GIS-based Framework for Wildfire Risk Assessment

Final Report

MINERVE 2

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1. Introduction

Managing a process as intricate and dynamic as wildfire requires a great variety of factors to be taken into account. The ecological components involved are no less complex than the economical aspects and organisational challenges of fire management. However in practice, the predominant aspect of wildfire is its role as a hazard to natural resources, human values and ultimately, life. Knowledge of the extent of that hazard as influenced by the environmental situation and fire management activities is therefore crucial for the implementation of an effective management policy. The objective of the research presented in this report was to come up with a framework that allowing the assessment of the extent of this hazard. The framework was to permit to do so in a spatially detailed way and to allow for the examination of the influence of management activities and environmental change. It is based on the methodology of risk assessment as it is used for many technical and natural hazards, and makes use of GIS (Geographical Information System) technology, for its ability to manage and analyse great amounts of spatial information.

The term wildfire risk is used here as a measure of the hazard posed by wildfire, expressing both the probability of damage to be caused, and the expected extent of that damage. Therefore, in the assessment of wildfire risk the probability of a fire to occur at any location and its impact on objects (both man-made and natural) in the burn area must be considered. Current approaches to the problem, however, mainly focus on the probability of fire occurrence respectively the expected frequency of wildfires for a time period. Usually, these results are calculated for relatively large regions. Only recently attempts are being made to tackle fire occurrence at a local scale. To get insight in wildfire risk as it is understood here, these methods must be combined with approaches to estimate the impact of wildfires. For this reason, the presented framework for wildfire risk assessment integrates fire occurrence modelling with methods for the assessment of fire effects, linking the two by models for fire behaviour and propagation. Hence, it brings together three major topics of wildfire research that are normally considered more or less isolated.

By explicitly examining the fire spread behaviour in the risk analysis, the framework permits assessing wildfire risk at high spatial resolution. While for many applications the focus on a regional level is sufficient, others require the relevant processes to be examined in greater detail. In some cases, the spatial pattern of high risk zones needs to be evaluated, e.g., when distributing limited fire suppression resources in the management area. Other situations require a means of assessing the effects of local changes to the fire environment, e.g., the prescription of green belts around settlement, or the construction of a road which may act as a fire barrier. Also, the assessment of the risk wildfire poses to individual objects can hardly be accomplished with sufficient accuracy without considering the complex spatial configuration of fuel distribution, terrain, ignition probability and fire barriers. Finally, the prediction of developments in the wildfire risk situation in reaction to climatic or land use change also benefits significantly from an explicit representation of the complex processes involved.

However, practical implementation of the risk assessment framework faces a problem arising from a peculiarity of wildfire risk. For most technical and many natural hazards, the risk source is limited to a finite number of well defined locations. Examples are factories, power plants or traffic ways on the one hand, avalanche paths on the other. In the case of wildfire risk, this is clearly not the case. Instead, wildfires can start at virtually any fuel-covered location. Whereas other hazards can be described with a limited number of scenarios, this cannot be accomplished in the case of wildfire due to the infinite number of potential ignition points. A solution to this problem involving a method named „fire spread backtracking“ is proposed.

It must be pointed out that within the proposed framework, there are still a series of issues that require further investigation in order to eventually provide a reliable risk assessment tool. For a test area in southern Switzerland, a case study focusing on the demonstration of the methodology has been carried out. Whether at the current stage the framework can already be employed in fire management practice remains still to be evaluated. There is a need for additional work in the areas fire occurrence, fire behaviour and fire effects research in order to enhance the components of the framework. On the other hand, the framework itself should be extended, e.g., with appropriate methods for handling uncertainty. In any case, the large potential benefit arising from the availability of a consistent and versatile method for wildfire risk assessment clearly justifies a joint effort of different areas of wildfire research and risk science.

2. The risk assessment framework

2.1. Outline

The structure of the wildfire risk assessment framework is based on the method for assessing technical risks outlined in Merz et al. (1995). To this basis, some modifications and extensions specific to wildfire risk have been made. The key elements of the framework are *scenarios*, *objects* and *situations* (Fig. 1).

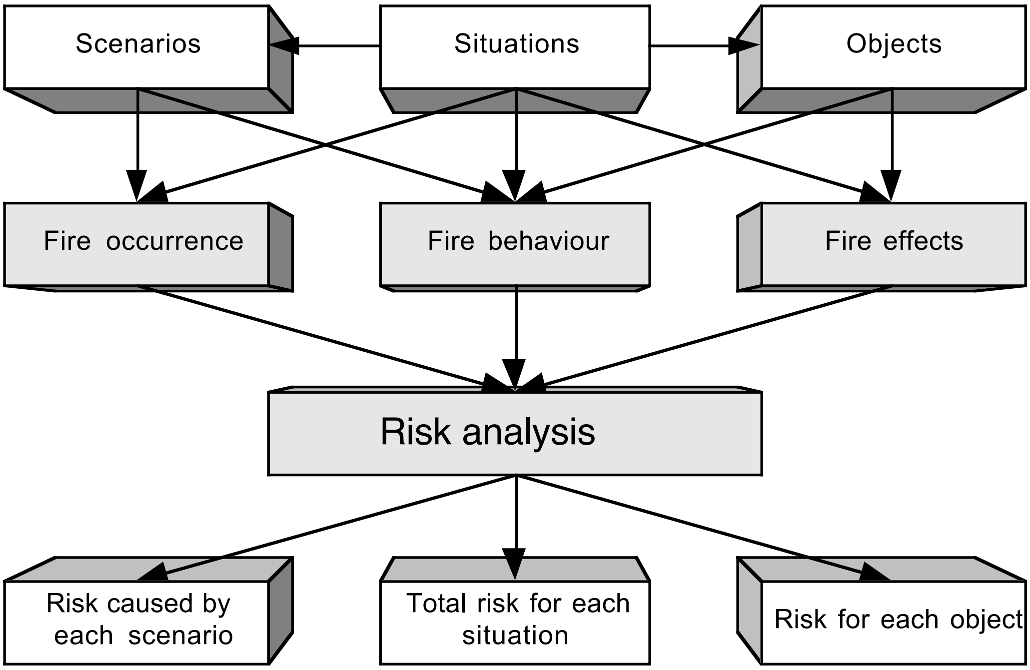

Fig. 1: The framework of wildfire risk assessment

- *Situations* define relevant states of the risk analysis parameters like weather, fuel, human behaviour, etc. Example: a spring weekend with föhn wind.
- *Scenarios* represent potential fire events. A scenario describes the ignition at a specific location during a defined situation. Example: the start of a wildfire at point XY with strong wind from south.
- *Objects* cover all natural or artificial entities which are considered as endangered by wildfire. Examples: settlements, traffic ways, forest stands, vegetation with protective function (avalanches, erosion, etc.). The objects considered may vary in different risk analysis contexts. An object may also depend in its properties and/or representation on the current situation (e.g., the susceptibility of traffic ways may be a function of traffic volume).

Using the methods of fire occurrence research, a probability must be assigned for each scenario to occur in the time span under consideration (i.e., the probability of ignition for each location in the study area, given a situation). Then, the probability is determined for each object to be affected by a given scenario. This is accomplished using appropriate fire behaviour models. Finally, the amount of damage each object will suffer given a scenario must be estimated. This is the issue of fire effects research. For the actual risk analysis, these parameters are combined in a risk matrix which depicts the relations between all scenarios and all objects for a given situation. The matrix permits the calculation of risk characteristics pertaining to scenarios, objects and the situation as a whole.

2.2. The risk matrix

The risk matrix represents the core of the wildfire risk assessment framework (Fig. 2). Each object is represented as a row, while the scenarios form the columns of the matrix. Each cell therefore represents the relationship between an object and a scenario. The last row contains the risk characteristics related to scenarios, the last column those related to objects. Consequently, the lower-right cell holds the total risk for the situation. For every situation, such a risk matrix can be constructed. It is then possible to compare the situations as to the wildfire risk they pose. Also, given a probability for each situation to take place, the risk characteristics for all situations can be combined to provide the correspondent results for the entire time span. This time span is defined by the period the fire occurrence probability is obtained for. Typical time spans might be a year, a decade etc.

