study, 17,852 fires were reported over a period of 5 years (1985–1990) affecting an area of 5.7 million ha, which represents an annual average of some 1.14 million ha (Saigal, 1989). While statistical data on fire loss are weak, it is estimated that the proportion of forest areas prone to fires annually ranges from 33% in some states to over 90% in others. The causes of the forest fires can be classified into three main categories (i) natural causes, (ii) intentionally/deliberately caused by man and (iii) unintentionally/accidentally caused by man. Around 90% of the forest fires in India are anthropogenic in nature. Preparation of the forest fire risk zone map is therefore the first step to averting disastrous and damaging incidents of forest fire.

Satellite remote sensing has opened up opportunities for qualitative analyses of forests and other ecosystems at all geographic and spatial scales. It has also been effectively used in the study, monitoring and detection of forest fires. Understanding the behaviour of forest fires, the factors that contribute to making an environment fire prone and the factors that influence fire behaviour is essential for forest fire risk zone mapping (Chuvieco and Congalton, 1989). In the present study, an attempt was made to prepare a forest fire risk zone map by integrating a satellite image, topographical and other ancillary data from a geographic information system (GIS) for the Gorna Subwatershed located in Shahdol district, Madhya Pradesh, India, (Fig. 1) where forest fires occur annually (Khan et al., 1992). This study is also an attempt to exploit the capabilities of remote sensing and GIS techniques and to suggest an appropriate methodology for forest fire risk zone mapping. This GIS-based model seems to be a reasonably good approach for the conditions in India, where a major part of the forested land is being encroached upon by the population (Jain et al., 1996; Roy et al., 1991). Such maps will help forest department officials prevent or minimize fire risk activities within the forest and take proper action when fire breaks out (Chuvieco and Sales, 1996).

2. Factors responsible for forest fires in the study area

The fire proneness of any area depends on many factors such as vegetation type/density, humidity of the area, proximity to settlements and distances from roads. The most important factors leading to accidental fires in the Gorna Subwatershed are the following:

2.1. Vegetation type

The Gorna Subwatershed stretches over an area of 135 km^2, which is rich in forest resources. Forests consisting mainly of sal, bamboo and dry mixed species cover 64% of the total area. Dry and dense vegetation, especially bamboo, constitutes a major portion (40%) of the forests of the study area. This vegetation is especially susceptible to fire.

2.2. Climate

The climatic regime determines the vegetation in a region and hence, plays a dominant role in creating fire prone areas. The drier the climate is in a particular region, the more fire prone the site will be. The study area has a dry subtropical climatic regime, making it vulnerable to forest fires.

2.3. Topography

Topography is an important physiographic factor, which is related to wind behaviour and hence, affects the fire proneness of the area. Fire travels most rapidly up slopes and least rapidly down slopes. A major portion of the forest in the study area is located on steep hills, which helps to spread a fire. The altitude of the area varies from 380 to 790 m above MSL. Aspect and altitude also play a vital role in spreading fire.

2.4. Distance from roads

Human, animal and vehicular movement and activities on roads provide ample opportunities for accidental/man-made fires. Forests located near roads are therefore more fire prone. The study area forests are traversed by many roads, allowing local people and graziers to become the cause of forest fires. The sale of Mahua/Tendu leaves is a main source of income for the population in this area. While collecting the leaves, people carelessly throw matches and burning ends of cigarettes, which are the major causes of forest fires in the study area.

2.5. Proximity to settlements

Forested areas near habitats/settlements are more prone to fire because the habitation/cultural practices of the inhabitants can lead to accidental fire. Very few settlements are located within the forest in the study area, but they still may be the cause of some forest fires.

3. Identification of fire-affected areas

Forest vegetation reflects strongly on the infrared portion of the electro-magnetic spectrum. A scorched area caused by fire shows considerable reduction of reflectance because of carbonisation: it appears black in false colour composites. In general, though, the reflectance of forest is low in the visible part of the spectrum (except for the green region) and high in the near-infrared part. The spectral curve of the forest after burning becomes flat, resulting in burnt areas having high contrast compared to the surroundings. These observations were used in interpreting the satellite imagery of the study area for forest fire mapping. Identification of fire-affected areas and assessment of the extent of fire damage were carried out using summer season (May) satellite data of Indian Remote Sensing Satellite (IRS) ID LISS III of 1999 (Fig. 2a).

