Modeling Urban/Wildland Interface Fire Hazards within a Geographic Information System

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Abstract

This paper models and assesses the risk of a class of uncontrollable fire, firestorms, in the East Bay hills, San Francisco Bay, California. A Geographic Information System (GIS) is constructed which provides a framework for quantifying fire hazard in a heterogeneous landscape. Two models, one to assess the wildland fire hazard and the other to assess the urban/residential fire hazard, are integrated and embedded within the GIS to map regional and neighbourhood risk. The models generate a hazard assessment map comprised of polygons which represent the results of quantitative multivariate analysis. The system allows for future adjustment of one or all of the parameters as policy is implemented and hazardous conditions are mitigated. This feature provides a mechanism for accounting and feedback allowing for the appraisal of the success of mitigation.

I. INTRODUCTION

Models that endeavour to measure environmental hazard and risk can play an important role in improving decision-making and in the development and formulation of policy. Models once considered too abstract for the real world may now be integrated into the decision-making process by developing the model within a geographic information system (GIS). By framing the analysis within a GIS, we create the ability to detect spatial patterns across regions wherein policy can be developed, administered and its impact measured.

Natural hazards do not recognize political boundaries, yet in order to effectively mitigate against disaster, policy must be generated and usually administered within politically defined boundaries. GIS have particular utility in modeling and analysis which transcend political boundaries, while providing the necessary structure for assisting the implementation of policy within spatially unique administrative areas.

In a similar vein, while natural hazards do not recognize land use differentiation, the cost and impact is often greatly affected by this land use differentiation. In some circumstances, for example, wild fires, the hazard itself is modified and often magnified by heterogeneous landscapes and land use, such as those found at the urban-wildland interface. These conditions are difficult to map and virtually impossible to model without the use of a GIS. In order to mitigate risk to human life and property, we must develop predictive models that are embedded within GIS.

The Oakland Firestorm

On October 20, 1991 a wildfire destroyed approximately 1,580 acres and destroyed over 2,700 structures near the Caldecott Tunnel within the cities of Oakland and Berkeley, California. The rectangle in Figure 1, delineates the study site in the East Bay and locates the 1991 Oakland Firestorm. The area of the 1991 firestorm can be clearly seen in the image in Figure 2, a 7 m2 false color composite of bands 2,3 and 4 from the NS001 scanner aboard a NASA low altitude aircraft. The fire took 25 lives and damage to infrastructure and dwellings exceeded $1.68 billion. This event became the most expensive fire disaster in California history.

Fire is not a new phenomenon in the East Bay Hills. The Mediterranean climate, the rugged topography, a shifting urban-wildland interface, and the prac-

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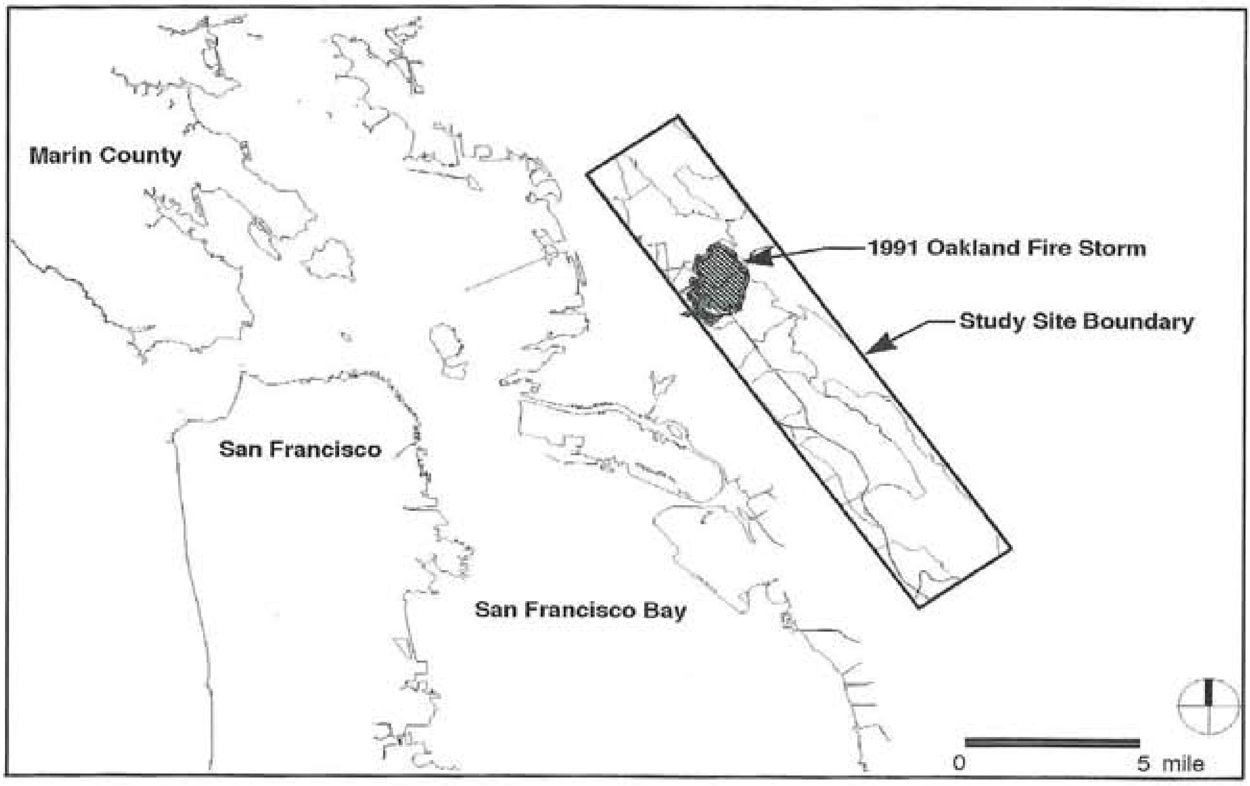


