Decision support and participatory modelling

6 GIS-supported modelling and diagnosis of fire risk at the wildland urban interface. A methodological approach for operational management

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Abstract
The recent evolution of the rural and urban areas has led to the progressive emergence of a complex and multiform wildland urban interface. Today this interface has turned into a fire threat which is omnipresent The evolution in progress raises in particular the question of the safety of the people and goods and, more generally, that of the management and durability of development of these territories. Taking into account these problems in installation and planning tasks requires a risk analysis, which is often too complex to be implemented by traditional techniques. The recourse to GIS-supported modelling is tested here as an integrated, dynamic and operational tool for spatial diagnosis, display and recommendation as regards to risk management. This chapter describes the original approach that was implemented, the constitution of the data base, and the resulting diagnosis and display of risk created by the model.

Keywords: Wildland urban interface, risk, fire diagnosis, modelling, GIS, urban planning.

6.1 Introduction

The evolution of rural and urban areas during the last thirty years has led to the progressive emergence of built-up spaces/natural spaces interfaces that is complex, multiform and mono-functional (Ewert 1993, Hardy 2005, Theobald et Romme 2007). It results from a double continuous process of creation: urban scattering of natural space by induced constructions (diffuse or grouped) and networks, progression of natural spaces due to plant regrowth/renewal and progressive incorporation of the anthropogenic elements. Today this interface is simultaneously an omnipresent, total and growing (see above) fire risk (Xanthopoulos 2004). Fire, confined for a long time in the heart of natural spaces, finds in this interface a new ground, favourable to its ignition and its propagation. It comes into contact and/or penetrates extremely prized spaces (hence the pressure in favour of development and extension of these zones of contact). It has specific stakes (notably human and economic) with very serious vulnerability issues (human presence, technical difficulties in controlling fires and keeping populations safe, combustible material expansion, surface-wise and biovolume-wise). Recent cases of fires, which received great media attention, demonstrate the negative ecological, economic and human impact. Initial stakes (protection of forest viewed as social and ecological legacy, financial impact of fires, etc.) have been caught up by new stakes related to keen and demanding social desires regarding living space, people and goods protection. This protection - dependent on durable and concerted development of these territories - requires a voluntary policy to secure existing interfaces and to control their future development (Haight RG et al. 2004). With this intention, tools that developers use for diagnosis must be powerful, reliable and adapted to the specificities of suburban fire. There is today no unifying and generalizing approach and such tools are cruelly lacking.

Specificities of wildland urban interface (WUI) make specific assessments and take into account risk. From this point of view, the needs expressed by those who are responsible for “informing about risk” and dealing efficiently with risk may be synthesized into four points (Galtié 2007): (1) to characterize existing constructions (and induced networks of infrastructures) risk-wise, in order to direct qualitatively and quantitatively the preservation of such installations; (2) to characterize - in the current context of pressure in favour of development of interface territories - potential support- spaces of constructions (and induced networks of infrastructures) risk wise, in order to prohibit, authorize or condition any realization to come; (3) to treat on a hierarchical basis installations to be realized considering the stakes (current and future) and the politico-administrative organization of the territory (local to regional scales); and (4) to have an interactive tool for management and simulation, allowing to evaluate, direct and optimize growth and development of interface territories.

Recent developments in spatially explicit GIS models [principally in knowledge-based index models (Dagorne 1990, Chou 1992, Chuvieco et al. 1997, Petrakis et al. 2005), spatially weighted index models (Clark et al. 1994, Setiawan et al. 2004), fire probability density function models (Chou et al. 1993, Preisler et al. 2003) and direct simulation models (Green et al. 1995, Finney 1998)] have contributed highly to fire risk diagnoses across large scales. These models allowed managers to map, combine and analyze different variables that contribute to fire occurrence and propagation, as well as to produce operational maps of differential sensibility to fire (Salas and Chuvieco 1994, Caprio et al. 1997). Comparative analysis of the models' methodology and accuracy is only very rarely (and with much difficulty) evaluated and discussed in a satisfactory way (Viegas et al. 1999, Farris et al. 2001). The quality of the latest results seems more related to the mode of abstraction of the phenomena (number and nature of variables taken into account, formalization of the risk, etc.) and more related to the constraints of treatment than to the level of complexity of the model (Keane et Long 1998); therefore, the choice of a model for diagnosis depends above all on the modelling purpose and, if need be, a hybrid approach can prove to be efficient (Keanes et al. 1996). The operational appropriation of the models by the developers is correlated to their apparent precision, to the conditions of implementations (required parameter settings, computing time, etc.) and to the institutional and social constraints surrounding the process (statutory environment for risk apprehension, required scales for observation of the phenomena, social representation of risk, etc.).

The purpose of this contribution is to set out an exploratory methodology of GIS-supported modelling and diagnosis of forest fire risk in the wildland-urban interface. This work falls under the recent context of restoration of the French statutory framework for taking into account the fire risk, translated in particular by the institution of a plan for prevention of the forest fire risks (Garry et al. 2002). It was initiated by a multidisciplinary group (researchers, foresters, authorities, etc.) with the prospect of satisfying the obligation of current and prospective managing of WUI territories. In this paper, Sect. 6.2 describes test areas and data sets (required data and initial data processing). Sect. 6.3 describes how to make diagnoses by developed observation scaling, how to post up risk and how to derive prevention orientations. Validation and discussion of results and processes are raised in Sect. 6.4 and 6.5, conclusions and outlooks in Sect. 6.6.

6.2 Test areas and data sets

6.2.1 Wildland urban interface support

Interface spaces are now widely represented in most parts of the world subject to fire risk. Despite local specificities in regards to how they are created and how they work, vocabulary used for risk diagnosis (and not solutions to be brought) is relatively similar, and therefore fairly easy to apply overall. Developments described in this text are based on extensive field exploration carried out at the scale of southwestern Europe (Spain, France, Italy and Portugal). They are applied to two test areas located in France. These test areas were chosen according to their differentiated sensitivity to fire and according to the opportunity of associating the method major institutional partners involved in fire risk management (foresters, fire-fighters, politicians, etc.). In the political and administrative French context, delimiting test zones was accomplished with the help of spatial levels of references, the department and the municipality.

The first test area is located in the eastern Pyrenees and covers the Pyrénées-Orientales department (Fig. 6.1). This department, the furthest south in France, stretches over more than 400,000 hectares, and encloses almost as many inhabitants. It has a triangular shape: its smallest side measures 65 km and runs along the sea and its height increases from east to west over 160 km culminating at 2,000 meters. This configuration provides a great variety of topography and landscape (seven major natural regions) as well as modes of enhancing the area (activities and populations). The climate tends to be Mediterranean and to be modified in altitude due to more or less strong mountain influences. Winds come from the west to the north or the south and are very frequent with critical speeds, respectively every other day and 1 day on 8. Woods (very diverse, from green oaks to black pine trees), moors and brown fields cover nearly two-thirds of the space with just one quarter for agricultural activities (vines, livestock, etc.), which is regressing everywhere. Continuity and fuel load increase steadily in the context of agricultural decline and of quite ineffective structural measures of prevention. Population is very unevenly scattered over the territory and largely concentrated in the lowlands, highly attractive for local populations and even more for those outside the department (a few thousands per year). It is mainly in this area that building/forest interfaces have developed over the last thirty years (particularly in the form of housing estates) and are problematic; however, current saturation in housing is leading to the extension of the phenomena to greater elevations. In this test area, sensitivity to fire is relatively important (about 3,700 fires for nearly 50,000 ha since 1973) even with its very strong gradient. For natural regions, sensitivity to risk is expressed in the number of days per year of severe to very severe weather conditions and it ranges from less than one day per year to more than 30 days per year.

The second test area (agglomeration of twenty municipalities) is located in the Lot department, a hundred kilometres north of Toulouse, in an area traditionally considered out of the area at risk (Fig. 6.1). It covers nearly 33,000 ha lie between 100 and 380 meters above sea level and has a little more than 32,000 inhabitants. This area presents a “bowl or funnel” topographic type, combining downs landscapes and great crossing valley. A double climatic influence, Mediterranean and Atlantic, sets up a fairly mild climate (750 to 900 mm of rainfall per year, 12° C for annual average): hot and dry in the summer, under the influence of weak west and southeast winds. Woods (pubescent oak dominates, mingled with a few conifer stands), moors and brown fields occupy almost 70% of the territory. Nearly two-thirds of the population is concentrated in 10% of the territory, corresponding to the physically saturated and isolated agglomeration of Cahors. The economic attraction produced by the latter increases the regular arrival of new populations and the development of interface areas. Except for a handful of striking events, fire risk is potentially quite great but so far fairly well-contained (397 fires for about 800 ha since 1984).

