GIS-grid-based and multi-criteria analysis for identifying and mapping peat swamp forest fire hazard in Pahang, Malaysia

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Keywords

Forests, Fire, Geographic information systems, Malaysia

Abstract

Peat swamp forest fire hazard areas were identified and mapped by integrating GIS-grid-based and multi-criteria analysis to provide valuable information about the areas most likely to be affected by fire in the Pekan District, south of Pahang, Malaysia. A spatially weighted index model was implemented to develop the fire hazard assessment model used in this study. Fire-causing factors such as land use, road network, slope, aspect and elevation data were used in this application. A two-mosaic Landsat TM scene was used to extract land use parameters of the study area. A triangle irregular network was generated from the digitized topographic map to produce a slope risk map, an aspect risk map and an elevation risk map. Spatial analysis was applied to reclassify and overlay all grid hazard maps to produce a final peat swamp forest fire hazard map. To validate the model, the actual fire occurrence map was compared with the fire hazard zone area derived from the model. The model can be used only for specific areas, and other criteria should be considered if the model is used for other areas. The results show that most of the actual fire spots are located in very high and high fire risk zones identified by the model.

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Introduction

Forest fires and their resulting smoke haze are a relatively new phenomenon in Malaysia. However, the problem of forest fires seems to be increasing and recurring periodically. In terms of the numbers of hectares affected by fire, the figure for 1997 was the worst since 1992. Most of the forest fires reported in Malaysia occur in degraded or logged-over peat swamp forests, on both the east and west coasts of peninsular Malaysia and on the coasts of Sabah and Sarawak. Fire has been identified as one of the major causes of the loss of peat swamp forests in several states in Malaysia (Wan Ahmad, 2002).

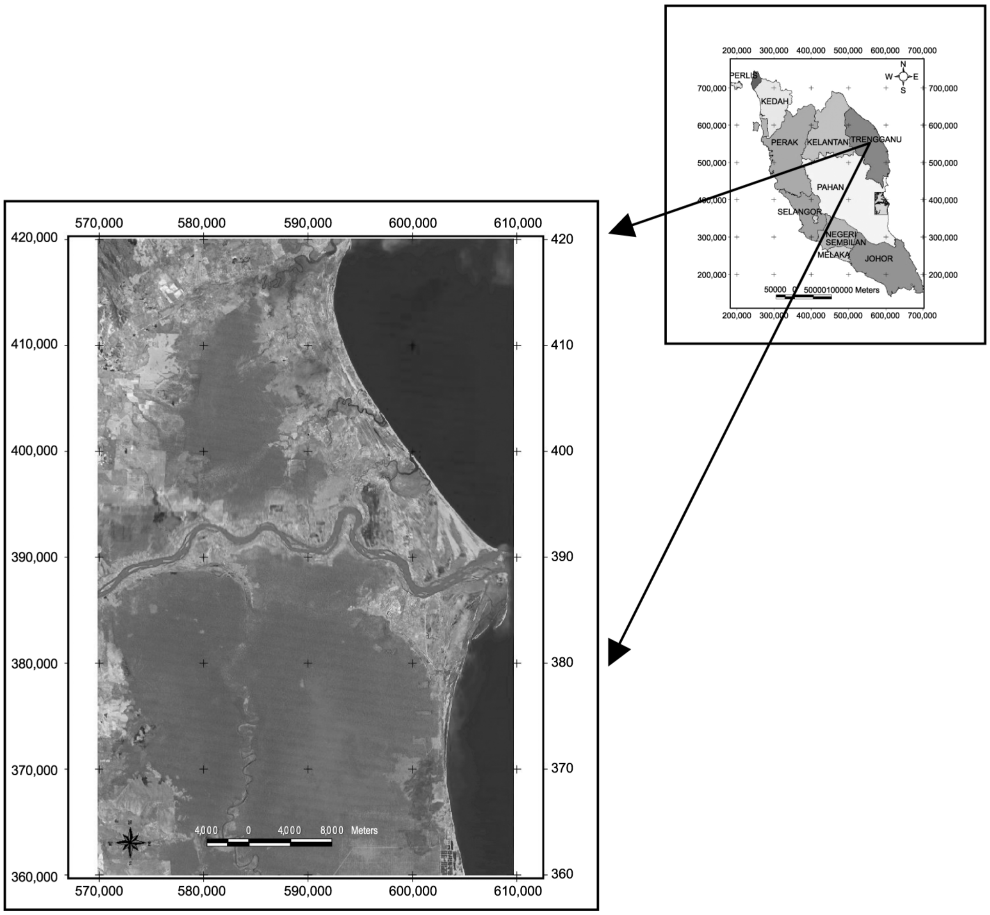
A study modeling fire hazard assessment is essential in establishing an effective forest fire management system, especially in controlling and preventing forest fires. Forest fire management is an important part of overall national forest policy. Geographic information systems (GIS), in combination with other forms of technology such as remote sensing and computer modeling, are being used increasingly in all aspects of wildland fire management. GIS technology has become a more common tool in the management of natural resources. Many research projects have developed wildfire hazard models for a specific region based on the physiographic or environmental factors that influence wildfire (Salas and Chuvieco, 1994). Identifying areas that have a high probability of burning is an important component of fire management planning. The development of spatially explicit GIS models has greatly facilitated this process by allowing managers to map and analyze the variables that contribute to the occurrence of fire across large, unique geographic units.