Figure 1. Study Site in The San Francisco Bay

tice of fire suppression in recent history have all collaborated to create the increased potential for catastrophic fires. An East Bay Hills fire, much like the 1991 firestorm, claimed 584 homes in 1923 and over the past hundred years dozens of fires in the East Bay Hills have been documented. These fires continue to portend of the potential hazards that exist in the urban-wildland interface. From 1920 to 1990 3,036 structures were lost to fire in the East Bay Hills. From 1990 to 1994 alone, the number of structures lost was 5,298.

The relentless urban spread into peripheral areas demands the implementation of a comprehensive fire response strategy. This response can take the traditional reactive strategy of spending resources once the fire has begun, or move toward the preemptive end of the spectrum and practice prevention. One of the best fire control strategies is to reduce and manage, on a long term basis, vegetation and structural conditions that fuel fire. Simply put, removing the firewood from the fire place will reduce the risk of a catastrophic firestorm.

Objectives

This paper describes an approach to assessing the risk of fire in an heterogeneous landscape. The approach integrates multisource spatial data with field observations and produces a GIS within which risk modeling is performed. Two models, one to assess the wildland fire hazard, and the other to assess the urban/residential fire hazard, are integrated and embedded within the GIS to map regional and neighbourhood risk. This modeling endeavour yields an efficient spatial decision support system (see Fedra and Reitsma, 1990) which now also serves fire hazard mitigation efforts in the East Bay Hills.

The results of this effort provide the information and mechanism necessary for decision-makers to better mitigate against future firestorms. In order to meet the study's objectives, a strategy is applied where: i) conditions are recognized that promote fire hazard (data for model inputs are defined), ii) a structure (the GIS) is designed and built within which hazardous conditions can be assessed, ana-

Table 1. Wildland Fire Hazard Data Dictionary

Vegetation Type

No Vegetation
Serpentine Grassland
Grassland
Oak Savannah
Wet North coastal scrub
Dry North coastal scrub
French Broom
Diablan Sage Scrub
North mixed charparral
Alameda Manzanita
Successional Scrub
Mixed Hardwood Woodland
Mixed Hardwood Forests
Riparian Forest
Pine Forest Plantation
Pine Forest Mature
Redwood/Douglas Fir Forests
Eucalyptus - 20 yr
Eucapytus - 1 to 5 yr
Eucalyptus - mature
Acacia
Cypress
Mature Pine/Eucalyptus Mix
Treated Forest with slash
Other Vegetation

Fuel Model (for the BEHAVE Model)

No Fuel Model
Short Grass
Timber/Grass
Tall Grass
Charparral
Brush
Dormant Brush
Southern Rough
Closed Timber Litter
Hardwood Litter
Timber Litter/Understory
Light Slash
Medium Slash
Heavy Slash
Other Fuel Model -w

Development Stage	**Crown Potential**	**Tree Height**
None Development Stage	None -- default	None -- default
Development Stage	Low	Short 20-30 ft
Moderate Development Stage	Moderate	Early mature 30-50 ft
High Development Stage	High	Mature 50-70 ft
Extreme Development Stage	Extreme	Dominant 70-90 ft
		Overmature > 90 ft

lyzed, integrated and mapped, iii) those data that contribute to fire hazard conditions are inventoried (data is compiled), and iv)information is generated about fire hazards in the East Bay Hills (the fire models are applied to the data in both the wildland and residential regions of the study site).

II. FIRE MODELING

Conditions That Promote Fire Hazards

The conditions necessary for catastrophic fire are well documented in the literature (McArthur [14],[15], Rothermel and Rinehart [22], Beer [3]) and include certain fuel types, weather and topographic conditions.

In this study, fuels consist of vegetation in the wildlands and both vegetation and built structures in the urban-wildland nexus. Major characteristics that determine how fuel types will burn are in two data dictionaries, one for wildlands (Table 1) and one for residential (Table 2). In the wildlands, the characteristics observed include: size of common vegetation patch, amount of fuel, presence of volatile products, moisture level (based on vegetation type), proportion of dead material, and distribution or continuity of fuel. In residential areas the characteristics observed covered both vegetation conditions and building structures and were defined by a committee of experts with first hand experience with fire behaviour in the East Bay Hills.

Weather conditions play a critical role in the risk of fire and the potential damage a fire can do once initiated. Temperature, wind velocity and relative humidity impact fuel moisture, ignition potential, flame length and rate of spread. From November to June the climate in the East Bay Hills is considered 'fire safe'. Although the dense summer fog adds moisture to the eucalyputs (Eucalyptus globulus) and Monterey pines (Pinus radiata), the afternoon westerly winds off San Francisco Bay reach velocities in excess of 20 miles per hour and can move a fire quickly in the hills. At least five historic fires have burned a cumulative 1200 acres under these conditions. These,however, are not the extreme conditions that fuel a catastrophic firestorm. Warm, dry easterly winds, commonly known as Diablo winds, regularly reach velocities in excess of 20 miles per hour, bring temperatures in excess of 80 degrees Fahrenheit and drop the humidity to less than 20 percent. Diablo winds occur on average 4 to 6 days a year usually in late September or early October. These were the weather conditions during the 1991 Oakland Firestorm.