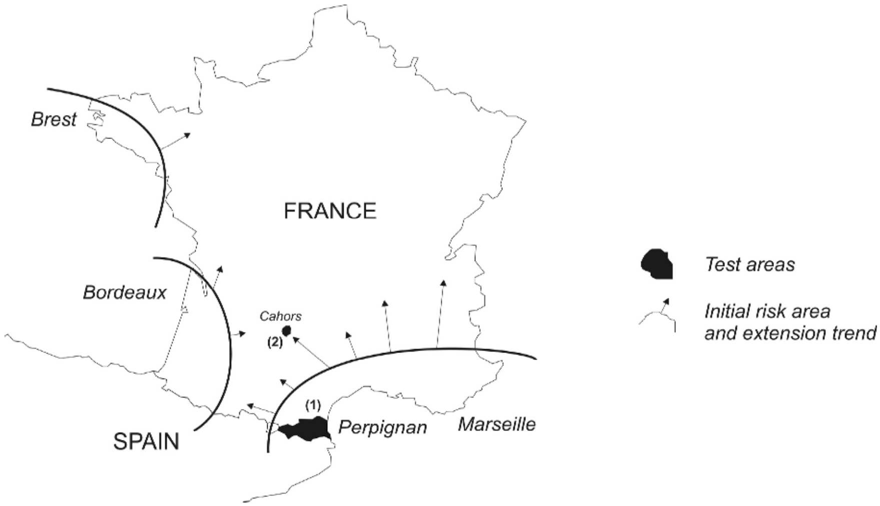


Fig. 6.1 Location of test-areas supporting

6.2.2 Statistical and geographic data

Fire diagnosis integrates the principal factors for fire risk (wind, topography, vegetable cover, human installations, etc.) following the logic of the principal practices and recommendations in that matter (Gouma et al. 1998, Garry et al. 2002). Statistical and cartographical basic data are elementary data (not yet valorised) mobilized by practicing the methodology described in Sect. 6.3. Table 6.1 specifies the type, items and origin of these data. They are mainly generic data, initially spatialized or derived from spatial extrapolation models. Generic data is used in order to make the methodology transferable, geographically comparable, as well as its results. Data integration and management (and treatments) are carried out under ESRI/ArcGIS 9.0, in both georeferenced raster and vector modes.

Table 6.1 Type, format and origin of main geographic data

TYPES	ITEMS	SOURCES		
		Macro-scale	Meso-scale	Micro-scale
Vegetation	Types, Structure, Dominant species and Biovolum	Generic maps (>1/50000) Remotely data (decametric data) Field (ponctual measurments)	Remotely data (metric data) Field (systematic measurem.)	Field obs.
Relief	Slope / Orientation	Altimetric data (decametric data)	Altimetric data (metric data)	Field obs.
Planimetry	Runway network / Building areas	Generic maps (>1/50000) Remotely data (decametric data)	Generic maps (>1/25000) Remotely data (decametric data) Field observations	Field obs.
Climate	Mean temperature and rain / Wind distribution	Regional climatic synthesis Regional wind models	Local climatic synthesis Field expertise	Field obs.
Fire	Fire history	Fire database (kilometric data)	Fire database (hectometric data)	Field obs.

6.3 Methodology and practical application to the data sets

6.3.1 Fire risk diagnosis

Diagnosing fire risk points at the same time towards evaluating (qualification and quantification), posting up (graphical and statistical transcription, hierarchization and zoning) and directing actions for risk prevention (Fig. 6.2). It meets the needs of the developers and respects their constraints, and it has three scales of observation, which are precise and have specific purposes, which fit into each other hierarchically in space and chronologically in the process (Fig. 6.2): (1) macro-scale observation (low level of precision / department scale or equivalent) hierarchically identify “basins at risk” (grouping of municipalities); (2) micro-scale of observation (intermediate level of precision / municipality scale or equivalent) aiming to hierarchically identify “basin of risk”; (3) medium-scale of observation (high level of precision / infra-municipality scale) aiming to specify “sensitive points”. The scale of observation determines the type of diagnosis and the level of geometrical and informational precision: ex situ diagnosis with macro and medium-scales, based on generic cartographic data enhanced by a good field knowledge (macro-scale) or by a precise and systematic field sampling (medium-scale); in situ diagnosis with micro-scale based on very precise field observations and directed grading of risk (evaluation grid).

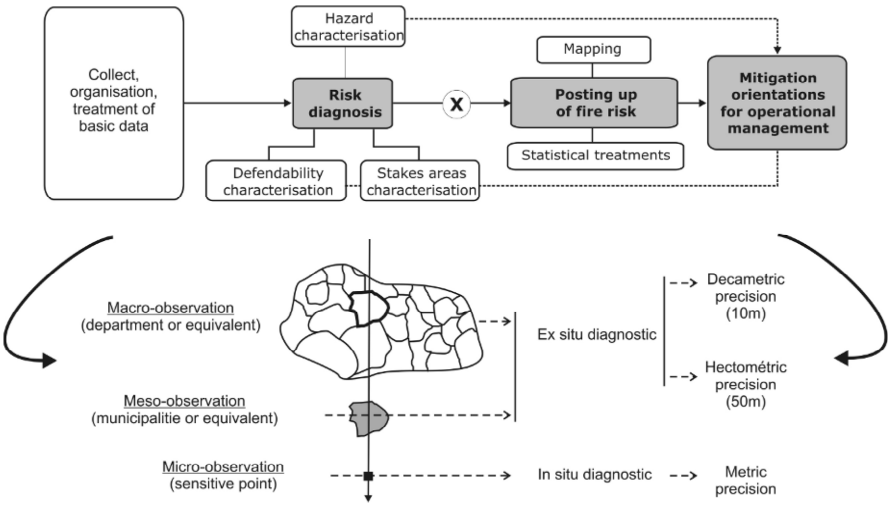


Fig. 6.2 Fire diagnosis approach

6.3.2 Fire risk modelling

6.3.2.1 Fire risk concept

The concept of fire risk is now fairly well understood even though it covers different realities that tend to be complex and generalizing. The definition used in this work refers to the superposition of three components. First, a risk related to the level of vulnerability for a given point of getting the occurrence and the uncontrolled development of a fire in a certain scope, intensity and duration, outside the context of any active or passive protection; this vulnerability is said to be “incurred” when it refers to the probability for that point to be affected by a fire because of its neighbourhood, or” induced “when it refers to the probability for that point to be the cause of a fire spreading to its neighbourhood. Secondly, a risk of fire for areas subject to fire risk related to the level of vulnerability of a given point to get potential damage caused by a fire with a determined intensity. This predisposition is proportional to the stakes, to the predictable effects of fire on these stakes and to the level of defensibility of these spaces, which reflects the responsiveness of society (deployment and utilization of emergency means). At a given point, level of risk is expressed in such a way (Eq. 6.1):

$$\text{RISK} = f\,(\text{susceptibility, defensibility, stakes}) \quad (6.1)$$

6.3.2.2 Hazard and defensibility modelling

- General modelling terms and calibration processes

Risk modelling, which means developing models only covers hazard and defensibility components; the stakes component mainly refers to an inventory work. Risk modelling was developed to study hazards and defensibility components.

Fire is regarded as a process of contagion and the level of hazard in a given point as the resultant from a local situation and an influence of the more or less immediate environment. The analysis of the hazard relies on empirical modelling of the phenomenon based on scientific knowledge and on field observations concerning fires starts and behaviours, field realities, human behaviours and hazard management practices. The suggested model fits in combinatorial types and it is a spatially-weighted index model. Hazard and defensibility are determined through a combination of synthetic indicators for hazards derived from intermediate indicators coupled in pairs. Each intermediate indicator is itself derived from statistical and cartographic basic data and incorporates one or more components identified as crucial in the level of hazard or defensibility.

