SPATIAL DATA ANALYSIS FOR THE ASSESSMENT OF SLOPE INSTABILITY; APPLICATION TO EIA FOR A CASE STUDY IN THE VERGARA-EIBAR AREA, GUIPUZCOA, SPAIN

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ABSTRACT

The assessment of both hazards and impacts of human activities on geomorphological processes must be based on a detailed analysis of terrain dynamics and behaviour, prior to the proposed new actions. Knowledge of former behaviour provides extremely useful clues for predicting probable impacts. In the case of slope instability processes, the analysis must include mapping of conditioning factors and past movements and identification of triggering factors.

This work presents the results of an analysis carried out in the Eibar-Vergara area. The analysis was based on the construction of digital maps for a variety of data layers. Thematic maps included the main conditioning factors of slope movements: surficial geology, geomorphology, DTM (from which several derivative maps were obtained), land cover, type and distribution of past landslides. Spatial data analysis was carried out by means of Favourability Functions, on the basis of statistical relationships between former movements and conditioning factors, to determine landslide susceptibility. The analyses were performed and tested through two types of comparisons: a) spatial comparison; a part of the study area was analysed and compared with another, used as test area; b) temporal comparison; movements prior to a certain date were analysed and later movements used as test group.

Landslide susceptibility maps thus obtained were then used as a basis for EIA of a proposed motorway. The least impacting alternative was selected through the intersection of potentially unstable areas and motorway routes. Using simple predictive models, based on a series of scenarios, potential impacts were estimated.

1 INTRODUCTION

The construction of transportation infrastructures can produce important impacts on slope instability. Those structures can affect hazard level, exposure and vulnerability and, therefore, risk level (Varnes, 1984). As shown by Cavallin et al. (1995) the interaction between a geomorphological process and a project can be both “passive” and “active”. This results in modifications of either “hazard level” (potential destructiveness of the natural process), element exposure (presence of persons/structures) or “vulnerability” (possibility of damage to human elements) or the three of them. Risk level is thus modified. According to this, impact on a risk could be expressed as:

$$I = R_{\textit{pre-project}} - R_{\textit{post-project}} \qquad (1)$$

Obviously, if risk with the project is higher the impact is negative. This concept is simple and clear, but its translation into operational, meaningful and quantifiable criteria is not.

A logical course of action would be to determine risks for the different parts of or land units in the study area (potential loss of life and property expressed in monetary terms), in the baseline situation. Then estimate those risks in the post-project situation and obtain the difference. This is normally not possible, even for the more or less known baseline conditions, much less for the future conditions implied by the project. Therefore, educated guesses or alternative procedures will be necessary in most cases.

An assessment of impacts on slope instability requires the prior knowledge of slope dynamics that can be obtained through the study of past (recent) activity. Detailed fieldwork and mapping off all movements and instability signs and conditioning factors is necessary, as well as the identification of age intervals for different groups of movements. The application of deterministic models is another possibility but this is not viable for large areas (Hutchinson, 1995) and for preliminary assessments, as is the case of most EIA studies.

Using another approach, it is possible to perform other kind of analysis to estimate landslide susceptibility and produce slope instability hazard maps. Different methods have been developed and tested in the past. Among others, those normally called statistical or probabilistic methods, provide satisfactory quantitative hazard maps. Interesting reviews and classifications of existing methods are available in Hansen (1984), Hartlén&Viberg (1988), Yan (1988), Gee (1991), Crozier (1995).

