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GEOGRAPHICAL INFORMATION SYSTEMS AND MULTIVARIATE MODELS IN LANDSLIDE HAZARD EVALUATION

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SUMMARY: *From a small drainage basin located in Central Italy, relevant geological and geomorphological factors were collected and processed, applying Geographical Information Systems (GIS) technology. The information acquired in this way was then analyzed by discriminant analysis which enabled the classification of stable and unstable slopes in the basin. The method proved to be a feasible and cost-effective approach to landslide susceptibility assessment and mapping.*

1. INTRODUCTION

In many countries regional landslide evaluation and mapping have long been a major task for government agencies or research institutions. A variety of methods and techniques for assessing the landslide hazard have been proposed or tested, each having both potential and drawbacks. Yet, some of them may be particularly suited to the solution of slope-instability problems of a specific area or fulfilling the requirements of a specific project (COTECCHIA, 1978; GODEFROY & HUMBERT, 1983; VARNES et Alii, 1984; BRABB, 1984; HANSEN, 1984; NIETO, 1989).

Late in the seventies, multivariate models were applied in assessing the landslide hazard of three geologically-geomorphologically different sample zones of Calabria (Southern Italy). As a result, it was proved that these "black-box" models are capable of successfully predicting actual and potential slope failure in each zone studied (CARRARA, 1983, 1989). This approach, however, had limitations and drawbacks, among them the great deal of time required to encode and digitize the large amount of data needed. Consequently, attention was given to seeking and developing methods and techniques to enable faster, more efficient acquisition and processing of those geological-geomorphological data which are both relevant in assessing landslide hazard and mappable at effective cost over wide regions (CARRARA et Alii, 1988; CARRARA, 1988).

By integrating the potential of these automated techniques with the capabilities of a modern, topologically-based, geographical information system (BURROUGH, 1986;

BONFATTI, 1988), it is feasible and cost-effective to both develop a geographical database of the region to be investigated and apply a multivariate approach to assess and map the landslide distribution hazard. This task is being currently carried out in a pilot drainage basin of Umbria, Central Italy. In this paper the techniques currently employed and the results obtained are briefly outlined.

2. TESCIO BASIN PILOT AREA

2.1. Geological and Morphological setting

The Tescio basin, a left tributary of the Tiber river, covers an area of 65 Km^2 in the Umbria region, near the town of Assisi.

The basin is underlain by rocks pertaining to the Umbria-Marche stratigraphic sequence, which can be broadly subdivided into three main classes. In the southernmost section of the basin (20% of the area), thinly-bedded limestone, marl, and shale of the Late Jurassic to the Cretaceous age (Maiolica, Scisti a Fucoidi and Scaglia Rossa Formations) crop out. In the central part (30% of the area), marl and shale of the Oligocene-Eocene age (Scaglia Cinerea, Bisciaro and Schlier Formations) predominate. In the northern and north-western section (50% of the area), alternating sandstone, calcarenite and marl of the Miocene age (Marnoso-Arenacea Formation) are prevalent. Several north-northwest south-southeast trending anticlines overturned on the eastern limb, and synclines of the Late Miocene age are present in the area; among them the Monte Subasio anticline is the most prominent. These structures have been cut by numerous dip-slip and strike-slip faults generated by a Late Paleocene-Olocene extensional tectonic phase that caused a general uplift of the region.

The morphological setting of the area is strictly related to the local geological and structural conditions. The southernmost section of the basin exhibits a characteristic parallel drainage network, with sub-basins strongly elongated in shape, and with very steep, low-order channels. In the central and northern sections, the drainage network is dendritic, the sub-basins circular in shape, and the valleys mostly V-shaped and asymmetrical, the steepest slope being generally a reverse-dip slope. The relative relief is greater and the slopes generally more regular, steeper and stable in areas underlain by competent rocks such as limestone and sandstone. Areas underlain by marl and clay have lower values of relative relief and more gentle irregular slopes. In the latter, landslides are abundant and landscape is extensively modeled by mass-movement processes.

A total of 243 landslides were recognized in the area, most of which typologically complex (VARNES, 1978). In general, they are rotational slides in the upper portion and almost everywhere present a flow component in the toe area. Small rockfalls, minor rockslides and topples occur along the scarps of major landslides as well as on other morphological scarps. A few small debris flows are also present in the scarp area of major landslides. Large, very old ("paleo") slide bodies are concentrated in the western section of the basin; they are generally stabilized or dormant but may be the site of small surficial movements, especially at the toe. It has to be pointed out that the recognition of instability features in the study area is complicated by intense human activity, especially farming.