The modelling implemented favours a pragmatic, complex and hierarchical approach of susceptibility, based on specific models and expert statements. The specific models are mainly physical ones (influence of the slope on the spread of the fire front, etc.) and statistical ones (spatial distribution of outbreaks, etc.) and they come from literature or they are developed on the occasion (for tests and/or statistics). Expert statements are developed or validated (for literature) within the framework of a multidisciplinary working group composed of researchers and field practitioners (foresters, firefighters, developer contractors). Preparation of an expert statement is prepared through collective discussions or individual anonymous questionnaires utilized in a statistical way. Experts say intervention both upstream (setting parameters) and downstream (validation) of modelling is necessary.

- Space and time considerations

Taking account of the neighbourhood favours the potential of the buffered neighbourhood (a ring with adjustable thickness) to initiate and spread a fire, in its direction and from its core. The determination of ring thickness responds to time-based technical argument (average propagation speed of an ordinary fire) and operational argument (presumed maximum reaction time of fighting services). In the case incurred hazard, it is estimated that for every fire triggered beyond the limit of the neighbourhood ring, fire-fighter teams will be able to secure the neighbourhood of concern, before the fire comes to close. Conversely, below this limit, and especially since the outbreak will be close to the considered point, the arrival of fire may precede the implementation of emergency means. In the case of induced hazard, it is estimated that the hazard of free spread (without intervention of fighting teams) is maximum in the close vicinity of the point and that it decreases gradually (at least for a time) with distance until becoming very low beyond the limits of 500-1,000 meters. In local contexts, average propagation speed of an ordinary fire and presumed maximum reaction time of fighting services are two variables that are differentially vary in time. The first variable is considered varying the time step ten according trends in land cover and land use changes. The second one may vary at a time step smallest in connection with the setting up of facilities and defence against fire (implantation of roads or fire stations, etc). For considered test areas, ring thickness has been determined at 500 (Lot area) and 1,000 meters (eastern Pyrenees area).

Because intervening in a differential way in the determinism of the hazard associated with the item considered, the portion of space covered by the 500 to 1,000 meter ring is the object of a double space weighting, according to the distance and dominant winds. The weighting according to the distance is based on a decametric and concentric discretization of neighbourhood. It is linear and decreases from the considered point towards the outer limit of the 500-1,000 meters (weighting factor from 1 to 10). The choice of the discretization step is mainly based on technical considerations (dynamic of the fire, opportunities of confinement and / or self-protection, minimum area of regulatory clearing of brushwood).

Azimuth weighting by wind sectors defined according to their vulnerability to blossom and to spread (Fig. 6.3a). These sectors, varying in number, in extension and in position according to the area in question and the nature of the hazard in question (induced or incurred), delimit isocritic portions of space for which any fire starting off in their centre will tend to spread towards the considered point (simplified model of elliptic propagation, using a 45 degree angular matrix (Fig. 6.3b).

Modelling is based on a short time scale including actual and recent multiannuel (last decade) data. Actual data reflect the state of the main components of risk (land cover, land use…) and the last reference state. The aim is to derive an instantaneous and quasi real-time updated level of risk; the update depends on the availability of data and the ability of users to perform and take into account this update. Modelling terms (components combination and calibration) relies on a decade training period, the last ten years preceding the risk assessment.

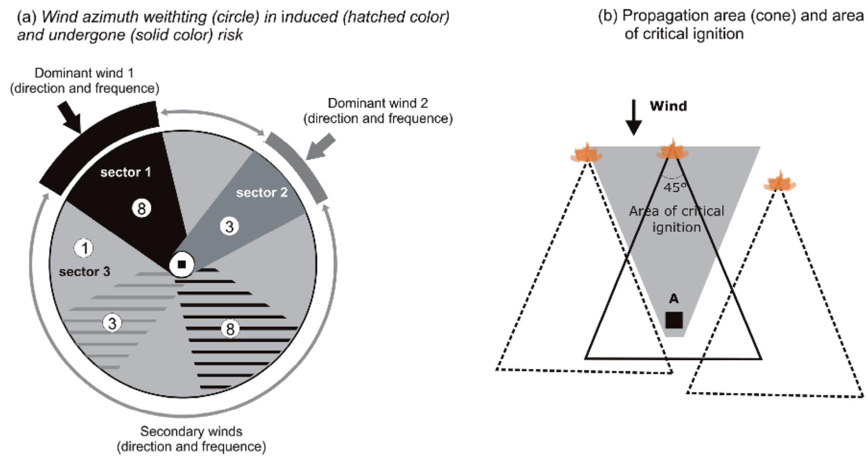


Fig. 6.3 Neighbourhood weighting related to distance and wind influences

6.3.2.3 Stakes mapping goals

The characterization of stakes aims to take inventory, identify and locate any component of the space carrying an existing stake, that is a challenge being currently present (urbanized areas, infrastructure…), or a future stake, that is resulting from a city planning action still to come (implanting a housing estate, closing a lane…). It is based on a typology of spaces and an inventory of specific stakes associated with them. The proposed typology (Table 6.2) observes three types of spaces and five subtypes to which are attached one or more of the four stakes identified (human, economic, natural and patrimonial).

Table 6.2 Type and subtypes of spaces and stakes

	Nature of considered stake and indicators		
Types and subtypes of spaces	*Macro-scale*	*Meso-scale*	*Micro-scale*
Urbanized areas			
Built-up areas	Human, Economic	Human, Economic, Patrimonial	Human, Economic
Areas of concentration of people	Human	Human	
Non-urbanized areas			
Natural or cultivated areas	(Economic)	Human, Economic	-
Natural areas of production	Economic	Economic	-
Sensitive and/or protected areas	Natural	Natural, Patrimonial	-
Infrastructures & aerial networks			
Travel lines	Human, Economic	Human, Economic	-
Energy transportation	Economic	Economic	-

6.3.3 Data processing

The development of intermediate indicators requires for input some statistical and cartographic basic data described in Sect. 6.2.2. These data are processed and valorised (intermediate data) so specific for each indicator intermediary. Each implements one or more intermediaries' spatial data and combined them in image mode and/or object. The changes in value of an indicator reflect its greater or lesser sensitivity test (x) (s) concerned (s). In the interest of getting in touch and comparability indicators among them, the values described by each indicator are normalized by coding in a range from 0 to 100, a 0 value is attributed to local sensitivities and the lowest value 100 to locally situations worst. The indicators are standardized and so-called "gross indicators." These "gross indicators" are then processed (matrix 50 m resolution) so as to apply the weighting associated with the incorporation of the neighbourhood; output data processing are the "intermediate indicators final." They describe in turn values in the range 0-100, but more often with reduced amplitude because of the "averaging" effect induced by taking into account the neighbourhood. Synthetic indicators are obtained by crossing two by two final intermediate indicators and by encoding into 5 levels of intensity (Table 6.3). Each intermediate indicator is discretized into five classes, according to a reclassifying method common to all indicators. The discretizating technique used here consists of splitting into five classes of variable amplitude (exponential growth of classes' size) at the lower limit of 99 percent (floating range). This method favours the magnification of local contrast to the detriment of a comparability of situations observed between separate areas of study (static range).

6.4 Results

6.4.1 Fire risk modelling

6.4.1.1 At macro and medium-scales of observation

- Characterization of forest fire hazard

The fire hazard reflects the level of susceptibility of a given point to the occurrence and uncontrolled development of a fire. It includes both a dimension of spatial occurrence and a dimension of probable intensity, out of the context of any active or passive protection. Determining the hazard is based on four synthetic indicators of hazard derived from eight intermediate indicators (Fig. 6.4).