Topographic data allows calculation of slope gradient and slope aspect which are critical parameters in fire models such as the Rothermel model. Furthermore, the behaviour of wildland fires responds to the morphology of the landscape. For instance, fire spreads more rapidly moving uphill as the heat generated from below heats and dries the fuel accelerating the ignition and burn mechanisms. A similar effect can occur during down-slope winds such as those that fanned the 1991 Oakland fire. Slope and aspect can also influence the micro climate and produce variations in temperature and fuel moisture content which influences the ignition potential of the fuel.

Wildland Fire Models

Although many wildland fire models have been proposed in the literature, only two empirically based models have been successfully applied on an operational basis (Beer [3]). The McArthur meters (McArthur [14], [15]) is widely used in eastern Australia and the Rothermel model (Rothermel [21]) is used in the United States as part of the US Forest Service's BEHAVE system of fire prediction (Burgan and Rothermel [4]). Both the McArthur and Rothermel models have similar data requirements for slope gradient, wind speed and wind direction, but differ in their treatment of fuel categories. While McArthur separates fuel type into two categories, grass and forest, Rothermel uses physical properties, such as the surface area to volume ratio, to classify fuel properties of all types of vegetation. The fuel properties measured for the Rothermel model require a separate entry for fuel moisture content. An empirical model used in Canada (Stocks et al. [24]) applies a wider choice of fuel types but only allows the fuel moisture content to be varied within

Table 2. Residential Neighborhood Fire Hazard Data Dictionary

	Fuel Characteristics	Measurement	Low	Moderate	High	Extreme
Structural Fuels:	Combustible Roof Materials	% structures with wood roofs	None	< 20%	20 - 50%	> 50
	Siding, decking & fencing	% structures with combustible siding,decking or fencing	None visible	< 20%	20 - 50%	> 50%
Vegetation Fuels:	Surface Fuel Density	% surface area supporting combustible surface uels	< 20%	20 - 50%	50 - 70%	> 70%
	Aerial Fuel Density	% surface area coveredby tree canopy	0 - 10%	10 - 30%	30 - 70%	> 70%
	Vertical Continuity	Presence of ladder fuels and crown fires potential	None	Isolated ladder fuels Individual trees to crown	Widespread ladder fuels Stand-wide crown firex crown fire	
	Tree Height	Tree height	Short =<50 ft	Intermediate = 50 - 90 ft	Tall => 90 ft	
	Flammability	Overall flammability of fuels	Irrigated grass, Ornamental hardwoods	Cured grasses Native hardwoods Cultivated landscapes	Pyrophytes (Juniper, pine, eucalyptus, etc.)	
	Fuel Clearance	Clearance distance of combustible material from structure	Poor =< 10 ft	Moderate = 10 - 30 ft	Good = 30 - 100 ft	Excellent => 100 ft
Risk Value Assignment:			1	2	3	4

Table 3. Relative Weighting of Factors to Assess Urban Wildland Intermix Hazard

	Fuel Characteristics	Weighting Factor
Structural Fuels:	Combustible Roof Materials Siding, decking & fencing	75% 25%
Vegetation Fuels:	Surface Fuel Density Aerial Fuel Density Vertical Continuity Tree Height Flammability Fuel Clearance	25% 10% 20% 10% 10% 25%

each type.

Recent experiments show the Rothermel model needs further refinement in the parameterization of mixed fuels to predict accurate intensity values (Catchpole et al. [6]). However, at this time it is the most appropriate model to predict the behaviour of fire in the wildland area in the East Bay Hills.

A Residential Fire Hazard Assessment Model

No mathematically derived or empirically calibrated fire model exists for the urban-wildland nexus where residences exist within a highly vegetated region. Such a model may be simulated in a combustion wind tunnel, as has been done with the Rothermel model, however, testing in field conditions would be expensive. Therefore, to assess and model fire hazard in the residential region of the study site, the knowledge of fire experts was assembled and a set of rules formulated to select criteria for fuel assessment and fire risk prediction. Knowledge gained from observation of the 1991 Oakland Firestorm showed that contribution to fire hazard at the urban-wildland nexus could be divided into two classes: i) vegetation type and its distribution with respect to structures, and ii) structural materials and building design. Each criterion, commensurate with its ordinal metric scheme derived from expert knowledge, comprised the data dictionary (Table 2) for the residential fire hazard assessment model (RFHAM). These two data classes fueled the model where risk was assessed separately for both structural and vegetation conditions on the advice of fire experts from the Oakland Firestorm.

In the RFHAM a relative weighting scheme was applied to the individual factors described inTable 2. The weights (Table 3) were derived from a survey of fire experts, many of whom had considerable experience fighting fires in the East Bay Hills. This knowledge-based model produces a residential fire hazard assessment framework valuable for both planners and decision makers.

III. THE STUDY SITE AND GIS DATABASE DEVELOPMENT

The study focuses on lands in an urban-wildland intermix region of the East Bay Hills. The site is 54.3 square miles and forms a rectangle approximately 3.25 miles wide by 16.72 miles long which follows the regional ridge line from Lake Chabot in the south to Wildcat Canyon in the north of the East Bay Hills.

GIS and A Strategy to Assess and Map Hazardous Fire Conditions

Any scheme designed to reduce the hazard of wild fire must include a sound approach to assembling existing environmental data. This information base can quickly become complex in nature and massive in size. To accommodate this evolving information base, the data must be assembled and analyzed within a highly structured framework. GIS, with their ability to deal with spatial characterization and association, are evolving into the medium necessary to satisfy such needs (Rejeski [20]).