The purpose of this study is to develop a forest fire hazard model and map in order to identify, classify and map fire hazard areas by integrating GIS with multi-criteria analysis (MCA) for a specific region in southern Pahang, Malaysia. The result of the study is a contribution towards implementing a fully operational GIS for forest fire management, especially fire prevention.

Material and method

Pekan District in southern Pahang, Malaysia (see Figure 1), was selected for this study because it faces an annual forest fire problem. The total area is about 183,992 ha, most which is covered by peat swamp forest (85,218.41 ha or 46.21 percent), with the rest being wetland (50,519.54 ha or 27.39 percent), arable land (22,395.58 ha or 12.14 percent), lowland forest (20,467.96 ha or 11.10

Figure 1 Map of peninsular Malaysia and southern Pahang, showing the study site



percent), and mangrove forest (4,108 ha or 2.23 percent). At the beginning of July 1997 this area was seriously affected by a dense haze arising from local wildfires in the peat swamp forest. There were about ten reported hotspots of wildfire occurrence in the study area during that time. Wildfire destroyed a PSF area totaling approximately 1,600 ha.

This study consists of image processing, multi-criteria analysis (MCA), GIS-grid based analysis and mapping of the fire hazard zone. Image processing was applied to Landsat TM data in order to classify land use. Based on GIS analysis and its integration with MCA, a fire hazard zone map is developed in order to provide useful information about the areas most likely to be affected by fire. The process for data collection and preparation in order to integrate the model with GIS is presented in Figure 2.