Table 6.3 Determination cross values synthetic indicators

SYNTHETHIC INDICATOR		*Intermediate indicator 1*				
		Class 1	***Class 2***	***Class 3***	***Class 4***	***Class 5***
Intermediate indicator 2	***Class 1***	1	1	1	2	2
	Class 2	1	2	2	3	3
	Class 3	1	2	3	4	4
	Class 4	2	3	4	4	5
	Class 5	2	3	4	5	5

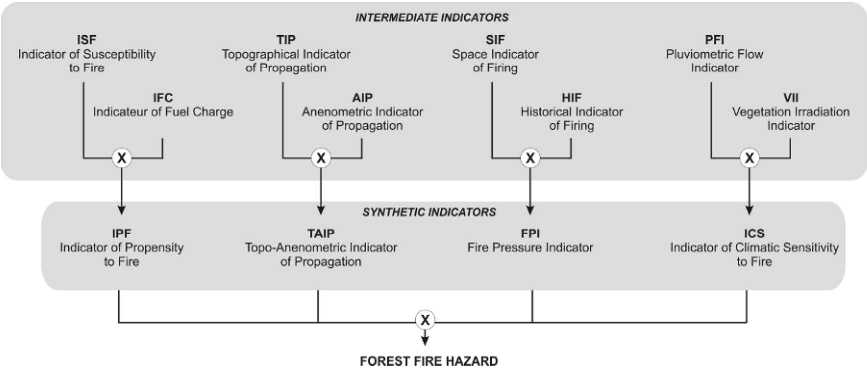


Fig. 6.4 Structure of the forest fire hazard model

IPF, indicator of propensity to fire, translates the propensity of the combustible layer to ignite under the action of a heat source and to stimulate blaze-to-fire transition. It combines two intermediate indicators:

– **ISF**, an ***indicator of susceptibility to fire***, mixing (1) a structural susceptibility defined by types of combustible layer (vegetable stratification combinations) and describing depth and behaviour of the layer regarding combustion deployment and (2), a specific susceptibility derived from the vegetable composition of the combustible layer.

The value of structural susceptibility (ISFst) represents a mark of sensitivity and vulnerability of the average vegetation (Table 6.4). The mark of sensitivity describes the ease with which the vegetation will be ignited by a heating source and ensure the initial spread of fire. It privileges complex open plants, both rich in fine combustible elements (initial combustibles for fire), and intermediate combustibles enabling fire to gain power and spread to high tree and wood strata (transition). Conversely, it penalizes vegetations with more limited potential for development to fire (herbaceous or low wood plants) or ones that are more closed and / or discontinuous in the vertical plane. The mark of vulnerability describes the behaviour of each type of vegetation in relation to the behaviour of the established fire. It gives importance to plants loaded with combustibles, constant in both dimensions and supplying high power of fire. Conversely, it penalizes plants with low load of combustibles forming a heating source less important and more ephemeral.

Table 6.4 Types of plant fuel structure and related susceptibility to fire

	Recovery of			*Susceptibility to fire*		
Types	High woody (>2 meters)	Low woody (<2 meters)	Herbaceous	Sensibility value	Vulnerability value	ISF_{sp} value
LHd	75-100%	0-100%	0-100%	3	10	6
Lhac	50-75%	0-100%	0-100%	8	8	8
LHc	25-50%	0-25%	0-25%	2	3	2
LHH	25-50%	0-25%	25-100%	7	5	5
LBH	0-25%	25-100%	25-100%	5	7	6
LHBH	25-50%	25-100%	25-100%	10	9	10
ZC	0%	0%	<25%	0	0	0

The specific susceptibility of vegetation (ISF_{sp}) is described from the dominant species composing high and low woody strata and herbaceous strata. Among the species forming the various vegetations, are taken into account the three most representative species in terms of abundance/dominance, regardless of connection stratum. In the case of multi-strata vegetations (covering of each stratum is at least more than 25%), the description considers at least one dominant species per stratum; and where for one of these strata, two or three species show a comparable abundance, the mark of sensitivity and vulnerability taken into account is constituted by the average of the respective marks. The different species are characterized by a mark of flammability and combustibility (IC) coded from 1 to 5 (Table 6.5). The mark of flammability (I) describes the ability of the species for ignition under a heating source; this mark is determined by the average time of ignition. The mark of combustibility (C) describes species' propensity to burn and to spread fire; this mark is based on the criterion of flame persistence and / or superior calorific power.

Table 6.5 Specific values of sensitivity, vulnerability and susceptibility to fire (extract)

High woody				**Low woody**				**Herbaceous**			
Species	**I**	**C**	**IC**	**Species**	**I**	**C**	**IC**	**Species**	**I**	**C**	**IC**
Quercus pubescens	3	5	4	*Erica arborea*	5	5	5	*Brachypodium ramosum*	5	2	4
Quercus ilex	4	5	4	*Cistus monsapeliensis*	4	2	3	*Dactylis glomerata*	4	1	3
Pinus nigra	3	5	4	*Ulex parviflorus*	5	4	4	*Polypodium vulgaris*	1	1	1
…				…				…			

ISF is determined as such in Eq. 6.2:

$$ISF = \sum 2(ISF_{st}), 2(j_{IC}), k_{IC}, l_{IC} \quad (6.2)$$

with ISF_{st}, the structural susceptibility and j_{IC}, k_{IC}, and l_{IC} the specific susceptibility described through flammability and combustibility values of the three mains species.

– ***IFC***, an ***indicator of fuel charge***, specifying the phytomasse that is available for combustion. The amount of combustible available for combustion is estimated at the scale of each plant by adding up observable availabilities for each stratum (high woods, low woods and herbaceous species). Combustible biomass is determined at the scale of each stratum produced by multiplying the covering rate of the stratum (by ten) and its thickness (meters). The considered thickness is limited to the thickness of the stratum of fine elements forming the main fuel for fire. CLM is determined such as in Eq. 6.3:

$$IFC = \Sigma(t \times R)_H, (t \times R)_{LW}, (t \times R)_{HW} \quad (6.3)$$

with t is t, layer thickness, R, layer recovery LB and LH, layer types [herbaceous (H), low woody (LW, < 2 meters) and high woody (HW, > 2 meters)]

TAIP, ***topo-anemometric indicator of propagation***, translates the propensity of the topo-anemometric environment to propagate a fire towards and from a given point. It combines two intermediate indicators:

– ***TIP***, a ***topographical indicator of propagation***, describing, in a given point, the heterogeneity of the surrounding relief and the conditions of propagation that result from it. The slope, upward or downward, exercises a direct influence on fire behaviour including propagation spread. This differential effect is described by a relative factor of propagation exponentially related to the percentage of slope (Van Wagner 1977): over the relative propagation factor, the greater the spread of the fire front is fast, and inversely.

Fig. 6.5 illustrates situations leading to different values of propagation factor on average divergent heterogeneity of the area of propagation (alternately, in the axis of propagation of the fire, upward and downward slopes) characterized by an average of the factors integrated in the linear propagation. It is determined from the weighted average (wind and distance) of the relative factors of propagation, established by topographical facet (50x50 meters). Each facet is described from points of view of its exposure ("to the wind" or "under the wind" in relation to an axis of propagation "facets in question/reference point") and of its slope ("upward" or "downward", slope value), then characterized by a relative factor of propagation.

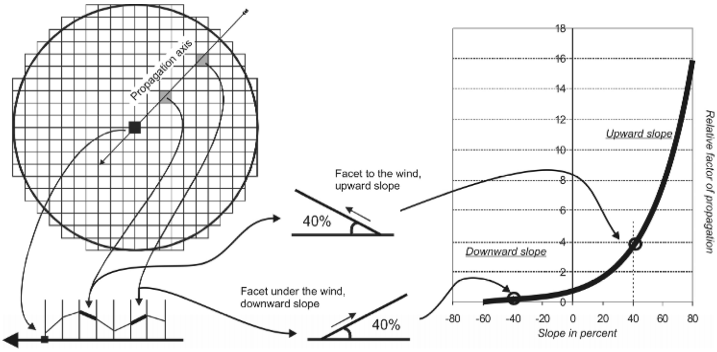


Fig. 6.5 Relative factor of propagation determination according to topographical factor

– ***AIP***, an ***anemometric indicator of propagation***, describing the differential influence of wind speed on the propagation of a fire. The wind has an all the more favourable action on the propagation of the fire because its speed grows and this up to a threshold from which the propagation loses some efficiency (partial combustion, blow-off of flames…). A statistical report carried out on a representative forest fire dataset analysis makes it possible to suggest a grading of the differential influence of the wind (Fig. 6.6). It is this grading that, spatialized on the basis of numerical wind simulation(s) at critical speed(s), determines the AIP.

