A STRATEGY FOR SUSTAINABLE DEVELOPMENT OF NATURAL RESOURCES BASED ON PREDICTION MODELS

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ABSTRACT

This contribution considers prediction models to anticipate the distribution of natural resources or of events that limit their accessibility. For this purpose, a very broad definition of resource has been used, i.e., any natural biotic or abiotic deposit or process that can be assigned a value once its use is contemplated. Prediction models are proposed at the core of a strategy for sustainable development. Exploration of resources requires that we identify reasonably or conveniently small sub-areas as targets for more detailed exploration. The smaller are those sub-areas, the more convenient our search becomes. This equally applies to the prediction of the environmental impact of the exploration activities and of the subsequent resource exploitation. The prediction strategy proposed in this contribution consists of spatial representations of integrated information on resources and their spatial context, of models for their integration into numerical maps expressing the likelihood of the occurrence of favorable or unfavorable conditions, of application examples of strategies for environmental impact assessment of transportation systems, and of considerations of the constraints associated with spatial predictive models.

1 INTRODUCTION: PREDICTION FOR SUSTAINABILITY AND EXPLORATION STRATEGY FOR ENVIRONMENTAL PROTECTION

This contribution considers prediction models to anticipate the distribution of natural resources or of events that limit their accessibility. For this purpose, a very broad definition of resource has been used, i.e., any natural biotic or abiotic deposit or process that can be assigned a value once its use is contemplated. We can also distinguish between renewable and nonrenewable resources depending on the reversibility of their generating process in a foreseeable future.

The term resource is linked with the term sustainability that deals with the availability of resources through time. Whenever resources appear to be scarce, a major concern becomes how to maintain their supply either by intensifying exploration, or by recycling waste, or by substituting alternative resources of a different kind but of a similar function. It has been argued that, even for nonrenewable resources, sustainability can still be considered when the resource discovery rate is maintained. Obviously, in such a situation, a prediction model is used that is based on historical discovery rates and on their extrapolation into the future. Indeed, we can consider predictability and sustainability as the pillars of resource and environmental management, two complementary activities if we look at environmental quality as a basic resource.

This contribution discusses prediction models at the core of a strategy for sustainable development. While the term “sustainable” implies the prediction in space or in time of the availability of resources, the term “natural” implies a whole set of valuable assets such as base metals, raw materials, arable soils, drinking water, clean air, forests, safe landscape, positive geomorphologic processes, and “good” environmental quality. Natural resources are the result of geological processes. For this reason, the knowledge of the mechanics, trend, speed, distribution and other characteristics of the processes, that often overlap and interact, is a prerequisite to predict their future distribution, occurrence and intensity.

Exploration of resources requires that we identify reasonably or conveniently small sub-areas as targets for more detailed exploration. The smaller are those sub-areas, the more convenient our search becomes. This equally applies to the prediction of the environmental impact of the exploration activities and of the subsequent resource exploitation. Obviously, the greater is the impact the greater are the sterilization of resources and the decrease in sustainability. It follows that the prediction of environmental impacts is an essential component of sustainable development.

The prediction strategy proposed in this contribution is discussed in the following sections. It consists of spatial representations of integrated information on resources and their spatial context, of models for their integration into numerical maps expressing the likelihood of the occurrence of favorable or unfavorable conditions, of application examples of strategies for environmental impact assessment of transportation systems, and of considerations of the constraints associated with spatial predictive models.

2 SPATIAL REPRESENTATION OF INTEGRATED INFORMATION

The diffusion of information technology in the geo-sciences today has provided a wealth of spatially distributed data that can be transformed and combined to represent thematic maps using predictive models. For instance, information can be extracted from airborne and space-borne sensors, including geophysical and geochemical sensors, that can be integrated with digital maps that are stored and processed in geographical information systems. In general a model of reality, i.e., of a complex process such as mineral deposition, geomorphologic hazard, pollution potential, or environmental impact, consists of a combination of spatial representations or data layers. Each layer is telling us something about the process and it contributes to define not only the distribution of resources but also the impact caused by the possible exploitation. Because each layer is telling us only part of the story that we try to reconstruct as a prediction, several layers will have to be combined to represent the interaction of process components within each layer and between the layers.