In this instance, a GIS provides a systematic framework to estimate potential fire risk over several political jurisdictions, towns, regions, park districts and private utility water sheds. This, in turn, aids in the formulation and implementation of policy to mitigate hazardous conditions in both wildland and urban areas.

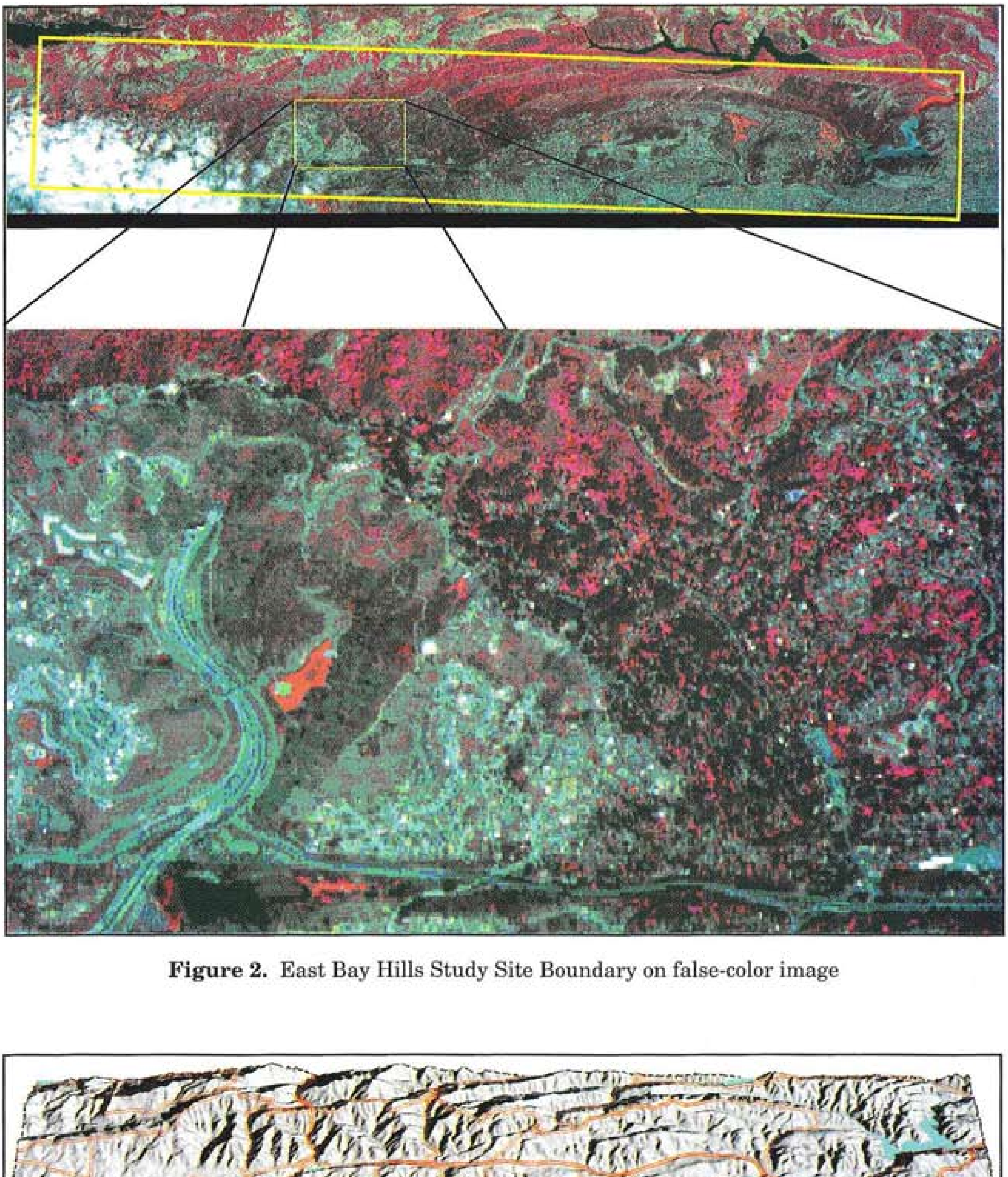
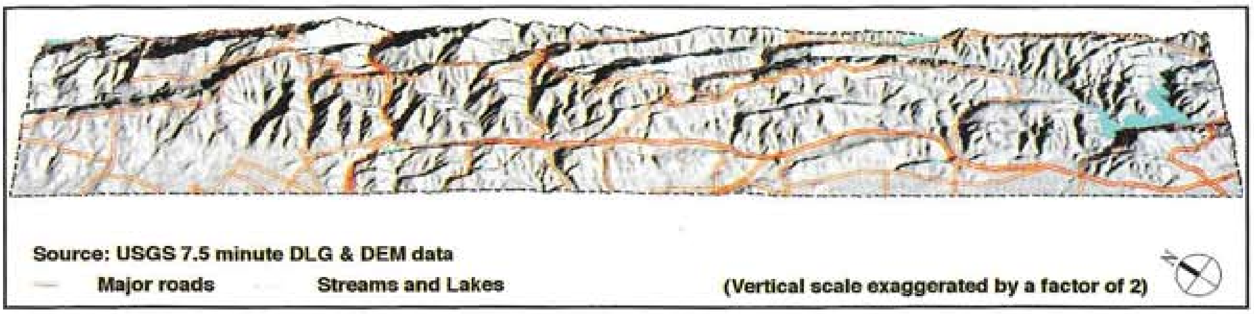


Figure 2. East Bay Hills Study Site Boundary on false-color image



Source: USGS 7.5 minute DLG & DEM data

(Vertical scale exaggerated by a factor of 2)

Figure 3. East Bay Hills Relief

Implications for System Design

This study was undertaken to construct a spatial decision support system so that decision makers could better manage and formulate policy that would help reduce the risk of a firestorm. The scale at which data is collected has a strong influence on the outcome of any modeling effort. The East Bay Hills Vegetation Management Consortium (VMC) determined that 5 acres would be the minimum patch size to be mapped in the wildland region. In the residential region, it would be too costly and impractical to manage individual parcels and therefore the block scale is selected at the appropriate scale for a management unit. These decisions make it possible to choose the standard scale of 1:24,000 for data collection.