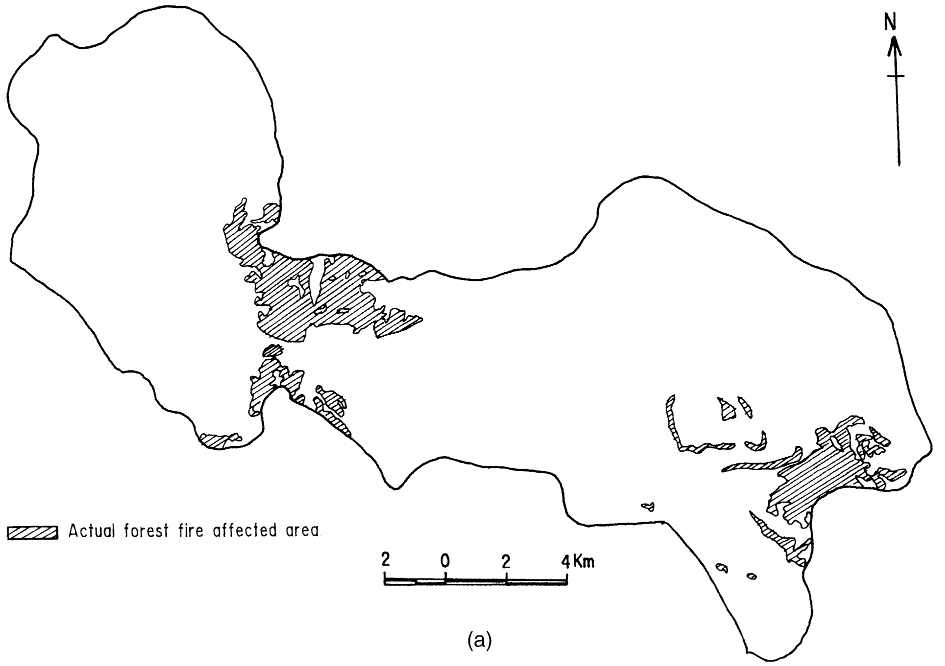
4. Method

Based on the factors responsible for forest fires according to the North Shahdol Forest Department, Madhya Pradesh, India, the present study was confined to the following parameters:

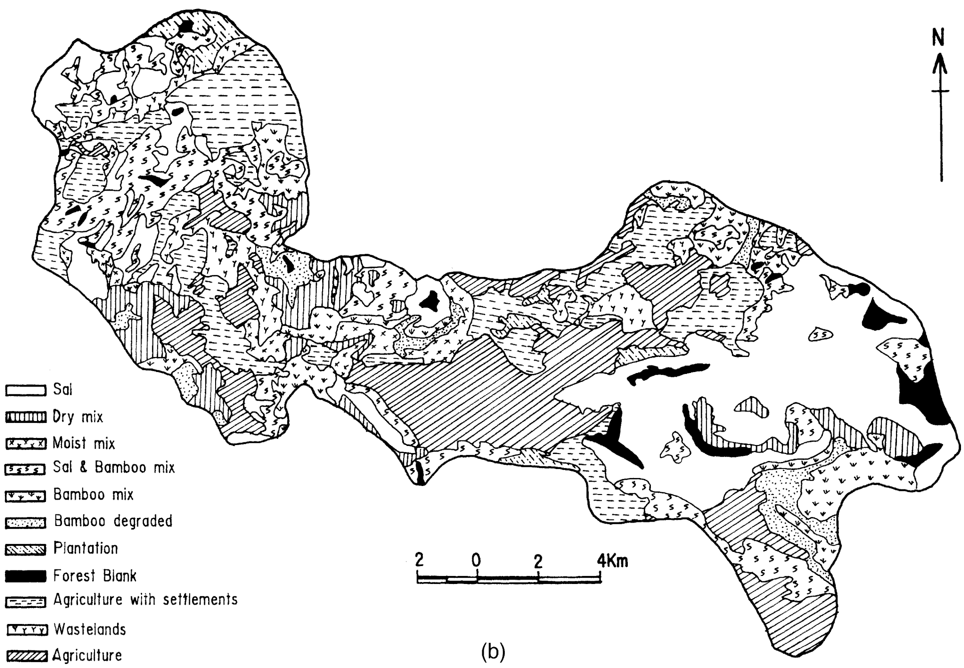
- Vegetation types
- Slope
- Proximity to settlements
- Distance from roads

