INFORMATICA, 2001, Vol. 12, No. 1, 25–44

GIS and Multicriteria Analysis to Evaluate and Map Erosion and Landslide Hazards

Anna CAVALLO
CSI- Piemonte, Direzione Territorio e Ambiente
Corso Unione Sovietica 216, 10134 Torino, Italy
e-mail: anna.cavallo@csi.it

Maria Franca NORESE
Dipartimento di Sistemi di Produzione ed Economia dell'Azienda, Politecnico di Torino
Corso Duca degli Abruzzi 24,10129 Torino, Italy
e-mail: norese@athena.polito.it

Received: November 2000

Abstract. A rich georeferenced data base on a flood event in the north west of Italy and the knowledge of experts from the different involved disciplines have been used as the basis for the application of an outranking method, ELECTRE III, oriented to the structuring and validation of consistent multicriteria models for hazard evaluation. The models were developed with the aim of explaining the multidimensional nature of slope instability and erosion phenomena in the study area and to help in the definition of a hazard map using criteria which synthesize different interpretations of these phenomena. The integrated use of multicriteria modeling and data analysis, in a GIS analysis context, resulted in a deeper insight into these natural phenomena and could be the proposal of a more 'flexible' information system oriented towards decision aiding.

Key words: multicriteria decision aid, knowledge structuring, ELECTRE III.

Introduction

In 1994 the Langhe, an area located in the southern part of the Piedmont Region in Italy, was subject to a severe flood. The natural processes that induced remarkable slope instability and erosion phenomena in this area have been analyzed in the context of a European Community Environment Program. The study has been developed to analyze the effect that several natural factors have on slope instability and to apply integrated techniques (such as remote sensing and differential interferometry), at a regional scale, to establish the intrinsic slope hazard state and to determine slope hazard thresholds, which are essential elements of knowledge for the management of natural and human resources.

During the first year of the project many different types of information were collected, in relation to morphology and topography, meteorology, land use, infrastructural data, geology and pedology. CSI-Piemonte, one of the Italian partners in the European project, provided the first five data sets in order to generate and store them in a Geographical

Information System (GIS) framework, while, as far as the last data sets are concerned, CSI was only involved in the storing and acquisition in a GIS environment.

In the second year this information base was analyzed in order to evaluate and map erosion and landslide hazards. The data base, which was elaborated in relation to the global study area, is large and can be studied using statistical techniques. This approach has been adopted by another partner in the European project, who has chosen the multivariate analysis to identify the factors which clearly distinguish areas at different erosion and landslide hazards. The CSI-Piemonte group has focused on a *pilot area* of a very limited size, which was however severely damaged by erosion and landslide phenomena in 1994 and which then became the subject of study and particular analyses that produced detailed knowledge on some relevant factors (1:25.000 scale for the pilot area and 1:50.000 or 1:100.000 for the study area). In relation to this information base, the CSI-Piemonte group decided to develop a multicriteria analysis and integrated this into a GIS analysis.

The two different approaches and the related analyses (the multicriteria analysis in relation to the pilot area and the statistical analysis in the study area) have been developed with the same aim, that is, to structure useful knowledge elements on this complex multidisciplinary phenomenon and on the management of this environmental problem. The knowledge of slope instability and erosion phenomena is rich, but dispersed and not globally defined or accepted and operationally structured. Specialists from different related fields (geology, geomorfology, lithology, pedology and so on) proposed several interpretations of the same phenomenon and suggested the use of different indicators. In the second phase of the project the main aim is that of facing and reducing this complexity, at least in relation to two geographic regions (one, the Langhe, in Italy and the other in Greece) that are similar, in terms of lithological structures and the presence of frequent and catastrophic natural events. The formulation and validation of consistent modeling hypotheses become the object of this project phase.

The adoption of two different approaches allows a comparison of the results, which may be useful to verify the robustness of this structuring and modeling process and the hazard map quality. At the same time the integration of these approaches within a GIS framework can be seen as a methodological proposal. The GIS analysis integration with statistical analysis procedures (when the data base is enough large) or multicriteria methods (when the data base is limited but accurate analyses allowed the development of detailed knowledge) could make a GIS application more flexible. A GIS analysis, if integrated with a procedure of data analysis and structuring, can be usefully developed when data are available but the decision context cannot indicate how these data have to be used to produce information and support decisions. An application of multicriteria decision aiding has been developed with this last aim in mind, whose basic elements are presented in the next section. The main modeling difficulties related to the problem, the principal elements of the multicriteria models and of the adopted decision-aid procedure are discussed in Section 2.

1. Problem Formulation and Modeling Approach

GIS is a software and hardware system that is designed to capture, manage, manipulate, analyze, model and display spatially-referenced data to solve complex planning and management problems, especially those concerning the natural environment (Maguire *et al.*, 1991). GIS, which combines computer graphic techniques and data bases, can become a platform which integrates knowledge and expertise from different disciplines and which is easily integrable with analytical techniques, such as remote sensing, interferometry, statistics and also operations research and management science (Fischbeck, 1994). Optimization techniques have been successfully integrated with GIS technology for route planning and facility location and multicriteria methods are useful within a GIS framework, with special reference to their joint use as a largely self-contained methodology for site selection and decision support (see for instance Janssen and Rietveld, 1990; Carver, 1991; Joerin, 1995; Laaribi, 1995).

The problem situation that in this case requires a strong connection between analytical techniques and GIS technology has to be seen in a global context of *knowledge structuring*. A rich data base is the result of acquisition processes which are related to the different involved fields (mainly geology, geomorfology, lithology, land use and pedology) and their different logics. The geological view of the problem is different from the lithological or the pedological one and the acquisition process may reproduce the action of a multiplicity of different but not integrated processes. The resulting data base can present a strong redundancy of information elements which are included in the elaborated indicators with different and perhaps conflicting meanings.

As second critical element, the data are related to areas that have been subject to a severe flood which induced different phenomena, such as erosion features, surface mass movements and mass movements involving the parent rock. A clear distinction between the different phenomena does not exist in literature and therefore it is not so easy to identify all the specific significant factors for each phenomenon. Furthermore, a complete distinction between the different phenomena does not exist even in reality because the involved areas often present erosion and different types of slope instability. This situation induces a new criticality in the data base use, mainly because the official project aim is the elaboration of a hazard map.