A general strategy to spatial integration modeling was the one proposed by Chung and Fabbri (1993). It considered "target patterns" as the distribution of unknown or undiscovered "resources", or unknown hazards, or impacts. Alternatively, such target patterns can be only partly known or discovered. Target patterns are what we would like to know and whose distribution we want to estimate because it is unknown. To do this, we have to use all spatial and non-spatial information about the targets. Such information is either directly related to them, such as their distribution in study areas different from, but similar to, the one being considered, or is indirectly related to them as indication of contextual conditions that we deem as typical of the presence of the target patterns. Such indicators we have termed as supporting patterns.

We can expect that the sharper is the definition of the target patterns (e.g., specific types of resources whose conditions of occurrence are well understood or familiar to experts), the sharper is the identification of their supporting patterns.

Let us assume that the spatial and non-spatial information can be extracted from a database. The question then is: "How can we transform such information into an input to predictive models?" The next question could then be: "Is the information available sufficient by itself for a prediction to be formulated or does it need complementary expert's opinion?" Furthermore, if a prediction is generated, in whatever form, "How reliable is it?" and "How can we say that one prediction is better than, or is preferable to, another?"

Such complex questions depend on both the quality of the information and on the level of expertise available about the target patterns, including their typical contextual conditions of occurrence. Assuming that the data available satisfy both requirements to a certain extent, we can proceed towards building a database from a variety of available analog and digital maps and tabular data. A first step is to construct "value functions" for all units in each map layer (or item values in the corresponding tables) with respect to the frequency of occurrence of the target pattern as estimated from outside the study area or from the knowledge of experts. Such functions are to express the degree of support expected towards the occurrence of the target pattern by each map layer, e.g., close to "0" is little or no support, and close to "1" is maximum or full support.

Value functions can either be computed from the database if the density of data permits a numerical expression or can be constructed by experts using a Delphi technique of structured group consultation and consensus generation.

Such step is to allow the construction of a proposition (or logical statement) that a given point "*p*" in the study area "**A**" is likely to be associated with, affected by, or otherwise explained by, the presence of the supporting patterns. The proposition structures a prediction problem in terms of a statement that can be demonstrated to be true or false. Some examples of propositions for different application problems are presented in Table 1.

For a proposition, a value function can be constructed based on the following assumptions:
(1) the database contains information relevant to the target pattern;
(2) the historical conditions represented by the supporting patterns are the same as, or similar to, the ones expected for the target pattern; and

(3) when the information in the database is perceived to be incomplete or insufficient, experts are available to provide the knowledge to complement the database with qualitative or semi-quantitative information to perform a prediction.

What is common to the propositions listed in Table 1, is the task of transforming each layer of spatial information into supporting patterns that then can be combined into a representation of the typical settings in which to expect the target patterns. Propositions, A to E in the table, correspond to various application areas and require different supporting patterns. Geographic information systems are computer programs that enable the construction, analysis and display of spatial databases. Processing by such systems can lead to the construction of prediction models, and the generation, visualization, evaluation of prediction results.

Identifier	Proposition	Application area	Examples of supporting spatial patterns
A	**T***p*: **"**a point *p* is affected by a landslide of shallow translational dynamic type"	Geomorphologic hazard	Slope , aspect , land use and lithologic map classes and the distribution of some of the past landslides of shallow translational dynamic type
B	**T***p***:** "a point *p* belongs to a gold vein type mineralization"	Mineral exploration	geological and structural maps, geophysical and geochemical anomaly maps, and the distribution of known gold vein mineral occurrences and other mineral indicators
C	**T***p*: **"**a point *p* is vulnerable to vertical aquifer pollution"	Aquifer vulnerability assessment	depth to water, net recharge, soil media, aquifer media, slope, impact of the vadose zone maps
D	**T***p***:** "a point *p* is likely to be flooded by a nearby stream"	Flooding hazard	slope, infrastructure, drainage, soil and lithology maps, simulation of water surface in time
E	**T***p***:** "a point *p* is impacted by the presence of a given transportation system in its vicinity"	Environmental impact assessment	Indicator maps for ecological, socioeconomic, geomorphologic factors, and alternative activity maps

Table 1. Examples of propositions used for different predictive applications.

The following section expands the concept of Favorability Functions for spatial data analysis and predictive modeling. Exploration and environmental security targets are only two aspects of a general task of spatial integration modeling.