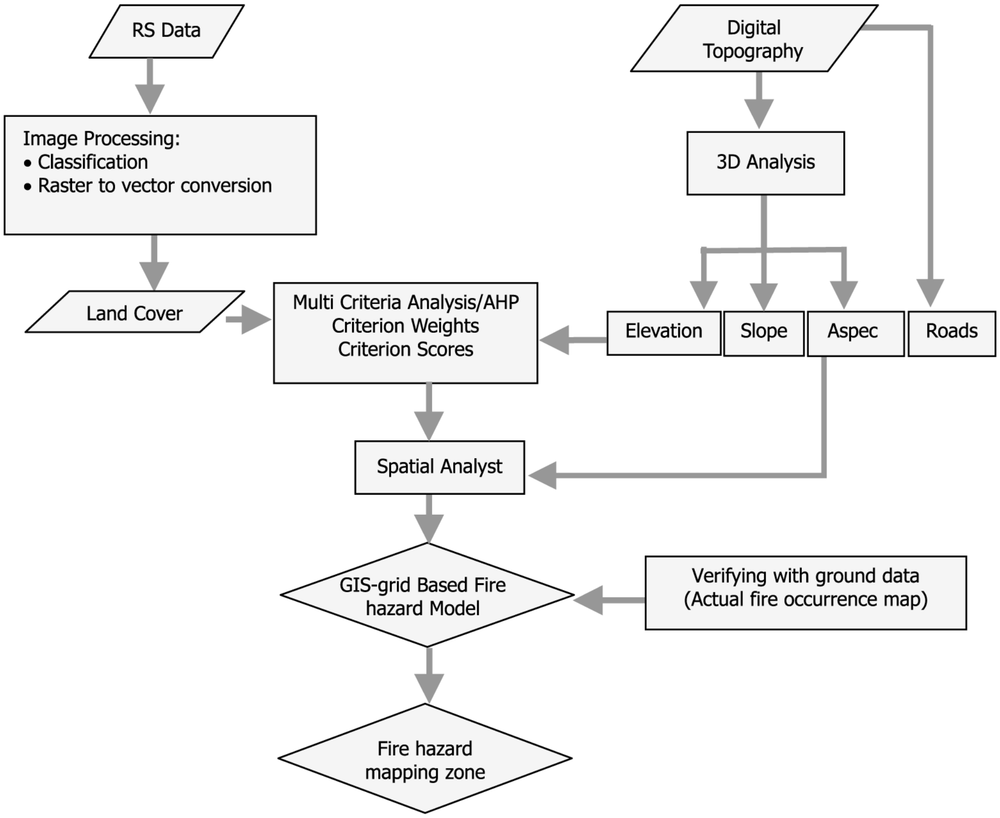
GIS analysis

To develop a map of the elevation, slope and aspect of the study area, 3D analysis was applied using a digital topographic map as the basic map. Using the triangle irregular network (TIN) facility in 3D analysis, aspect, elevation and slope maps can be derived. Spatial Analyst was used to classify and reclassify the grid data of all factors. Several functions of Spatial Analyst (such as overlay analysis) and surface analysis calculations were applied to generate a fire hazard zone map.

GIS-grid-based fire hazard assessment model development

A GIS-grid-based fire hazard model was developed to determine the level of severity of wildfire hazard zones in terms of mapping vulnerability to wildfire by assessing the relative importance between wildfire factors and the location of fire ignition. A spatially weighted index model was used to develop the fire hazard model. This model was developed based on the work of Chuvieco and Congalton (1989), considering the influence of several factors in forest fires. For this research, the methodology was modified so that an analytical hierarchy process (AHP) was used to identify the score and weight of each factor. Potential factors which can have an effect on forest fire – including aspect, elevation, slope, distance to road and vegetation – are extracted for probability analysis

Figure 2 Flow chart of methodology



for the study area. With a weighted linear combination, factors are combined by applying a weight to each followed by a summation of the results to yield a fire hazard model:

$$H = \sum W_i X_i,$$

where H is the composite fire hazard value, W is the weight of factors i, and X is the vulnerability criterion score of factors i.

To determine weights, the AHP method developed by Saaty (1980) was applied. AHP is a theory-based approach to computing the weights representing the relative importance of criteria. Weights are not assigned directly, but represent a "best fit" set of weights derived from the eigenvector of the square reciprocal matrix used to compare all possible pairs of criteria.

Determination of fire hazard factors

The selection of variables affecting forest fire hazard is an important step in this research. According to Castro and Chuvieco (1998) there are two main factors affecting the spread of forest fires: the human hazard index (HHI) and the topography index (TI). They include several human activities related to fire hazard such as agricultural practices, accessibility for recreational use and proximity to urban areas. The cause of forest fires can be classified into three main categories (Jaiswal *et al.*, 2002):

(1) natural causes;
(2) intentionally/deliberately caused by man; and
(3) unintentionally/accidentally caused by man.

Several factors are important in fire hazard (i.e. slope, topography, soil, vegetation, hydrographic and land use, streams and aspect).

Mapping of fire hazard by combining weights and scoring in GIS Spatial Analyst

The final step is to combine all the weights and scores using the equation:

$$H = \sum W_i X_i.$$

The summation of all the weights values for each factor (i.e. multiplying together with scoring factors) was done using the map calculator in GIS Spatial Analyst. The final map of fire hazard is developed using this method in order to provide information about the areas mostly likely to be affected by fire.