In relation to a part of the global study area, *the pilot area,* the data base can be integrated with the results of an accurate in situ analysis of the field that allowed the definition of the damage inventory with a 1:10.000 scale map and the collecting of specific information elements. A multicriteria decision aid (MCDA) application can be developed, in relation to this information base, to integrate all these elements in a structured model which can be used in a GIS analysis, as a support for an “environmental risk management” action. The information elements and the detailed inventory of the pilot area damage can be used as a reference for the analysis, firstly to distinguish areas characterized by only one elementary slope instability type and then to test the modeling hypotheses (criteria which represent the significant factors of each phenomenon and the different importance of each criterion/factor) and their results.

A multicriteria decision problem is a situation in which, having defined a set A of actions and a consistent family F of criteria on A, one wishes (Roy, 1996):

- to determine a subset of actions that are considered to be the best with respect to F (choice problem),
- to divide A into subsets according to some norms (sorting problem),
- to rank the actions of A from best to worst (ranking problem).

In this case, a set A of comparable actions can be identified as the subset of areas which are characterized by only one (and the same) phenomenon type (*homogenous units*). The units can be ranked from higher to lower landslide hazard and then compared with a measure of their actual criticality level, in terms of involvement in the phenomenon area or percentage, and then with their ranking from the most to the least damaged during the flood, as can be deducted from the inventory. The main factors that induce slope instability and erosion are easily deducible from the literature on this subject. The criteria that represent all the significant factors for each phenomenon can easily be deduced. The problem is their validation, i.e., the testing of their coherence, in terms of exhaustiveness, cohesiveness and nonredundancy, legibility and operationality. The second problem is the conformity of the acquired data to these criteria. The data base is the result of the first year research project; it is an important resource and should however be used.

In real-world studies, defining possible actions and coherent criteria represents the greatest part of the analyst's work (Bouyssou, 1990; Norese, 1996). Very often, the search for a legible, operational and coherent family of criteria leads the analyst to reconsider the definition of some criteria, to introduce new ones into the family and to aggregate some of them. Thus the choice of a coherent family of criteria interacts with the construction of the various criteria. When the analyst gradually progresses towards the elements that are necessary to solve a problem, some initial data can cease to be pertinent, others may appear, new questions may be substituted for the original ones, even though the initial problem has not fundamentally changed (Roy, 1993). If the nature of the actions and/or the problem statement partially or globally change(s), the dimensions and criteria of the previous model have to be re-analyzed because they can change nature or meaning, but are always an essential and formalized information base and enable one to move more easily towards a coherent family of criteria.

An outranking method (ELECTRE III, Roy, 1978; 1990), which ranks actions from best to worst in relation to a preference system, is here used to test different modeling hypotheses, in terms of several sets of criteria and importance coefficients in relation to different sets of possible actions. Changes in the hypothesis formulation process arise from the analysis of critical deviations between the ELECTRE application results and reality. Critical deviations induce a phenomenon re-examination until a new modeling hypothesis is defined.

This interactive use of ELECTRE III allows the model to gradually progress towards a convergence on the specific phenomenon explanation; some initial elements, which are suggested in literature, cease to be pertinent because inconsistencies in the results or between results and reality have been collectively examined and compared with these elements. Others are then inserted with the proposal of a new reading of the phenomenon; the logical and operational validity of these new modeling hypotheses have to be tested by the involved experts. At each marginal change, criteria and importance coefficients of the previous model have to be globally re-analyzed. When the results are almost good, because they globally fit the "picture" of the flood event consequences, but are not yet completely consistent, residual critical elements and, finally their codes in the GIS are directly examined by experts and sometimes by a person who has developed an accurate analysis in the field. Code re-definition in the data base is sometimes an indirect result of this model-in situ analysis comparison.

1.1. *Action Definition*

The first procedural step in multicriteria modeling is that of problem bounding and action definition. The main elements which characterizes the area that have been subject to a flood event are derived from field surveys and allow one to formulate a specific classification of the phenomena which are present in the pilot area. Two phenomena are chosen to perform separate analyses. They are *erosion features* (type I phenomenon) and *mass movements involving the parent rock* (type III) and have been chosen because they are considered as the most "different" in the classification, as type I phenomenon usually involves only the surface while type III also involves the parent rocks. In order to define a set of actions for each separate analysis, different homogenous units are identified from the geographical point of view. They present one and only one value for each of the considered terrain factors and are characterized by the presence or absence of terrain movements and by an associated data base which includes all the terrain factors. These homogenous units, called multi-thematic units (MU), were generated using typical GIS procedures, such as map overlay, and the procedural steps have been: intersection of all the coverages which represent each considered factor, mean value calculation of some factors that refer to the new units and association of the terrain movements to the involved MU. There are 5 600 MU in the pilot area and 33 MU are related to the different events involved in the phenomenon defined as *erosion features* (or type I phenomenon); there are 146 units involved in type III phenomenon (*mass movements involving the parent rock*) but only 127 are characterized by the presence of a damaged area percentage that is greater than 10%. The percentage of damaged area contained in the MU is used to grade the units from the most to the least critical.

Two multicriteria models have been developed to represent type I and type III phenomena and the MU are considered, in these models, as two sets of *actions* that can serve as application points for this specific decision aid (Roy, 1996) which is oriented to structure the available knowledge of the relationship between natural factors and slope instability and to establish the intrinsic slope hazard state of each MU. The 33 actions related to the type I model and the 127 to the type III model are presented in Tables 1 and 2 and are characterized in terms of damaged area identifier and surface measurement, MU area and percentage of damaged area contained in the MU.