From the definition of a scenario and the nature of wildfire risk mentioned above, it is obvious that the matrix will normally be fairly large. Actually, it only gets down to a finite size when applying some sampling scheme to the potential ignition points. Issues concerning the implementation of the risk assessment framework are discussed in chapter 3. In the case study presented in chapter 4, a total of 90 objects were evaluated against about 10^6 scenarios for each situation.

Risk matrix for E_s		Scenarios					Risk values related to objects
		S_1	...	S_j	...	S_m	
		p_1	...	p_j	...	p_m	
	O_1						
	...						
Ob	O_i			$a_{ij} = \Omega(t_{ij})$ $k_{ij} = p_j a_{ij}$ $d_{ij} = \Phi_i(I_{ij})$			$k_{is} = \sum_{j=1}^{m} k_{ij}$ $d_{is} = \sum_{j=1}^{m} k_{ij} d_{ij}$
	...						
	O_n						
Risk values related to scenarios				$k_j = \sum_{i=1}^{n} k_{ij}$ $d_j = \sum_{i=1}^{n} k_{ij} d_{ij}$			$K_s = \sum_{i=1}^{n} k_{is}$ $D_s = \sum_{i=1}^{n} d_{is}$

Fig. 2: the risk matrix for one situation

Where:

E_s = The situation for which the risk analysis is performed.

S_j = Scenario (potential fire event defined by a ignition location and the situation).

O_i = Object (any man-made or natural entity considered as endangered by wildfire).

p_j = Conditional probability that scenario j takes place, given situation s. Can be determined using methods of fire occurrence modelling (by statistical analysis of past fire events, refer to section 3.1 for a more detailed discussion).

t_{ij} = Time for fire to spread from ignition point to object i, given scenario j. Can be determined using fire behaviour and propagation models (section 3.2).

Ω = Function to transform spread time into spread probability (section 3.2).

a_{ij} = Conditional probability that object i is affected by scenario j, given scenario j. Thus represents the probability of fire spread between ignition point and object location.

k_{ij} = Probability that object i is affected by scenario j.

I_{ij} = Fire intensity impacting on object i under the assumption that the fire reaches the object, given scenario j. Can be determined using fire behaviour models (section 3.2).

Φ_i = Function to estimate damage suffered by object i based on fire intensity. This function may be specific to individual objects or classes of object (section 3.3).

d_{ij} = Damage caused at object i under the assumption that the fire reaches the object, given scenario j (see 3.3).

k_{is} = Probability that object i will be affected by a fire, given situation s (Fig. 3). The equation shown is actually a simplification which is valid only for small k_{ij} (Since the probabilities p_j of individual scenarios are very small, it can safely be used). The correct equation is:

$$k_{is} = 1 - \prod_{j=1}^{m} \left(1 - k_{ij}\right) \qquad \textit{Eq. 1}$$

d_{is} = Expected damage caused by fire at object i, given situation s (Fig. 3).

k_j = Expected number of objects that will be affected by scenario j (Fig. 4).

d_j = Expected damage caused by scenario j at any object in its burn area (Fig. 4).

K_s = Expected total number of objects affected by fire, given situation s (Fig. 5).

D_s = Expected total damage caused by fire, given situation s (Fig. 5).

Figures 3 to 5 illustrate the meaning of the various risk analysis results. One output is the risk all possible scenarios combined pose to one single object (Fig. 3). It is thus possible to identify objects which are in great peril of being affected by wildfire. For each such object has, it can further be determined which scenarios contribute most to the risk. Possible measures for reducing the risk for that object can then be efficiently planned and evaluated. On the other hand, for each scenario, the collective risk it poses to all objects is calculated (Fig. 4). Since for each situation, every possible ignition point is represented by one scenario, zones that produce a high wildfire hazard can immediately be identified. The objects that are most affected by this hazard and thus add up significantly to the risk can then be found. Finally, the risk analysis outputs total risk resulting from all scenarios as affecting all objects (Fig. 5). All of the mentioned results consist of both the expected extent of damage to be caused by wildfire and the frequency respectively the probability of objects to be affected.

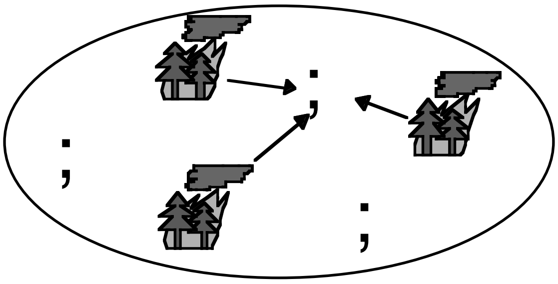

Fig. 3: Individual risk of an object

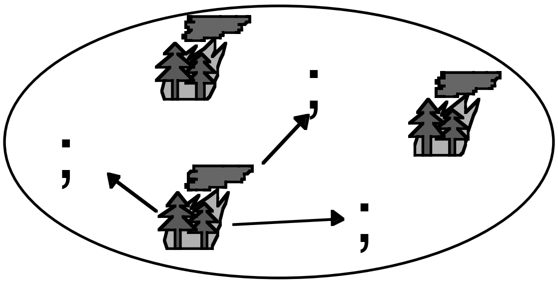

Fig. 4: Collective risk of a scenario

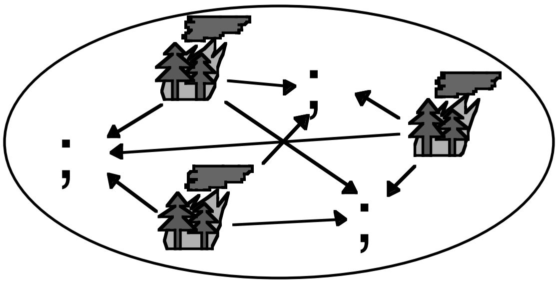

Fig. 5: Collective risk of the study area

Since a risk matrix is taken to represent one situation, all the results mentioned above correspond to this situation. Since the risk for different situations is calculated independently, the situations can be compared as to the various aspects of wildfire risk. The overall risk (scenario-related, object-related and situation-related) can also be obtained by summing the correspondent risk results for the situations weighted by the probability of each situation to occur.

3. Implementing the framework in a GIS

The application of the proposed risk assessment framework involves handling large amounts of data, most of which being spatially referenced. For the entire study area, a detailed description of the environment relevant to the risk analysis is required, involving information about fuel, topography, weather parameters, fire barriers, endangered objects etc. Also, the information represented by the risk matrix outlined above must also be managed in an appropriate way. An implementation platform for the framework must be able to handle these data. Furthermore, it must permit a close link to the wildfire-specific models required to produce the input to the risk analysis. Namely, statistical methods to estimate fire occurrence, fire behaviour models and fire propagation simulation methods as well as methods to estimate fire effects need to be integrated. The platform must then be able to perform the risk analysis calculations in an efficient way. Finally, the extensive results should be presented in a manner that facilitates interpretation and use in further analysis.

Geographical Information Systems (GIS) appear to cover much of the mentioned requirements. The are capable of handling large amounts of spatial information and provide an extensive set of tools for complex spatial analysis and presentation in a variety of forms. In fact, the entire implementation outlined below has been realised using the scripting language of a commercial GIS software (ARC/INFO). However, this procedure has been chosen because of the exploratory nature of the current implementation. The architecture of a operational wildfire risk assessment system might more realistically be composed of GIS software, statistical analysis packages and specialised modelling software. At this stage, the prototype implementation focused mainly on the evaluation of the framework as a whole and the suitability of GIS as a main platform. Consequently, in some unresolved issues related to component models, simplifying assumptions have been made. It has however been attempted to arrive at specifications for the component models for their successful integration in the risk analysis framework.

The following sections discuss some of the issues related to practical implementation of the risk assessment framework. Chapter 4 presents an application of the framework to a study area in southern Switzerland. However, because of the focus on the methodology itself and the mentioned simplifications, an interpretation as to the actual risk situation in the area should be done only with great caution.