Results and discussion

Fuel type classification and scoring map

A fuel type map was derived from land use/cover map combined with a forest type map analyzed previously by supervised classification of a Landsat TM image. The results of the fuel type map classification are shown in Figure 3. Four categories of fuel type were derived as a result of the reclassification of the fuel type map shown in Figure 4 as follows:

(1) very high vulnerability to fire;
(2) high vulnerability to fire;
(3) moderate vulnerability to fire; and
(4) low vulnerability to fire.

Figure 3 Fuel type classification map of the study area

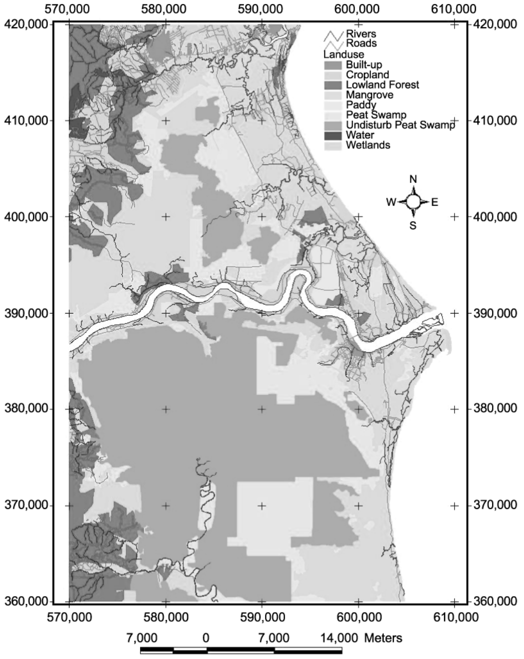
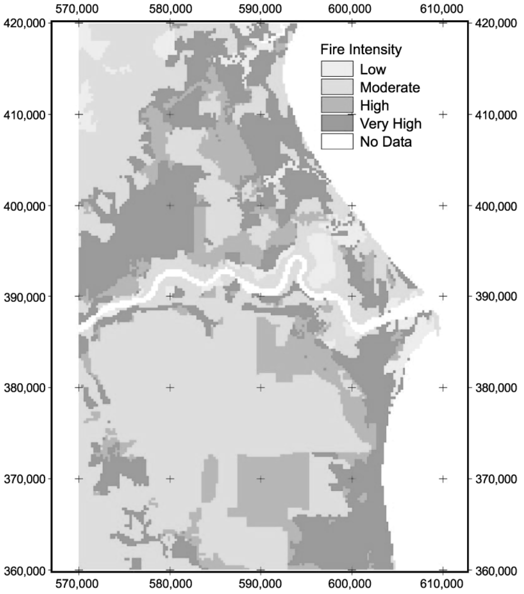


Figure 4 Reclassification of fuel type into four categories



The first category is wetland (logged-over peat swamp forest, which is about 23,000 ha of the total area), the second category includes arable land, the third category includes lowland forest and undisturbed peat swamp forest, and the final category includes built-up areas, mangrove forest, paddy and water bodies.

The fuel type derived from different types of land use must be considered because some areas, such as logged-over peat swamp forest, have a greater potential for fire based on their fire history data. An area's vegetation must be considered because some vegetation types are more flammable than others, thereby increasing the fire hazard. Fuels represent the organic matter available for fire ignition and combustion, and they represent the one factor relating to fire that humans can control (Rothermel, 1972; Albini, 1976; Salas and Chuvieco, 1994). Fire managers need to describe fuel characteristics across many spatial scales to aid in fire management decision-making (Mutch *et al.*, 1993; Covington *et al.*, 1994; Ferry *et al.*, 1995; Leenhouts, 1998). A spatial description of fuels is fundamental to assessing fire hazards across a landscape so that management projects can be prioritized and designed. Accurate, spatially explicit fuel data has become increasingly important as land management agencies embrace prescribing fire as a viable alternative for reducing the potential for severe fires over large land areas.

Logged-over peat swamp forest is in the "very high" fire hazard category. From the fire history data, all of the actual fire spots are located in this area. The scoring of this category is done by referring to Table I: the scoring categories are based on fire history data and previous research as well as a review of the literature. In order to overlay the reclassified land use map with another map of factors affecting fire, the map must be converted into a grid format and then reclassified into four categories. GIS Spatial Analyst was used for this process.