3 FAVORABILITY FUNCTION MODELS FOR STRATEGIC TARGETING

Favorability Function, FF, is the term used to refer to a very general expression of the potential of a study area of containing resources (or alternatively of containing threats or impediments to such resources). The term was chosen to cover a property to be defined by the presence of spatial attributes that typically accompany the occurrence of resources (or of impediments). When such typicality can be extracted from a spatial database, mathematical models can be used to provide predictive strength to the integration of the spatial attributes, termed supporting patterns in the previous section. Chung and Fabbri (1993) (see also Fabbri and Chung, 1996) discussed several interpretations of FFs in terms of Bayesian probability, Zadeh's fuzzy sets and Dempster-Shafer evidential theory. Those interpretations provide a unified theoretical framework to predictive spatial data analysis. Also, they allow applications that adapt to the different degrees of information sufficiency and completeness. Applications to different prediction areas, from mineral exploration to landslide hazard zonation, have been discussed by Chung and Fabbri (1998; 1999; 2000), and Chung (1999). Here we want to discuss the basic strategy of FF models.

FF modeling is to optimize the use of available information for estimating the values, over a study area, that represent the degree of "sureness" in terms of probability, or possibility, or belief. Optimization is used here to refer to the adaptability of modeling to the different levels of expertise usable to characterize the occurrence of resources and of their settings. Chung and Fabbri (1993) introduced the relationships between probability, possibility and belief. The same authors later on (1998) discussed the relationships between three probability interpretations: Bayesian probability, certainty and weight of evidence. More recently (1999) they exemplified how the results of different interpretations and degrees of expert's knowledge introduction can be validated and compared.

Table 2 describes the strategy implied in FF modeling. The strategy is being applied to decision problems that require the introduction of geomorphologic spatial components to assess the environmental impact of transportation systems in geomorphologically active areas.

Step	Task	Description
1	**Preparation**	Consider a set of layers for a study of the occurrences of future events (or unknown objects) in a study area **A**. The target pattern represents the locations of the occurrences.
2		Select the direct supporting layer containing the locations of the occurrences of the past events (or known objects) in **A** and *m* indirect supporting layers containing the causal (or correlated) factors of the occurrences. Each indirect supporting layer consists of a number of mapping units and provides evidences for finding the target pattern.
3		Co-register all the layers using the georeference and select a FF model for analysis.
4	**Estimation**	Estimate FF values for all the mapping units in each layer by using: (i) the empirical frequency distribution functions between the mapping units and the direct supporting layer; or (ii) expert's knowledge; or (iii) combination of (i) and (ii). Whenever possible, obtain both (i) and (ii). Then compare the statistics in (i) with the values assigned to the functions by the experts in (ii). Make sure that these two corresponding values are compatible.
5		Compute unique-condition sub-areas by overlaying all the m indirect supporting layers. All points in each unique-condition sub-area have identical FF values.
6	**Integration**	Combine *m* FFs (one for each layer) by using the combination rules of the corresponding FF model. Each FF model has its own assumptions.
7		Apply the combination rules to the unique-condition sub-areas.
8	**Visualization**	To visualize the predicted values as a map, sort all predicted values (one for each pixel). At each pixel, replace the predicted value by its rank-order between 1 and N, the total number of pixels in **A**. Normally we re-scale the rank into the percentile value: multiplying the rank by 100 and then dividing it by N. Each pixel value ranges between 100/N and 100. Construct a pseudo-color look-up table for convenient study area percentiles, e.g., 0 - 0.5%, 0.5% - 1%, 1% - 5%, 5% - 10%, 10% - 100%.
9	**Validation**	Validate the prediction results obtained by **Steps 2-8**. For this step, the direct supporting layer is an essential component. The occurrences in the direct supporting layer are divided into two groups, **Group 1** and **Group 2** by: (i) time-periods; (ii) sub-areas; or (iii) random division. In **Step 2**, the occurrences in **Group 1** are represented in the direct supporting layer. Perform **Steps 3-8**. Compare the prediction results with the occurrences in **Group 2**. Construct the prediction rate curve and the statistics shown in the curve shows the validation results.
10	**Data mining**	Perform sensitivity analysis by using **Step 9 - Validation** technique to understand the input data. Some of the issues are 1. Selection of layers to the model; 2. Understanding the contribution of each layer to the model; 3. Differences in scales and "accuracy" of the layers; 4. Inter-correlation between layers; 5. Contradiction to expert's knowledge. This requires repeating **Steps 2 - 9** for each new combination of layers and supporting pattern configuration.
11	**Model testing**	Select different FF models and compare the prediction rate curve. This requires repeating **Steps 2-10** for each FF model and for each input data set.
12	**Field verification**	If results are satisfactory and indicate sub-areas worthy of further field verification, survey a conveniently small area with the highest predicted values. If results are unsatisfactory, reexamine the database and possibly construct a better one.