A vegetation type map was prepared using IRS 1D LISS III data and collateral data (Fig. 2b). Vegetation of the area was classified into eight forest types and three non-forest classes. A slope map was prepared using a SOI topographic sheet of the corresponding area (Fig. 2c). A settlement location and road map was prepared using a SOI topographic sheet. Createbuffer utility of ARC/INFO was used to create buffer zones around the road and settlement locations. Corridors of 1000, 2000 and 3000 m perimeter were created around the settlement locations and digitised as polygon data. Similarly, buffer zones of 100, 200, 300 and 400 m intervals were created around the roads (Fig. 2d and e).

1. The different classes in the thematic maps were labelled separately based on their sensitivity to forest fire as very high, high, moderate or low. Then suitable weights were assigned (Table 1).



(a)



(b)

Fig. 2. (a) Forest fire-affected areas during 1999; (b) vegetation type map of the study area; (c) slope map of the study area; (d) settlement buffer map of the study area; (e) road corridor map of the study area.

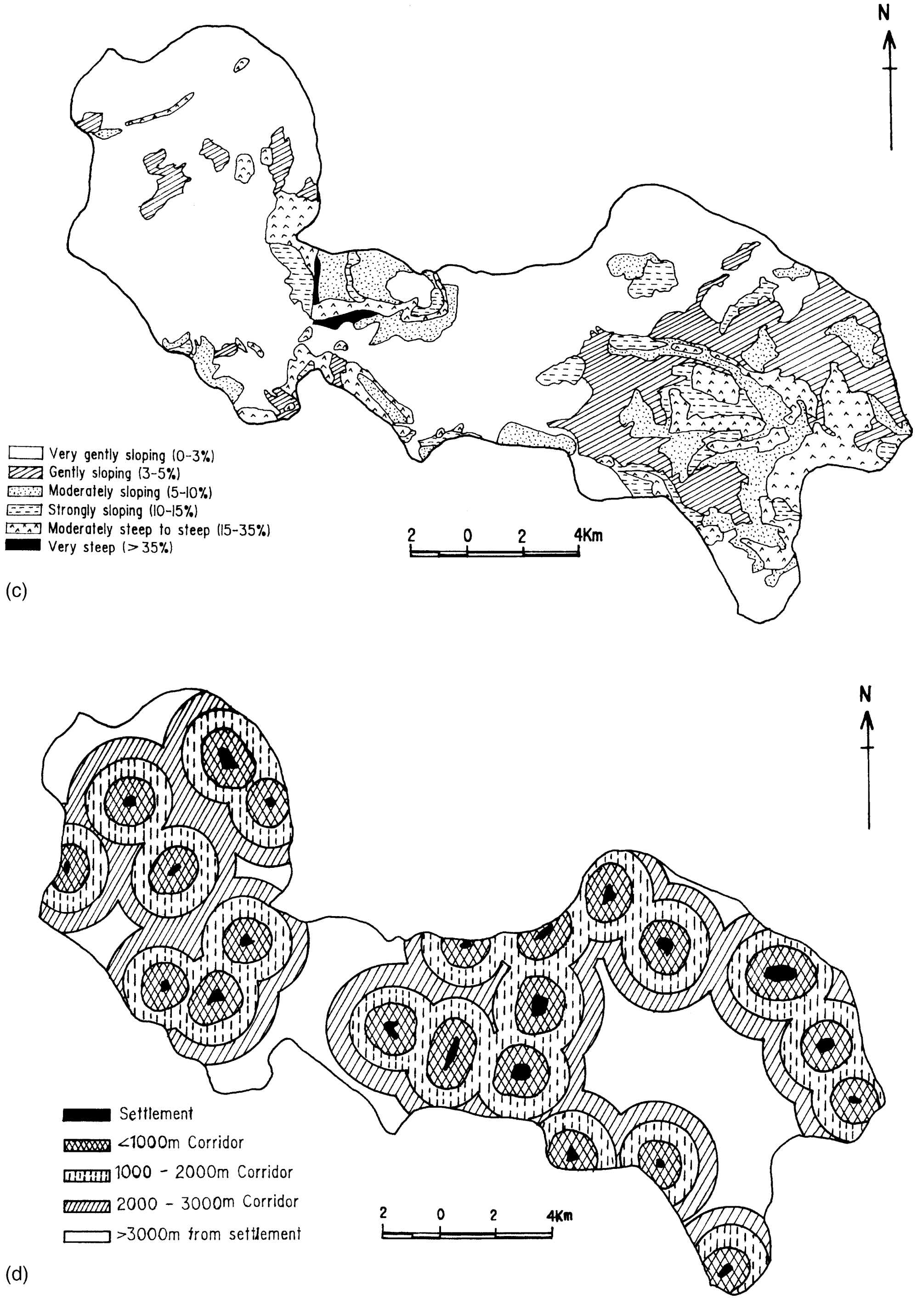


Fig. 2 (*Continued*).

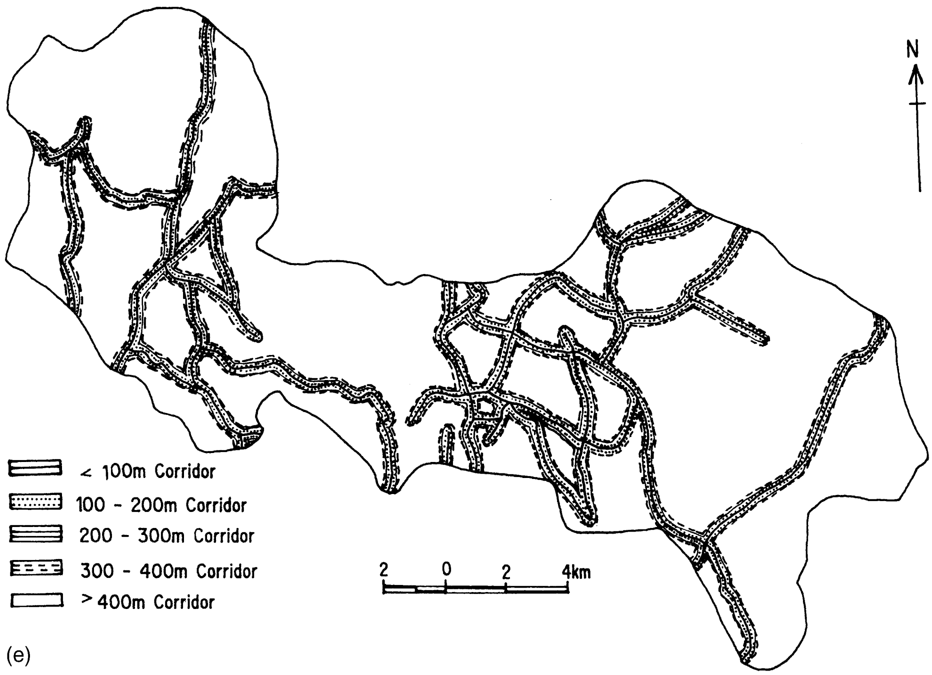


Fig. 2 (*Continued*).

2. All the thematic maps (layers) were then integrated using the union process of GISs. The equation used in a GIS for the fire risk modelling and for mapping the fire risk areas is:

$$\mathrm{FR} = 10F_{i=1\text{–}11} + 2H_{j=1\text{–}4} + 2R_{k=1\text{–}4} + 3S_{l=1\text{–}6}$$

   where FR is the numerical index of fire risk, F the vegetation variable (with 1–11 classes), H indicates proximity to human habitation (with 1–4 classes), R the road factor (with 1–4 classes) and S indicates slope factor (with 1–6 classes). The superscripts i, j, k, l indicate subclasses based on importance in determining the fire risk.
3. Finally, criterion-based analysis (Table 2) was carried out to create the fire risk zone map showing different categories (Fig. 3).