Topographic factors

The digital 20 m contour interval was used and generated to obtain elevation, slope and aspect maps. 3D analysis in ArcView was used to obtain the TIN model in order to derive the slope and aspect maps as shown in Figures 5-7.

Topography affects the amount of solar radiation an area receives, and can modify wind speed and direction and create wind eddies. Important factors associated with topography include aspect, elevation and steep slopes. Aspect is the direction the slope

Table I Classification of fire hazard factors and criteria scores

Factors	Sub-factors	Score	Fire hazard class
Distance to road (m)	0-500	4	Very high
	500-1,000	3	High
	1,000-1,500	2	Moderate
	>1500	1	Low
Land use	Wetland	4	Very high
	Peat swamp forest	3	High
	Arable land	2	Moderate
	Lowland forest	2	Moderate
	Undisturbed peat swamp forest	2	Low
	Built-up areas	1	Low
	Mangrove	1	Low
	Paddy	1	Low
	Water bodies	1	Very high
Aspect	Flat	4	Very high
	South	4	High
	West	3	Moderate
	East	2	Low
	North	1	Very high
Slope (percent)	0-8	4	High
	8-15	3	Moderate
	15-30	2	Low
	>30	1	Very high
Elevation (m)	0-10	4	High
	10-50	3	Moderate
	50-100	2	Low

Figure 5 Classification of aspect factor map

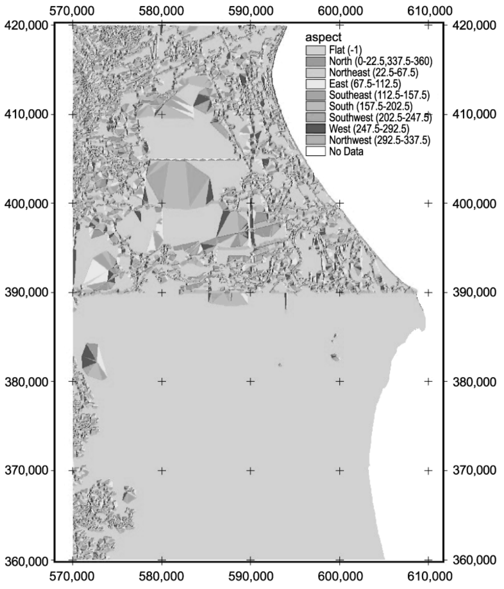
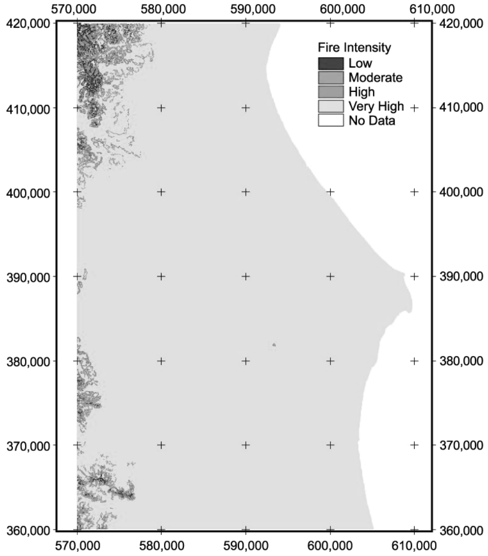
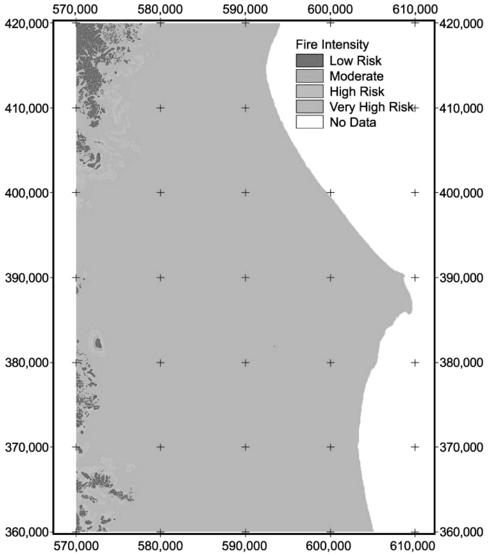


Figure 6 Reclassification of slope factor map



faces, i.e. its exposure in relation to the sun. Fire conditions vary dramatically according to aspect. Southern exposures suffer the greatest solar and wind influences, while northern slopes suffer the least. Generally, eastern aspects receive early heating from the sun and early slope winds, while western aspects receive late heating and transitional wind flows. Aspect is related to the amount of sunshine an area receives. In general, cases of forest fire occur more in areas of southern aspect than in areas of northern aspect, because areas of southern exposure have higher burning points. More than 40 percent of forest fires occur in areas of southern aspect.