Table 1

Type I sample

Action	Erosion phenomenon		MU	MU/Slope
	Identifier	Area	Area	% area
1	220	1695.117	1695.117	100%
2	121	778.000	778.000	100%
3	204	662.406	662.406	100%
4	0	44.945	44.945	100%
5	190	933.180	933.180	100%
6	214	1761.547	1761.547	100%
7	221	633.953	633.953	100%
8	224	865.844	865.844	100%
9	228	671.516	671.516	100%
10	179	1024.477	1013.273	99%
11	180	1241.336	1198.562	97%
12	213	690.336	626.758	91%
13	215	932.086	740.852	80%
14	208	1222.523	689.969	56%
15	192	1032.500	530.547	51%
16	324	3570.852	1629.422	46%
17	212	1097.320	416.766	38%
18	212	1097.320	410.195	37%
19	208	1222.523	396.852	33%
20	192	1032.500	324.625	31%
21	324	3570.852	879.758	25%
22	324	3570.852	797.742	22%
23	215	932.086	193.305	21%
24	192	1032.500	174.914	17%
25	212	1097.320	164.055	15%
26	208	1222.523	136.102	11%
27	213	690.336	62.859	9%
28	212	1097.320	91.734	8%
29	324	3570.852	220.516	6%
30	180	1241.336	36.906	3%
31	324	3570.852	46.328	1%
32	179	1024.477	10.781	1%
33	180	1241.336	13.648	1%

1.2. *Dimensions and Criteria*

The second important step in multicriteria modeling is the definition of all the *dimensions* (Roy, 1996), i.e., all the points of view that are considered important and significant to model slope instability and erosion phenomena from all the involved methodological fields, and then of the coherent *criteria*, that is, the tools which allow one to compare

Table 2

Type III sample

Action	Mass movement		MU	Slope/MU
	Identifier	Area	Area	% area
1	471	1082.41	1082.41	100.0%
2	429	3962.16	3962.16	100.0%
3	374	1379.01	1379.01	100.0%
4	428	2154.56	2154.56	100.0%
5	202	1191.38	1191.38	100.0%
6	481	2870.27	2870.27	100.0%
7	524	1174.21	1174.21	100.0%
8	217	2085.50	2085.50	100.0%
9	538	6083.60	6095.79	99.8%
10	504	2937.69	2946.53	99.7%
11	502	12366.75	12453.93	99.3%
12	244	5552.09	5642.37	98.4%
13	155	1133.03	1162.08	97.5%
14	216	2199.59	2298.43	95.7%
15	527	11421.79	11972.53	95.4%
16	411	1127.17	1189.00	94.8%
17	117	3810.28	4044.88	94.2%
18	306	1840.66	1994.21	92.3%
19	325	1763.92	1932.01	91.3%
20	410	812.38	920.02	88.3%
21	311	2631.84	3099.92	84.9%
22	262	3801.23	4652.67	81.7%
23	536	23060.17	28469.35	81.0%
24	427	19536.48	24390.12	80.1%
25	205	7644.97	9580.16	79.8%
26	188	42874.30	57395.31	74.7%
27	528	7134.70	9602.56	74.3%
28	219	1681.84	2348.94	71.6%
29	414	5631.99	8045.70	70.0%
30	245	10695.79	15367.51	69.6%
31	519	7546.88	10905.90	69.2%
32	211	42011.13	60885.70	69.0%
33	209	1170.97	1745.11	67.1%
34	473	902.39	1352.91	66.7%
35	529	36683.97	56436.88	65.0%
36	535	15981.20	24777.05	64.5%
37	149	1647.75	2558.62	64.4%
38	175	1773.50	2970.69	59.7%
39	430	3188.21	5367.36	59.4%
40	413	2468.24	4162.30	59.3%
41	474	1673.04	2869.71	58.3%
42	201	7971.31	13696.41	58.2%
43	475	4047.51	7014.75	57.7%
50	426	94434.20	192330.35	49.1%
51	323	2629.64	5455.69	48.2%
52	514	3926.97	8319.85	47.2%

To be continued

Continuation of Table 2

Action	Mass movement		MU	Slope/MU
	Identifier	Area	Area	% area
53	261	7741.37	16470.99	47.0%
54	152	3402.28	7543.86	45.1%
66	540	26273.73	68779.39	38.2%
67	430	3188.21	8782.95	36.3%
68	149	1647.75	4602.65	35.8%
69	239	18310.27	51723.94	35.4%
70	535	15981.20	45401.12	35.2%
71	206	37284.47	107448.04	34.7%
72	323	2629.64	7600.12	34.6%
73	475	4047.51	11939.55	33.9%
74	261	7741.37	23893.11	32.4%
75	239	18310.27	56513.19	32.4%
76	473	902.39	2837.71	31.8%
77	209	1170.97	3890.26	30.1%
78	510	11361.45	37998.14	29.9%
79	210	2585.00	8913.79	29.0%
80	210	2585.00	8913.79	29.0%
81	152	3402.28	11979.86	28.4%
82	540	26273.73	92513.12	28.4%
83	194	4348.03	15364.07	28.3%
84	472	1259.31	4681.46	26.9%
85	175	1773.50	6642.32	26.7%
86	245	10695.79	40361.47	26.5%
87	529	36683.97	140551.61	26.1%
88	414	5631.99	23864.37	23.6%
89	211	42011.13	179534.76	23.4%
90	510	11361.45	48553.18	23.4%
91	201	7971.31	36565.65	21.8%
92	528	7134.70	33184.67	21.5%
93	413	2468.24	11697.83	21.1%
94	261	7741.37	38134.81	20.3%
95	433	4707.57	23537.85	20.0%
96	157	3368.38	16841.88	20.0%
97	519	7546.88	38115.57	19.8%
104	188	42874.30	243603.96	17.6%
105	194	4348.03	24704.72	17.6%
106	472	1259.31	7451.55	16.9%
107	263	18216.60	111076.84	16.4%
108	427	19536.48	122103.03	16.0%
121	410	812.38	6769.79	12.0%
122	432	5651.18	47093.17	12.0%
123	219	1681.84	14374.74	11.7%
124	432	5651.18	48300.68	11.7%
125	519	7546.88	66200.73	11.4%
126	206	37284.47	338949.72	11.0%
127	239	18310.27	171124.05	10.7%

actions according to a particular problem dimension, the operational counterpart of a specific point of view (aspect, factor, characteristic). In the context of slope instability, five different dimensions can represent the multiplicity of the relevant elements. For each dimension one or more relevant factors could be transformed into criteria.