Lastly, the climatic conditions of the area are characterized by a Mediterranean, strongly seasonal precipitation, and catastrophic rainfalls having a 20-25 year return period.

3. METHODS AND TECHNIQUES

3.1. Data collection

The data needed for this investigation were derived from or obtained by existing topographic maps, aerial photographs and field surveys. Contour lines of topographic maps (scale 1:25,000) were automatically digitized using a raster scanner available at the Military Geographical Institute of Florence After error checking and validation, contours were interpolated by means of a new adaptive technique, named Morphology-Dependent Interpolation Method (MDIP), which interpolates each point of a grid by means of the algorithm most suited to the morphological characteristics of the neighboring area. This is the method by which a skillful reader would determine the height of that point on a contour map (CARLA' et Alii, 1987; CARRARA, 1988). Tests performed on a variety of cases proved that MDIP technique generates high-fidelity, grid-based DTMs which faithfully reflect the most common topographical configurations found in nature. Using this technique for the Tescio basin area, a very dense, high-quality, elevation grid (25x25m in spacing) was produced.

Geological data were obtained by mapping the basin at the 1:10,000 scale. Geological units that might influence the distribution of landslides, such as sandstone-rich and calcarenite-rich sequences out of the predominantly marl/clay flysch formation "Marnoso-Arenacea", were mapped separately. A total of 10 significant rock units were recognized (Fig. 1). In addition, a large number of structural (bedding planes, joints, minor faults, etc.) measurements were taken as uniformly as possible throughout the study area. In order to assess the hydrogeological conditions of the slopes, simple parameters were estimated in the field or from topographic/geological maps, namely, bedding attitude, slope aspect and the spatial relations between permeable and impermeable rock units (Fig. 2).

Land use/cover data were derived from aerial photographs with minor field checking. In this way the basin area was subdivided into 10 classes making up over 3,000 land unit parcels. Likewise, landslide distribution and classification (according to relative age, activity and typology) were determined both by aerial photos flown in different periods (1954/55 and 1977), and by systematic field surveys carried out mainly in the summers of 1988-89 (Fig. 3).

3.2. Data processing

Starting from DTM data, drainage lines and related divides were automatically identified by means of a procedure, named BACINI 1/2 (CARRARA et Alii., 1988). Consequently for the Tescio basin the following data were obtained (for terminology see JARVIS, 1984):

-a) a fully connected drainage network rooted at and progressively coded from the outlet;
-b) a fully connected complementary divide network;
-c) the sub-basin area appertaining to each drainage channel;
-d) a complete set of morphological parameters, among which:
    -i. channel order, magnitude, length and slope;
    -ii. channel sub-basin area and perimeter;
    -iii. total area drained by the downstream node of the channel;
    -vi. area and perimeter of right/left sides of each sub-basin ("slope-unit");
    -v. aspect, slope and height of right/left sides of each sub-basin.

Base maps (scale 1:10,000) regarding basin lithology, land use/cover and landslide distribution were digitized, using the UTM Kilometric Network as reference system, and stored in the database of a vector-based geographical information system (ARC/INFO) running on a personal computer. Each landslide polygon was assigned a set of attributes regarding slope-failure morphology, typology, activity, and relative age (Fig. 3).

Since the data on basin geomorphometry, obtained by means of the procedures outlined, were in raster form, they needed to be converted into vector structure. To accomplish this task, a special module was written which reduces the loss of spatial information invariably associated with this operation. Then the map displaying the Tescio basin partitioned into 266 *slope-units* (right/left sides of each sub-basin) was also stored in the ARC/INFO database, along with the above listed morphometric attributes characterizing each slope-unit (Fig. 4).

Lithological and land use/cover polygons were first reclassified into 10 and 6 classes, respectively, then processed in such a way (through clipping, union and attribute file relating; cf. BURROUGH, 1986) that for each slope-unit the relative percentages of the different rock types and land cover, respectively, were determined. Likewise, for each slope-unit the percentage of unstable area was derived as the weighted summation of the landslide areas existing in the unit. Weights were defined by taking into consideration the degree of certainty in mapping the landslide bodies, the degree of activity of the failed mass and its relative age.