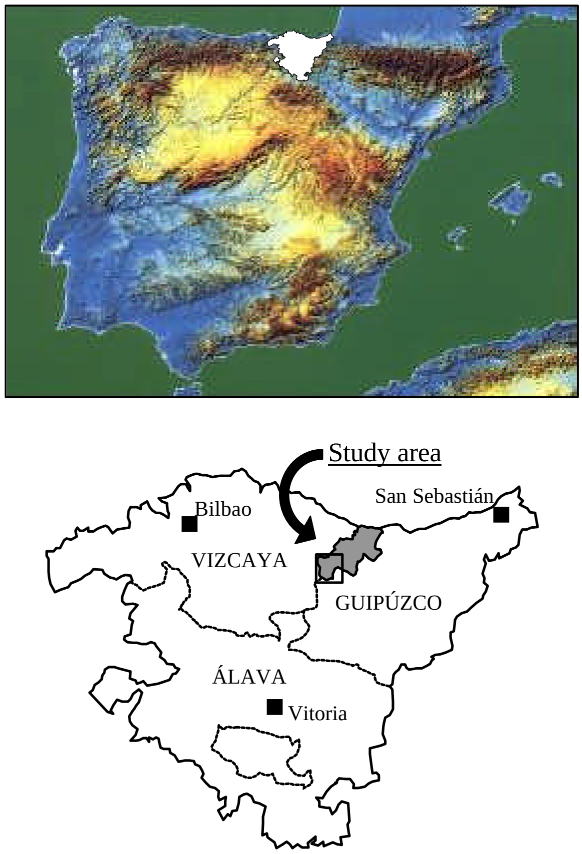

Figure 1. Location map.

SDA methods developed during the last decade on Geographical Information Systems (Bonham-Carter, 1994) offer the possibility to apply probabilistic models that enable a satisfactory determination of potential instability. Slope instability or landslide susceptibility maps thus obtained can be used as a basis for impact assessment and prediction.

A quantitative methodology for the assessment of slope instability and its application to impact assessment on slope processes is described and its application to a case study (a new motorway in northern Spain; Figure 1) presented.

2 METHODOLOGY

The methodology proposed is shown in Figures 2 and 3, which represent two distinct stages in the application of the method.

2.1 Data Used

A database of 16 thematic layers (insolation, rugosity, curvature perpendicular to slope gradient, curvature along slope gradient, general curvature, average slope gradient, basin length, upstream area, aspect, slope gradient, upstream surfacial formation length, upstream surficial formation area, lithology, surficial formation thickness, vegetation and mass movements) was used. The main layer -corresponding to past terrain behavior- is the one representing mass movements ("past slope instability signs"). Out of the 16 data layers, 10 are directly derived from DEM; the other 6 must be totally or partially obtained through air-photo interpretation and field work (unless, of course, the corresponding thematic maps are already available). It can easily be appreciated that certain variables represent terrain geometry, others type of surface materials (including land cover) and a third group “hydrologically significant” factors. That is, a series of conditioning factors (and to a certain extend, triggering factors) which, in principle, determine shallow landslide occurrence; this type of landslides are practically the only ones occurring in the area and the ones relevant for EIA assessment.

The total population of “instability signs” is split into two, one for analysis and the other for validation; the latter phase is crucial for the whole process. Pre-processing, including error-filtering, derivation of new data layers from DEM, analysis of dependency relationships and categorization of continuous variables (Figure 2), must be carried out.

2.2 Prediction Model

In order to analyse spatial data consisting of different patterns (points, lines, polygons) and attribute data of different nature (qualitative and quantitative, yes/no type, continuous and discrete, etc.), Chung and Fabbri (1993) have introduced the Favourability Functions (FF) method. In this work two mathematical frameworks, based on FF, have been applied to the design of the prediction raster model: a) Probability theory (Conditional probability function, Certainty function, Weights of evidence); b) Zadeh’s fuzzy set theory (Fuzzy membership function).

The models were applied to specific types of slope movements and are based on the following assumptions: a) future movements of a given type will occur in the future under circumstances similar to those in the past; b) all conditioning factors are known and included in the database; c) all past movements for the period analysed have been identified and included in the map of instability signs. Of course, these assumptions might not be totally correct; validation at the end of the process should determine their correctness.

The operating steps for the application of the model are: a) creation of unique condition sub-areas by overlay off all thematic layers; b) estimation of FF by means of bivariate relationships between map of past movements and individual thematic layers; c) integration of bivariate tables; d) re-classification of study area into 200 susceptibility classes (each one with 0.5% of the final values).

In order to estimate the conditional probability, which is necessary to build the models described under the Probability Theory, the following function was used:

$$Favorability\_value = 1 - \left(1 - \frac{1}{S_T}\right)^{S_M} \qquad (2)$$

where:

S_T = Total area of map unit.

S_M = Area of map unit affected by mass movements.

For the Fuzzy model it was assumed that the estimator for computing conditional probability is also valid as fuzzy membership value. The Fuzzy Membership Function was thus built by using the Gamma operator:

$$m_z = \left[\prod_{k=1}^{n} m_{zk}\right]^{1-g} \left[1 - \prod_{k=1}^{n}\left(1 - m_{zk}\right)\right]^{g} \qquad (3)$$

where:

m_z = Fuzzy Membership Function (Gamma operator).