3.1. Fire occurrence

For each scenario to be considered in the risk analysis, an estimate of the probability p_j for its occurrence must be provided. Therefore, a method is required which permits the calculation of the probability for a fire starting in a given unit of space and under conditions defined by a specified situation. There exist a variety of approaches to calculate a fire occurrence estimation for entire regions (e.g., Martell et al., 1987, Marcozzi et al., 1994. Bolognesi (1994) describes a method developed in avalanche research and currently being applied in fire occurrence modelling). They apply different statistical methods to the analysis of historical fire events. While these methods often provide accurate results for relatively large regions, their spatial resolution might not be sufficient in order to ensure the high detail required by the risk analysis. In order to get an estimate of fire occurrence for smaller units of space, the statistical analysis should also include the variables which influence the local pattern of fire occurrence (e.g., distance from closest road, slope angle, fuel moisture content). Chou (1992) presented such an approach, employing logistic regression. The same method was used for the risk analysis implementation (although with different independent variables and spatial subdivision scheme). From the pattern of ignition points of past fire events and a series of independent variables assumed to influence this pattern, the probability of fire ignition is calculated for each cell in a regular grid. This is achieved by estimating the parameters of the logistic function

$$P_{fire} = \frac{1}{1 + e^{\left(-\beta_0 - \sum_{i=1}^{n} \beta_i x_i\right)}} \qquad \textit{Eq. 2}$$

where x_i are the independent variables and β_i the correspondent regression parameters. The β_i are calculated by Maximum Likelihood estimation. The independent variables used described the accessibility of each cell (distances to closest road/settlement) and other parameters like slope angle and solar illumination. The cell size was chosen to be 25m. The analysis results showed that the chosen approach was indeed capable of providing the results required by the risk analysis. Also, it showed that the GIS was a valuable instrument for the fire occurrence estimation. It readily provided the independent variables and, given the parameters of the logistic regression, also the probability of fire occurrence for each cell. The GIS software used was even capable of calculating the regression parameters, a step that might normally be carried out using a statistical analysis package. However, it was also clear that a thorough statistical examination was required which was beyond the scope and the focus of this implementation. Given the importance of fire occurrence in the risk analysis, it must be pointed out that the statistical analysis should be carried out with greatest care.

3.2. Fire behaviour

Once the probability for a scenario to occur is known, it must be examined which objects might be affected by the resulting fire. Intuitively, it must be some measure of proximity of an object to the ignition location of the scenario that determines whether the object falls within the range of the scenario. For simple risk analysis at a regional level, it might be sufficient to apply a Euclidean distance threshold to model the impact range of scenarios. However, if a more detailed insight to the risk situation is required, this is clearly not the case. As Fig. 6 illustrates, an object may be much less exposed to a scenario than other objects equally distanced because of some barrier separating it from the risk source. Less obvious differences in

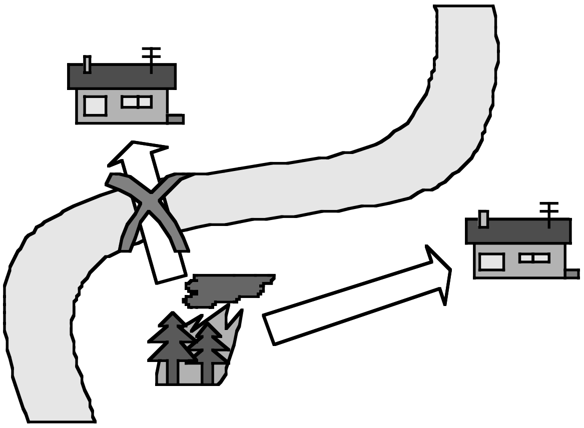

Fig. 6: The importance of fire behaviour for the scenario-object-relation

object exposure arise from other factors in the fire environment, like fuel distribution, wind direction or topography. Hence, to get a clear image of the risk situation, one has to take into account the fire behaviour to be expected for each scenario. Particularly, the spatial processes of fire propagation needs to be examined in order to assess the impact range of a given scenario. Other aspects of fire behaviour, e.g., fire intensity and flame dimensions, have an important role in the estimation of fire effects.

In order to represent fire behaviour in the risk analysis, a model developed by the US Forest Service in the early seventies and named after it's „father“ Richard D. Rothermel is used (Rothermel, 1972, Albini 1976, Rothermel, 1983). The Rothermel model has found a broad range of application in the entire world, being the most widely employed method for fire behaviour modelling to day. It calculates the behaviour of a surface fire spreading in steady state, using a set of stationary equations for the energy balance at the fire front. Fig. 7 shows the inputs and outputs of the Rothermel model.

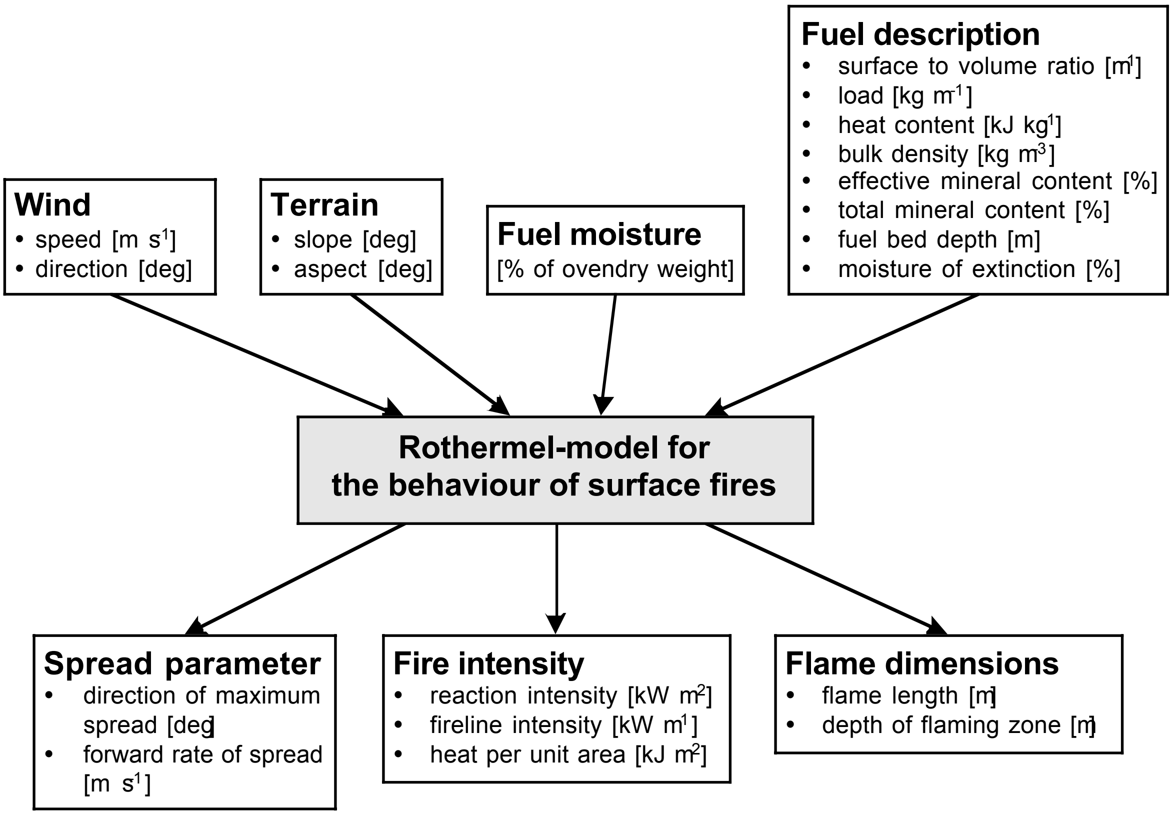

Fig. 7: Inputs and outputs for the Rothermel model

The Rothermel model has been implemented in the GIS environment used for the risk analysis by Schöning (1996).