4. ANALYSIS AND CONCLUDING REMARKS

In order to carry out a statistical analysis on the data collected and processed in this way, a data set was created where each slope-unit was associated with a subset (44 variables) of the morphological, geological and vegetational attributes collected (some not yet in suitable form for analysis). Then such data were transferred to and analyzed by means of a statistical package (SPSS).

Notice that while in previous investigations each land attribute referred to a purely statistical geometrical element of the terrain examined: the land-unit parcel or grid cell (cf. BERNKNOPF et Alii, 1988; PIKE, 1988), in the current work, land characteristics are associated to a *geomorphologically meaningful* slope-unit within which geomorphic processes, such as landsliding, take place (Fig. 1-4).

Stepwise discriminant analysis (cf. AGTERBERG, 1974) was applied in an attempt to classify stable and unstable slope-units on the basis of their morphological and geological characteristics (CARRARA, 1983, 1989). Unstable and stable groups were defined as slope-units having more and less than 2% of landsliding area, respectively. Nineteen slope-units having an area smaller than 1 ha were excluded from the analysis because their morphological parameters were interpreted as being poorly significant. Several variables were normalized through log-transformation (FORM, MAGN, MAXCA, DENUD; see Tab. 1), while a few (IDR_A, IDR_D, FRA_TR) could be expressed only by a binary code (0/1). As a result, 15 variables (Tab. 1) entered into the discriminant function, which is characterized by a relatively large eigenvalue (0.82), namely the ratio of the between-groups to within-groups sums of squares, and by a canonical correlation coefficient equal to 0.67 (nearly 50% of variance explained). Centroids (group means) of *stable* and *unstable* slope-unit groups are -0.85 and 0.96, respectively.