Clarke [7] suggests that the individual mapping criteria should influence the spatial data model chosen, but in this instance the variety of sampling and data gathering techniques used made it possible to choose either a raster or vector spatial data model for the GIS. The current analysis could have been undertaken within either of these spatial frameworks, however the decision to frame the study within the vector model was made to accommodate future modeling efforts which might involve the use of vector based network analysis. Within the vector spatial model, a polygon model (Goodchild [10]) was used to delineate fire hazard.

The individual data sets collected in this study are classified into separate themes, each theme being characterized as a layer in the GIS (McHarg [16]). Several layers exist as part of the GIS to: 1) support the input necessary for the fire models; 2) aid in the construction and georeferencing or positioning of other layers; and 3) to be used in future modeling efforts.

Data Compilation

The data gathering for this study is organized into several discrete operations. Some of the data already existed as ancillary data[1] and served the purposes of this study. Of the ancillary datsome existed in digital form and some in paper form. Other data were gathered through field work which were either transferred directly to the data base from a field computer or later digitized in a computer laboratory.

Several data sets are generated in digital form as Digital Line Graphs (DLG) from the United States Geological Survey (USGS) at a scale of 1:24,000. Hypsography and hydrography along with Digital Elevation Model (DEM) data are combined to construct a surface or digital terrain model to satisfy the topographical needs of the wildland modeling. These data were assembled to form a set of surface sample points (x, y, z coordinates) which represented samples of elevation in the study site. The Delauney Triangulation (Getis and Boots [9]), commonly referred to as a Triangulated Irregular Network (TIN) (Peucker et al [18]), is used to create the surface in Figure 3. Information on slope gradient and aspect are obtained from this surface model.

Ancillary data obtained from the USGS-DLG were used to construct the road layer. This layer was updated and refined using a combination of aerial photography and field surveys where a Trimble Navigation Global Positioning System (GPS) was used for accurate positioning. Two GPS receivers were used, one a base station and the other a mobile receiver mounted on an automobile. Differential GPS was employed and error was corrected to obtain accuracy to within 2 meters (see Huxhold [11]).

The wildland vegetation layer was delineated using aerial photographs and images obtained from a NASA low altitude data gathering flight in August of 1993. Homogeneous patches of vegetation were registered, digitized and then visited in the field for identification. The time required for field visits was considerably reduced and the locational accuracy greatly enhanced with the use of the GPS units. The wildland fire hazard data dictionary (Table 1) was loaded into the memory of the GPS unit which then allowed patch identification to be easily recorded along with the positional information as the observer moved through the vegetation patch. At the end of each day the data were downloaded from the mobile GPS unit and differentially corrected with data

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[1] These are data that have been gathered by both the government (for example the United States Geological Survey - Digital Line Graphs (USGS-DLG), the United States Geological Survey - Digital Elevation Model (USGS-DEM), the Soil Conservation Survey (SCS) - Soil Series, and other entities such as the East Bay Municipal Utility District.

from the GPS base station. After this locational correction, the data were loaded directly to the GIS and the vegetation layer updated. The time savings obtained from this process made it possible for each vegetation polygon in the wildlands to be visited and identified. The GPS units also served as navigation aids for the human observers as they moved through the wildlands.

A combination of road data, images from the NASA low altitude flight, and data obtained from the local utility company, East Bay Municipal Utilities District (EBMUD), provided the necessary information to delineate residential areas. EBMUD provided a digital map series of utility drawings which had been scanned and vectorized. Although these maps were edge matched, they were not in any map projection nor were they georeferenced. The road layer was used to correctly position the EBMUD data. From this, information on water service location proved valuable in modeling the potential location of houses. The results of this strategy were then checked with aerial photographs and block data obtained from the US Census, to obtain an accurate delineation of the residential region.

The fire hazard classification scheme applied in the residential region could not use the scheme developed for the wildlands. Observed patches of vegetation in the wildlands, where natural processes of succession and invasion apply, tended to be homogenous. In contrast, urban-wildland nexus areas, which are predominantly occupied and dominated by humans, appear to be more heterogeneous with a great variety of structural as well as vegetation conditions. These conditions are not necessarily bounded by political interests or physical barriers, such as streets. As a result, the residential regions are not delineated as polygons and then classified, but rather, observations are taken at point locations distributed throughout the study site and later synthesized into a data layer. The conditions observed were not based on an individual property or structure, but on the characteristics of a neighbourhood. The observer evaluated groups of structures to establish the sample neighbourhood of similar attributes.