Table 2. General strategy in Favorability Function modeling.

Figure 1 shows how maps can be transformed into unique-condition sub-areas maps by overlays associated with the frequency of occurrence of resources and the complementary expert's knowledge into FF values. Confirmation of the goodness of the integration of the FF for several supporting pattern is based upon a validation pattern that consists of known resource distribution not used to compute the FF values.

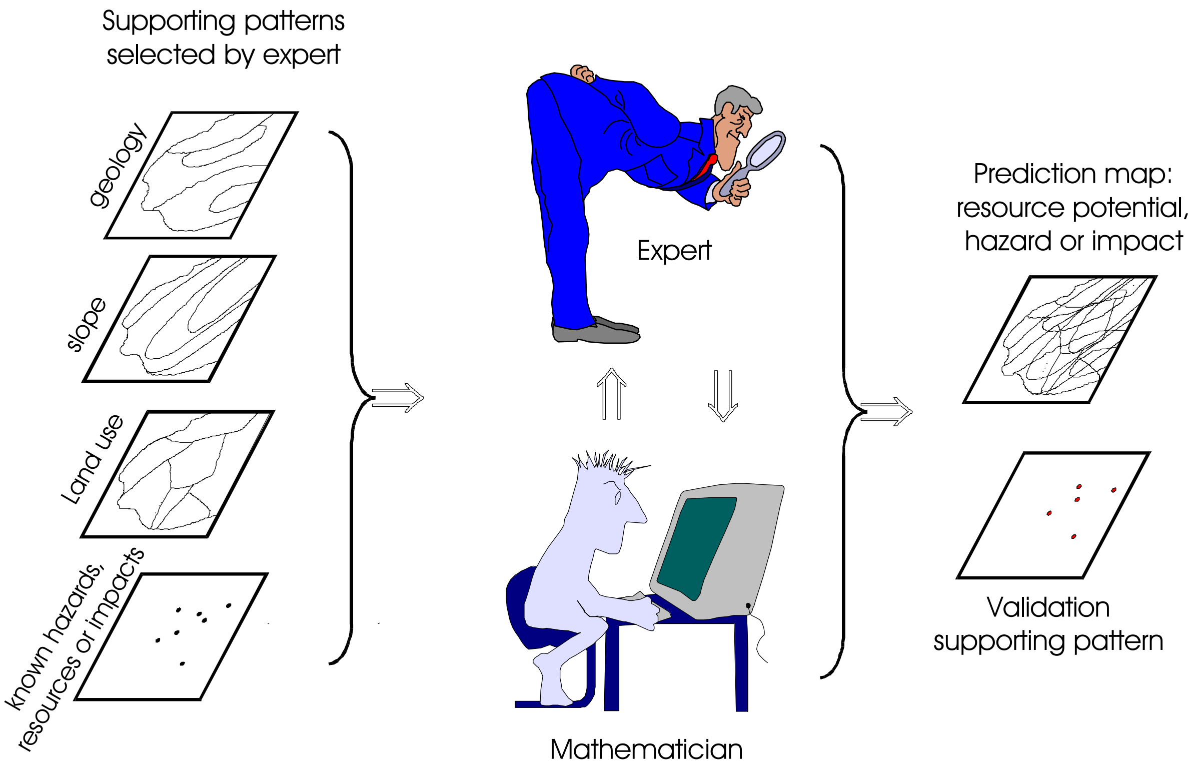

Figure 1: Prediction using both mathematical model and expert's knowledge.

4 EXAMPLES OF APPLICATIONS TO ENVIRONMENTAL MANAGEMENT

4.1 Introduction

This section introduces two case studies in Austria and Spain, respectively, where human activities related to transportation systems strongly interact with geomorphologic processes, resources and assets. To maintain sustainability, access to resources is to be secured and degradation of assets needs to be minimized. The decisional challenge is to identify alternative transportation systems or their modifications (possibly including impact mitigation measures) that correspond to lower and acceptably small environmental impacts. The case studies have been developed as part of the activity of GETS, a research network of the European Commission's Training and Mobility Programme. GETS is to link geomorphologic hazard, assets and resources to the environmental impact assessment of transportation systems in Europe.

