FUZZY AND GEOSTATISTICS APPROACHES FOR RISK ASSESSMENT IN RESOURCES MANAGEMENT IN MEDITERRANEAN AREAS

VITO D'AGOSTINO (*) - COSIMO LACIRIGNOLA (**) - GIULIANA TRISORIO-LIUZZI (***)

Abstract

A fundamental step in resources management and environmental planning is the assessment of the risk expected after the occurrence of natural or anthropic events and changes to the land.
Such events may cause critical conditions of instability, worsen conditions of precarious equilibrium, cause damages and destroy non renewable resources, and jeopardise the survival or the security of populations.
In this paper, two problems related to risk assessment are conceptually approached: the extension of the hazard concept to the space-time dimension and the interpretation of the combination between hazard (H) and vulnerability (V) to obtain the risk: R=f (H,V).
As for the former problem, the proposed solution is within the techniques and the methods of geostatistics, for the latter the solution is within a systemic view of the risk, with the required conditions solvable by "fuzzy" reasoning.
Through the spatial knowledge of H and V and thanks to the flexibility characteristics of the adopted methodology, it is then possible to obtain risk maps, at different intensity levels, for given detail levels, that can be effectively used in decision-making processes concerning environmental planning and resources management.

Résumé

Une étape fondamentale de l'activité de gestion des ressources et de la planification environnementale est l'évaluation du risque attendu à la suite de l'occurrence d'événements naturels et anthropiques et de modifications du territoire.
De tels événements peuvent donner lieu à des conditions critiques d'instabilité, aggraver des conditions d'équilibre précaire, provoquant ainsi des dégâts et la destruction de ressources non renouvelables, et compromettre la survie ou la sécurité des populations.
Dans ce travail on aborde, suivant une approche conceptuelle, deux problèmes liés à l'évaluation du risque: l'extension du concept d'hazard à la dimension spatio-temporelle et l'interprétation de la combinaison entre dangerosité (hazard, H) et vulnérabilité (vulnerability, V) pour obtenir le risque: R=f (H, V).
Quant au premier problème, la solution proposée est recherchée à l'intérieur des techniques et des méthodes de la géostatistique; pour la deuxième, la solution se trouve à l'intérieur d'une vision systémique du risque, avec des conditions de départ que l'on peut résoudre en appliquant l'approche "fuzzy".
A travers la connaissance spatiale de H et de V il est ainsi possible d'obtenir, grâce aux caractéristiques de flexibilité de la méthodologie adoptée, des cartes de risque, à différents niveaux d'intensité, pour les niveaux de détails souhaités, qui peuvent être effectivement utilisées dans les processus de prise de décisions qui concernent la planification environnementale et la gestion des ressources.

Introduction

Land planning and resources management call for the urgent definition of adequate risk maps relative to a number of natural or anthropic events, that is actions that change land and are detrimental to security and/or the preservation of resources.
Looking, for instance to the agro-forest space as related to the built-up areas, the problem still remains to define, for the purpose of sustainable development, the suitability and capability as modified over time and especially after choices that didn't take into account the global effects on environment.
The agro-forest space is subject to multiple risks due to both the numerous and diversified phenomena that impact on the production sector and to those that cause environmental and territorial changes. This means that one should assess, quantify and plan over time, measures and actions to be adopted relative to any critical event or any observed change: degradation, loss of useful areas and fertility, floods, water resources management, diseases, cropping pattern changes, optimisation of agricultural production, set-up of structures and infrastructures, etc.
All these problems call for more detailed analyses of the occurrence mechanisms, of the predisposing and triggering causes, of the involved space-time variables, of complex natural and anthropic events: severe meteorological events, flooding, frost, hail, water erosion, wind erosion, landslide, earthquakes, drought, desertification, ground water resources impoverishment, pollution.
The present technological development can still leave room for experimenting innovatory solutions that have seemed hard to assume so far. The Geographic Information Systems (GIS) allow to manage the geometric and alphanumeric data resulting from any format (maps, remote sensing data, topographic data) and scale, within a unique continuous model of the land where all pieces of information are immediately accessible, homogeneous and consistent (Burrough, 1986).
The possibility to manage and analyse information and the complexity of actions that interact with each other and modify environment allow to test new methodologies. In addition to the quantitative and econometric aspects, such methodologies also focus on landform, transformations and their effects on environment, morphology of sites and the integration of evolutionary processes.
The state of the art about the assessment problems of the risk maps is the following (Sherif, 1991):
- the knowledge of processes capable of producing environmental changes that pave the way to predisposing and triggering causes of conditions of instability and critical states of precarious equilibrium is systematic and rich. The mechanism of action, causes and evolution are continuously analysed and theoretical and applied research make new results available (Hansen, 1984, Dargahi-Noubary, 1992(a), Dargahi-Noubary 1992(b)).
Faced with the clear identification, ac-