5. Weighting factors for different groups

The input information on forest fire influencing factors is in descriptive form and reveals the parameters favouring the fire risk. In order to achieve effective conclusions through computation and other mathematical operations in the subsequent GIS analysis, the descriptive information was converted into a forest fire risk index and a rating system. The factors that influence the fire risk in an area were analysed in the following order of importance: vegetation, accessibility, road network and slope. After determining the influence of each factor on forest fire risk, the different classes of each factor were given suitable ratings. A higher rating indicates that the factor has a high degree of influence on the fire risk in an area. The considered factors were then integrated for calculating the forest fire risk index (Table 1).

The vegetation types were rated on a scale of 1–10. During analysis, vegetation was given the highest weight because even though an environment may be favourable to fire, a forest fire cannot occur unless inflammable material is present. Bamboo has been almost wiped out from many parts of the study area because it is extremely sensitive to fire damage. Each class of forest type was rated according to its composition of species. Since the altitude variation in the study area is low, the forest type does not change

Table 1
Weights and ratings assigned to variables and classes for forest fire risk modelling

Serial no.	Variables	Classes	Ratings	Fire sensitivity
1	Vegetation type (weight = 10)	(1) Dry mix	10	Very high
		(2) Bamboo mix	9	Very high
		(3) Sal + bamboo	8	High
		(4) Bamboo degraded	6	High
		(5) Sal	6	High
		(6) Plantation	4	Moderate
		(7) Moist mix	3	Moderate
		(8) Blank	1	Low
		(9) Agriculture	2	Low
		(10) Wasteland	1	Low
		(11) Agriculture with settlement	1	Low
2	Habitation (weight = 2)	(12) Settlement area	8	Very high
		(13) <1000 m corridor	7	High
		(14) 1000–2000 m	5	Moderate
		(15) 2000–3000 m	2	Low
3	Road (weight = 2)	(16) <100 m corridor	8	Very high
		(17) 100–200 m	7	High
		(18) 200–300 m	5	Moderate
		(19) 300–400 m	3	Low
4	Slope (weight = 3)	(20) 0–3%	2	Low
		(21) 3–5%	3	Moderate
		(22) 5–10%	4	Moderate
		(23) 10–15%	5	High
		(24) 15–35%	6	Very high
		(25) >35%	10	Very high

Table 2
Criterion-based analysis for forest fire risk zoning

Vegetation weighting category (F)	Slope weighting category (S)	Settlement buffer weighting category (H)	Road buffer weighting category (R)	Forest fire risk weighting category	Fire risk index ($10F_{i=1\text{–}11}+2H_{j=1\text{–}4}+2R_{k=1\text{–}4}+3S_{l=1\text{–}6}$)
V_F	V_S	V_H	V_R	V	162
V_F	V_S	H_H	H_R	V	158
V_F	H_S	H_H	H_R	V	146
H_F	V_S	H_H	H_R	V	138
V_F	M_S	H_H	H_R	V	135
H_F	H_S	H_H	H_R	V	126
H_F	M_S	H_H	H_R	V	115
M_F	V_S	H_H	H_R	V	98
M_F	V_S	M_H	M_R	H	90
M_F	M_S	M_H	M_R	M	75
M_F	L_S	M_H	M_R	L	66
M_F	L_S	L_H	M_R	L	60
M_F	L_S	L_H	L_R	L	54

Subscript: F: vegetation variable, S: slope factor, H: human habitation, R: road factor. Letter: V: very high, H: high, M: moderate, L: low.