The GPS units made it possible to automate the residential spatial point sampling scheme by entering eight different attribute observations (Table 2) at each sampling location. A light pen and bar code method is used to quickly assign a preloaded residential hazardous condition data dictionary (the eight different variables) to each sample point. Observations are taken at regular intervals (approximately every block) and adjusted where changes occurred in any one or all of the eight sampled attributes. Over 3200 observations were made by the same observer to eliminate variation in interpretation[2]

Due to the nature of land management, polygons are considered the best spatial decomposition for the observed point set. The theoretical properties of the Voronoi graph (Radke [18]) makes it possible to effectively assign all space in the residential region to the most proximal of the 3200 observation points. Figure 4 represents a sample of the Voronoi graph for the residential region. Both the efficiency of the GPS units and the decomposition to the Voronoi graph allowed the spatial sampling procedure to be iterative in nature. Each day maps were generated showing the region sampled and pointing to areas within that region where more sample points were needed to complete the data set. Areas inaccessible by vehicle were sampled in a helicopter equipped with a GPS unit. Again, interpretations were performed by the same observer as with the surface survey.

IV. RESULTS OF THE FIRE HAZARD ASSESSMENT

The Wildland Fire Model (BEHAVE)

The BEHAVE model is applied to each vegetation polygon delineated in the wildland region for the extreme Diablo wind conditions. Figure 5 maps the vegetation types in the wildland region. These are conditions that can lead to a catastrophic firestorm and the results will indicate the extant fire hazard and extreme risk. The topographic gradients are averaged for each polygon and the results are further classified into categories with 10% ranges. Many extreme slopes exist within the study site and are classified in an upper range slope category of >40% slope. The final parameter, the physical properties of vegetation, are assembled from a compiled

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[2] By using the same human observer, it would render any bias a constant which could be adjusted in the model.

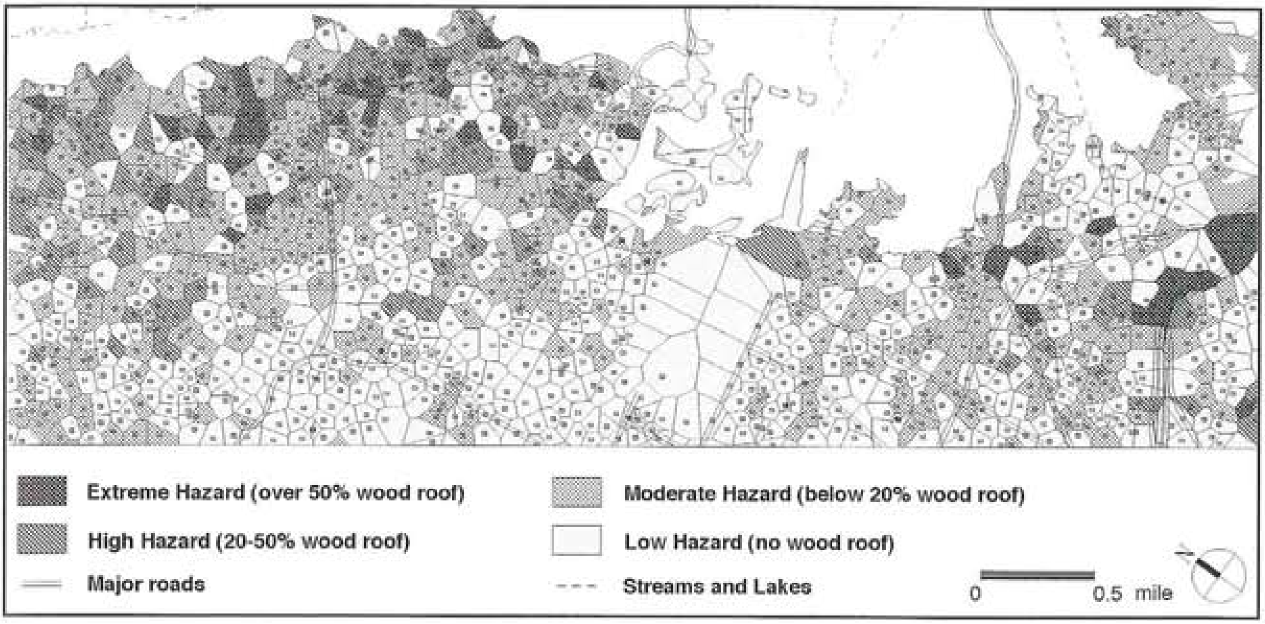

Figure 4. Sampling Technique - Roof

set of conditions: vegetation type, fuel model, and development stage (detailed in Table 1).

The results of this modeling effort classify each vegetation polygon for flame length (ft), rate of spread (BTUs/square ft), heat released per unit area (BTUs/square ft), and crowning potential where crowning potential refers to the probability of fire reaching the crown of an entire stand of trees or shrubs. From these results we generate hazard assessment maps with patterns of polygons which indicate spatially cumulative risk. For example, juxtaposed polygons which are classified as different vegetation types may result in similar fire hazard conditions and produce very large contiguous polygons. Similarly, vegetation types may result in dissimilar fire hazard conditions and produce a quilted pattern of fire hazard polygons. This property is invaluable for decision makers as they can visualize the potential movement of fire through time and space[3].

Two critical components that can lead to firestorm conditions are vegetation that can produce flame lengths over eight feet or vegetation with high crowning potential. When flame lengths surpass 8 feet in length erratic fire behaviour results and a fire becomes uncontrollable (Andrews and Rothermel [1]). The results of the BEHAVE model show that approximately 10,500 acres or over half of the wildlands in the study area have the ability to fuel and produce a firestorm in Diablo wind conditions. Figure 6 maps these hazardous areas where either flame length is > 8' for all types of vegetation or the trees had high crowning potential.