(*) Tecnopolis, CSATA scrl.
(**) Mediterranean Agronomic Institute, Bari.
(***) Istituto di Sistemazioni Idraulico-Forestali, University of Bari.

quisition and survey, monitoring, selection, management of the involved variables, the question is still open on the organisation of data banks to make diffusion and survey of data homogeneous;
- it is generally possible to assess the probability of occurrence of given critical events (*hazard*). But, this can be made at the points where a statistically significant historical series is available, taking into account the generating causes and the characteristics of the concerned land. The probability of occurrence of the event is then punctual, referred to the place where the ground station is present.
Different authors faced the problem of extending *hazard* at generic points, although they are not equipped with instruments (Journel and Hujbregts 1978, Matheron 1970).
The specificities of some situations and the difficulty to generalise them leave the problem of space distribution of the *hazard* still open;
- within the economic-estimatory assessment, based on theoretical-applied approaches, it is possible to assess the damages produced by extreme events resulting from an intrinsic vulnerability of the considered system: for instance, for the agricultural system one can define the damages produced by some meteoric events like hail, frost, drought and so on. The techniques used are generally accepted by scientists. Still open is, however, the discussion on the quantification of the environmental damage produced by a critical event (Wu et al., 1990);
- scientific literature generally agrees on the general definition of risk as a combination of hazard (H) for the vulnerability (V).
The need is evident, however, of adopting such an approach in resources management and land planning. This is true not only for the management of areas and interests by now consolidated and accomplished, including the programmes of civil defence - but also and especially for any future modification or in the comparison of several alternatives to be presented to the decision-makers and to public opinion. The debate is still open, however, on the meaning of the connection between H and V and of the resulting measurement unit.
In this work only some of the above-mentioned problems are faced and debated: in particular, the problem of the methodological approach relative to the formula of risk and of hazard assessment in a spatial scale.
Some examples will be illustrated in the following.

The integrated concept of risk

According to the international standardisation (Varnes D.J. et al., 1984) of the meaning of hazard, vulnerability and risk it is stated that:
- hazard P (natural hazard H) is the probability that a potentially detrimental phenomenon of given characteristics occurs at a given area within a given time lapse;
- vulnerability V is the degree of loss of a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is translated into the purchasable value of the set of human lives, property and services exposed to the damage in case of occurrence of the event;
- the total risk R is the expected number of loss of human lives, damaged persons, damages to property or destruction of the economic activity due to a special phenomenon, that is associated with a hazard of a given magnitude.
This has led to the need of evaluating the risk, going beyond the approaches based on the use only of the concept of hazard, through methodological approaches that take account also the effective vulnerability.
So, in systemic terms, R is the response whereas H and V are the input variables (**figure 1**).
The problem to be solved is the definition of the function capable of transforming the input H and V in an output that represents the risk the agro-forest system is subject to.
The different nature of input variables introduces a methodological difficulty in the functional expression relating H to V: H is a spatial probability; V can be expressed through the estimate of damages.

A possible reference framework to be taken to relate H to V is fuzzy mathematics: through some rules it is possible to combine fuzzy sets and to transform them in a response of a fuzzy system (Moon-Hyan Chun and Kwang-Il Ahn, 1992). The rules associate ideas and relate one thing, an event or a process with another thing, another event or process. In both natural and computer languages the rules are expressed in terms of *IF-THEN*. If a zone is subject to hazard and it is vulnerable, then there is a risk. This rule can apply to different situations. *If* a zone is at *high hazard* and at high vulnerability then the risk is high; *if the hazard* and the vulnerability are low the risk is low; and so on.
This being said, the following should be emphasised:
- is it possible to transform a probability in a measurement of the grade of membership to classes that can qualify the *hazard*, of the *low, medium, high, etc., hazard type?*
- is it possible to transform an estimate of damage into a measurement of membership to classes capable of qualifying vulnerability, of the *low, medium, high, etc., vulnerability type?*
- is it possible to define risk in terms of *low, medium, high, etc., risk type?*
- is it possible to state the rules that associate classes of hazard and vulnerability to those of risk?
Our intention is to systematise the response to these questions within fuzzy mathematics.
Each qualification class of *hazard, vulnerability* or risk represents a fuzzy set. FUZZY rules relate fuzzy sets.