3.2.1. Fire propagation modelling

Using the Rothermel model, the velocity and direction of maximum spread of a surface fire can be calculated for every location in a study area. With these spread parameters, it is possible to simulate the propagation of an individual fire event. However, since the output of the Rothermel model relates to the direction of maximum spread only, an additional method is required to approximate the local fire spread pattern and thus provide spread rates for arbitrary directions (e.g., for backing and flanking fire). For this purpose, an appropriate fire shape model may be selected. The shape of a fire spreading under uniform conditions has been described using ellipses (Van Wagner, 1969), ovoids (Green et al., 1983) and double ellipses (Anderson, 1983), where the shape parameters usually depend on (effective) wind speed. Knowing the complete spread pattern for any location, the simulation of fire propagation from an arbitrary ignition point is then conceptually simple. A variety of methods have been proposed, which either accumulate the fire spread time in a regular grid or propagate the fire perimeter using Huygen's principle of wave movement. For a review of fire propagation models, refer to Schöning (1996). For the risk analysis, a grid-based approach has been selected (Fig. 8). However, other methods might equally be applicable.

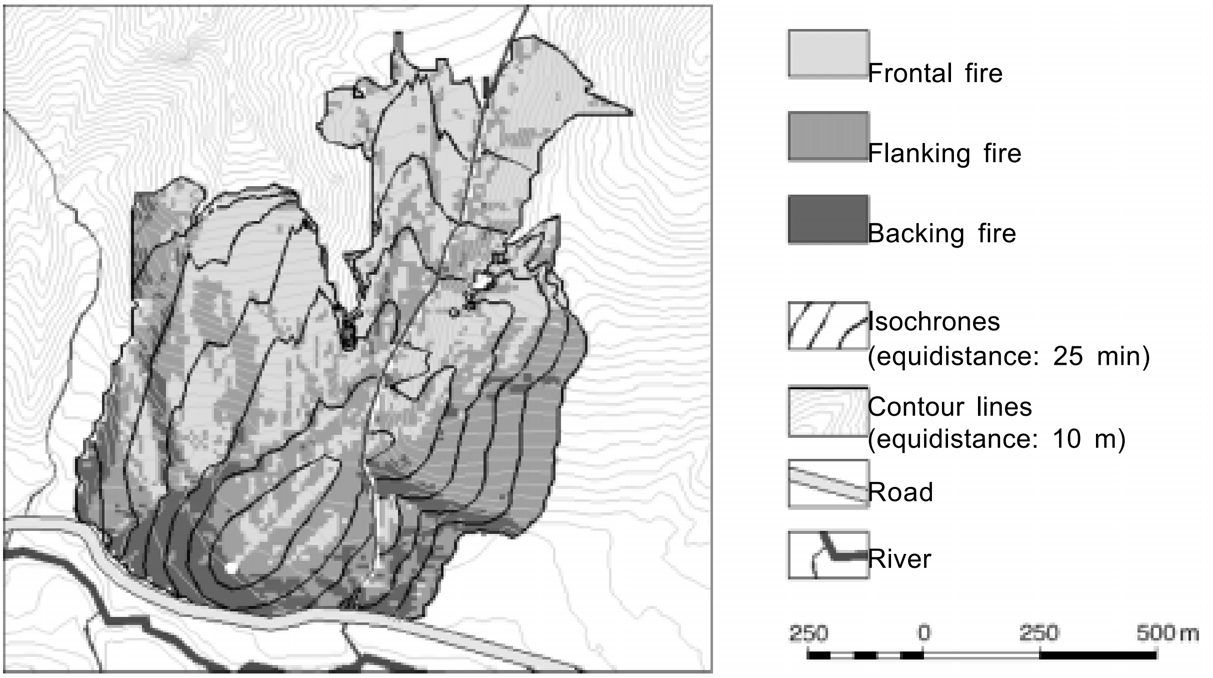

Fig. 8: Results of the fire propagation simulation (Data from the Swiss National Park GIS)

A problem that needs special attention when examining the propagation of a wildfire is the influence of barriers which may stop or slow down the advance of the flames. Many linear features may act as barriers, e.g., rivers, roads, walking tracks. In most cases, barriers will significantly influence potential fire behaviour and thus wildfire risk in a study area. Also, it is obvious that not all features will have the same effect on a spreading fire. However, while there are some approaches to model medium to long range spotting phenomena (Albini, 1979, 1981 and 1983, Morris, 1987), it appears that relatively little attention is being paid to the processes involved in the reaction of spreading fires to barriers. In order to still take into account barriers in the propagation simulation, Schöning (1996) has proposed a simple method for approximating the probability for a fire to cross a barrier (Fig. 9).

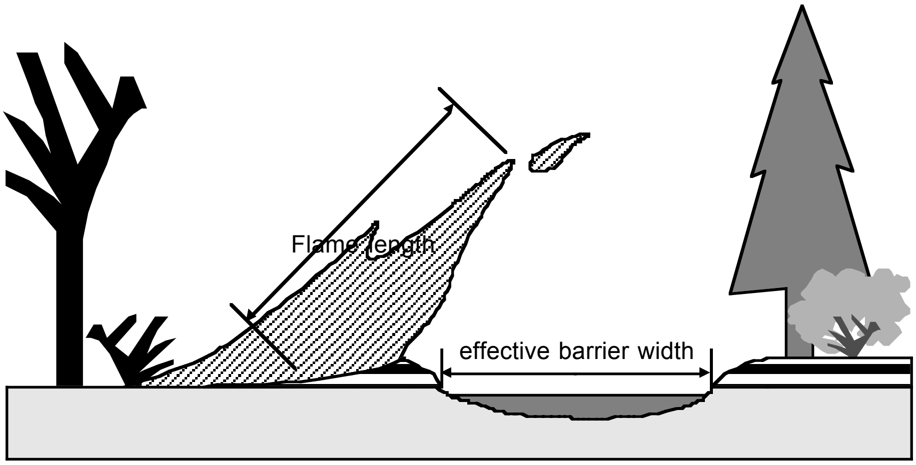

Fig. 9: Dimensions used for approximating the probability of barrier crossing.

It is assumed that the main factor for the ability of a fire to cross a barrier is its flame length as compared to the effective width of the barrier. The quotient of the two dimensions is then taken to calculate a probability for the fire to cross the barrier, using a logistic function (Fig. 9). The actual form of the function can be calibrated giving these quotients for two key crossing probabilities ($r_{0.1}$ and $r_{0.9}$). This method as outlined above has been implemented in the GIS. However, it was until now not possible to do any validation. For more accurate prediction of barrier influence, it might be necessary to consider additional factors like wind direction and speed or the moisture content of fine fuels.

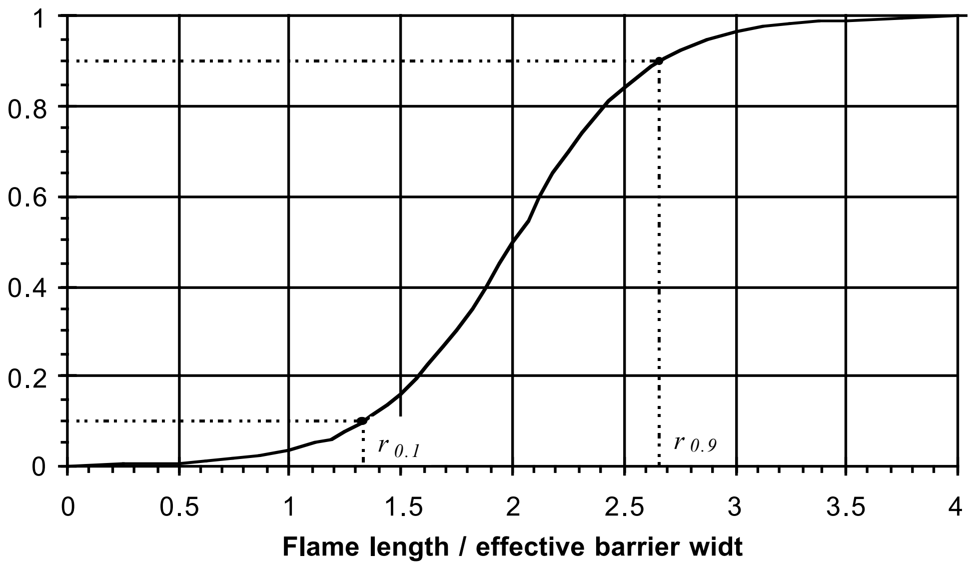

Fig. 10: Logistic function for estimating the probability of barrier crossing based on the ratio of flame length to effective barrier width.