Figure 7 Reclassification of elevation factor map



Slope is a critical factor in fire behavior, and aspect is clearly related to insulation and air humidity. Typically, in the temperate zones of the northern hemisphere, south-facing slopes receive more solar radiation than north-facing slopes. Therefore, south-facing slope are hotter, drier and pose greater fire hazards. More than 60 percent of forest fires happen on slopes of between zero and 20 degrees and in areas of southern and south western aspect (Jo *et al.*, 2000). Sixty-five percent of all forest fires occur on slopes of between zero and 20 degrees. The rate of forest fires decreases remarkably as slope increases (Jo *et al.*, 2000). Slope increases fire hazard: as a surface's slope increases, so does fire hazard.

Elevation influences vegetation composition, fuel moisture and air humidity. More than 90 percent of cases of forest fire occur at 100 m above sea level. Most of these disasters take place in areas which are lower above sea level. Fires are less severe at higher elevations due to higher rainfall. Two factors to consider are elevation above sea level and elevation changes in relation to the surrounding topography. It has been reported that fire behavior trends to be less severe at higher elevation due to higher rainfall. Step gradient increases the rate of fire spread because of more efficient convective preheating and ignition, and gradients facing east receive more ultraviolet during the day. As a consequence, eastern aspects dry faster (Chuvieco and Congalton, 1989).

Roads

Roads are an important factor in forest fire because their presence indicates human activity (Jo *et al.*, 2000). Trail and road locations are also important factors in fire hazard mapping. Two major effects can be considered. First, roads can serve as fire breaks or as pathways for the suppression of fire. In this sense, they are a factor which reduces fire hazard. Second, they are potential routes to hiking or camping areas. In this context, they increase the hazard of forest fire because of more intense human activity (Chuvieco and Congalton, 1989). In this study, roads were buffered by an area of 500 meters. These buffered zones were assumed to be the most likely areas for fires to start with respect to roads. The buffered map was converted to a grid to derive the final hazard map, as shown in Figure 8.

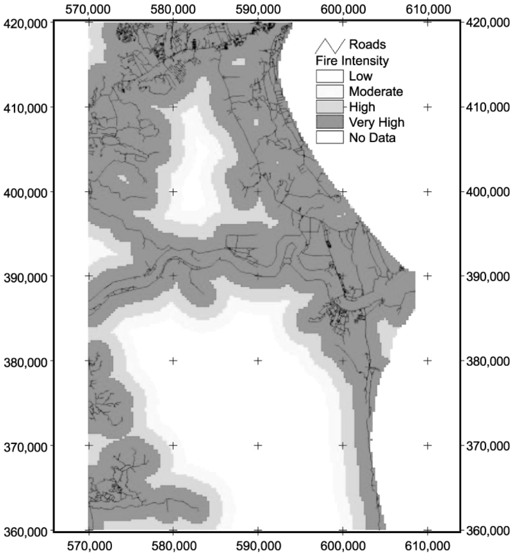
Fire hazard modeling and mapping

The weightings for each factor shown in Table I were entered into the equation of the fire hazard model as follows:

$$H = 0.432V + 0.289PR + 0.135A + 0.108S + 0.045E,$$

where V, PR, A, S and E are coefficients applied to vegetation, proximity to roads, aspect, slope and elevation. Combining elevation, dangerous topographic features, slope, aspect, and fuel type into one raster data set accurately classifies the danger of forest fire hazards in the area. After the probability/scoring grid map was created, a final fire hazard assessment map was generated by multiplying all of the scoring factors with the weighting value derived from the AHP method, as show in the above equation. This yielded the areas of forest fire hazard in Pekan District. To do this,

Figure 8 Distance to roads as a factor affecting fire hazard



the raster calculator/map calculator in ArcView Spatial Analyst was used to combine these grids. The final fire hazard map is displayed in Figure 9.