4.2 The Sölden case study, Austria.

The suitability of ski runs and ski lifts in a mountainous area of the Austrian Alps, near the tourist resort village of Sölden, is the main concern of a case study in an active geomorphologic setting. The Alpine environment is rather sensitive to modifications of any kind, and natural hazards, in particular soil erosion, landslides, rock falls and snow avalanches frequently occur. Small changes, for example smoothing the surface roughness, or modifying the vegetation cover, may be followed by serious consequences such as triggering surface runoff. Natural hazards become risks as soon as people are involved.

The study considers the integration of bio-geophysical, social, and economic aspects for the identification and assessment of the impacts caused by skiing infrastructure development and the evaluation of hazard zones. Such integration is to become part of standard procedures in the planning of socio-economic infrastructures and the management of existing skiing facilities. Up to now, decisions regarding environmental aspects were mainly based on the legal framework and on the qualitative assessments of individual experts, without the employment of automatic and objective procedures and the use of spatial databases.

The study covers three tasks:
(1) the identification of the geomorphologic impacts (on processes, resources and assets) of the skiing infrastructures in terms of valuable surface loss;
(2) the assessment of the impact of the skiing infrastructures expressed as a decrease in biomass production of grassy vegetation; and
(3) the prediction of avalanches and the construction of a probability map of the distribution of avalanche trigger areas.

Potential areas for new ski runs and for mitigation alternatives are to be extracted from the impact maps to be generated..

A comprehensive database of 25m resolution was constructed for this study. It is based on digital topographic data, the interpretation of aerial photographs of different years, land use maps, geomorphologic maps, meteorological data, infrastructure development data from public offices and private companies, and systematic surveying of the study area in several field campaigns. The database contains spatially distributed data and associated tabular data processed by several different geographical information systems, statistical analysis and spatial simulation programs. For the database, an analytical “tool-box” is being constructed to be used by local administrations and skiing companies in the planning phase of new projects.

The analytical strategy is to predict the distribution of the individual geomorphologic hazards, including the avalanche-prone areas, and that of potential decrease of biomass production below acceptable levels. The supporting patterns are all extracted from the database. The prediction results will be estimations of the target patterns. The individual predictions will be further integrated into an impact map for each of the alternatives considered. Another target pattern contemplated, is a more general impact potential map for planning future alternative skiing facilities, their extensions and the mitigation of their impacts.

4.3 The Vitoria-Eibar case study, Spain.

The construction of a motorway linking the towns of Vitoria and Eibar in the Basque countryside of northern Spain is the project activity analyzed in the Spanish case study. The motorway is to provide a shorter and faster link between the northern Castilian plateau, the city of San Sebastián, and the French border. Goals of its construction are:
(1) providing better conditions of economic development in the area serviced;
(2) reducing congestion and accidents on another National I road; and
(3) improving environmental quality of the urban areas serviced.

Main concerns related with the potential impact of the planned motorway are:
(a) traffic increase and consequent increase of noise, air and water pollution and their effects on ecosystems and public health;
(b) introduction of a physical barrier between the two sides of the Deba valley, traversed by the motorway;
(c) visual impact in broad areas of rural character and of landscapes of fairly high quality;
(d) land occupation or degradation in areas of limited available land with high potential for use;
(e) destruction or damage to areas of high natural value or productivity; and
(f) interference with natural processes and hazards such as landslides, soil erosion and flooding.

Table 3 shows the strategic elements of the planned assessment of geomorphologic impacts in the Spanish case study. Geomorphologic processes, resources/assets, the database, the results of analytical processing and the expected output themes are listed in the table.