$m_{zk} = m_{z1}, m_{z2}, \dots, m_{zn}$ = Fuzzy membership values for units in the different thematic layers.

$0 \leq g \leq 1$

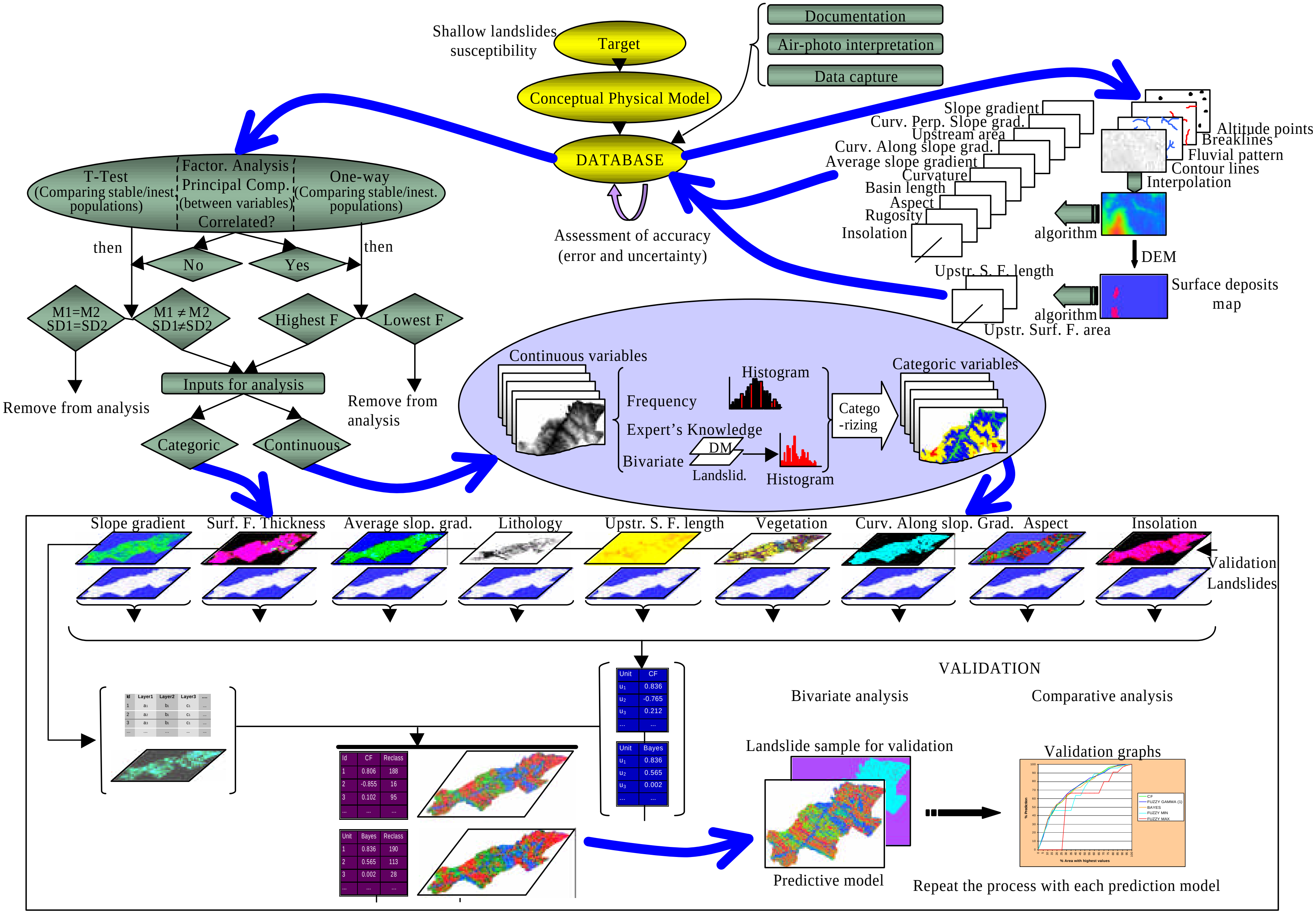

Figure 2. Methodological flow diagram; landslide susceptibility assessment

2.3 Validation

The susceptibility maps obtained represent a hypothesis that must be validated. Validation can be made by: a) splitting the study area into two (analysis and control); b) splitting past movements into two time groups ("older" for analysis and "younger" for control); c) random split of landslide population into analysis and control groups; d) variations on the above methods.