FPI, ***firing pressure indicator***, translates the sensitivity of the neighbourhood of a given point to fire starts. It combines two intermediate indicators:

– ***SIF***, a ***space indicator of firing***, describing the starting risk at the level of the point in question and at the level of its neighbourhood, via the relative importance of critical spaces for fire starts. The latter are determined according to two criteria commonly judged as deciding: proximity of transportation routes and proximity of dwellings (Table 6.6). Critical spaces are materialized with the means of buffer zones marked out around dwelling and transportation routes. The close proximity of flammable vegetation is a selection criterion for buildings or portions of roads to be considered. The selection of channels of communication is limited to tracks easily and freely accessible to the public and used by it. The communication channels meeting the criteria are ranked according to their potential frequenting into three categories: low (Type 3), medium (Type 2) and high utilization (Type 1). On the basis of entities thus selected, near areas of concentric proximity (buffer zones) are delineated around each building and each portion of road. The distances listed are respectively 15, 50 and 100 m for buildings and 50 and 100 m for communication channels.

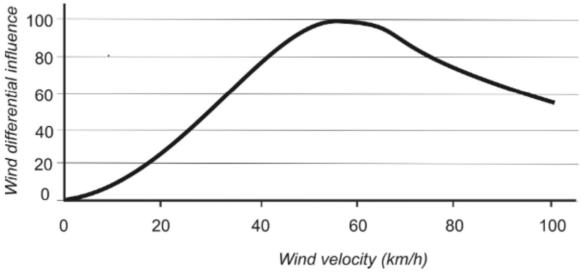


Fig. 6.6 Differential influence of wind on fire propagation

Table 6.6 Fire hazard related to roads proximity versus buildings proximity

		Proximity to road								
		0-50m			50-100m			>100m		
		Type 1	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3
Proximity to buildings	0-15m	20	16	10	10	8	5	5	4	2
	15-50m	60	48	30	30	24	15	20	10	10
	50-100m	100	80	50	40	32	20	20	16	10
	>100m	70	56	35	30	24	15	5	4	2

– ***HIF***, a ***historical indicator of firing***, describing, by geographical reference unit, the cumulated number of significant fires occurring during the last decade.

ICS, ***indicator of climatic sensitivity to fire***, translates the specific sensitivity of a given place to start and development of a fire, according to its climatic characteristics. It combines two intermediate indicators:

– ***PFI***, a ***pluviometric flow indicator***, describing local climatic characteristics as regard air and soil dryness parameters (amplitude and duration). It is based on the link between air and soil dryness and biological status of the combustible (hydric state, flammability and combustibility).

– ***VII***, a ***vegetation irradiation indicator***, integrating duration of sunshine and amount of solar energy received and cumulated in a given location at the critical point of the diurnal cycle of burning. The illumination received in this place is subject to a number of parameters (including astronomical and topographical parameters), and affects environmental and biological burning conditions (relative humidity, air temperature, air phenomena, heating of combustible…). Conditions of reference for calculating VII are determined from the characteristics of the critical burning period (diurnal seasons and windows). Calculating VII is based on simulations of illumination calendar with astronomical conditions of the burning season's median date, from sunrise till the worst time of the day. These simulations are integrated over time in order to determine, at each point of the space, a period of sunshine and received cumulated solar flux. The intersection of these two variables determines the irradiation indicator of vegetation.

The indicial formulation of the hazard relies on the weighted linear combination of the four synthetic indicators of risk: IPI, ITAP, IPMF and ISC. Various combinations of possible situations for indicators values between 1 and 5 were submitted to a group of experts; for each one of them, the group of experts came to a conclusion about a level of hazard itself spread out between 1 and 5. The statistical processing of the result-data (multiple regressions) allowed the formulation hereafter (Eq. 6.4):

$$\text{Hazard} = 0.45\ \text{IPF} + 0{,}13\ \text{ICS} + 0{,}13\ \text{FPI} + 0{,}29\ \text{TAIP} \tag{6.4}$$

- Characterization of defensibility to fire

The self-defence ability of areas subject to forest fire risk describes their level of predisposition for deployment and action of emergency means. The scope of action of emergency teams - especially in the initial phase of fire development- largely determines the more or less favourable outcome of a disaster and the impact of the fire phenomenon at a particular point.

The self-defence ability model implemented is a structural model for areas subject to fire risk. Regardless of the more or less favourable conditions at the time (exceptional dryness, abnormal unavailability of fighting means related to simultaneity of several fires…), each point of the area presents, because of its geographical location and its equipment, an intrinsic ability to be defended. Thus, an area badly served by lines of communication, about ten kilometers away from emergency facilities and with no defence equipment against fire, is comparatively more difficult to defend than a identical area located along a national highway, in the immediate vicinity of an emergency structure and having unlimited water supplies.

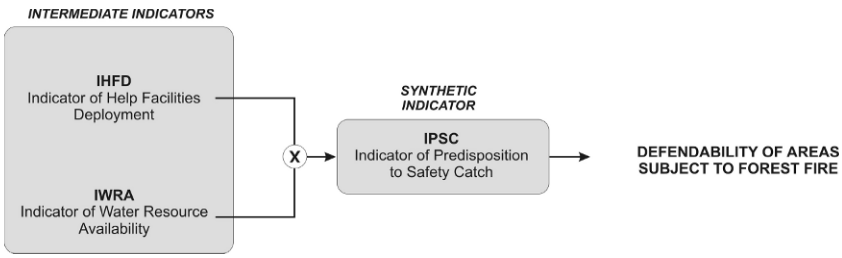


Fig. 6.7 Structure of the forest fire risk model

Determining vulnerability is based on a synthetic indicator (IPSC) derived from combination of two intermediate indicators (Fig. 6.7). ***IPSC***, ***indicator of predisposition to safety catch***, describes the potentiality of the neighbourhood of a given point to ease the action of terrestrial helps in order to limit the risk of seeing a fire being propagated until reaching the aforementioned point. It integrates:

– ***IHFD***, an ***indicator of help facilities deployment***, describing the risk covering level via the relative importance of rescuable spaces described in terms of times for intervention and possibilities for action. The ability of fighting means to move across space and to act quickly on a disaster structurally depends on two factors: on one hand, the presence of a network of channels of communication enabling crews to travel from their parking spot to the fire area; on the other hand, the distance between these two points, which affects the intervention spell. A rapid deployment of the emergency crew most often enables attacking fire in the early stages of its development. This initial attack is crucial and critical since it corresponds to a stage where the fire, easily challengeable, is going to turn into a fire more difficult to contain, consuming more fighting means and much more damaging.

  Times for intervention are determined from transit isochrones (10, 20, 30, more than 30 minutes), established from parking places for help facilities, on the basis of standard vehicle of intervention. Calculation considers three types of lanes to which are associated specific speeds, indexed on the percentage of slope (Table 6.7). It also integrates, for a given time of intervention, the possible starting points of help facilities: from one parking place or at least two parking places (Table 6.8). Given that the possibilities of action of the terrestrial help facilities decrease according to the distance from the transportation routes on which they move, space is cut out in four geographical sectors with optimal (0 to 100 m), reduced (100 to 200 m), minimal (200 to 300 m) and inexistent (beyond 300 m) possibilities of action.

Table 6.7 Relationship between road types, slope and speed (km/h).

	Slope values			
Types of roads	Zero slope (0-10%)	Low slope (0-30%)	Moderate slope (30-60%)	High slope (>60%)
Main roads [highways]	60 [70]	50 [70]	40 [60]	25
Secondary and minors roads	30	25	15	10
Access paths				

Table 6.8 Relationships between, road proximity, help nature and transit times

Transit times		Proximity of road 0/100 m	100/200 m	>200 m
d<5’	*Help from one parking place*	80	60	20
	Help from several parking place	100	80	30
5<d<10’	*Help from one parking place*	50	30	10
	Help from several parking place	70	50	20
10<d<15’	*Help from one parking place*	20	10	5
	Help from several parking place	40	20	10
15<d<20’	*Help from one parking place*	10	7	2
	Help from several parking place	15	10	5
d>20’	-	5	2	1

– ***IWRA***, an ***indicator of water resource availability***, describing the level of water cover via the relative importance of spaces where the availability of the resource is real and continuous. In a given point, this availability is determined from geographical position that it occupies and theoretical time of rotation. Theoretical time of rotation (TTR) is defined like the time taken by a fighting vehicle to reach a water point, fill its tanks, reach back its starting point and get back to its duty. This theoretical time of rotation is calculated according to four variables: medium flow of watering per machine, water capacity of the machines, flow of aspiration or feeding and time of manoeuvring. Around each usable water point, one defines limits of zones for which theoretical time of rotation is equal to once, two and three times the watering time of a machine (WTM) (Table 6.9). For each zone, one also considers the number of usable water points (one or two at least).