The first dimension is that of "Land use". The vegetation cover and its use can positively or negatively effect the stability of a slope, surface erosion and therefore soil preservation. The distribution of disorders compared to the distinct land use classes (see Fig. 1) makes the difference between the type I and type III phenomena evident, but it is not sufficient to define the real criticality of these classes in relation to the slope instability and erosion phenomena. For example, classes such as 322 (moors and heath land) or 324 (transitional woodland shrubs) are considered very critical even though they are characterized by a low percentage of disorders in the studied area; a multiplicity of factors, such as specific cultivation patterns and an agricultural calendar, can directly influence slope phenomena especially those of type III. A *Land use* criterion can be defined in relation to this dimension and an expert judgment becomes fundamental to create the ranking of Land use classes from more to less critical.

The second dimension is "Litho-Geology" which constitutes a relevant factor, mainly for mass movements that involve parent rocks (type III phenomenon). The relationship between the slope occurrence and different geological and lithotechnical classes is shown in Fig. 2. A *Lithology* criterion can be defined; the mass movement (or erosion) occurrence, the lithology of formations and an expert judgment allow the ranking of lithological classes from more to less critical. In relation to the same dimension, another relevant factor, for only mass movements that involve parent rocks, is the strata dip direction. This information, which represents the dip direction of geological strata to the topographical dip, allows one to distinguish reverse scarp slopes, which are less susceptible to mass

	Land Use Classes	Type I Percentage	Type III Percentage
21	**Arable land**		
	Non irrigated arable land	30.30	19.49
22	**Permanent crops**		
	Vineyards	6.06	4.24
	Hazelnuts	21.21	6.78
23	**Pastures**		
231	Pastures	9.09	14.83
24	**Heterogeneous agricultural areas**		
242	Complex cultivation patterns	18.18	15.25
243	Land principally occupied by agriculture, with significant areas of natural vegetation	3.03	9.32
31	**Forest**		
311	Broad-leaved forest	12.12	27.97
32	**Shrub and/or herbaceous vegetation associations**		
322	Moors and heath land	0.00	0.42
324	Transitional woodland shrub	0.00	0.85
33	**Open space with little or no vegetation**	0.00	0.85
331	Beaches, dunes and sand plains	0.00	0.85

Fig. 1. Landslide and erosion (percentage distribution) with respect to Land Use classes (nomenclature defined in the Land Cover project of the European program CORINE).

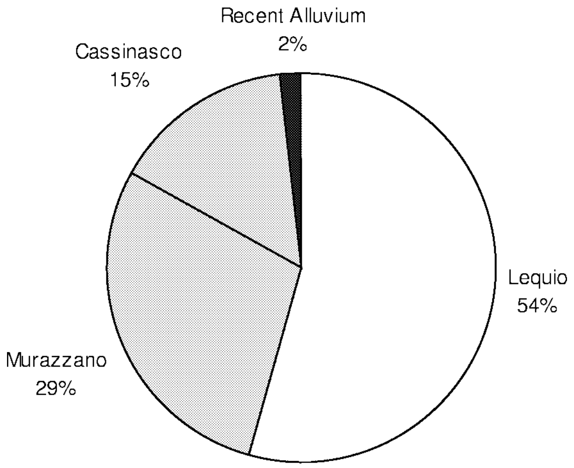

Fig. 2. Mass movement occurrence on different geologic formations, in the pilot area.

movements that involve parent rocks, from dip slopes. A strata dip direction, according to experts, can be considered critical when it is parallel to the topographical dip, and not susceptible to hazards when it is perpendicular. A *Stratigraphy* criterion can be defined for this factor.

The third dimension is "Morphology". Morphological factors, such as slope geometry and basin characteristics, provide fundamental information on landslide and erosion processes. Characteristics such as slopes, exposures and convexities are the result of elevation data handling using GIS techniques. Slopes represent a morphological factor that is critical for the two considered phenomena, therefore a *Slope* criterion could be defined. As far as erosion is concerned, a study of the phenomenon distribution has been performed on exposure classes (see Fig. 3). Erosion features generally lie on slopes that are characterized by the same exposures (North West and West) which are the most representative of cuestas backs, the morphological form that is usually affected by this kind of disorder. Exposure cannot be considered a significant factor for the type I phenomenon,

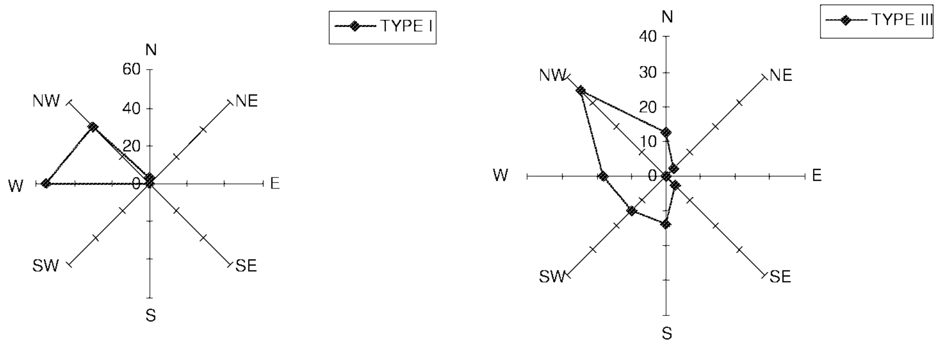

Fig. 3. Slope distribution for exposure classes.

as its variability is too small. As far as distribution of mass movements is concerned, with respect to exposure classes, a more representative phenomenon distribution is visible. In this case it is, in fact, possible to find a more direct correlation between the phenomenon effects and exposures, and this factor therefore becomes representative for the analysis.

Vertical *convexity* has been analyzed in relation to mass movements that involve parent rock occurrence. A direct correlation between mass movement occurrence and convexity was not found. This is mainly due to the fact that the vertical convexity has been considered as a morphological factor that characterizes the whole slope unit, while, in order to use it in the analysis, it should refer to the different parts of each single mass movement (especially the top of the mass movement), but these were not available for the current inventory.

"Soil", the fourth dimension, represents a relevant factor for surface erosion (type I phenomenon). A *Soil* criterion can be defined and a classification is available for the current inventory; the soil definition itself, and its relevance in erosion occurrence, was obtained in the first year of the project research from a synthetic work carried out by experts on the basis of considerations of several parameters. The *Erodibility K* factor (Wishmeyer and Smith, 1978) has also been included, in relation to the same "Soil" dimension,. The Erodibility classification and relevance was directly derived from the experts who carried out the field tests (see Leone, 1990; Tossell, 1990).