The Residential Fire Hazard Assessment Model (RFHAM)

RFHAM is applied to each Voronoi polygon delineated in the residential region. The model is applied separately for the two types of fire hazard: i) vegetation and its distribution with respect to structures, and ii) structural materials and building design. Expert knowledge helped select the components to be measured and also rated the components with a risk value (1 to 4) to the observed conditions for each type of fuel characteristic in Table 2. This assignment of risk was later refined to assist the integration of the different types of fuel characteristics observed at the same sample point. Relative weights were assigned according to the most critical factors in fire behaviour and structural proper-

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[3] Knowing the rate of spread, flame length and crowning potential can aid in scenario building of where and how fast a fire might spread.

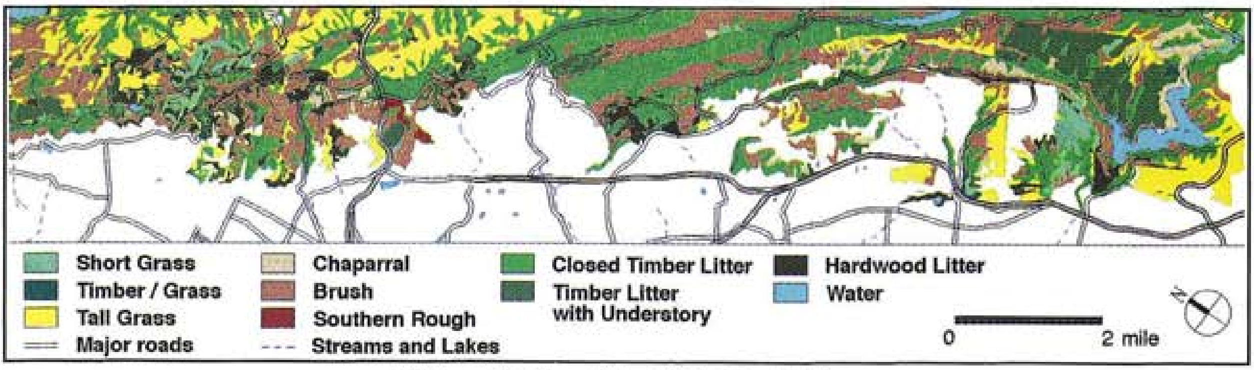

Figure 5. East Bay Hills Vegetation

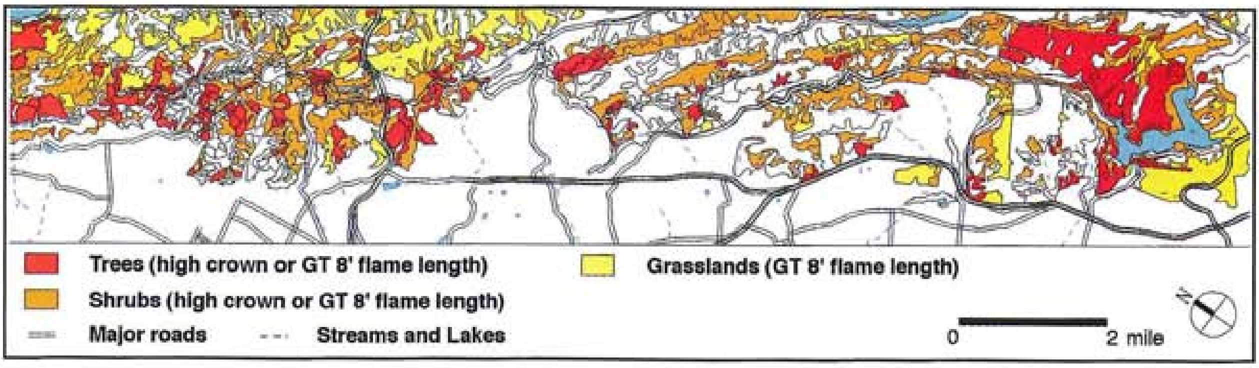

Figure 6. High Hazard Polygons in the Wildlands

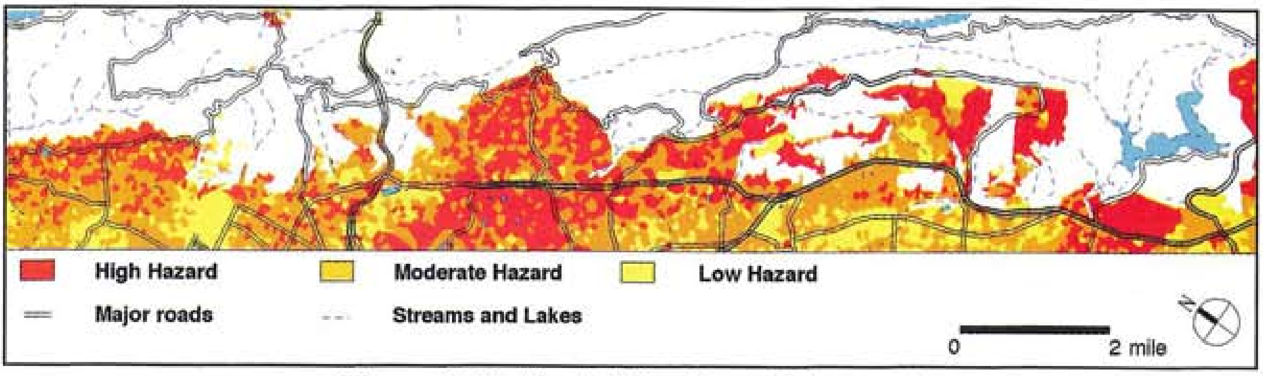

Figure 7. Residential Fire Hazard (Structure)