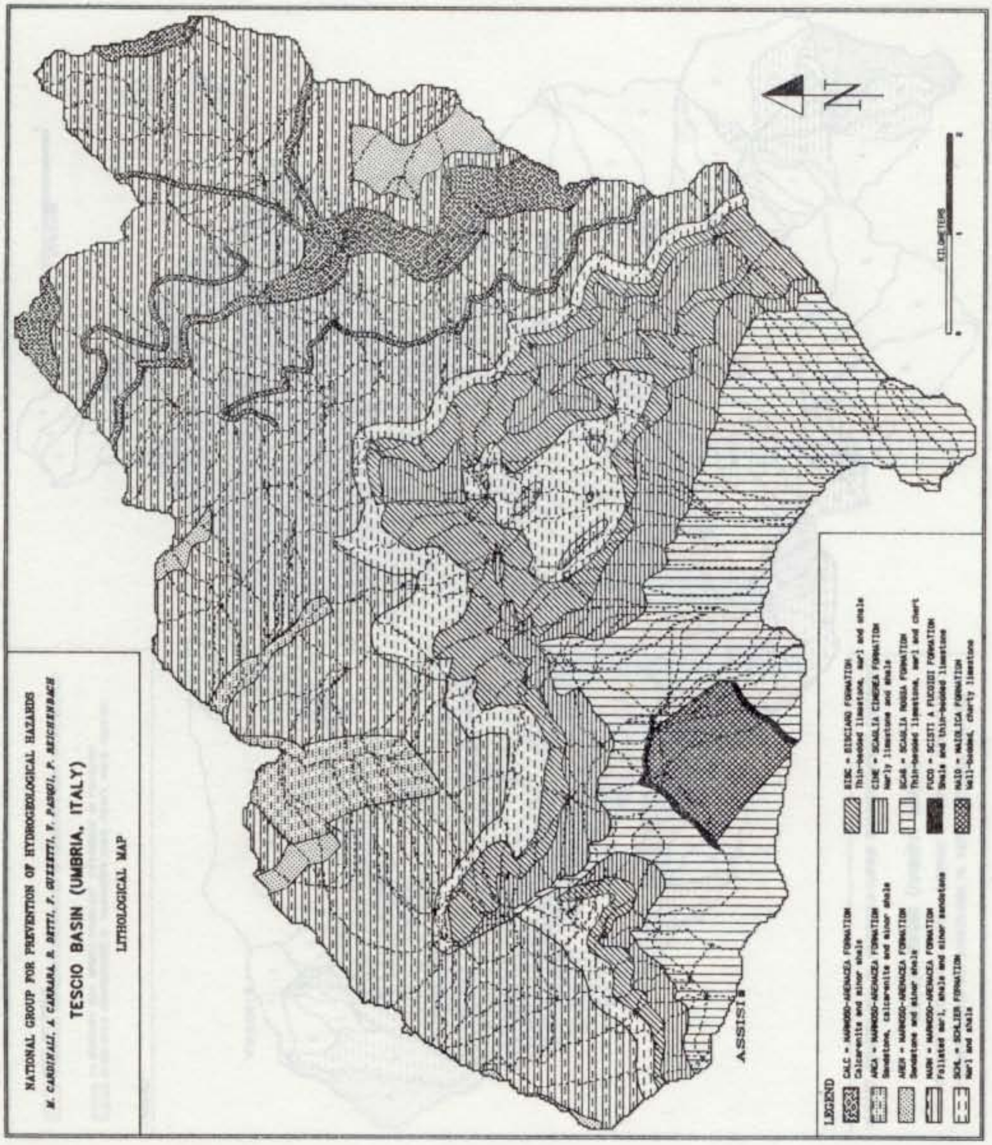

Fig. 1. Lithological map. Drainage-divide networks shown by dashed lines.
Fig. 1. Carta litologica. Impluvi e displuvi indicati da linee tratteggiate .

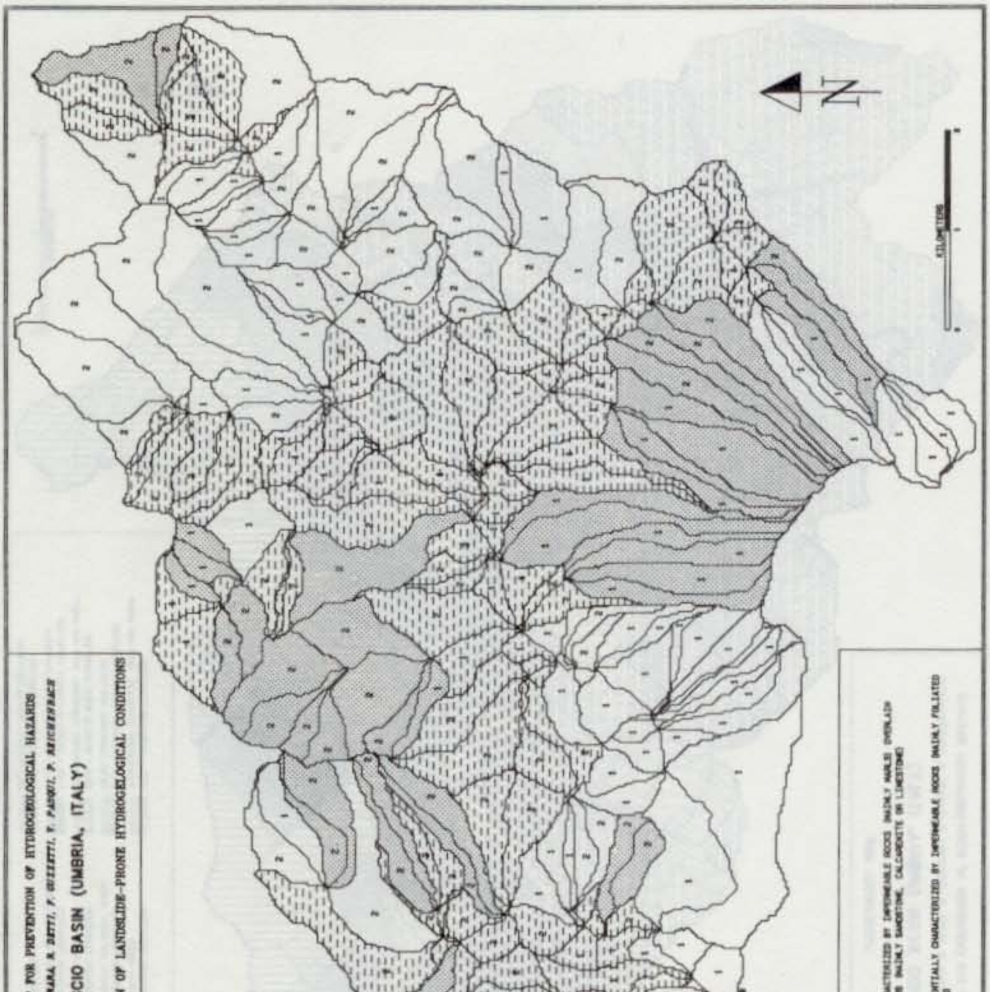

Fig. 2. Spatial distribution of landslide-prone hydrogeological conditions. Numbers 1 and 2 indicate stable and unstable slope-units, respectively.