Vulnerability and hazard fuzzy sets

Vulnerability expresses the degree of intrinsic weakness of the system with

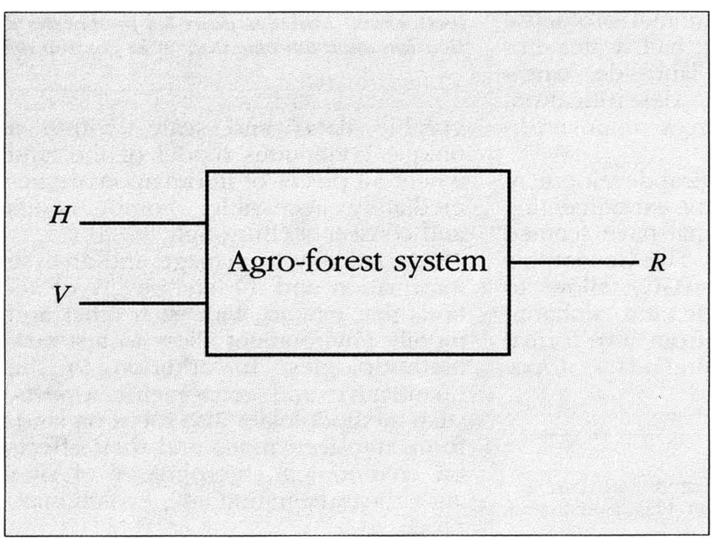
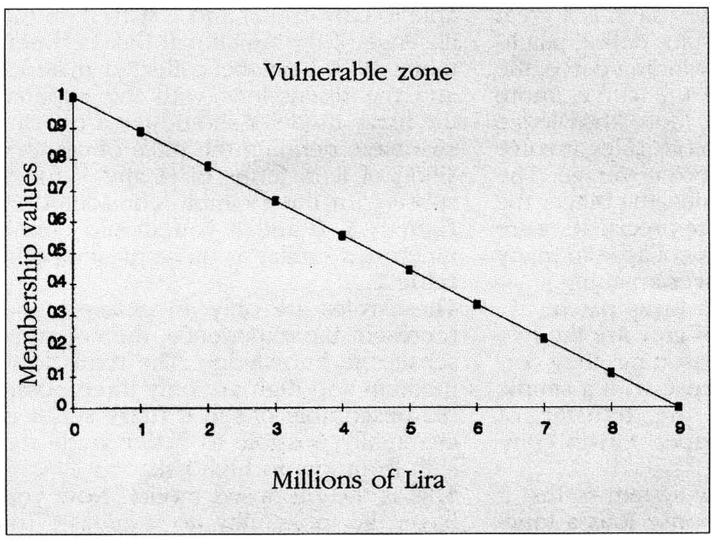
1


Figure 1 - The systemic view of the risk R versus the hazard (H) and vulnerability (V).

respect to an event of a given intensity and then it conditions the effective incidence, in terms of damages provoked by the event to the system.
Vulnerability refers to the methods more related to the economic-estimatory sphere. This is true not only for the categories of public and private "traditional material goods", but also for those of "environmental goods" considered as a destructible, non renewable resource, associated with the collectivity.
Vulnerability can be considered as the summation of several components:
- intrinsic, that is specific to the considered special use or structure or infrastructure (damage to crops, houses, etc.);
- of the system, that is induced by the direct and indirect effects resulting from all the activities that interact and that are related to the peculiar settlement;
- relative to sudden or deceitful losses of human lives;
- of restoration, that is derived from the global costs of emergency actions.
It is evident that experts of the sector should quantify the different components that can be expressed through the assessment of the potential damage or the previously occurred damage.
Concrete possible situations are then as follows:
- the damage is directly measurable and historical data are available since the critical event has already occurred;
- the damage is directly measurable but a change on the land (for instance crop rotation) allows vulnerability assessment only referring to the present situation of land use;
- the damage has not occurred yet and it has to be assessed in relation to the foreseen project alternatives.
The measurement unit by which vulnerability is expressed depends on the type of estimate made for the damage; for instance, it can be expressed in terms of liras of damage. Another indicator can be the number of deaths, independently if they occur because of natural or technological catastrophes. In other works the damage can be presented as a continuous sequence of values between 0 (no damage) and 1 (total destruction).
Although the estimates of damage can be objective, it is common sense that governs the damage/vulnerability association: relative to any natural risk for the system, a greater vulnerability is assumed of its components based on the magnitude of events that, in the past, have produced a damage.
A statement on the vulnerability of a zone based on common sense is, however, related to assertions on facts that, by their nature, can be "true" for some people and a little bit less "true" for others. Common sense can hardly change the level of truth of a statement into a statement of falseness. It could never be proved that assertions on facts are 100% true.
The fuzzy reasoning and the subsequent theory state that it is basically a matter of measure.
In 1965 Prof. Lofti Zadeh from Berkeley University laid the bases of the theory of the so-called fuzzy sets. A fuzzy set is mathematically represented by a function that measures the grade of membership of an element to the set (Giles, 1988). In a non-fuzzy set, an element belongs to the set or not, in a fuzzy set an element may belong to the set to various degrees . In the fuzzy reasoning, you cannot exclude the possibility that the same element may belong and, at the same time, not belong to the set: it is only a matter of measure.
The fuzzy reasoning may be used to describe the vulnerability and the hazard sets.
If you designate appropriately V and H in terms of fuzzy subsets of the type very low, low, etc. or through a numerical scale (for example from 1 to 10) it is the common sense that guides the damage/vulnerability subsets and probability/hazard subsets associations, without excluding the possibility that some elements may belong to several subsets and to each of them, to various degrees.
The latter characteristic distinguishes very sharply the classical operation of adoption of a continuous sequence of values from an estimate of the damage for V or of the probability for H.
They belong either integrally or not at all to the set of numbers: there is nothing intermediate, no half-way. In the fuzzy theory it is possible to interpret numbers as fuzzy sets (Zadeh, 1978).
To define a fuzzy set you should describe a curve of membership that correlates a quantity (either measurable or not) with a given set.
The *Vulnerable zone* set with respect to the quantification of a damage (in Liras), produced by a given event in a given period, may be expressed by the fuzzy set of **figure 2**.
For each damage received we have the grade of membership to the *Vulnerable zone* set. Each zone will be vulnerable to a given extent and non vulnerable to another extent, so that the *non Vulnerable Zone* is the reciprocal of the *Vulnerable Zone* curve (**figure 3**).
The two curves plotted on the same graph cross at the point equal to 0.5 where the membership to the *Vulnerable Zone* set is equal to that of the *Non Vulnerable Zone* set (**figure 4**).
You can do the same for the *Hazard Zone* and *Non Hazard Zone* fuzzy sets. In this case, the *probabilities* of occurrence or the return periods are associated with grades of membership to fuzzy sets.
Fuzzy sets permit treating in the same way the different nature and unit in which the state variables H and V are expressed. You can also perform some operations on fuzzy sets (Kandell and Byatt 1978) and this might be a solution to the problem of combining H and V in the risk formula.