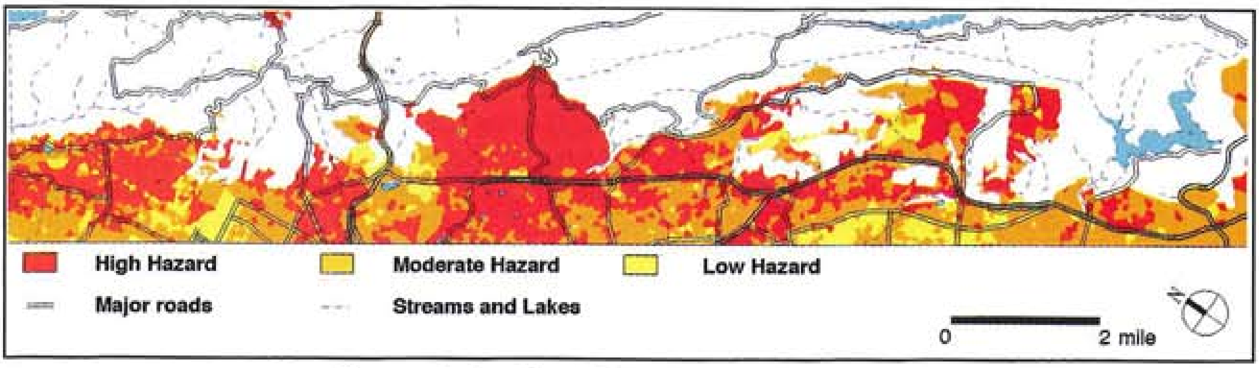

Figure 8. Residential Fire Hazard (Vegetation)

ties. The weighted factors in Table 3 were assigned using direct knowledge gained from the Oakland Firestorm. For example, fire experts rated roof materials as being three times more hazardous than siding, decking and fencing in the structural fuels class, while surface and fuel clearance made up half the hazardous rating in the vegetation fuels class.

To effectively visualize the results of the model, the output is synthesized into three categories: high, moderate and low hazard for both structural and vegetation conditions. Figure 7 maps the residential fire hazard for structural conditions. The results of the RFHAM indicate that 5,664 acres or 35% of the residential region is in the high hazard category for structural fuels and would likely contribute to the development of a firestorm in Diablo wind conditions. Figure 8 maps the RFHAM results for vegetation fuels and shows 7,679 acres or 47% of the residential region labeled as high hazard. This high hazard acreage is almost five times the area burned by the Oakland Firestorm and would potentially fuel another firestorm given the right weather conditions.

V. DISCUSSION

In order to assess and predict the risk of a potential fire hazard, the natural, as well as human environment, must be assessed and measured. The approach adopted in this study uses antecedent conditions to infer the ambient hazardous or potentially hazardous state of a number of environmental variables and estimate the potential for future hazard.

The results mapped in Figures 5, 6 and 7 indicate that high fire hazard conditions exist in areas with similar conditions to those in the burn area of the Oakland Firestorm. Two canyons to the north and one canyon to the south of the Oakland Firestorm area all show vast acreage of high fire hazard conditions. Field visits and consultation with fire experts confirmed the high hazard ranking in these canyons. In contrast, areas approximately 10 miles to the south of the Oakland Firestorm mapped as low fire hazard and were confirmed in the field. The results of the study appear promising.

As in all studies of this kind, sources of error and a certain degree of spatial uncertainty exist. The digital terrain surface model constructed was more than adequate to predict the slope needed for input to the BEHAVE model. The delineation and classification of vegetation type was also adequate for the BEHAVE model. However, the averaging of slope within each vegetation polygon may have added error to the calculation of fire hazard by eliminating the variation of slope within each polygon. Although the slope categories were grouped in 10% intervals, the extreme relief in the area could result in greater than 10% variation in slope within a vegetation polygon.

The use of the Voronoi graph makes it possible to effectively assign all space in the residential region to the closest of the 3200 observation points. The formation of a Voronoi polygon can be described as a process of growing a circle about some point. Its outer edge is defined when it meets the outer edge of a neighbouring polygon. Since the observation is made at the sample point or centroid of the Voronoi polygon, the assessment is more accurate there than at the edge. Great care was taken to increase the number of sample points to reduce this source of boundary error, however, error is likely to be greatest on the boundary between dissimilar polygons.

The residential fire model was constructed using the knowledge of fire experts, many with direct experience from Oakland Firestorm. Although there are many wildland fires in California each year, few become catastrophic events and expertise for this model is based on limited experience. As knowledge improves with regard to residential fire events, the residential fire model (RFHAM) will likely require modification and re-parameterization.

VI. CONCLUSIONS

Improved prediction of fire risk in the complex landscape of the East Bay Hills will require quantification and modeling. The method developed here integrates multisource spatial data with field observations and produces a GIS wherein risk modeling is undertaken. The results show that almost half of the study site can be classified as high risk and could experience conditions similar to those that occurred during the Oakland Firestorm.

The results of this study provide the policy makers, in this instance the East Bay Hills Vegetation Management Consortium (VMC), with a spatial decision support system that maps where and how great the current fire risks are. With this tool the VMC can and are now drafting policy to mitigate and reduce the risk of firestorms in both the urban and wildland regions.

Further tools are needed for improved fire modeling and landscape design that can reduce the risk of fire hazard. Models, such as the Rothermel model, need to be calibrated for urban-wildland conditions. Further research in expert systems must include not only information about the individual properties, but also information about the existing 'response infrastructure' and the capability of the community to respond in an emergency. Predictive models which measure rates of change in fuels need to be built in order to track the success of the mitigation efforts now being prescribed by the VMC. Until such research is conducted, this study provides an effective method of predicting risk of fire in the East Bay Hills.

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