One important issue already mentioned before arises from the fact that wildfires can start from virtually any fuel-covered location. The number of scenarios to be considered for the risk analysis is thus theoretically infinite. Of course, a sample of representative ignition points can be constructed (e.g., through rasterisation of the study area). For reasonably-sized areas, even the sample might still be too large for a simulation of all scenarios to be feasible. On the other hand, the number of objects at risk is typically finite and relatively small. The problem could therefore be solved if it was possible to „look back“ from the objects to all starting points and calculate the time it would take a fire from any location to reach the object. In other words, the solution would consist in filling the risk matrix using one fire spread simulation per row instead of per object. With a simplifying restriction to the fire propagation method, this can indeed be accomplished.

3.2.2. Fire spread backtracking

The procedure is based on the assumption that the spread time between a fire start point A and point B can also be attained by an inverse simulation which starts at B and calculates backwards to all possible ignition points, among them A. Note that the fire is not considered to spread from B to A (the spread times would then obviously not be identical in most of the cases), but the time of *forward* spread from A to B is calculated by „backtracking“ from B. For this to be possible, two assumptions as to the fire propagation have to be made:

1. The vector of maximum spread of a fire front passing at a location can be calculated locally and in advance of the actual spread simulation, neglecting spatial and temporal dependencies. In other words, the movement of the fire front itself does not influence the spread parameters (direction and velocity of maximum spread).
2. The spread pattern at a location can be described with a geometrical model.

Considering the actual dynamics of wildfire, assumption 1 appears to be rather incisive. However, current wildfire modelling practice is often based on the same simplification. The Rothermel model (Rothermel, 1972) used for the risk analysis, for instance, addresses steady state spread of a linear surface fire front of infinite length. While there is an urgent need for more sophisticated models when predicting the fire spread of individual events, the limited accuracy resulting from the assumption may be acceptable in wildfire risk analysis. Even a simplified fire spread simulation still dramatically increases insight in the risk situation in comparison to the application of Euclidean distance thresholds to represent impact ranges for scenarios.

Assumption 2 is also compatible with current modelling practice. Any of the models for fire shape mentioned above can be used to approximate the directional distribution of the rate of spread at a location. Fig. 11 shows a double ellipse model of local fire shape, where r_m represents maximum rate of spread, and r_d the rate of spread in the corresponding direction.

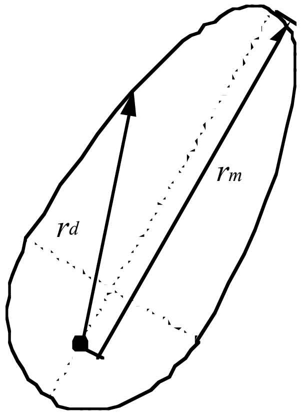

Fig. 11: Double ellipse fire shape and rate of spread vectors

The input for the fire spread simulation then consists in the vector field of maximum spread and the associated fire shapes. The result is the spread time from the ignition to any location. Isolines derived from this „time surface“ represent the fire perimeter at different points in time. This time surface can also be viewed as the result of the fire spreading along *paths* through the vector field of spread parameters. The time $t(S)$ it takes to move through this vector field along a path of length S can then be written as:

$$t(S) = \int_0^S r(s)^{-1}\, ds \qquad \textit{Eq. 3}$$

where $r(s)$ is the rate of spread at position s along the path. Fig. 12 illustrates this same fact. It is now easy to see that the same spread time can be attained when moving along the same path in the inverse direction, once the vector field of maximum spread has been rotated about 180°.

Fig. 13 shows the effect of this inversion of local fire shape on the directional rate of spread. It can be seen that the length of r_s and r_s' for any orientation of the path are identical. From equation 3 and Fig. 13 then follows that the total spread time along the complete path must also be the same. From this identity of spread time along a path in the respective spread vector field, the general equivalence of spread simulation results can be directly deduced. Once it is shown that the spread time along *any* path from A to B can be exactly reproduced by spreading from B to A in the inverse spread field, path p_{min} with the *shortest* associated spread time from A to B must be identical to path p_{min}' found when backtracking from B to A. If there was a path with $t(p') < t(p_{min})$, then its associated $t(p)$ would also be smaller than $t(p_{min})$, which by definition is impossible.

Since $t(p_{min})$ is the time it actually takes the fire to spread between A and B (any section of the fire front spreading along a path other than p_{min} obviously would reach B *after* the section moving along p_{min}), the validity of the proposed fire spread backtracking method under the mentioned assumptions has been demonstrated.

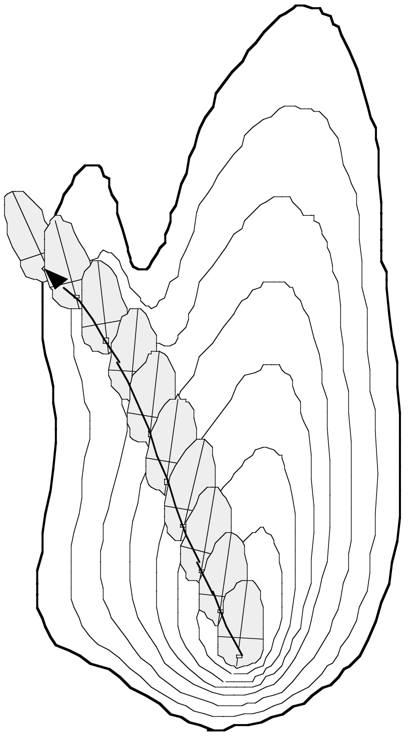

Fig. 12: Influence of fire spread parameters on the movement along a spread path.

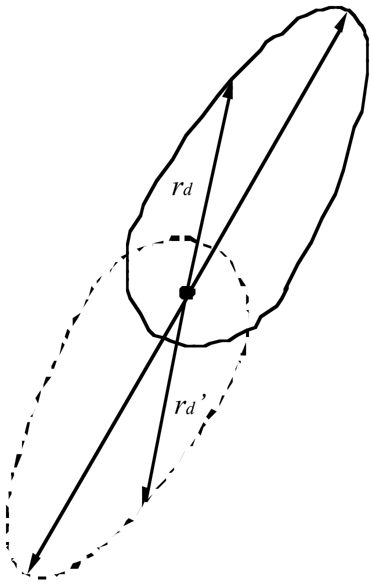

Fig. 13: Inverting the direction of maximum rate of spread.

3.2.3. Deriving spread probabilities

Given the predicted time it takes a fire occurring under a scenario to spread from its ignition point to an object, a probability for the object to be actually reached must be estimated (a_{ij} in the risk matrix, Fig. 2). Ideally, a perfect model would clearly identify the objects within the burn area of the fire, being the ones with finite spread times assigned. However, considering the currently available models and their role in the risk analysis framework, this appears not to be appropriate. Instead, objects with very large spread times might in fact not be reached by the fire. Apart from the increasing probability of the fire being put out by suppression activities, there are other reasons for this behaviour. In the case of the Rothermel model (Rothermel, 1972) used for the risk analysis, it is well known that the extinction of the fire is not well handled. Wilson (1990) has proposed significant extensions to the model, covering among others marginal burning states. It might be beneficial to include them in the risk analysis. More important, however, might be simplifications resulting from the integration of the fire behaviour model in the risk analysis framework. In this context, no specific fire event, but „typical“ conditions are examined which together are considered to make up the overall risk situation. Also, for this first implementation, the fire spread simulation is looked at primarily as a means for improving on the application of Euclidean distance threshold for the identification of impact ranges. For both reasons, no effort was made to represent the temporal variation of fire environment parameters during the spread simulation. Particularly the cooling and increased moisture during the night will in fact significantly increase the probability of fire extinction. Instead, an exponential function was used to relate the predicted spread time to spread probability (Eq. 4).

$$a_{ij} = e^{\beta \cdot t_{ij}} \qquad \textit{Eq. 4}$$

The parameter t_{ij} denotes the fire spread time for an object and a given scenario. For the coefficient β, an appropriate value needs to be assigned based on knowledge or assumptions on the fire propagation behaviour in the study area. The choice of an exponential function is motivated from an analogy with potential models used in quantitative Geography (e.g., Yeates and Garner, 1976, Rich, 1980, Geertman and Ritsema van Eck, 1995). In this context, the same type of function is employed for estimating probabilities of some kind of interaction based on a measure of proximity.