Hazard meant as response of a fuzzy system

Zadeh (1978) stated the principle of incompatibility: as the system gets more complicated, it becomes more difficult to make precise and significant assertions on its behaviour, till a threshold is



2

Figure 2 - The "Vulnerable zone" fuzzy set.

3

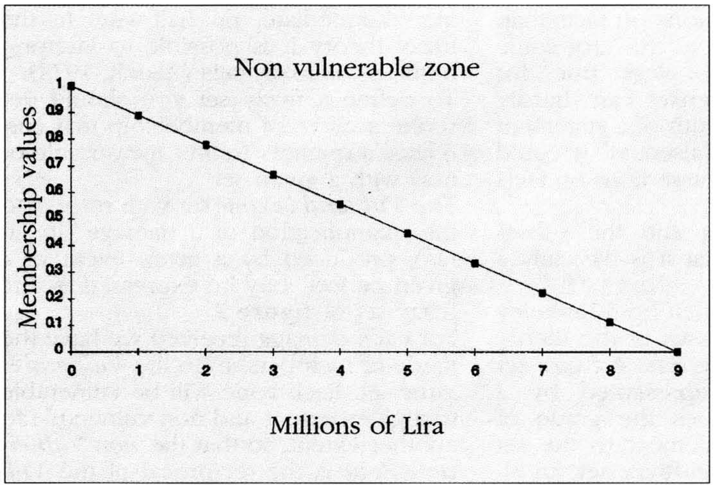


Figure 3 - The "Non vulnerable zone" fuzzy set.

4

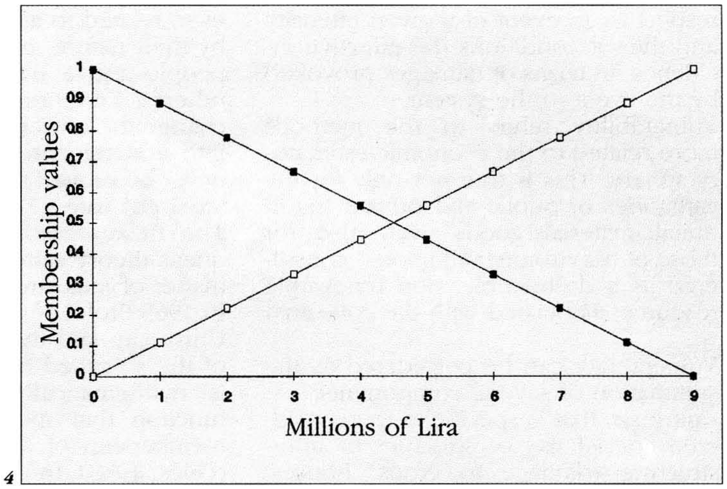
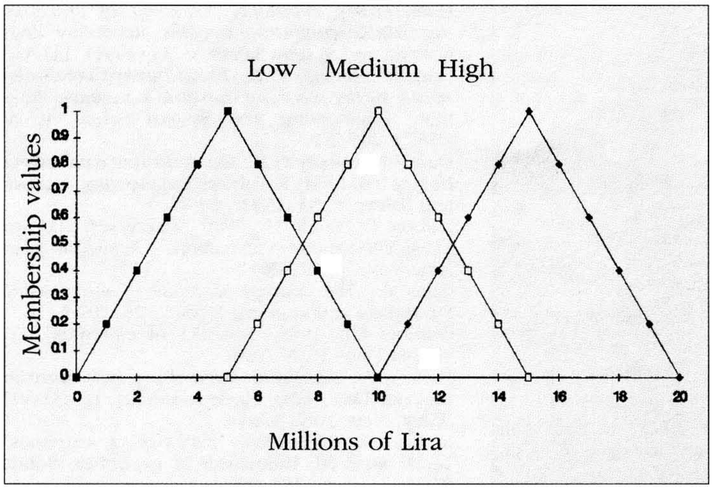