The final map of the fire hazard zone showed that about 49,678 ha or 27 percent of the total area is categorized as being very high fire risk, with 10.76, 41.73 and 20.51 percent, respectively, being in the categories of high, moderate and low risk. Comparing the predicted fire hazard zone map and the map showing the actual occurrence of hotspots recorded in 1997 in the study area (Figure 10), it can be seen that most of the actual hotspots are located in areas categorized by the model as being very high and high fire risk zones. It can be concluded that the model provides valuable information about the areas most likely to be affected by fire.

Conclusion

A GIS-based method combined with multi-criteria analysis can be a reliable method to determine the vulnerability value of each wildlife risk class and to develop a fire hazard model. This model can predict fire hazard areas by deriving a forest fire hazard model using GIS combined with multi-criteria analysis. Topographic factors which influence the spread of fire are incorporated with the proximity of roads and land use as human activity factors in this model. Approximately 49,678 ha or 27 percent of the total area is located in the very high fire hazard category, followed by 10.76, 41.73 and 20.51 percent, respectively, in the categories of high, moderate and low hazard.

Figure 9 Final map of fire hazard in the study area

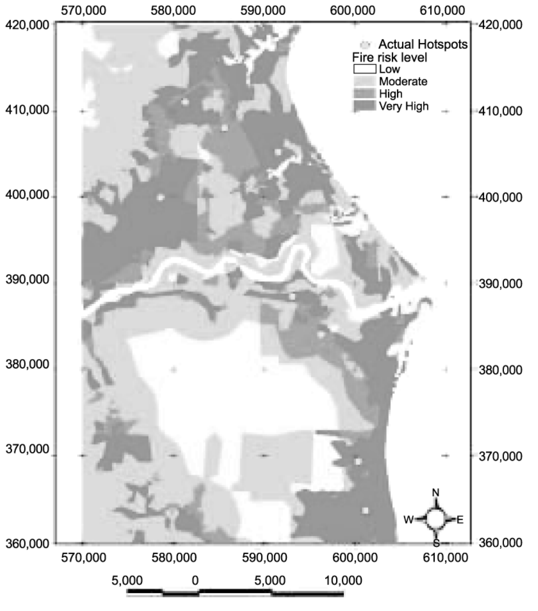
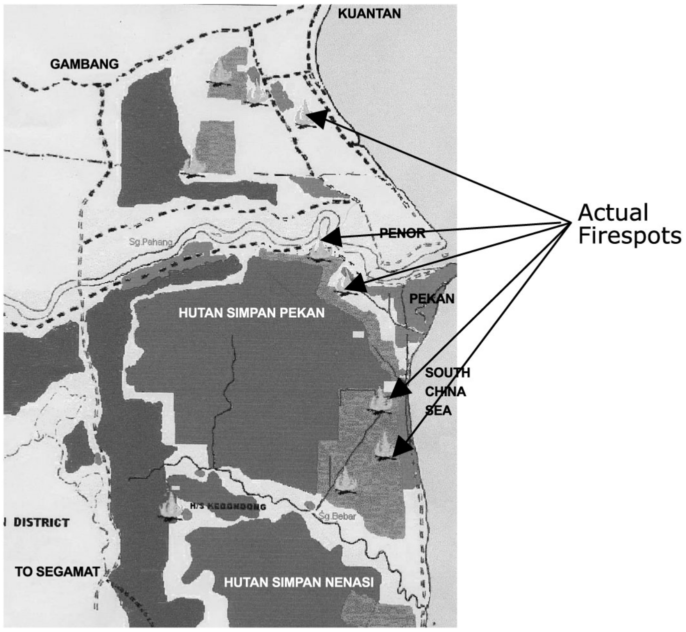


Figure 10 Actual fire spots in the study area, 1997



This model and map provide valuable information about the areas most likely to be affected by fire. It will be a useful tool in forest fire prevention and management in order to minimize wildfire hazard.

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