The estimation of spread probabilities should be carried out with great care, since both the frequency and damage estimates directly depend on it. Also, the uncertainties in the fire propagation modelling and the probability estimation should be carefully examined. This points to an issue which might be one of the major areas of future research in the assessment of wildfire risk.

3.3. Fire effects

In order to arrive at an estimate of wildfire damage pertaining to scenarios, objects and situations, the damage an object will suffer once being reached by a fire occurring under a given scenario must be supplied (d_{ij} in the risk matrix, Fig. 2). The definition and estimation of damage to be caused by hazardous events is one of the more difficult issues in practical risk analysis. In the case of wildfire risk, some characteristics of the wildfire process may make it especially intricate. Talking about the potential for rigorous economic analysis in fire management planning, Chandler et al. (1983) name three of them:

- Many effects of wildfire are hard to express in monetary terms. Examples are ecological consequences or the impact of fire on aesthetical aspects of landscape.
- The functional dependencies of fire effects on size and intensity of a wildfire are highly nonlinear, making accurate predictions difficult.
- The longevity of fire effects makes it hard to predict the total damage caused by a fire.

The issue is complicated further by the fact that wildfire may also have beneficial effects (e.g., they may influence vegetation structure in a desirable way). However, it appears to be more appropriate to separate the assessment of these positive effects from the risk analysis instead of attempting to balance out positive and negative effects. The risk analysis should focus solely on the role of wildfire as a hazard. In the overall assessment of the wildfire situation, however, the positive role wildfire may play in the ecosystem must be taken into account.

In spite of the mentioned difficulties, it should still be attempted to arrive at a quantitative description of wildfire damage which can be employed in the risk analysis. Whenever possible, this quantification should be done using monetary terms. This is based on the notion that they represent a better foundation for a transparent decision process than qualitative statements, since they facilitate the review and discussion of a particular assessment of wildfire damage (Merz et al., 1995).

Generally, the damage that will be caused at an object appears to depend primarily on object properties (mainly its „value“ and sensitivity to fire) and the characteristics of the wildfire impacting on the object (mainly fire intensity). For different types of object, functional expressions (Φ_i in the risk matrix, Fig. 2) should be found relating these fire characteristics to the expected damage. The form and/or parameters of these functions would then depend on the properties of the objects. There already exist a variety of methods for determining the impact of wildfire on different types of objects. Examples are the *SIAM* model for assessing structure ignition (Cohen et al., 1991), or a model proposed by Reinhardt and Ryan (1988) to estimate tree mortality. It has to be evaluated how these approaches might be integrated in the proposed framework. Also, the spatial properties of objects has some influence on their treatment in the risk analysis. While the handling of point features (e.g., isolated buildings) is straightforward, in the case of larger linear or area features (e.g., traffic ways or forest stands, respectively) an appropriate representation of the objects might require a sample of representative points to be taken.

For the exploratory implementation of the risk assessment framework, no in-depth treatment of these issues was attempted. Instead, a simple approach involving some of the critical elements of damage estimation was employed. With settlements represented as area features, only one class of objects was considered. The procedure starts by identifying settlement within the reach of wildfires, i.e., within a certain distance (taken to be 25m) of burnable fuels. From the resulting areas, a regular point sample was taken. For the subsequent analysis, each sample point was weighted according to the area it was effectively representative for. The flame length calculated by the Rothermel model was then used as an indicator of fire impact. No attempt was made to relate flame length to some damage measure, instead it was directly multiplicated with the object weight to give the final damage estimate (meaning thus „flame length per unit object area“). Before, the flame length for the direction of maximum spread as it is output by the Rothermel model had to be converted to the respective flame length for each scenario affecting the object. This is due to the fact that a fire rushing towards an object in its main spread direction has a much larger flame length than a fire creeping upwind to the same object. The actual flame length for a scenario was obtained by calculating the angular difference between the maximum spread direction and the arrival direction for the scenario. Given the local spread pattern, the directional flame length could be estimated.

In the entire procedure for calculating damage, the GIS has proved to be a very valuable tool. While more elaborate approaches need to be taken for the identification of objects and the definition of damage functions for different types of objects, in an operational risk analysis the issue of scenario-specific fire intensities might be handled with similar methods as outlined above. Once the probability to be reached and the resulting damage for each object in each scenario are obtained, the calculation of the wildfire risk characteristics as present in the risk matrix (Fig. 2) is straightforward.

4. Case study

The entire risk analysis as described above has been applied to a study area in southern Switzerland. The objective of this case study has been the validation of the risk assessment framework as a whole, knowing that many of the components of the risk analysis require further work for the method to be operational. Also, only an incomplete data set has been available for the area. As a consequence, some parameters for the risk analysis were available only with limited accuracy, others had to be generated based on simple assumptions. For these reasons, the results presented may clearly not be used as a basis for assessing the wildfire risk in this specific area.

The entire study area covers a rectangular region of 5 by 5 kilometres in the Malcantone area of canton Ticino. The following figures show a part thereof, measuring 3 by 3 kilometres. The analysis has been carried out using a raster representation of the area, with the cell size being 25m. Four situations have been considered, differing only in wind direction and speed:

Situation	Wind direction	Wind speed [ms^{-1}]
1	North	4
2	West	2.5
3	South	2.5
4	East	1.5