Figure 4 - The "Non vulnerable zone" and "Vulnerable zone" fuzzy sets.

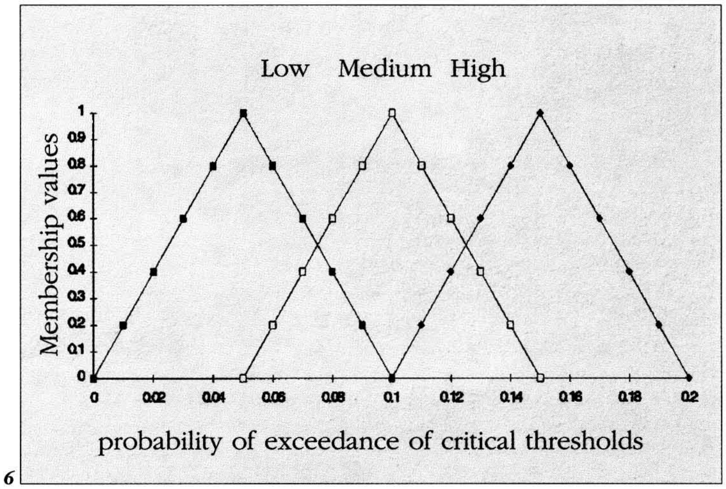
reached beyond which, the accuracy, on one hand, and the meaning (or adherence) on the other, become characteristics that tend to exclude each other.
The following addition may be shortly stated: the closer a problem to the real world, the fuzzier the solution.
The response in terms of risk of a complex system, like agro-forestry, induces to reflect on the fuzzy nature of the solution.
A group of proposals is referred to as fuzzy system.
In the simplest case, somebody, the expert, formulates the proposals. The latter provides an experienced view, his empirical rules based on common sense. A fuzzy system acquires this knowledge and on this basis, it constructs an operating model of the system itself.
In 1990 Kosko demonstrated that a fuzzy system may provide a model or approximate any system. The fuzzy approximation theory follows the idea that any piece of human knowledge, any rule of the form *IF-THEN* defines a patch. So that, a fuzzy system is a great pile of patches. The rules define patches that try to cover a winding curve; the better patches cover the curve, more intelligent the system. More knowledge implies more rules, more rules involve more patches and more coverage. The more uncertain the rules, the bigger the patches. If the rules are precise they are not fuzzy and patches collapse in many points and do not cover anything.
A fuzzy rule defines a fuzzy patch.
Patches and shades of grey are the two keq ideas of fuzzy reasoning; they correlate the common sense with a simple geometry allowing the transfer of knowledge on the paper and in computers.
To construct the fuzzy system so that it might model the response R as a function of entries H and V, you should go through different steps.
The aim is the risk assessment in any cell or homogeneous area of a land, assuming any data, map, table or other materials may be recovered and even introduced in a GIS.
In the fuzzy approach we assume the three sets H, V and R are fuzzy and you should qualify them in more subsets, each of them identified by a number (1, 2, 3 etc.) or a property (*elevated, high, medium, good, poor, etc.*).
The functions of membership to subsets may be represented in the same graph as triangles. Other possible appropriate forms of the risk problem may be the bell-shaped or trapezoidal curves.
Figures 5, **6** and **7** are an example of fuzzy modelling for the problem.
You can plot triangles varying in size as related to the idea that the fuzzy modeler has acquired on the basis of experts' opinions. In the case of the risk you may adopt a scale of intensity: from 0 to 20, in the case of **figure 7**.
The problem is to define fuzzy rules able to correlate H and V with R, in the absence of the functional link between them. Based on the collected material and the discussions with the experts, the fuzzy modeler should get a conclusive table defining the rules of composition of R in terms of H and V fuzzy subsets. In the example considered in **figures 5**, **6** and **7** you should define nine rules similar to those presented in **table 1**.
These rules are only an example and represent the experience, the common sense, the knowledge. The terms low, medium and high are only three possible descriptors of the R fuzzy set: it is eventually possible to better grade the shift from low to high risk.
This is the proposed model. Now you have the possibility to evaluate, for each cell or for each homogeneous area, the risk level. This implies the use of techniques able to reconstruct information at any desired position. Geostatistics permits the hazard regionalization. The GISs allow having access to any relevant geographic information.
In the cell you can estimate a quantity that has been already sampled in other positions and thus estimate the probability of exceedance of critical thresholds.
Through the membership functions you can identify the grades of membership of the cell to each hazard and vulnerability subset.
The combinations of H and V fuzzy subsets excite, to a different extent, all the rules of the fuzzy model. In the fuzzy reasoning, the principle of extension (Dubois and Prade, 1980) states that the measure to associate to the rule activated with measure p by a subset of H and with measure q by a V subset is the minimum between p and q. This value also measures the R fuzzy subset activated by the rule under analysis.
Through a process of "defuzzification" (Cai Kai-Yuan et al., 1991) of the R fuzzy set you can identify the risk level quantified, in the selected scale, by the different measures at which rules have