The last dimension, "Climatology", is a relevant factor for the two considered phenomena. The meteorological data was derived from a GIS elaboration of rainfall values provided by the Piedmont Region and referred to different time series, the first (cumulated rainfall) pertained to the period around the flood (six days) and the second (mean rainfall) was related to the August-November 1994 period. The limited number of thermo-pluviometric stations (only one in the study area) led to a generation of approximate results, in terms of main rainfall, and to an insignificant rainfall variability in the pilot area. This dimension was therefore excluded from the analysis.

2. Multicriteria Method and Models

An ELECTRE class method is used to compare homogenous units (MU) characterized by the same phenomenon type and to classify them in decreasing order of slope hazard. ELECTRE III starts by comparing each unit to each of the others. It builds the model for the fuzzy outranking relation by the notion of concordance and discordance and the computation of a concordance index, a discordance index and an outranking degree (phase I of the method). The method uses this result in the second phase of fuzzy relation exploitation, to construct two complete preorders and a partial preorder as the final result. The two complete preorders are constructed through a descending and an ascending distillation procedure. For details of the ELECTRE III procedures, see e.g. Skalka, Bouyssou and Bernabeu (1983) and Vinke (1992). The two rankings are usually not the same; when they are similar but present 'problematic actions', a partial preorder should be elaborated as the intersection of the two complete preorders. When the two rankings are too divergent a model re-analysis is necessary to arrive at a final result. Kendall's tau coefficient could be used to compare the two complete preorders in terms of ‘proximity’ when repetitive applications of methods, to the same set of actions, allow comparison of the result (see for instance Hokkanen and Salminen, 1997) and orient the model stabilization.

One of the purposes of this ELECTRE III application is to arrive at a ‘good’ model which allows the comparison of its results with the information elements from the pilot area, here used as a reference for the analysis (a measure of the actual disorder level, in terms of disorder area or percentage which characterize each unit, and then the unit ranking from the most to the least damaged during the flood). The correlation between the two descending and ascending rankings of an ELECTRE III application (Kendall’s tau coefficient) may be seen as a internal sign of a model and result ‘quality’. The second element which has been used to state model criticality or acceptability is the analysis of the partial preorder provided by ELECTRE III in comparison to the actual damage level.

The choice of ELECTRE III was mainly related to the imprecise and uncertain nature of the available data. Indifference and preference thresholds are introduced in this method on the criteria used in the comparison of the actions, which then constitute pseudo-criteria. The concept of pseudo-criterion and the use of the two thresholds allow the imprecision and uncertainty to be taken into account (Roy and Vinke, 1984; Roy *et al.*, 1986). Some significant factors of the analyzed phenomena are seen in their context (mainly geology and lithology) and elaborated for the data base as true-criteria (which do not require thresholds); they have been introduced into the model in this form.

For each separate analysis (one for Type I phenomenon and the other for Type III) three different multicriteria models are developed in succession. The last model proposes the resulting set of significant factors, which is coincident with the coherent family of criteria, and their relative importance. The result analysis, which is combined with a robustness analysis of the model, is used to distinguish subsets of areas at different hazards in the analyzed rankings. Each subset analysis allows the definition of multicriteria profiles which are combinations of evaluation states on the different criteria that have been recognized as relevant and whose different importances are “calibrated”. These profiles have been used, in a GIS framework, as an internal rule to map erosion and landslide hazards in the pilot area.

2.1. *Type I Model*

The main elements that induce a type I phenomenon are related to the four considered dimensions. A first model is developed and includes four criteria with decreasing relative importance: Land use, Soil, Slope and Lithology.

Slope and Soil are pseudo-criteria; the percentage of slope constitutes the scale of the Slope criterion and the states are ordered according to a decreasing value; the threshold values are proportional, the indifference threshold $q_j(g)$ is 0.15g, the preference threshold $p_j(g)$ is 0.30g and the veto threshold $v_j(g)$ is 0.80g. A soil factor was elaborated by the experts who worked in the previous phase of the project. This factor constitutes a 1–100 scale for the Soil criterion, which uses constant thresholds (q_j is 10, p_j is 25 and v_j is 75). Land use and Lithology are elaborated as true-criteria and therefore do not require thresholds; land use and lithological classes define two sets of states which form preference scales with nine degrees of criticality for the first scale and four degrees for the second. To reduce this strange interpretation of uncertain data as true-criteria, Land use is also treated as a quasi-criterion with $q_j = 0$, as two successive land use classes cannot be indifferent, and $p_j = 2$ because a strict preference is obligatory between classes with a difference of at least two degrees of criticality.

ELECTRE III is applied to the first model with different importance coefficients related to the suggested classification of the criteria (Land use is the most important, then Soil, Slope and Lithology, in this order), however the rankings always result to be illogical, because they are completely different from the damage inventory. A tentative redefinition of the criteria importance classification does not reduce the ranking criticality. The analysis of these results suggests that they may mainly be due to an improper choice of the Soil and Lithology criteria. The soil factor is defined taking different factors into account and can introduce a great redundancy into the process. Soil is related to a specific soil typology and the problem is that at least thirty different factors can be used to classify the soil into different typologies and each classification is the result of a factor choice. In order to create the adopted Soil scale, experts mainly used the texture of the surface horizon, soil depth, lithology and geological strata, thus creating a redundancy of factors in which lithology is considered both in the soil classification and as a specific criterion. In order to avoid redundancy, the *Texture* of the surface horizon, *Horizon sequence* and *Erodibility* (or K factor) are chosen, at this point, to describe the soil, while *Lithology* is excluded.

The second model includes five criteria (Land use, Erodibility, Texture, Horizon sequence and Slope). Land use and Slope are the same criteria as in the previous model. Erodibility is characterized by the K factor (Wishmeyer and Smith, 1978) which constitutes a 0.25–1 scale with constant thresholds (q_j is 0.02, p_j is 0.05 and v_j is 0.25). Texture and Horizon are true-criteria; soil texture and horizon sequence classes define two sets of states which form preference scales with three degrees of criticality for each criterion.