Fig. 14 Wind situations considered in the case study

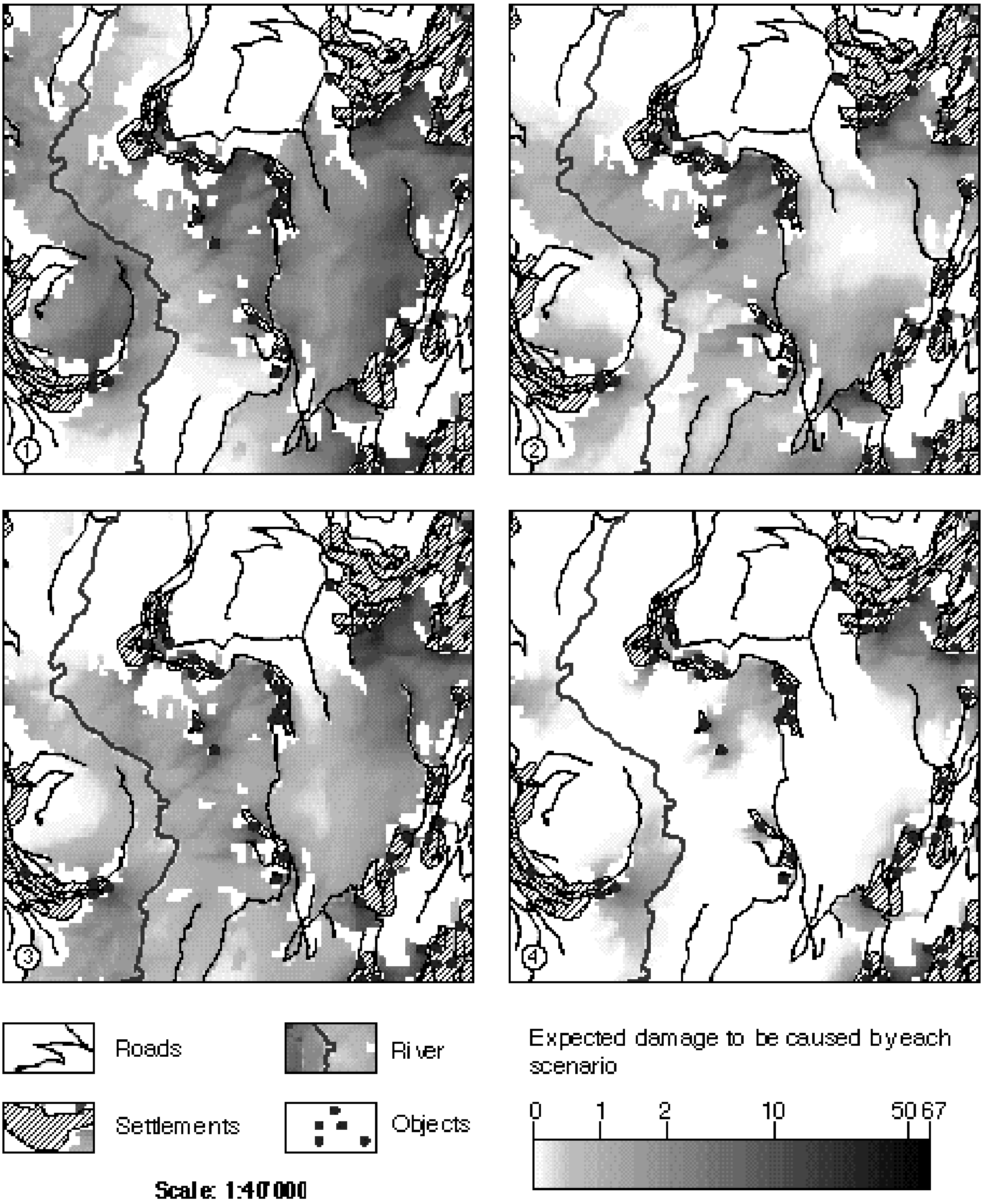

Fig. 15: The expected damage to be caused by each scenario

The endangered objects have been defined based on generalised settlement areas. From these areas, a point sample of 90 objects has been selected. Since no fire occurrence data for the area have been available to us, an ignition point pattern has been generated approximating a possible pattern to be expected for a time span of about two decades. Thus, the resultant risk characteristics also refer to this time span. Fig. 15 shows the expected damage to be caused by each scenario (dj in the risk matrix, Fig. 2), while Fig. 16 illustrates the risk characteristics related to the endangered objects.

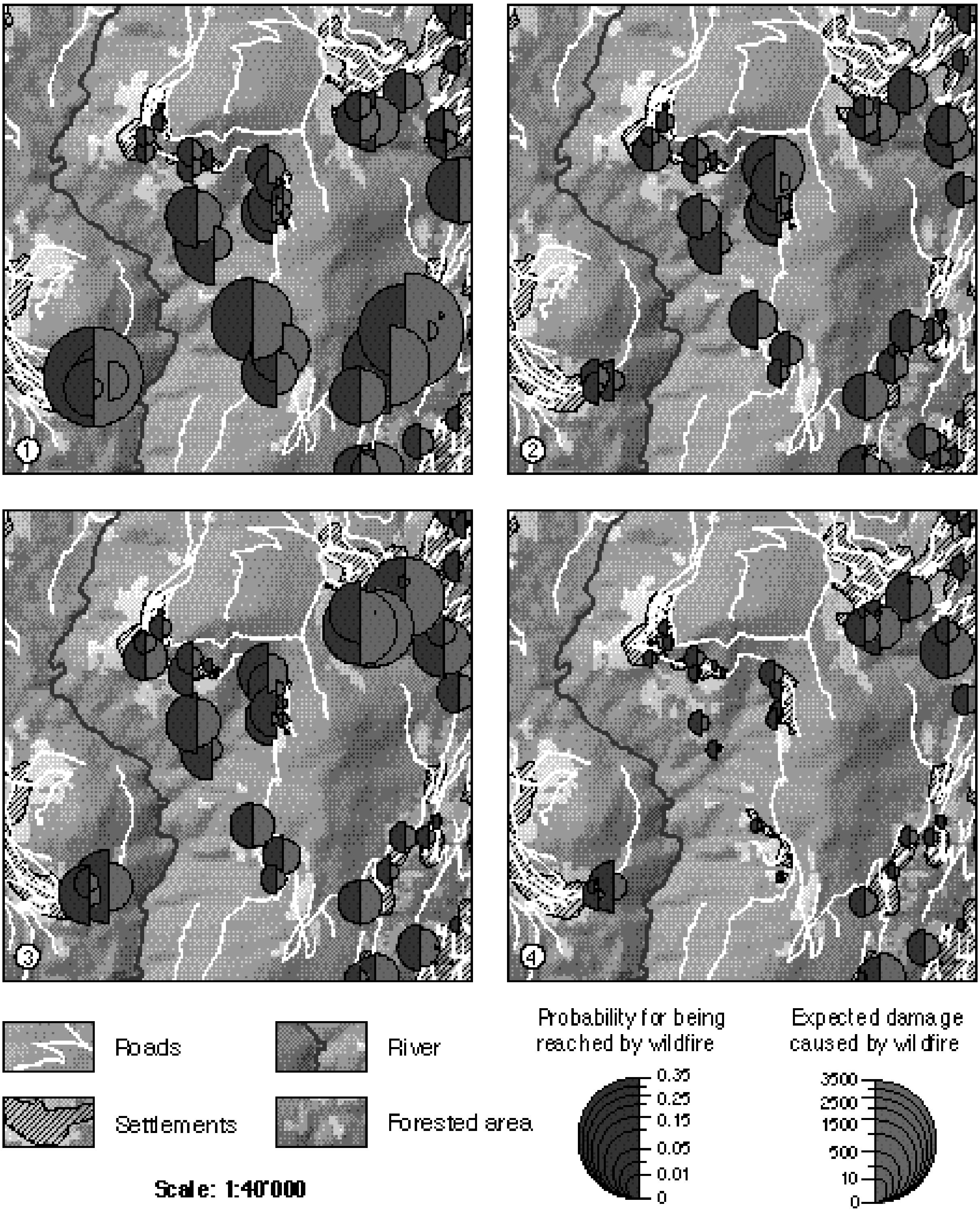

Fig. 16: The expected damage to be suffered by each endangered object. Terrain data (DHM25) reproduced with the permission of the Swiss Federal Office of Topography, 12.2.1997.

Carrying out the risk analysis for one situation required about one hour of computation on a Sun SparcULTRA 170e 167MHz/64Mb. This included the fire behaviour modelling and damage estimation for all scenarios (numbering approximately 10^6) and objects.

A result that may be obtained by further processing the results from the risk matrix is shown in Fig. 17. It contains a frequently used representation of risk results named F-N-diagram (Frequency vs. Number of Fatalities, Merz et al., 1995). The diagram shows for a given level given level of damage the frequency with which it will be reached or surpassed. The diagram is constructed by cumulating the frequency of all scenarios in descending order of damage. The diagram has the additional property of representing the total risk of a situation as the area under the corresponding curve. Thus, it is an effective means for comparing the risk characteristics of different situations. It even allows the risk posed by different hazards to be compared.

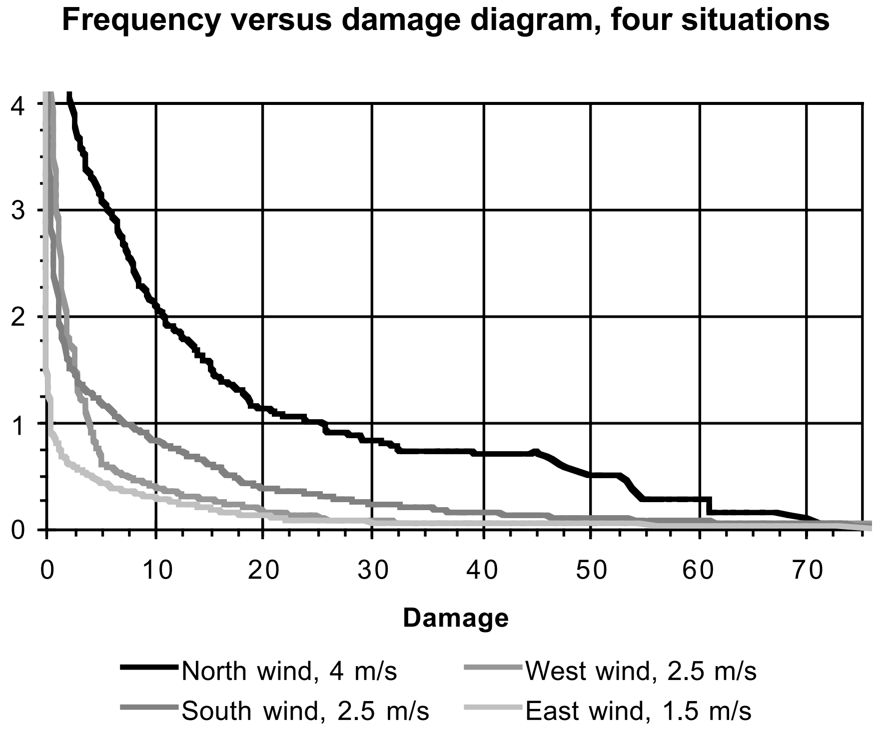

Fig. 17: Frequency versus damage diagrams as a means for assessing wildfire risk for different situations.