Table 1 ***Possible rules of H and V fuzzy composition.***

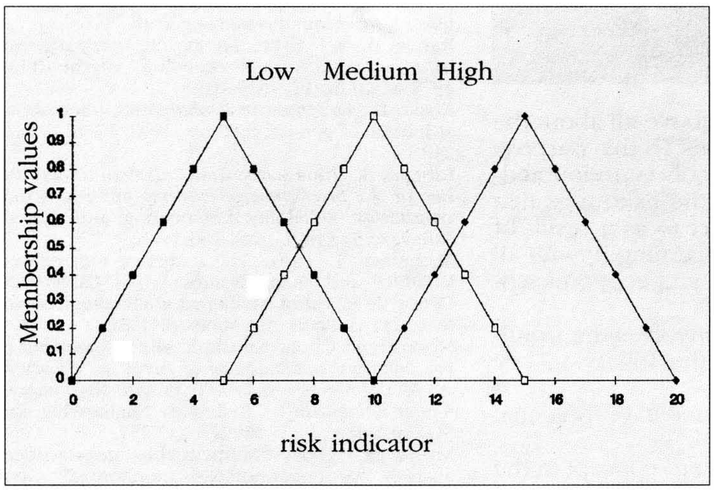
If H is low, V is low THEN R is low
If H is low, V is medium THEN R is low
If H is low, V is high THEN R is medium
If H is medium, V is low THEN R is low
If H is medium, V is medium THEN R is medium
If H is medium, V is high THEN R is medium
If H is high, V is low THEN R is high
If H is high, V is medium, THEN R is high
If H is high, V is high, THEN R is high.



5



6



7

Figure 5 - Possible fuzzy subsets of vulnerability.

Figure 6 - Possible fuzzy subsets of hazard.

Figure 7 - Possible fuzzy subsets of risk.

been activated. The mostly used defuzzification process is the method of calculation of the centroid (Terenuma et al., 1990).
The cell may be assigned a risk level. You can shift to the analysis of the subsequent cell using the same procedure. At the end of the process, all cells will be assigned a risk level and the use of a GIS will allow them to be represented as maps.