Three different ELECTRE III applications are developed with different importance coefficients (0.2 for each criterion in the first application; 0.30, 0.27, 0.18, 0.15 and 0.10 for the second; 0.10, 0.27, 0.18, 0.15 and 0.30 for the last). Kendall's tau coefficient between the two complete preorders (which are respectively construed through a descending distillation and an ascending distillation procedure) is higher than in the first model and passes from 0.866 to 0.881 and to 0.924, but also in this case the rankings of the units present some strange and quite illogical elements, in relation to the actual damage levels.

The experts involved in the result analysis suggest the elimination of the last criterion (Slope), which is important but not discriminating for actions with a mean slope greater than 7%. In the current case Slope could not be included in the factors that are useful in the analysis since the whole pilot area is characterized by slopes that are steeper than 7% and the factor variability is therefore null. At this point, another criterion related to the soil dimension is introduced, Soil depth, which is a pseudo-criterion; the depth of the soil, expressed in centimeters, constitutes the scale and the states are ordered according to decreasing values; the thresholds are constant (q_j is 10, p_j is 50 and v_j 150).

A new model, with five criteria (Land use, Erodibility, Texture, Horizon sequence and Soil depth) and the importance coefficients, which in the previous model were indicated and perceived as the most suitable (0.30, 0.27, 0.18, 0.15 and 0.10), is tested by ELECTRE III. The two complete preorders, from the descending and the ascending distillation procedures, are quite similar and Kendall's tau coefficient is 0.866. The partial preorder results to be reasonable when it is compared to the damage inventory.

The study of the final partial preorder, that is, a special analysis of the units whose position resulted to be different from the two descending and ascending distillation procedures, is combined with a robustness analysis of the model, relative to the thresholds and the importance coefficients. The importance coefficient variation, from minimum and maximum acceptable values (an interval of 0.10 for the first criterion , 0.04 for the second and the third and 0.02 for the fourth), suggests the definition of four classes of multi-thematic units at different landslide hazards between the 33 MU which were analyzed. Different combinations of evaluation states on the five criteria are then identified and compared with the four hazard classes. These multicriteria profiles, at different criticality levels, are stabilized and oriented to a GIS analysis and slope hazard mapping through some tentative changes of the indifference and preference thresholds which suggest a reclassification of the data that is more consistent with a GIS analysis.

2.2. *Type III Model*

Litho-Geology constitutes an important dimension of the type III phenomenon analysis; the relevant factors are therefore convexity, exposure and slope, which are all related to the Morphology dimension. Land use is also important but, in this case, it represents a complex point of view that includes a great deal of different elements, which are sometimes related to the other problem dimensions. A model which includes this element could be very critical.

The first model, elaborated in relation to this multidimensional situation and the global knowledge state, includes four criteria: Lithology, Stratigraphy, Slope and Exposure. Four lithological classes (Lequio, Murazzano, Cassinasco and Recent Alluvium) define a set of states which form a preference scale with four degrees of decreasing criticality. Lithology is then elaborated as a true-criterion. A stratigraphy factor was elaborated by the experts who worked in the previous phase of the project, that compared strata dip direction with the topographical dip. This factor constitutes a 0–10 scale for the Stratigraphy criterion, which uses constant thresholds (q_j is 1, p_j is 2,5 and v_j is 7,5). Slope is elaborated as in the Type I model; the percentage of slope constitutes the scale of the criterion and the states are ordered according to decreasing value, the threshold values are proportional, the indifference threshold $q_j(g)$ is 0.15g, the preference threshold $p_j(g)$ is 0.30g and the veto threshold $v_j(g)$ is 0.80g. Exposure classes (N, NW, W, NE, E, SE, S and SW) define a set of states which form a preference scale with eight degrees of decreasing criticality. Exposure is treated as a pseudo-criterion with $q_j = 1.5$, as two successive land use classes are indifferent, while $p_j = 3$ because a strict preference is obligatory between classes with a difference of at least three degrees of criticality.

The application of ELECTRE III to the model generates unsatisfactory results: Kendall's tau coefficient between the two complete preorders is less or equal to 0.68 with each tentative combination of importance coefficients. The experts involved in the result analysis explain that, as far as mass movements are concerned, the related literature considers a quite low threshold value for mass movement and suggests splitting the slope values into lower ones which are considered not to be critical and higher ones considered to be critical: in this case, the slope factor could not be included in the analysis because the whole pilot area is characterized by a critical slope value. The experts suggest the elimination of the Slope criterion, as in the Type I model, and the introduction of the Land use criterion, which is also treated in this model as a quasi-criterion (with $q_j = 0$ and $p_j = 2$), but with nine Land use classes which are different from the Type I model criterion (see Fig. 4).

This new criterion changes the situation and the results of the ELECTRE III application to the second model become quite satisfactory, above all with the last set of importance coefficients (0.35, 0.25 0.15 and 0.25). Kendall's tau coefficient is 0.783 and the complete intermediate preorder can easily be compared to the actual disorder situation. The ranking of the units presents only some critical elements: they have a position in the preorder which is completely different from their criticality level in reality.

The information base related to these residual critical elements and, at the end, their code in the GIS, are directly examined by experts and sometimes by the person who developed accurate analyses in the field. The criticality level connected to some Land use classes is redefined, the GIS code updated and the set of states which form the criterion

Land use classes in Type I model	Re-class	Land use classes in Type III model	Re-class
331 Beaches, dunes and sand plains	9	**331** Beaches, dunes and sand plains	9
211 Non irrigated arable land	8	**324** Transitional woodland shrub	8
242, 2221 Complex cultivation patterns Hazelnuts	7	**322** Moors and heath land	7
221 Vineyards	6	**311** Broad-leaved forest	6
324 Transitional woodland shrub	5	**243** Land principally occupied by agriculture, with significant areas of natural vegetation	5
243 Land principally occupied by agriculture, with significant areas of natural vegetation	4	**242** Complex cultivation patterns	4
311 Broad-leaved forest	3	**231** Pastures	3
231 Pastures	2	**221** Vineyards **2221** Hazelnuts	2
322 Moors and heath land	1	**211** Non irrigated arable land	1

Fig. 4. Land use classes from the more critical to the less.

preference scale reclassified. The application of ELECTRE III to the previous model, now with the redefined Land use criterion, proposes better results, in terms of comparison to the actual situation and allows a phase of importance coefficient variation which stabilizes the best result with the set of coefficients 0.33, 0.30, 0.20 and 0.17. At this point, the 127 units involved in type III disorders are divided into three sets for the last ELECTRE III applications. Kendall's tau coefficient results to be equal to 0.809 for the first set of 37 units, 0.787 for the second (45 units), and 0.89 for the last.