Table 6.9 Time-based water availability

TTR / TAE		Proximity of road network 0/100 m	100/200 m	>200 m
TTR=WTM	*Access to one water point*	80	60	15
	Access to more than one water point	80 → 100	60 → 80	
TTR=2WTM	*Access to one water point*	40	30	10
	Access to more than one water point	40 → 60	'30 → 40	
TTR=3WTM	*Access to one water point*	15	10	5
	Access to more than one water point	15 → 30	10 → 15	

6.4.1.2 At micro-scale of observation

Risk is appreciated thanks to a field expertise directed and synthesized in a grid of pre-formatted evaluation (Table 6.10). For each “sensitive point”, the expert comes to a conclusion about the levels of hazard and vulnerability in relation to the criterion identified by the grid. The selected criteria describe either one or the other of the hazard /vulnerability components of the hazard, or both. With each criterion several methods are associated, which describe the local configuration, and with each method, a mark of danger is associated. The level of risk is obtained by the average of the various marks of danger.

6.4.2 Fire risk display

Displaying constitutes the bring-to-knowledge of the risk. It pursues three major goals: graphical and statistical transcription of the risk, its hierarchization and the establishment of a regulatory zoning of the territory for development. Fig. 6.9 synthesizes the risk displaying procedure. The four maps which support the display are presented thanks to a variable scale that differs according to the observation scale (macro, medium or micro-scale). Hazard, defensibility and hazard-defensibility synthesis ones share the same colour code (from yellow (weak risk) to red (very high risk)) that materializes the five levels of risk. These maps are analyzed as such and are coupled with a multi-scale cartography of the current or future stakes. Stakes are associated to types of space, to a nature (human, economic and patrimonial) and to an indicator of stakes.

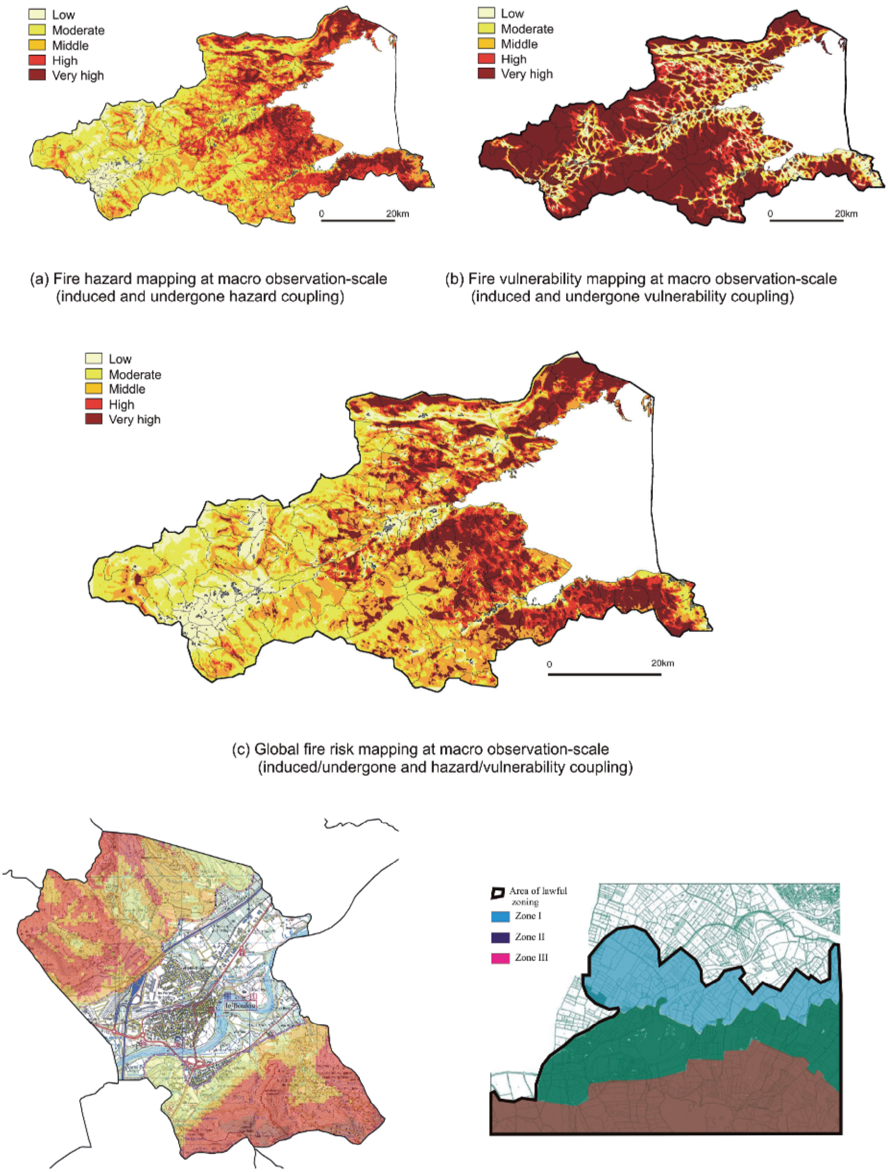
At macro-observation scale (department or equivalent), risk display is based on a 1/100,000 cartography (risk and stakes). The basic risk display unit is the municipality (or equivalent). For each municipality, one automatically determines the ventilation of the municipal territory by types of induced, undergone and global risk. One then evaluates the proportion of spaces with current and future stakes (by type and nature) by municipality. This method makes it possible to organize municipalities into a hierarchy, by levels of sensitivity to the risk, and to delimit "basins of risk" grouping municipalities of equal sensitivity. Three profiles of groupings are identified: municipalities having priority for a more detailed approach of the risk (medium and micro approach); municipalities for which a more detailed approach of the risk is advised (medium approach); municipalities that do not require a more detailed analysis of the risk.

At medium-observation scale, the risk display is based on a 1/10,000 municipal cartography (risk and stakes). According to a procedure comparable with the preceding one, one identifies "basin of risk", which are classified in five levels of increasing sensitivity. Each soil of level III, IV and V is analyzed more finely (micro-observation) and is the object of a 1/1,000 cartography characterizing sensitive points that are more or less strongly subjected to the risk (classification in five levels of risk).

Table 6.10 Presentation of the pre-formatted grid evaluation (micro-observation)

Expert identification: **Date :**
Municipality identication: **Sensitive point identification :**
Observations :

Criterious	Identification keys	Modalities and notation of risk 1	2	3	4	5	Note
I. VEGETATION							
1. Charge combustible	Relative vegetation recovery (aerial and ground fuels)	<10%	10-30%	30-50%	50-70%	>70%	
	Biovolume combustible total	<20	20-40	40-60	60-80	>80	
	Vertical continuity	Low	Moderate	Middle	High	Very high	
	Fractionnement du combustible (fine fuels versus total biovolum)	<20%	20-40%	40-60%	60-80%	80%	
2. Vegetation/bulding interface	Relative independance of houses (distance between house and vegetation)	>40m	30-40m	20-30m	<20m	Contact	
	Mean vulnerability to fire of vegetation	1	2	3	4	5	
II. TOPOGRAPHIC CONTEXTE							
1. Position	Bulding location	Down side		Middle side		Top side	
2. Slope	Mean slope	<10%	10-25% uniform	10-25% gullied	>25% uniform	>25% gullied	
III. ACCESSIBILITY SERVICES							
1. Characteristics of access	Number of access	>3	3	2 two-lane road	2 one-lane road	1 dean end road	
	Principal access type	Tared road (high size)	Tared road (médium size)	Tared road (low size)	Access path suitable for vehicle	Access path no suitable for vehicle	
	Predisposition to facilities deployment (safety parking / about-turn areas / crossing areas / tactical evolutions)	All criteria with satisfactory level	At least 3 criteria with satisfactory level	At least 2 criteria with satisfactory level	At least 2 criteria with satisfactory level	No criteria with satisfactory level	
	Accessibility to aerial facilities (helicopter)	Drop zone <300m	Landing possibilities <300m	Drop zone <500m	Landing possibilities <300m	No landing possibilities <500m	
2. Access	Laying out of runway	Very high quality	High quality	Moderate quality	Low quality	No laying out	
	Human pressure on safety access	Very high	High	Moderate	Low	No pressure	
IV. BULDINGS AND RESIDENTS VULNERABILITY							
1. Vulnerability to fire of buldings	Fire resistance of construction materials to termal punctual exposition (structure / shutter / roof)	High		Moderate		Low	
	Efficiency and regularity of clearing	Clearing efficient and regular	Clearing efficient and irregular	Clearing partial and regular	Clearing partial and irregular	No clearing	
	Presence/absence of sensibles equipments (gas tanker, barbecue…)	No sensible equipments		Safety implantation		Non-safety implantation	
2. Residents safety	Awarness programme to people safety and human behaviour in critical situations	Regular actions with written instructions	Regular actions with oral instructions	Ponctual actions with written instructions	Ponctual actions with oral instructions	No action	
	Presence/absence of self-defence equipments	Appropriate and autonomous equipments	Appropriate and low autonomous equipments		No appropriate equipments	No equipments	