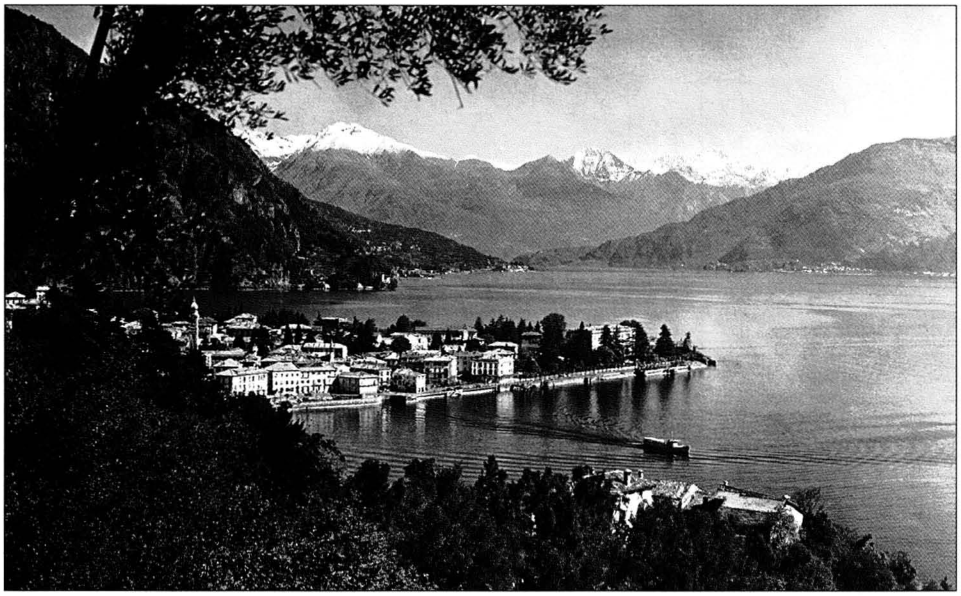
Spatial assessment of the hazard

One of the main problems in the risk assessment of a land is the difficulty to have access to tools to measure variables of interest, in each desired position. The knowledge of the spatial-temporal behaviour of extreme weather events for a land is still a crucial topic in the assessment of various forms of risk. The characterisation of the hazard concerning these extreme events necessitates appropriate techniques.
The analysis of the time records available in an equipped site enables obtaining for example:
- the theoretical distribution of extreme values and the calculation of related return periods (Suzuki Oahashit and Hongo, 1980; Labeyrie 1991, Jenkinson 1969, Gumbel 1958);
- the identification of trends and of periodic components, models of temporal estimate (Box and Jenkins, 1970).

The geostatistical analysis of a spatial-temporal record enables knowing, for instance:
- the probability to exceed a given threshold for a critical factor, that is spatially influenced by the measures being sampled;
- the estimate of the critical factor in each cell.

The geostatistical approach enables, therefore, the spatial assessment of the hazard. Geostatistics is the term by which you identify a set of spatial methods and techniques based on probabilistic assumptions (Matheron, 1970). It prioritises a general approach for the interpretative model of the phenomenon, in order to fit it to the data. The classical alternative is to force data to the model, once you establish a criterion (for instance the least squares) and a functional form neglecting, however, what is intrinsically contained in the data. Geostatistics makes available the tools for the investigation, analysis and modelling of the spatial variations of a variable under analysis starting from data. Such an approach benefits by the a priori knowledge of the physical and territorial conditions under which the phenomenon occurs or of what is helpful for its interpretation. As such it cannot be used as a black box.
The three following steps may be distinguished in the geostatistical analysis of data:
1. *exploratory*, by which you visualise the spatial distribution of the sample to get information on the minimum sampling distance, the mean and sample variance, the normality of the population distribution;
2. *structural*, by which you identify the spatial structure, said variogram, of the sampled variable. The variogram behaviour should respond to a prerequisite of spatial continuity of the following type: the closer the points to each other, the lower the value of the quantity being analysed. The aim of the structural analysis is the identification of this continuity on the basis of the available data and of the model that best represents it. The models incorporate three parameters: the *sill*, that can represent the variance of the sample; the *range*, that can represent the maximum distance of influence between couples of points; the *nugget*, that can represent a factor of scale in the case of inappropriate sampling in relation to the scale of variation of the phenomenon.

After the structural analysis of data you can respond to the objective of the hazard estimate using different techniques, designated as kriging. To reconstruct the estimate of the variable under analysis at any desired point you can use the kriging techniques of linear geostatistics (Myers, 1988). The probabilities of occurrence of critical events



are determined by the kriging techniques of non linear geostatistics that are more consistent with decision-making problems. (Yates and Warrick 1986, Yates et al., 1986(a), Yates et al., 1986(b)). The Disjunctive Kriging (DK) is for instance the most appropriate technique to provide the estimate of the conditioned probability that an indicator variable exceeds pre-established risk thresholds. The application of the DK involves the following steps:

- the verification of the possible lognormal or normal form of data distribution
- the calculation of coefficients that allow the distribution of data to be transformed in a normal
- structural analysis of data for the identification and validation of the variogram model
- calculation of the spatial probability distribution influenced by the spatial sample.

The alternative to the DK is provided by the geostatistical simulation techniques that based on the variogram model, can simulate values several times, on the entire land, thus permitting to evaluate the probabilities of exceedance of critical thresholds.

Conclusions

The globalization of the environmental issue and of resource management and safeguard, imposes to decision-makers and to the authorities the need for being supplied with tools that can support their decisions on the basis of well-defined and common criteria. Despite the practical possibility to identify the areas of potential danger, the absence of such tools does not allow an easy and concrete indication about the possible use of that land and above all about the possible safety margins.To this purpose one of the possible tools is undoubtedly the assessment of the risk range that a land may be subject to as a result of events or actions concerning it, with all the possible physical and economic-social implications.

The risk assessment involves the simultaneous solution of the following key problems:

- experienced assessment of potential or effective damage;
- extension of the hazard concept in the space, for any desired point of land and not only in the sites equipped for;
- need for managing and combining the multiple forms in which information on land is represented (maps, on-the-ground surveys, photos, satellite images);
- need to combine hazard levels, expressed by probabilities, with vulnerability levels, expressed by damage estimates;
- need to achieve results to be used as planning tools on a a wide scale, i.e. containing all the elements to decide on land use considering the economic and social outfalls for the concerned populations.