Fig. 2. Carta della distribuzione delle condizioni idrogeologiche favorevoli all'instabilita' dei versanti. I numeri 1 e 2 indicano i versanti rispettivamente stabili ed instabili.

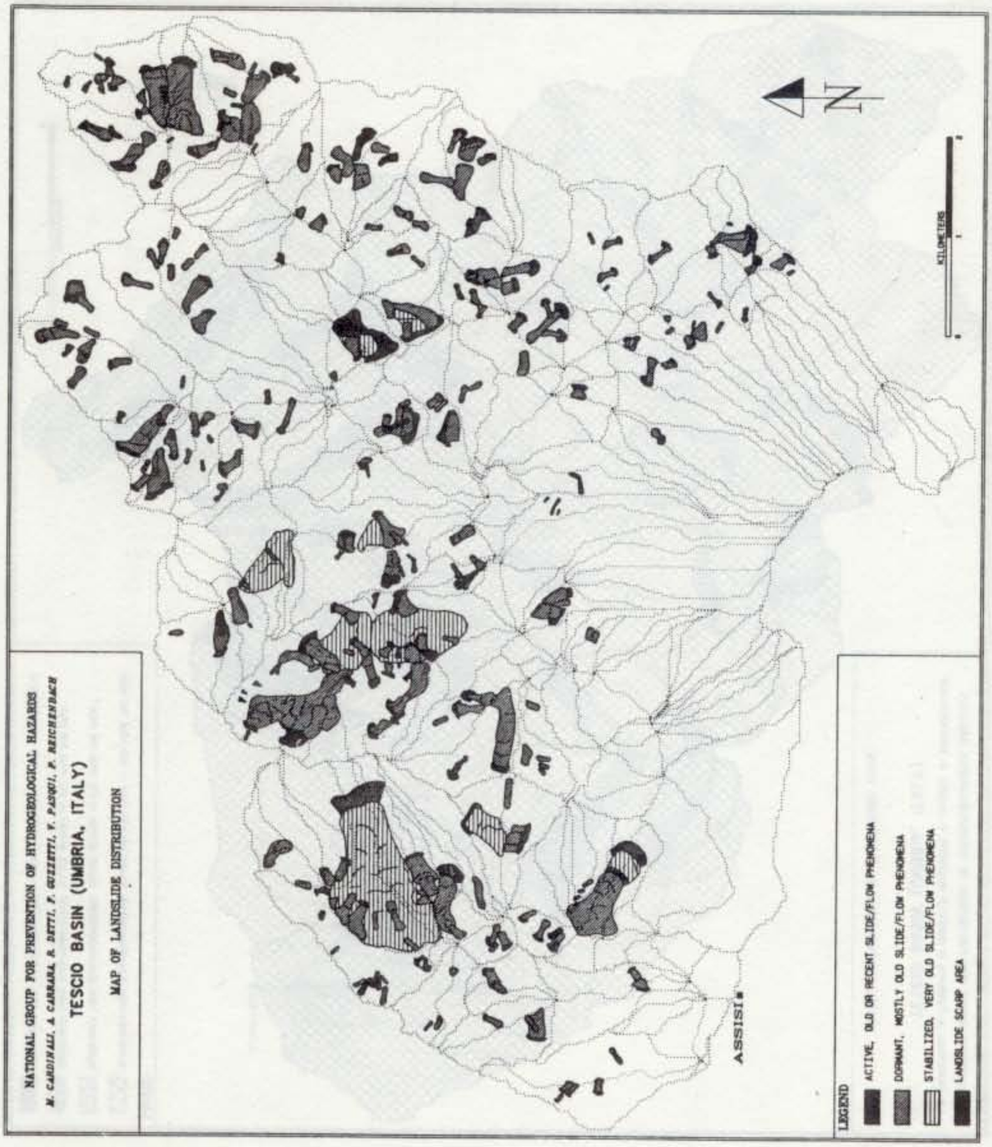

Fig. 3. Map of landslide spatial distribution.
Fig. 3. Carta della distribuzione spaziale delle frane.