(a) Fire hazard mapping at macro observation-scale (induced and undergone hazard coupling)

(b) Fire vulnerability mapping at macro observation-scale (induced and undergone vulnerability coupling)

(c) Global fire risk mapping at macro observation-scale (induced/undergone and hazard/vulnerability coupling)

(d) Fire risk mapping at meso observation-scale

(e) Exemple of landscape lawful zoning for urban control and management

Fig. 6.8 Examples of based-methodology fire mapping issues

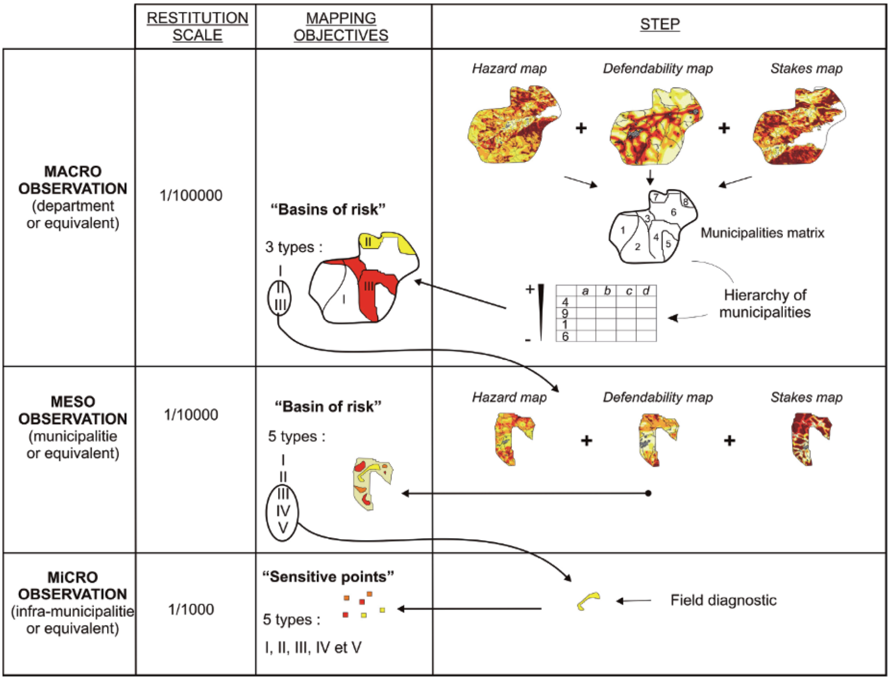


Fig. 6.9 Posting up of fire risk

6.4.3 Fire mitigation orientations

In a given point, actions of mitigation proceed from the diagnosis phase. For a same risk level, the importance of one or the other of the indicators of risk can vary significantly. Therefore, actions must be defined by taking account of the specific determinants of the risk through observed values of indicators. Considering the current and future situation, it has been defined, for each indicator, thresholds of risk acceptability with respect to these values; thresholds are not determined once for all and can vary locally according to field realities and general ambitions in terms of prevention (Table 6.11). For each indicator, orientations are offered, for risk treatment in favour of regional development.

6.5 Validation and discussion of results

Processes and results obtained lead to discussing three main points. The first relates to the validity of modelling approach. Model validation is of primary importance since the diagnosis of the risk resulting from it, meant correspond to reality and to appear in the regulation, conditions the nature and the importance of the development of the territories concerned. It is very difficult to establish, both from qualitative and quantitative point of view. Three techniques were undertaken. Validation by crossing risk values and historical and current fire occurrences doesn't give a very satisfactory indication. This method of validation imposes a significant number of events that can be achieved, as a rule, only after several years. And this, with the risk that the components of the fire risk evolves at the same time (encroachment, new construction…). With regard to the two areas considered tests, the observation period post-diagnostic is too short to implement this type of validation (less than one year to Cahors test area, one to four years depending the scales of observation considered for the Pyrénées-Orientales test areas). Yet with the exception of a few firings atypical (less than 3% of all fires), there is a close spatial correlation between the areas identified as critical (severe risks to very severe) and the distribution of fires once the diagnosis risk established ($r^2 = 0.92$ and $r^2 = 0.88$ respectively to macro and micro scales observation in the Pyrénées-Orientales test areas). For the same test area, it notes that the fires whose area burned is more than 5 hectares are hatched in areas with severe hazards or very severe ($r^2 = 0.91$) and then spread (at least in the initial phase of propagation) sectors with low levels of défendability ($r^2 = 0.99$).Validation by comparison of the results issued from various methods (knowledge-based, spatially weighted and fire probability density function methods) is the second track validation explored. Areas tests that support this study have not been to date comparable spatial analysis. Several simulations risk levels were performed with the methods of Dagorne (1990), Chou (1993), Gouma and Chronopoulou-Sereli (1998), Preisler et al. (2003), NFB (2003) and Petrakis et al. (2005). Because of the cumbersome implementation of the various methods, these simulations were generated on experimental plots square 4 km aside selected in the test area of Eastern Pyrenees. Results comparison is quite as difficult and results comprise differences that are sometimes important. Submitted according to experts, different zoning obtained appear broadly consistent but with wide disparities in detail. The correlative analysis simulations (two in relation to two of all the simulations) show coefficients coefficient of determination (r^2) staggered between 0.31 and 0.79. Among the explanatory factors, spoke to the special characteristics of the plots and, most importantly, predominantly, the nature and number of variables involved. Validation by expert statements –baring its limits in mind– is the third mode of validation tested and the one that has been selected. The validity of this approach holds for the most in the objectivity of the expertise and its definition. Each expert has tried (and often in an objective manner) to guide its position based on his experience, his training and his own beliefs at the time. Objectivity is a sought objectivity college at the expense of a detached objectivity and categorical: then considered objectively as the sum of multiple viewpoints. To do this, several independent and external experts (at least two scientists, two foresters and two firemen, always in equal proportions) are brought to disclose the risk associated to several referential sites. The number of sites is based on the heterogeneity of the study area, by all five sites maximum. At the end of their evaluation, results are compared and the group of experts carries out a critical analysis of the result at the model output. In practice, a moderator is responsible for guiding the critical analysis by promoting consensus. The technique is renewed several times on other five sites, after adjustments of the model, until evaluations conformity.

The second point relates to the question of hazard display, its contents and the contribution of the GIS. One of the major contributions of GIS technology resides in the incomparable capacity to mobilize, combine, and enhance dense and variable space informations. Thus the variables in question tend to becoming more and more complex and often more precise (propagation speed of fire, time of help facilities transit…). The relation between variables as well as the respective contribution of each one of them becomes difficult to establish. Arises then the fundamental question of the optimal level of complexity and precision to be sought. Since hazard display has for vocation to serve as "official support" (and often statutory support as well) to hazard management, the elements it encloses become the reference. Excess of complexity and/or precision (one is not always the consequence nor the condition of the other), when not justified, can lead to an erroneous representation of the hazard level (often heading towards an over-estimate of the hazard) and to an exacerbation of the institutional responsibilities. In terms of operational management, an erroneous representation of hazard tends to go against a durable and sedentary development of the interface territories: on one hand, development or reinforcement of areas sensitive to fire; on the other hand, abusive restriction of the potential of development that any territory must have. Integration of variables such as effectiveness of a planning for fire fighting or such as time of intervention by help facilities is important but sets up a reference to put at fault qualified institutions. During our work, we have been able to measure the importance managing and institutional entities attached to the avoidance of these ways. Such ways do not question at all fundamental contributions of GIS technology. They only ask modalisators for rigour and pragmatism.