The results are used to define five classes of landslide hazard that are easily recognizable in each subset of units. Very few thresholds characterize the Type III model and, in this case, a reclassification of the data oriented to a GIS analysis is almost immediate and more connected to the comparison of the three models than to the tentative changes of the thresholds. The five classes are represented as ordered profiles from less to more critical in hazard evaluation.

2.3. *Hazard Maps*

In order to create a final map, all the previously generated multi-thematic units (5.600 MU) are compared to the profiles that are derived from the representative sample (Figs. 5 and 6) and classified in terms of erosion and landslide hazard. A good correlation between the estimated hazard and the real situation is found concerning mass movements. The areas characterized by high hazards are the ones in which most of the slopes lie. Not only the slopes that occurred after the flood of November 1994, but also the ones that have occurred in recent years are taken into account for this comparison.

Furthermore, the comparison between the hazard map obtained with the described integrated approach, and that obtained by another partner using a Multi-variate analysis show similar results, thus confirming the suitability of the present approach for environmental analysis when the presence of a phenomenon does not have a relevance which would allow a statistical approach to data analysis.

As far as erosion features are concerned, the obtained results clearly show that the available sample is not sufficiently representative for the whole area. On one hand, the areas characterized by the high hazard are in fact the ones in which it is also possible to observe most of the erosion features, however, on the other hand, most of the pilot area is not included in any hazard class. This is mainly due to the small number of considered ac-

Land Use	Erodibility	Texture	Horizon sequence	Soil depth	Hazard
7	0.7	2	2	>50	High
8	0.4	2	2	>50	
4	0.4	3	3	0–50	
6/7	0.35	2	2	>50	Medium
7/8	0.3	2	2	>50	
3	0.3	2	2	>50	Low
3	0.3	2	1	>50	
7	0.3	1	1	>50	
All the other combinations					Very low

Fig. 5. Type I profiles.

Stratigrafy	Lithology	Land Use	Exposure	Hazard
8.1–10	3	$\geqslant 3$	$\geqslant 6$	Very high
6.1–8	3	$\geqslant 6$	$\geqslant 6$	
8.1–10	4	$\geqslant 6$	$\geqslant 6$	
0–8	$\geqslant 1$	9	$\geqslant 1$	
6.1 – 8	3	4–5	$\geqslant 6$	High
8.1–10	4	4–5	$\geqslant 6$	
4.1 – 6	3	$\geqslant 6$	$\geqslant 6$	
6.1 – 8	4	$\geqslant 6$	$\geqslant 6$	
4.1 – 6	5	$\geqslant 6$	$\geqslant 6$	
6.1 – 8	5	$\geqslant 6$	$\geqslant 6$	
8.1–10	5	$\geqslant 6$	$\geqslant 6$	
8.1–10	4	3	$\geqslant 6$	Medium
2.1–4	4	$\geqslant 6$	1–5	
2.1–4	3	$\geqslant 4$	1–5	
0–2	3	$\geqslant 6$	1–5	
6.1–8	3	3	$\geqslant 6$	
4.1–6	3	$\leqslant 5$	$\geqslant 6$	
6.1–8	4	$\leqslant 5$	$\geqslant 6$	
4.1–6	5	$\leqslant 5$	$\geqslant 6$	
6.1–8	5	$\leqslant 5$	$\geqslant 6$	
2.1–4	4	$\leqslant 5$	1–5	Low
0–2	3	$\leqslant 5$	1–5	
2.1–4	3	$\leqslant 3$	1–5	
6.1–8	6	$\geqslant 3$	$\geqslant 6$	
2.1–4	5	$\geqslant 3$	1–5	
0–2	4	$\geqslant 3$	1–5	
0–2	5	$\geqslant 3$	1–5	Very low
4.1–6	6	$\geqslant 3$	1–5	
4.1–6	6	$\geqslant 3$	$\geqslant 6$	
0–2	5	$\geqslant 3$	$\geqslant 6$	

Fig. 6. Type III profiles.

tions of the sample (only 33), which cannot include all the possible criteria combinations, thus leading to the generation of partial and fragmentary profiles.

3. Final Considerations

A study has been developed in the context of a European Community Environment Program to analyze the effect that several natural factors have on slope instability. Experts from different disciplines have been involved in the study to acquire significant information elements and integrate them in a Geographical Information System. The richness of these data and their uncertainties, related to the multiple interpretations of their possible contribution to hazard evaluation, led to an integrated GIS and data analysis approach to identify all the significant factors and the different importances of these factors.

The Multi-variate Analysis was adopted by another partner in the European project, to study the data related to the global study area in Italy. The CSI-Piemonte group instead focused on a pilot area and developed a multicriteria decision aid (MCDA) application. This analysis is presented in this paper together with the main elements that characterize the application of ELECTRE III to a rich knowledge base and its result, in terms of sets of significant factors with their relative importance and multicriteria profiles as norms to distinguish the different hazard areas. A more general result of the global project was that of the compatibility, which resulted to be real, of two different kinds of analysis oriented to different information situations, to treat a large data base (the first, the classical data analysis) or a quite small data base combined with a great deal of different knowledge elements (the second, which proposes a multicriteria method in a technical decision-aiding context). The project proposal is therefore a more flexible integration of different tools in a GIS framework, which can better answer specific requirements in a technical context.

The adopted approach, which integrates GIS overlay and MCDA, leads to some interesting considerations. GIS provides a suitable framework for the application of methods which do not have their own data management facilities for capturing, storing, retrieving, editing or displaying spatial data. MCDA provides GIS with the means of performing complex analysis on multiple and often conflicting objectives, while taking multiple criteria and expert knowledge into account. It is also useful to establish how the threshold values used in the overlay analyses can be defined; the threshold values used in this case to map the slope hazard are actually one of the application results.