5. Conclusions

The main field of application kept in mind while designing the risk assessment framework was fire management planning. The framework indeed appears to have a large potential for supporting the planning and evaluation of management activities. Fig. 18 illustrates the role it might play in a larger fire management decision support system. When setting up a management plan for an area, several constraints need to be met in order for the plan to be successful. The ecological consequences must be considered as well as the financial implications, the compliance with the overall management policy and, last but not least, wildfire risk. The plan may describe measures to be taken to influence the wildfire process in a desirable way. These measures can be grouped into four types of management activities (Chandler et al., 1983), i.e., prevention, presuppression, suppression and the use of fire. Containing wildfire risk at an acceptable level will certainly be a primary objective of the management plan. The risk analysis can be used to evaluate planned activities as to their effect on the risk situation. It may thus greatly facilitate the identification of cost-effective measures to control wildfire risk. Furthermore, the management plan must take into account the future development of the area, resulting from climate change, vegetation dynamics or changing land use. The risk analysis can also be used to assess how these changes affect the risk situation, and how they interact with planned management measures.

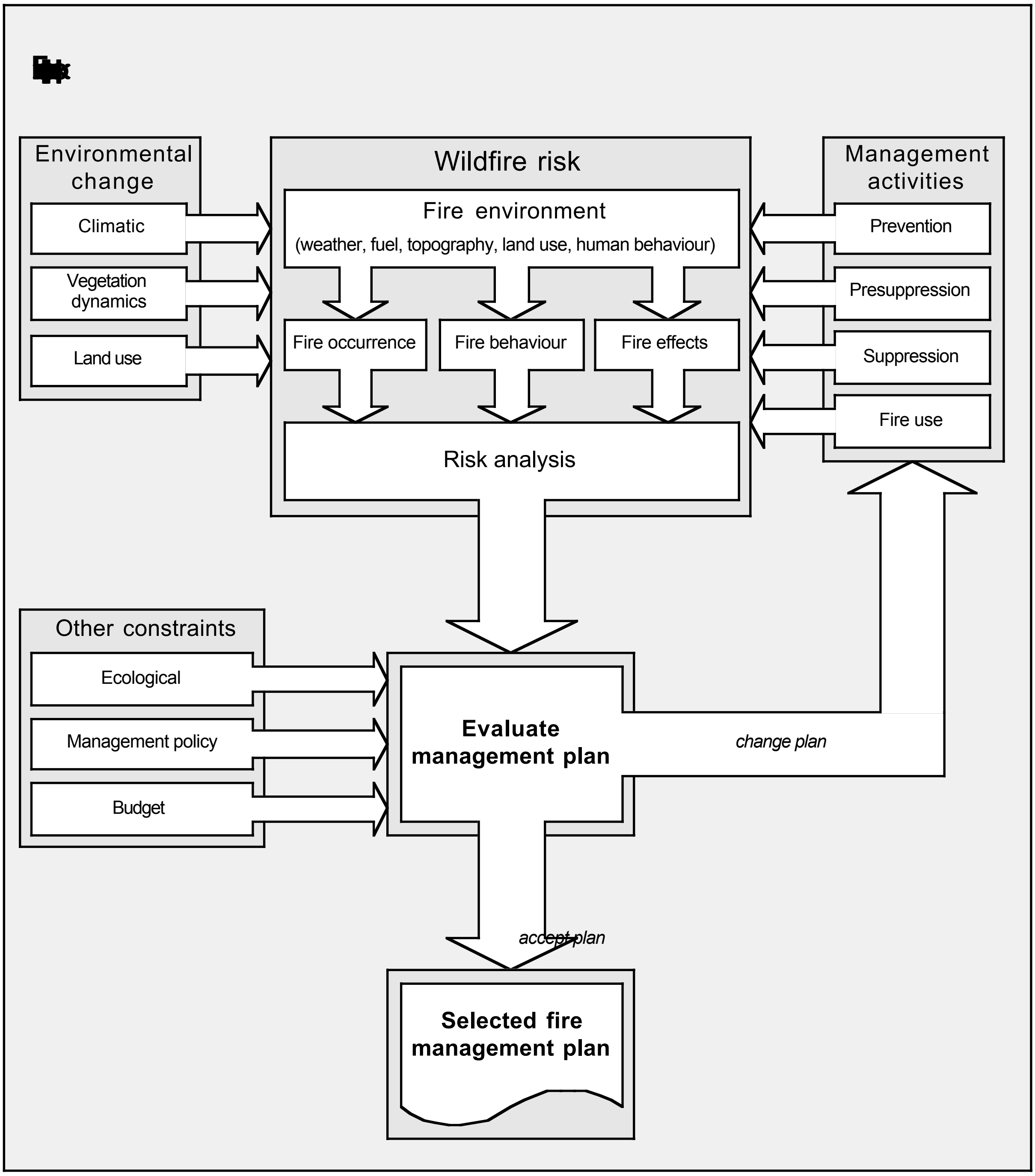

Fig. 18: Integrating the risk assessment framework in a decision support system for fire management planning (the emphasis on the risk analysis results from it being the issue of this paper and does not represent its relative importance compared to the other constraints relevant for the management planning process).

Many of the factors mentioned above influencing the risk situation can be analysed using the current structure of the framework. For example, measures intended to alter fuel properties at selected locations or increased construction at the urban-wildland interface may be directly evaluated by appropriately defining situations as input to the risk analysis. Other applications, however, require the framework to be extended, e.g., to cover the influence of presuppression activities on wildfire risk. Bachmann (1996) has proposed an approach to integrate the accessibility of locations to fire suppression forces. It consists in modelling the intervention time for an object (the time passed after ignition until suppression may begin) and modifying the fire spread probability (a_{ij} in the risk matrix, Fig. 2) by comparing spread time with intervention time.

The exploratory implementation has demonstrated that the framework provides a consistent and flexible methodology to analyse wildfire risk. Also, it has turned out that GIS technology indeed provides the powerful and flexible platform required for the various data management and analysis tasks. The framework heavily relies on the capability of GIS to integrate models and data from a variety of research fields. However, it has also clearly shown that many issues still require further work in order to supply a reliable and ready-to-use tool for fire management planning.

- In fire occurrence research, the methods for assessing the local probability of ignition should be enhanced. Thus, it would be possible to reveal temporal *and* spatial patterns of fire occurrence and to identify the relevant parameters for these patterns.
- Within the context of wildfire risk analysis, fire propagation models are required to both efficiently and accurately predict the probability for a fire to reach a specified location. Instead of the currently used transformation of spread times into spread probabilities, direct ways to arrive at the latter might turn out to be more appropriate. Examining the probabilistic nature of spread phenomena is the issue of percolation modelling. Whether those approaches may be of use for the wildfire risk analysis remains to be examined.
- A crucial component of the framework is the estimation of damage caused by wildfire. A consistent method for assessing damage caused at a variety of object types, both natural and man-made, is needed.

An important issue which pertains to the framework as a whole is the handling of uncertainty information. Both the input data and the component models themselves may introduce considerable error in the risk analysis. An estimate of the uncertainties should therefore be supplied by these models. The framework must then be able to handle these uncertainties, namely, to track the error propagation using appropriate methods. Finally, ways to efficiently communicate the uncertainties in the risk results to the decision maker must be found.

Apart from its intended use in fire management planning, the risk assessment framework might also have a range of applications in other areas. Examples are land use planning, civil safety, and insurance companies, to name only a few. Moreover, it may be assumed that a reliable prediction of the reaction of wildfire risk to environmental change might be of interest in a great variety of fields.

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