GEOMORPHOLOGICAL ELEMENT/PROCESS	DATA INPUT	PROCESSING	OUTPUT
RUNOFF/EROSION	DEM, rainfall, soils, geology, land cover	- Distributed hydrological model - Soil erosion model - Sediment transport model	CHANGES IN: - Soil loss - Stream flow - Suspended sediment load
SLOPE INSTABILITY	DEM, geology, surface materials, land cover	- Probabilistic models for SDI (Spatial Data Integration) - Scenarios	- Landslide susceptibility - Comparison of alternatives - Impact "prediction"
CONSUMABLE RESOURCES	Surface deposits (nature, distribution), population and road network, resource values, resource abundance	- "Economic loss" model	- Potential value loss
SITES OF GEOMORPHOLOGIC INTEREST	SGI type and distribution, population and road network	- SGI impact model	- Loss in SGI number and quality
LAND UNITS WITH HIGH POTENTIAL FOR USE	DEM, population and road network, integrated environmental units, hazards, geotechnical conditions	- Land value model	- Land area and value loss
LAND UNITS WITH NATURAL VALUE OR PRODUCTIVITY	Integrated environmental units, land cover, soil capability, protected areas, data on yield/productivity	- Land quality model - Productivity assessment	- Area, quality and potential productivity loss
VISUAL LANDSCAPE	DEM, population and road network, integrated environmental units, geomorphology, land cover, standard of reference for visual intrusion	- Visual quality model - Determination of visual basins - Generation of realistic views	- Visual impact magnitude and intensity

Table 3. Strategy for the assessment of geomorphologic impacts

General criteria of sustainability for the evaluation of specific impacts are based on several fundamental environmental factors according to a pressure-state-response (PRS) framework (Dumanski and Pieri, 1997). Indicators to measure or estimate sustainability with respect to those factors have been discussed by Cendrero and Fisher (1997).

Different impact prediction methods, data requirements, mitigation and compensation measures are being considered for several alternative routes, including modifications of the ones presently being contemplated in the study area. Besides the ranking of different alternatives, target patterns are the areas where general potential impact is below a conveniently chosen threshold for roadway planning. Such a threshold is to integrate the likely impacts on land resources, for instance hindering future uses due not only to the occupations of land units with high potential for other uses, but also due to the presence of the motorway in the vicinity of the resources.

4.4 Considerations on the case studies.

In both the case studies described, conflicts exist between goals and impacts, activities and processes. Spatially distributed data are available in digital databases to characterize quantitatively human and natural settings. Predictive models are to generate the spatial indicators of the environmental impacts. The integration of the impacts into manageable and understandable representations are the goals of the strategies that are to assist the various local administrations that contribute to the research and development activity.

5 ADVANTAGES AND LIMITATIONS OF THE PREDICTION STRATEGY.

The predictive strategy of FF modeling presents several advantages but also a number of limitations or constraints.

Amongst the advantages we can consider the following aspects:
1. it is focused on the isolation of spatial indicators and indices;
2. it provides criteria for transforming raw data into indicators using the FF;
3. it provides prediction power due to its theoretical foundations;
4. it offers validation techniques that make sensitivity and comparability analysis meaningful;
5. it allows to normalize the indicators so that they can be combined into indices that can be further combined into more complex aggregations;
6. it allows various “data-driven” and “model-driven” approaches to be combined; and
7. it also allows to understand the input data through "data mining", which consists of sensitivity and comparability analysis.

Amongst the limitations or constraints of FFs we can consider the following ones:
1. it requires interaction with experts who are willing to provide partial input to modify the statistics computed from the spatial database, or even to construct the value function completely;
2. it requires spatial expressions of all supporting patterns;
3. it requires to model the spatial relationships between the layers of supporting patterns and of the units within the layers;
4. not all environmental components and not all alternatives have convenient spatial representations;
5. it requires the isolation of the elementary spatial features necessary for the construction of indicators/supporting patterns;
6. it cannot deal with predictions in time, but it only indicates sub-areas worthy of further study at greater resolution;
7. a proper co-registration of all supporting layers using a georeference is not a simple task. In practice, this task has been overlooked.

6 CONCLUDING REMARKS.

We propose a general-purpose favourability function at the core of predictive modeling in space. A strategy for the application of such a function has to consider: (1) density of observations in space and in time; (2) coherence of indicators with the process to represent and predict; (3) validation of predicted patterns and comparability of different predictions; (4) introduction of expert’s knowledge in situations where data are incomplete or insufficient; and (6) visualization of complex predicted patterns in dynamic, possibly three-dimensional and multimedia interactive environments. An example of the strategy proposed here comes from a research project of the European Union that links geomorphologic hazard and environmental impact assessment in the study of transportation systems in Europe.

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