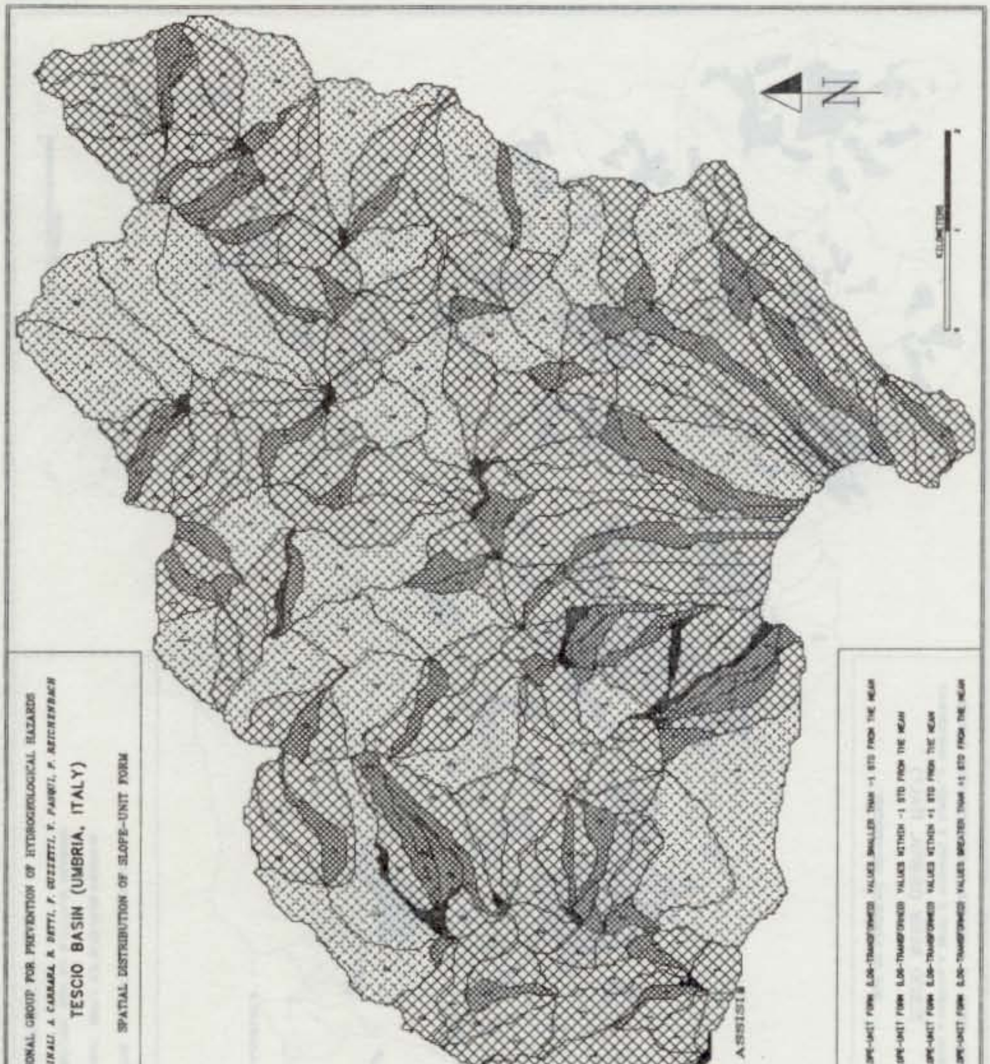

Fig. 4. Spatial distribution of slope-unit form.
Fig. 4. Carta della distribuzione spaziale dell'indice di forma dei versanti.

Tab. 1. List of variables entered into the discriminant function and their relative importance as expressed by the standardized discriminant function coefficients (SDFC).
Tav. 1. Elenco delle variabili scelte dalla funzione discriminante e loro importanza relativa espressa dai coefficienti standardizzati della funzione canonica (SDFC).