All three methods have been tried and give results which are quite similar. Roughly speaking we can say that 20% of the pixels analysed (those with susceptibility values above 160) explain about 60% of the movements occurring in the control groups.

The result of the initial application of the method to a part of the study area is presented at the end of the flow diagram of figure 2 (map of landslide susceptibility and cross validation diagram). The best results were obtained with the fuzzy membership gamma function model.

The cross-validation diagram shows the percentage of movements explained by the model (ordinates) in relation to percentile susceptibility values (abscissa; 0-200). Expressed in sinple terms, the further away the graph is from the diagonal line, the better the predictive value of the model.

Landslide susceptibility maps thus obtained represent a firm, quantitative and validated basis on which the next step of the method described can be soundly based.

3 IMPACT ASSESSMENT

The above analysis represents the basis for the second step of the methodology: impact prediction and assessment.

Impact indicators considered in this analysis were: a) absolute or relative length of motorway intersecting high-instability zones (particularly relevant for comparing alternatives); b) km of motorway potentially affected by movements not influenced by it; c) area likely to be affected by movements triggered by the road (extent, intensity). Other possible indicators are: relative change in landslide susceptibility as a result of landform and surface material modifications (per pixel; for the whole road); number of new movements likely to be triggered by the road; km of road in which significant decreases of the safety factor of slopes would take place.

It is obvious that the performance of the solution chosen (from the geomorphological point of view) will be good, acceptable or bad, if the rate of future movements is respectively lower, similar or higher than in the past. The latter rates can easily be determined but future ones must be estimated, as they correspond to a new situation.

The assessment of impacts has been carried out by means of an empirical model based on the analysis of past terrain behaviour (a few decades) reflected on the distribution and temporal occurrence of past movements. Figure 3 shows the methodological flow diagram of this stage of the analysis. The relative impact of different alternatives can be easily compared; the best alternative is the one which intersects the lowest number of "high instability " pixels (Table 1).

Impact "prediction" is more difficult. A scenario approach has been initially used. The following scenarios have being considered: a) all pixels with a certain level of susceptibility will actually experience slope movements triggered by the new road, within a certain time interval and the run and reach of movements will be similar to the maximum ones occurred during the control period (the few decades covered by aerial photographs); b) only a small percentage of pixels with the maximum potential instability will experience movements in the projected period and the area affected by them will be equivalent to the one affected by past small movements; c) realistic; the percentage of "unstable" pixels affected during the projected period will be the same and the size of movements similar to the average during the control period.

Data on damages due to past movements can be used to calculate potential losses for each scenario. This can be done, again, through the consideration of new scenarios (maximum, average and minimum damage per movement in the past) or by intersection between the "affectable areas" obtained using the scenarios above and the "elements" and "vulnerability" in the area. An alternative procedure is to determine changes in landslide susceptibility as a result of landform and surface material modifications, using the quantitative model described for the first step.

The procedure followed to quantitatively compare the impacts of alternative routes is illustrated in Figure 3 and Table 1. A width of 25 m from the axis of the motorway has been defined as the affected strip. The routes are only for testing the method and do not necessarily correspond to project alternatives.