The use of threshold values to map continuous variables on a nominal basis is seen (Janssen and Rietveld, 1990) as a limitation which leads to substantial loss of information. A combined GIS-MCDA approach could reduce this risk but implies a contemporaneous start in data handling; some difficulties can actually arise from the integrated approach when the Multicriteria analysis operates at a late stage of the GIS analysis.

The natural tendency in the GIS analysis context (but also in contexts such as Geology, Land use and Lithology) is to discretize each factor in a limited number of states which can easily be associated to each geographical portion of the territory. When this process of "factor classification" does not come to an end quickly the situation is perceived as critical and the reason for this is connected to the elements of uncertainty which are present in the data acquisition or interpretation, and in data processing, mainly when multiple factors have to be used to define a synthetic indicator.

At the start of the intervention, the uncertain nature of the available data was clearly indicated as an element of the problem and this oriented the choice of approach, decision-aid procedure and multicriteria method. The passage from one model to another made a different vision of the data nature evident and the use of the available classifications became inevitable as some original data were definitely lost. When a classification has been produced, the normal attitude, in the GIS context, is in fact to preserve this result as much as possible, while the original rough data are lost because their conservation is too expensive. A better temporal integration between the two approaches could reduce these methodological limitations and improve the global results.

Acknowledgements

This research was supported by the European Community Environment Programme, Climate change contract n°EV5V-CT94-0452.

References

Bouyssou, D. (1990). Building criteria: a prerequisite for MCDA. In C.A. Bana e Costa (Ed.), *Readings in Multiple Criteria Decision Aid*, Springer-Verlag, Heidelberg, pp. 58–80.

Carver, S.J. (1991). Integrating multi-criteria evaluation with geographical information systems, *Int. J. Geographical Information Systems*, **5**(3), 321–339.

Fischbeck, P. (1994). GIS: more then a map, *OR/MS Today*, August 1994, 42–45.

Janssen, R., P. Rietveld (1990). Multicriteria analysis and GIS: an application to agricultural landuse in The Netherlands. In Scholten and Stillwell (Eds.) *Geographical Information Systems for Urban and Regional Planning*, Kluwer, Dordrecht.

Joerin, F. (1995). Méthodes multicritères d'aide à la décision et SIG pour la recherche d'un site, *Revue internationale de géomatique*, **5**(1), 37–51.

Hokkanen J., P. Salminen (1997). ELECTRE III and IV decision aids in an environmental problem, *Journal of Multi-Criteria Decision Analysis,* **6**(4), 215–226.

Laaribi, A. (1995). Systèmes d'information géographique et analyse multicritère: intégration pour l'aide à la décision à référence spatiale, *Thèse de Ph.D.*, Faculté de foresterie et de géomatique, Université Laval, Québec.

Leone, A. (1990). Il contributo dei simulatori di pioggia alla ricerca sperimentale', *Quad. Idronom. Mont. 10, Associazione Italiana Idronomia,* 15–31.

Maguire, D.J., M.F. Goodchild, D.W. Rhind (1991). *Geographical Information System*, Longman Scientific & Technical, New York.

Norese, M.F. (1996). A process perspective and multicriteria approach in decision-aiding contexts, *Journal of Multi-Criteria Decision Analysis*, **5**, 133–144.

Roy, B. (1978). ELECTRE III: Un algorithme de classements fondé sur une représentation floue en présence de critères multiples, *Cahier du CERO,* **20**, 3–24.

Roy, B. (1990). The outranking approach and the foundations of ELECTRE methods. In C.A. Bana e Costa (Ed.), *Readings in Multiple Criteria Decision Aid*, Springer-Verlag, Heidelberg, pp. 155–184.

Roy, B. (1993). Decision science or decision-aid science? *European Journal of Operational Research*, **66**, 184–203.

Roy, B. (1996). *Multicriteria Methodology for Decision Aiding*, Kluwer, Dordrecht.

Roy, B., P. Vinke (1984). Relational systems of preference with one or more pseudo-criteria: some new concepts and results, *Management Science*, II, 1323–1335.

Roy, B., M. Présent, D. Silhol (1986). A programming method for determining which Paris metro stations should be renovated, *European Journal of Operational Research*, **24**, 318–334.

Skalka, J.M., D. Bouyssou, Y.A. Bernabeu (1983). Manuel d'utilisation du programme ELECTRE III, Université de Paris-Dauphine, *Cahier LAMSADE*, n° 25.

Tossel, J. (1990). The Guelph rainfall simulator II. A comparison of natural and simulated rainfall characteristics, *Canad. Agric. Eng.,* **32**, 215–223.

Vincke, P. (1992). *Multicriteria Decision-Aid*, Wiley, Chichester.

Wishmeyer W.H., D.D. Smith (1978). Predicting rainfall erosion losses: a guide to conservation planning, *USDA Agr. Handbook*, **5**, 5–37.

M.F. Norese is an assistant professor of Operational Research in the Faculty of Engineering from the Politecnico of Torino (Technical University of Turin). She has been involved with direct analyses of organizational change processes and the use of classical and new tools in organizations for ten years. Her current research interests focus on the use of multicriteria methods to support individual and collective decision and problem structuring.

A. Cavallo is currently employed at CSI Piemonte as project manager for GIS application implemented as support for the public administration. Her special expertise includes analysis of customer information system applied to environmental themes especially concerning water resources and agriculture.

GIS ir daugiakriterinė analizė vertinant erozijos žemėlapius ir gamtinius įvykius

Anna CAVALLO, Maria Franca NORESE

Remiantis ELECTRE III metodu nagrinėjamos įvairių sričių ekspertų žinios bei didelė duomenų bazė apie potvynius šiaurės vakarų Italijoje. Sudaryti modeliai yra skirti daugiafaktorinei šlaitų kitimo prigimčiai ir erozijos reiškiniams išsiaiškinti. Remiantis šiais modeliais yra nustatomi yrimo reiškiniai, atsižvelgiant į kriterijus, apjungiančius skirtingas šių reiškinių interpretacijas. Integruotas daugiakriterinis modeliavimas ir duomenų analizė leido geriau suprasti GIS analizės požiūriu natūralius reiškinius bei pasitarnavo kuriant lankstesnes sprendimų priėmimo sistemas.