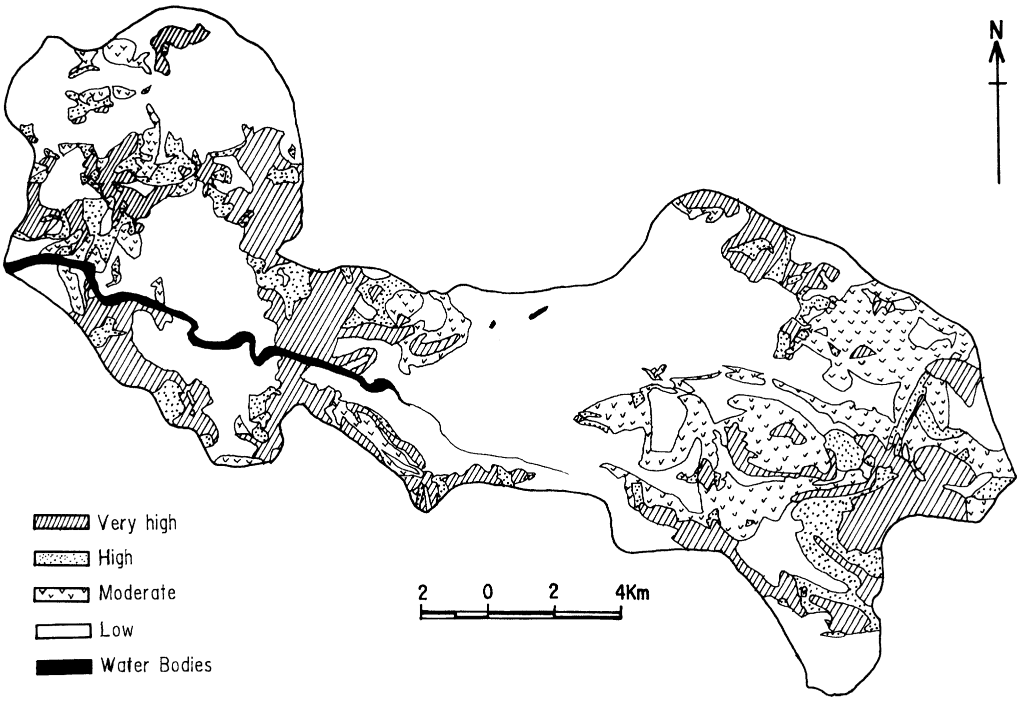


Fig. 3. Forest risk zone map of the study area.

with altitude and hence altitude is not an important parameter in the study. Slope, which does not necessarily influence the probability of an ignition but has a strong influence on the behaviour of fire, was assigned the second highest weight. The different slope classes were rated according to the likelihood that a fire ignited on the slope will spread. In addition to influencing fire behaviour, slope also plays a role in the consequent suppression operation.

Proximity to human activity is a key variable for predicting the probability of an ignition, though it does not influence the behaviour of a fire. The proximity factor was assigned the third highest weight, as anthropogenic actions are the main cause of initiation of the forest fires. Roads inside the forest provide possible access routes. Therefore, road variables were assigned equal weights. A zone in close proximity to the settlement area was assigned a higher rating. The risk factor decreases farther from these features. Surface water bodies which falls under no fire risk zones has been knocked out from the final map.

6. Modelling from a GIS

Before integration, the thematic layers representing vegetation type, slope, settlement corridors and road corridors had 177, 79, 66 and 114 polygons, respectively. After integration using the fire risk model, the final map contained 4757 polygons, each having a minimum weighting of 26 and maximum weighting of 141. Forest fire risk zones were delineated by grouping the polygons of the integrated layer into different risk zones. A criterion-based analysis has been performed for demarcating the upper and lower limits of the forest fire index (Table 2).

The criterion analysis was applied to classify this map into four fire risk zone classes. The area of very high fire risk was delineated by grouping the polygons that have weights >98 in the final integrated layer. The lower weight limit (98) of the very high fire risk zone was derived by adding together the very high fire prone weight of slope, moderate fire prone weight of vegetation type and high fire prone weight of road/settlement corridors. The polygon corresponding to the high fire risk zone was obtained by grouping polygons having weights between 90 and 97. The lower weight limit (90) was derived by adding very high fire prone weight of the slope layer and moderate fire prone weight of all other layers. The polygon corresponding to the moderate fire risk zone was obtained by grouping polygons having weights between 75 and 89. The lower limit (75) for the moderate fire risk zone was derived by adding the moderate fire prone weight of all the layers. Polygons having a weight of <75 were categorised under low forest fire risk zones.

To eliminate the surface water areas from the resultant map, a map of surface water bodies having zero weighting was intersected with the resultant map. The final weighting for the forest fire risk map was achieved by multiplying it with the weights on the surface water bodies map, which resulted in polygons with zero weights or no fire risk zones. These were classified separately on the final forest fire risk zone map (Fig. 3).