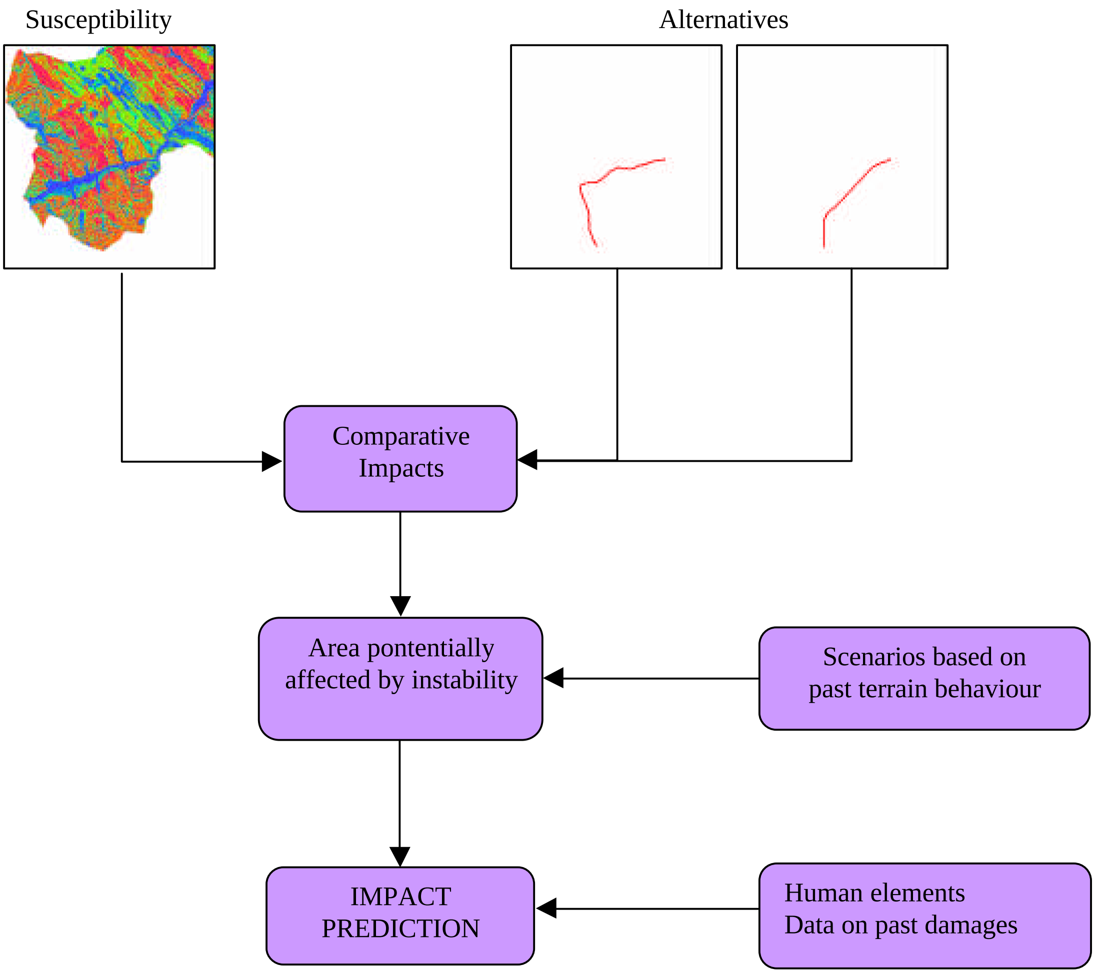

Figure 3. Methodological flow diagram; impact assessment/prediction.

As shown in Table 1 a final “impact” value for each alternative is obtained by adding up, for all pixels affected, the product susceptibility x area. The higher this value, the greater the impact. In the example shown, alternative 2, although affecting a much smaller number of pixels, has about twice the “impact value”.

INTRSECTION altern./suscept.	**ALTERNATIVE**	**SUSCEPTIBILITY CLASS**	**No. PIXELS**	**AREA**	**SUSCEPTIBILITY x AREA**
alternative1*1	alternative1	1	8	800	800
alternative1*2	alternative1	2	4	400	800
alternative1*3	alternative1	3	1	100	300
...	...	...	...	...	...
alternative1*196	alternative1	196	3	300	58800
alternative1*197	alternative1	197	10	1000	197000
alternative1*198	alternative1	198	8	800	158400
alternative1*199	alternative1	199	1	100	19900
alternative1*200	alternative1	200	5	500	100000
TOTAL			2757	275700	12096900

Table 1a. Data derived through overlay of susceptibility map and motorway alternative 1.

INTRSECTION altern./suscept.	ALTERNATIVE	SUSCEPTIBILITY CLASS	No. PIXELS	AREA	SUSCEPTIBILITY x AREA
alternative2*1	alternative2	1	1	800	100
alternative2*2	alternative2	2	2	200	400
alternative2*3	alternative2	3	2	200	600
...	...	...	...	...	...
alternative2*196	alternative2	196	14	1400	274400
alternative2*197	alternative2	197	6	600	118200
alternative2*198	alternative2	198	5	500	99000
alternative2*199	alternative2	199	9	900	179100
alternative2*200	alternative2	200	2	200	40000
TOTAL			2058	205800	26497500

Table 1b. Data derived through overlay of susceptibility map and motorway alternative 2.