Table 6.11 Acceptability thresholds of fire risk in management strategies

	Indicators	Current	*Acceptability Thresholds / Prenscription Management Orientations*	Future
MACRO AND MESO - OBSERVATION	Indicator of propensity to fire (IPF)			
	Low	●		●
	Moderate	●	Fuel reduction	●
	Moderate	●	Forestry management	○
	High	●		○
	Very high	○		○
	Firing presure indicator (FPI)			
	Low	●		●
	Moderate	●	Awarness actions	●
	Moderate	●	Use codification	○
	High	○	Fuel reduction	○
	Very high	○		○
	Indicator of predisposition of safety catch (IPSC)			
	Low	●	Preventive means of fire attack	●
	Moderate	●	Realisation/improvment of access	○
	Moderate	○	path and water tank	○
	High	○		○
	Very high	○		○
MICRO - OBSERVATION	VEGETATION			
	Low	●		●
	Moderate	●	Fuel reducián	○
	Moderate	○	Fuel treatment	○
	High	○	Forestry management	○
	Very high	○		○
	ACCESIBILITY / SERVICING			
	Low	●	Realization/improvment of access	●
	Moderate	●	path	●
	Moderate	○	Accessibility codification	●
	High	○	Laying out of runway	●
	Very high	○		○
	HOUSES / RESIDENTS VULNERABILITY			
	Low	●	Building prescriptions	●
	Moderate	●	Improvment of equipmens safety	●
	Moderate	●	Awarness actions	○
	High	○		○
	Very high	○		○

The third point relates to operational implementation and method transposability. The methodology demonstrated in this paper is today implemented in the experimentation department (macro and medium- scales of observation) and is used as reference for departmental policy as regards fire hazard management. Several plans for prevention of forest fire hazards in the course of instruction are based on this methodology of hazard diagnosis. It was also successfully applied in other departments of the south of France. The multi-scale and relative aspects of this diagnosis partake of generalization of that methodology to all types of territories. Experiment has confirmed that the conditions favourable to operational transposition depend: on the context of the process (initial expression of the needs by end-users, collegial structure researchers/developers/institutions…); on the nature and the availability of data requested at the input of the model (generic geographical data, easily accessible, not very expensive and regularly reactualized); on the man-machine interfacing and in particular on the characteristics of processes (computing time, interactivity of procedures…) and of hardware and software environment; on the institutional environment and on its aptitude to adjust its vision of the hazard.

6.6 Conclusion and outlook

The objective of this research was to provide operational support tool and methodology allowing managers to diagnose, display and manage fire risk for wildland urban interface. Articulating the process around GIS and development of a spatially weighted index model makes it possible to answer to main expectations expressed by risk managers. It allows to take into account and to compare a significant number of factors conditioning risk, following the logic of methodological concepts that are at present the authoritative work (concepts of risk and vulnerability, induced risk and undergone risk…). Information provided by synthetic output maps represents a strong added value in the global and localised perception of risk. The multi-scale approach at the root of the process allows a gradual, comparative and downward hierarchical approach of the risk; it thus supports establishing and justification of priorities and choices of management in a context of growing risk and strong social pressure. The interactive dimension of tools and methodology also argues in this direction, with the possibility given to the developer: to give a dynamic point of view to the risk reality and to the regional management, via direct integration of the modifications for the ground occupation (new constructions, parcels reforestation, stakes evolution…) and via automatic update of the fire risk diagnosis and of its graphical and statistical transcription; to simulate impact of a new installation (construction, preventive installation…) on the level of risk; to make plans of installation (proposal for an orientation in terms of mitigation) and of development (town planning documents) from various scenarios.

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References

Bonazountas M, Kallidromitou D, Kassomenos PA, Passas N (2005) Forest fire risk analysis. Human and Ecological Risk Assessment 11, pp 617-626

Caprio AC, Conover C, Keifer M, Lineback P (1997) Fire management and GIS: a framework for identifying and prioritizing fire planning needs. Proceedings of the Conference on Fire in California Ecosystems: Integrating Ecology, Prevention, and Management, Nov. 17-20, 1997, San Diego, CA

Chou YH (1992) Management of wildfire with GIS. International Journal of GIS 6, pp 123-140

Chou YH, Minnich RA, Chase RA (1993) Mapping probability of fire occurrence in San Jacinto mountains, California, USA. Environmental Management 17-1, pp 129-140

Chuvieco E, Salas FS, Vega C (1997) Remote sensing and GIS for long-term fire risk mapping. In: Chuvieco E (ed) A review of remote sensing methods for study of large wildland fires. Spain, Megafires Project, ENV-CT96-0256, pp 91-108

Clarke KC, Brass JA, Riggan PJ (1994) A cellular automaton model of wildfire propagation and extinction. Photogrametric Engineering and Remote Sensing 60-11, pp 1355-1367

Dagorne A (1990) Application d'un système d'information géographique pour l'évaluation de la vulnérabilité au feu et la prévention. Bulletin Commission Française de Cartographie 126, pp 16-26

Ewert AW (1992) The wildland-urban interface: introduction and overview. Journal of Leisure Research 25-1, pp 1-5

Farris CA, Pezeshki C, Neuenschwander LF (2001) A comparison of fire probability maps derived from GIS modeling and direct simulation techniques. Proceedings from the Joint Fire Science Conference and Workshop Crossing the Millennium: Integrating Spatial Technologies and Ecological Principles for a New Age in Fire Management, June 15-17, 1999; Boise, Idaho, pp 131-138

Finney MA (1998) FARSITE: Fire Area Simulator – model for development and evaluation. USDA Forest Service, Rocky Mountain Research Station RP, RMRS-RP-4 (revised February 2004)

Garry G, Hubert T, Beroud L, Serrus L (2002) Plans de prévention des risques naturels (PPR) / Risque incendies de forêt: Guide méthodologique. La documentation française, 88 pp

Gouma V, Chronopoulou-Sereli A (1998) Wildlife fire danger zoning – a methodology. International Journal of wildland fire 8-1, pp 37-43

Green K, Finney M, Campbell J, Weinstein D, Landrum V (1995) Using GIS to predict fire behaviour. Journal of Forestry 93-5, pp 21-25

Haight RG, Cleland, DT, Hammer RB, Volker C, Radeloff C, Scott Rupp T (2004) Assessing fire risk in the wildland-urban interface. Journal of Forestry, pp 41-48

Hardy CC (2005) Wildland fire hazard and risk: problems, definitions and context. Forest Ecology and Management 211, pp 73-82

Keane RE, Long DG (1998) A comparaison of coarse scale fire effects simulations strategies. Northwest Science 72-2, pp 76-90

Petrakis M, Psiloglou B, Lianou M, Keramitsoglou I, Cartalis C (2005) Evaluation of forest fire risk and fire extinction difficulty at the mountainous park of Vikos-Aoos, Northern Greece: use of remote sensing and GIS techniques. International Journal Risk Assessment and Management 5-1, pp 50-65

Preisler HK, Brillinger DR, Burgan RE, Benoit JW (2003) Probability based models for estimation of wildfire risk. International Journal of wildland fire 13-2, pp 133-142

Salas FJ, Chuvieco E (1994) Geographical information systems for wildland fire risk mapping. Wildfire 3-2, pp 7-13

Setiawan I, Mahmud AR, Mansor S, Mohamed Shariff AR, Nuruddin AA (2004) GIS-grid-based and multi-criteria analysis for identifying and mapping peat swamp forest fire hazard in Pahang, Malaysia. Disaster Prevention and Management 13-5, pp 379-386

Theobald DM, Romme WH (2007) Expansion of the US wildland-urban interface. Landscape and Urban Planning 83-4, pp 340-354

Viegas X, Bovio G, Ferreira A, Nosenzo A, Sol B (1999) Comparative study of various methods of fire danger evaluation in southern europe. International Journal of wildland fire 9-4, pp 235-246

Xanthopoulos G (ed) (2004) Proceedings of Fires in the wildland-urban interface and rural areas in Europe – an integral planning and management challenge, Athens, greece, May 15-16/2003, National Agricultural Research Foundation, Institute for Mediterranean Forest Ecosystems and Forest Products Technology