VARIABLE		**SDFC**
CINE	(slope-unit % of Scaglia Cinerea unit)	-.202
SCHL	(slope-unit % of Schlier)	-.355
ARCA	(slope-unit % of sandstone-rich unit)	.331
MAXCA	(slope-unit % of marl-rich by calcarenite-rich units)	.639
DENUD	(slope-unit % of uncultivated area)	.314
BOSCO	(slope-unit % of forest)	-.601
AN	(slope-unit facing N)	.199
AW	(slope-unit facing W)	.293
MAGN	(sub-basin magnitude)	-.492
ELV_M	(slope-unit mean elevation)	-.295
FORM	(slope-unit form - perimeter/area)	-.503
RXGR	(slope-unit surface roughness index)	-.260
FRA_TR	(bedding dipping toward slope-unit free face)	.251
IDR_A	(permeable beds capping impermeable ones)	.545
IDR_D	(impermeable beds throughout slope-unit)	.840

From Tab. 1, it is apparent that the variables having the highest discriminant power are:

- -a) the hydrogeological conditions characterized by the presence of impermeable rocks (IDR_D) on the slope-unit, and the occurrence on the upper part of the slope of permeable beds capping impermeable rocks (IDR_A);
- -b) the relative percentages within each slope-unit of the multiplicative term between the Marnoso-Arenacea and the calcarenite-rich member of this formation (MAXCA);
- -c) the relative percentage of forested area (BOSCO) within each slope-unit;
- -d) the slope-unit form (FORM) and sub-basin magnitude (MAGN).

Classification of stable and unstable slope-units yielded the following results:

	No.Cases	*Predicted Group Membership*	
Actual Group		1	2
Group 1 (STABLE SLOPES)	131	84.7%	15.3%
Group 2 (UNSTABLE SLOPES)	116	18.1%	81.9%

Percentage of "grouped" cases correctly classified: 83.40%

This high percentage of correctly classified slope-units was obtained through a set of variables which bear a clear physical meaning with the natural conditions leading to slope-failure. Association of clay-rich, impermeable materials and competent permeable beds (MAXCA, IDR_A, IDR_D) is a well-known lithological and hydrogeological setting prone to mass-movement. Likewise, forested areas (BOSCO) are generally less affected by surficial landsliding. Slope-unit form is an index well-correlated to slope height and length, both of which are important parameters of slope stability. Results of the analysis were used to produce the graph of Fig. 5 and the map of Fig. 6. From the first, a clear separation of stable and unstable slope-units on the basis of their discriminant scores, is apparent. From the second, it is readily possible to derive the information needed to assess the landslide risk related to each slope-unit into which the Tescio basin was subdivided.

From the above results it is proved that the geological-morphological statistical model developed constitutes a rather powerful tool for predicting the spatial distribution of landslide hazard in the study area. It is worth noting that this result confirms the outcome of similar studies carried out in three sample areas of Calabria, characterized by very different geological-geomorphological settings (CARRARA, 1983). Consequently, it is demonstrated that these *black-box* (or *functional*) models, although unable to readily unravel the internal structure of the process involved, constitute a feasible approach to environmental hazard assessment (CARRARA, 1989).

Future work along this line of investigation will attempt to seek and acquire different, better landslide predictors through both field surveys and remotely sensed imageries. In particular, from high-fidelity DTMs it should be possible to simulate the visual perception of the topographic form, the latter being the fundamental element in any geomorphologic analysis (PIKE, 1988). Lastly, the ever increasing advancement and diffusion of GIS technology and environmental data modeling will greatly facilitate the application of the methods outlined to large regions or even to whole countries.

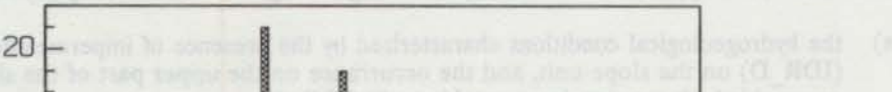

Fig. 5.Discriminant score frequency distributions of stable and unstable slope-units.
Fig. 5. Distribuzioni di frequenza dei punteggi discriminanti dei versanti rispettivamente stabili ed instabili.