7. Results and conclusion

The fire risk in our study reflects both the likelihood of ignition and the risk of spreading. The slope factor, which influences the risk of spreading, thus increases the fire risk and has been incorporated in our present model. An interesting feature of the model is that it explains the important fact that even if a forest type has a low risk weighting, the probability of a forest fire occurring there can be high due to other factors. This explains why the northwestern part of the study area contains a very high fire risk zone. Table 3 describes the resultant fire risk zones and the corresponding degree of fire risk. Out of the total area of 135 km^2, 20% falls in the category of 'very high' fire risk, followed by 10, 15 and 55%, respectively, in the categories 'high', 'moderate' and 'low'. Finally, the fire risk zone map was compared with the actual sites affected by fire. It was found that the starting points of fire were concentrated in areas adjacent to settlements, roads, etc. Interestingly, most of the points representing burnt areas (Fig. 2a) were located in the very high and high-risk zones predicted from the model. Correlation of the risk areas with actual sites affected was assumed to be a major test for the reliability of our approach.

The areas shown under very high, high and moderate 'fire risk' zones are those areas where fire can be unintentionally caused by human activities, and where fire could thus certainly be averted by taking precautionary measures. Hence, despite the fact that no fire prone areas can be demarcated where fire occurs due to natural or intentional human causes, it is advantageous to have a fire risk map to avert possible disasters caused by fire due to human activities. It should prove to be helpful to the Forest Department, as this type of fire risk zone map would enable the department to set up an appropriate fire-fighting infrastructure for the areas more prone to fire damage. Such a map would help in planning the main roads, subsidiary roads, inspection paths, etc. and may lead to a reliable communication and transport system to efficiently fight small and large forest fires.

Table 3
Extent of fire risk zones

Fire risk zones	Degree of fire risk	Description of fire risk zones	Propn of total area (%)
I	Very high	Areas with bamboo and dry mix type of forest; high and very high ignition value on high and very high slopes	20
II	High	Areas with a forest type dominated by bamboo; high ignition value on high slopes	10
III	Moderate	Areas with mainly sal forest; moderate ignition value on moderate and high slopes	15
IV	Low	Areas with agriculture and less forest; low ignition value and moderate slope	55

Acknowledgements

The authors are grateful to Dr. V Jayaraman, Director, Earth Observation Systems Programme Office, Indian Space Research Organisation Headquarters, Bangalore, for providing valuable support during the analysis of the present work.

References

Chuvieco, E., Congalton, R.G., 1989. Application of remote sensing and geographic information system to forest fire hazard mapping. Remote Sens. Environ. 29, 147–159.

Chuvieco, E., Sales, J., 1996. Mapping the spatial distribution of forest fire danger using GIS. Int. J. Geogr. Inform. Systems 10, 333–345.

Jain, A., Ravan, S.A., Singh, R.K., Das, K.K., Roy, P.S., 1996. Forest fire risk modelling using remote sensing and GIS. Curr. Sci. 70 (10), 928–933.

Kandya, A.K., Kimothi, M.M., Jadhav, R.N., Agarwal, J.P., 1998. Application of GIS in identification of fire prone areas—a feasibility study in parts of Junagarh (Gujrat, India). Indian For. 124 (7), 531–535.

Khan, S., Bokil, S., Khare, N., 1992. Mapping of fire-affected areas in Bandhogarh National Park, Shahdol district, Madhya Pradesh, using IRS LISS II data. In: Karale, R.L. (Ed.), Natural Resources Management—A New Perspective. Indian Space Research Organisation, Bangalore, pp. 325–330.

Roy, P.S., Ranganath, B.K., Diwakar, P.G., Vohra, T.P.S., Bhan, S.K., Singh, I.J., Pandhan, V.C., 1991. Tropical forest type mapping and monitoring using remote sensing. Int. J. Remote Sens. 12 (11), 2205–2228.

Saigal, P.M., 1989. A suggested classification of forest fires in India by types and causes. In: Proceedings of the National Seminar on Forest Fire Fighting, Kulamaru, Kerala, India, 2–3 November 1989.