Impact "prediction" for a given alternative is illustrated in Figure 4. Motorway sectors affecting pixels of landslide susceptibility above 190 (out of a maximum value of 200) are identified. The three scenarios described above have been applied to obtain three possible "impact maps". Intersection of these maps with the map of human elements, together with data on past landslide damages can be used to express impacts in terms of "potential losses".

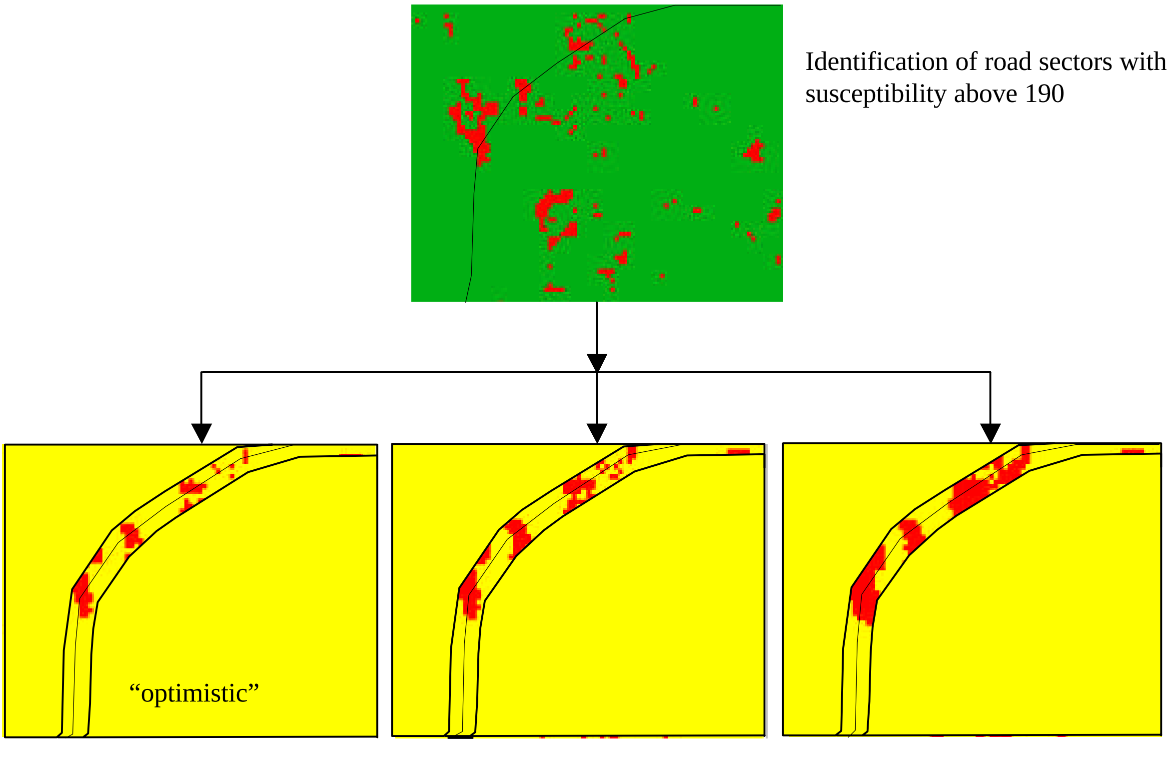

Figure 4. Impact prediction maps derived through the application of scenarios based on the historical analysis of instability.

4 CONCLUDING REMARKS

The method proposed provides satisfactory and validated landslide susceptibility maps. These maps can then be incorporated into impact assessment and prediction. Impact comparisons and predictions can be made in quantitative terms. It must be pointed out that susceptibility, although directly related to probability, should not be considered as such from the mathematical point of view. The "total impact value" obtained is thus a dimensionless figure. Similarly, "potential losses" have the meaning of "average losses" for a given period of time and for each scenario. These figures are useful for comparing impacts on slope instability processes with other impacts, but should not be interpreted as a prediction of actual monetary losses.

The reliability of the approach proposed depends, obviously, on the amount and quality of the data available. Nevertheless, with just a DTM and a bedrock/surface deposits map useful results can be obtained.

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