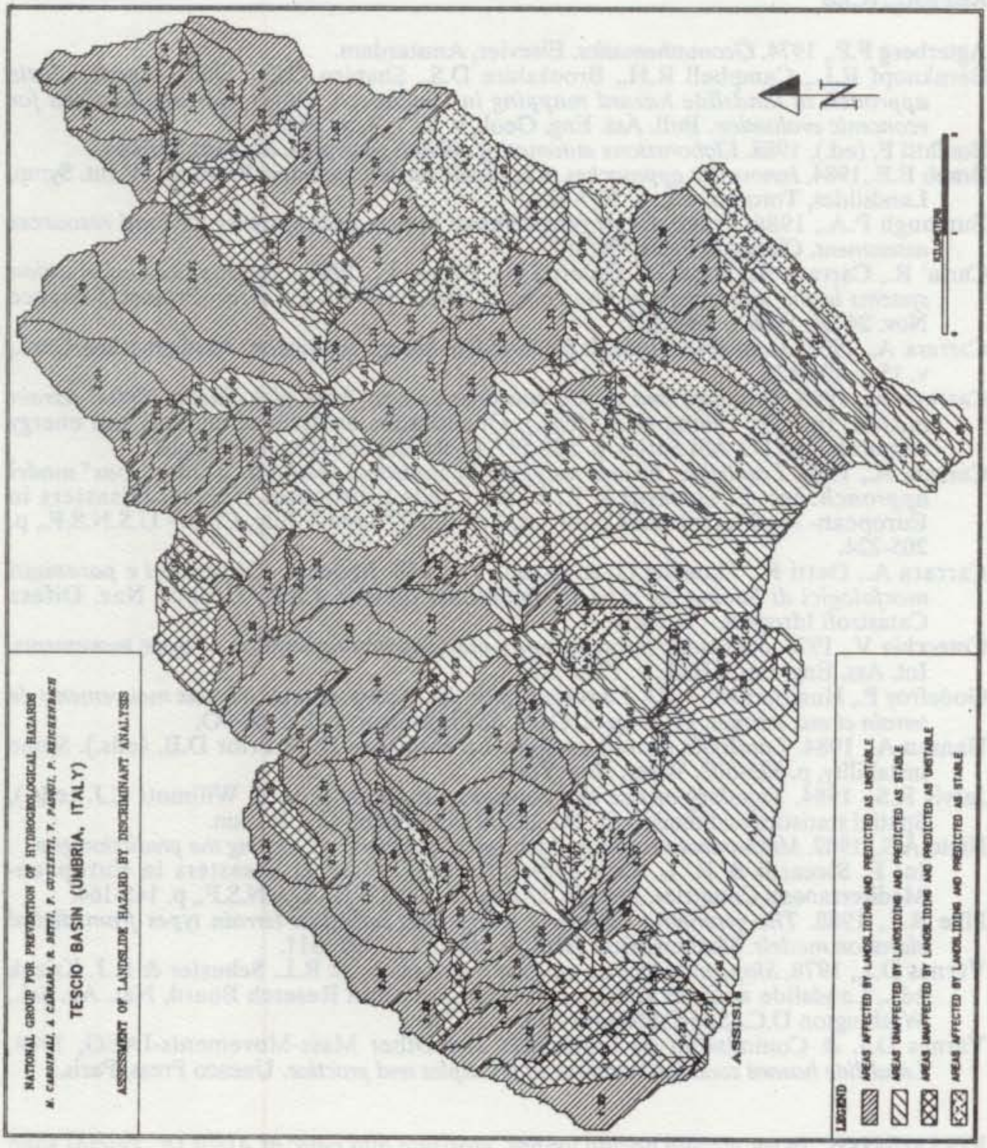

Fig. 6. Map of landslide hazard assessment by discriminant analysis.
Fig. 6. Carta della pericolosita' franosa valutata sulla base di un modello discriminante.

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RIASSUNTO: *In un piccolo bacino umbro, prossimo alla citta' di Assisi (F. Tescio) sono stati cartografati tutti i corpi franosi, nonche' rilevati i principali dati geologici, geomorfologici e vegetazionali dello stesso. E' stato altresi' generato un modello digitale del terreno ad alta precisione e da questo ottenuta la suddivisione automatica dell'area nei suoi sottobacini elementari. Attraverso le tecnologie proprie dei sistemi informativi geografici (GIS), tutti i dati raccolti sono stati archiviati, elaborati, visualizzati e, quindi, analizzati tramite metodologie multivariate discriminanti. In tal modo, e' stato possibile classificare i versanti in stabili ed instabili, nonche' valutare e cartografare la pericolosita' franosa di ciascun versante. L'indagine in oggetto ha confermato la fattibilita' e l'efficienza di un approccio basato su tecnologie GIS per la realizzazione di carte della pericolosita' franosa.*