The GISs, the fuzzy reasoning and geostatistics are the technological and methodological frameworks within which a possible approach to the problem is presented. ●

References

Box G.E.P., Jenkins G.M., 1970, “Time series analysis: forecasting and control”. S. Francisco, Holden-Day.

Burrough P.A.: *Principles of Geographic Information Systems for land resources assessment.* Claredon Press, Oxford, 1986.

Cai Kai-Yaun, Wen Chuan-Yuan, Zhang Ming-Lian: *Fuzzy Reliability Modeling of gracefully degradable computing systems,* Reliability Engineering and System Safety, v. 33 (1991), 141-157.

Dargahi-Noubary G.R.: *Flood hazard assessment based on the theory of outstanding values,* Reliability Engineering and System Safety, v. 38 (1992), 245-252.

Dargahi-Noubary G.R.: *On definition and estimation of wind risk,* Reliability Engineering and System Safety, v. 35 (1992), 83-87.

Dubois D., Prade H., 1980, “Fuzzy sets and systems; Theory and Applications”, Academic press New York, p. 277-296.

Giles R.: *The concept of grade of membership,* Fuzzy sets and systems, 1988, v. 25, 297-323.

Gumbel E.J., 1958, “Statistics of extremes”. Columbia Univ. P., N. York.

Hansen A.: *Landslide hazard analysis.* Brunsen D&Prior D.B. (eds). Slope instability, p. 532-602, Wiley, New York, 1984.

Jenkinson, A.F., 1969, “Statistics of extremes”. Tech. Note 98. Estimation of maximum floods. WMO. Geneva. 183-228.

Journel A., Hujbregts C.J., 1978, “Mining geostatistics”. Academic Press. New York.

Kandel A, W.J. Byatt: *Fuzzy sets, fuzzy algebra, and fuzzy statistics,* Proceedings of the IEEE, 1978, v. 66, n. 12, 1619-1639.

Kosko B.: *Fuzziness vs Probabilities,* International Journal of general Systems, 1990, 17, n. 2, 211-240.

Labeyrie J.: *Time scales and statistical uncertainties in the prediction pf extreme environmental conditions,* Reliability Engineering and System Safety, v. 32 (1991), 243-266.

Matheron, G., 1970, “The theory of regionalised variables and its applications”. Les Cahiers du Centre de Morphol. Mathemat. de Fointainebleau, N. 5, 211 p. Ecole des Mines de Paris.

Moon-Hyun Chun, Kwang-Il Ahn: *Assessment of the potential applicability of fuzzy set theory to accident progression event trees with phenomenological uncertainties,* Reliability Engineering and System Safety, v. 37 (1992), 237-252.

Myers D., 1988, “Multivariable geostatistical analysis for environmental monitoring”, Geomathematics and Geostatistics analysis applied to space and time dependent data, Science de la terre, Ser. Informatique, Nancy, n. 27, 411-427.

Sherif S.: *On risk and risk analysis,* Reliability Engineering and System Safety, v. 31 (1991), 155-178.

Suzuki E., Oahashit T., Hongo S., 1980, “Statistical prediction of climatological extreme values and return period in the case of small samples”. Statistical climatology. Elsevier Pub. Company.

Terenuma S., K. Kishiwada, H. Takahashi, T. Iijima, H. Hayashi: *A simulation study on the application of a fuzzy algorithm to a feedwater control system in a nuclear power plant,* Reliability Engineering and System Safety, v. 28 (1990), 319-335.

Varnes D.J.: *Commision on Landslides and other mass-movements-IAEG. Landslide hazard zonation: a review of priciples and practices.* The Unesco Press, Paris, 6.3.1984.

Wu J. S., G.E. Apostolakis, D. Okrent: *Uncertainties in system analysis: probabilistic versus non probabilistis theories,* Reliability Engineering and System Safety, v. 30 (1990), 163-181.

Yates S.R., Warrick A.W., D.E. Myers: *Disjunctive Kriging 1. Overview of estimation and conditional probability,* Water Resources Research, 1986, v. 22, n. 5, 615-621.

Yates S.R., Warrick A.W., D.E. Myers: *Disjunctive Kriging 2. Examples,* Water Resources Research, 1986, v. 22, n. 5, 623-630.

Yates S.R., Warrick A.W., D.E. Myers: *A Disjunctive Kriging program for two dimensions,* Computer & Geosciences, 1986, v. 12, n. 3, 281-313.

Zadeh L.A.: *Fuzzy sets as a basis for a theory of possibility,* Fuzzy sets and systems, 1978, v. 1, 3-28.

Zadeh L., 1965, “Fuzzy sets”, Information Control., v. 8, p. 338-353.