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Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy

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Abstract

In recent years, growing population and expansion of settlements and life-lines over hazardous areas have largely increased the impact of natural disasters both in industrialized and developing countries. Third world countries have difficulty meeting the high costs of controlling natural hazards through major engineering works and rational land-use planning. Industrialized societies are increasingly reluctant to invest money in structural measures that can reduce natural risks. Hence, the new issue is to implement warning systems and land utilization regulations aimed at minimizing the loss of lives and property without investing in long-term, costly projects of ground stabilization. Government and research institutions worldwide have long attempted to assess landslide hazard and risks and to portray its spatial distribution in maps. Several different methods for assessing landslide hazard were proposed or implemented. The reliability of these maps and the criteria behind these hazard evaluations are ill-formalized or poorly documented. Geomorphological information remains largely descriptive and subjective. It is, hence, somewhat unsuitable to engineers, policy-makers or developers when planning land resources and mitigating the effects of geological hazards. In the Umbria and Marche Regions of Central Italy, attempts at testing the proficiency and limitations of multivariate statistical techniques and of different methodologies for dividing the territory into suitable areas for landslide hazard assessment have been completed, or are in progress, at various scales. These experiments showed that, despite the operational and conceptual limitations, landslide hazard assessment may indeed constitute a suitable, cost-effective aid to land-use planning. Within this framework, engineering geomorphology may play a renewed role in assessing areas at high landslide hazard, and helping mitigate the associated risk. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

A hundred years ago, the world population totalled 1.1 billion, and about 5% of people lived in cities. Today, the population has risen to 5.3 billion and approximately 45% of it is concentrated in urban areas. The most explosive growth has been in the developing world, where urban populations have tripled in the last 30 years. Between 1950 and 1995, the number of cities with population of more than one million increased sixfold in the third world (Helmore, 1996).

The population growth and the expansion of settlements and life-lines over hazardous areas are in-

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creasing the impact of natural disasters both in the developed and developing world (Rosenfeld, 1994; Alexander, 1995). In many countries, the economic losses and casualties due to landslides are greater than commonly recognized and generate a yearly loss of property larger than that from any other natural disaster, including earthquakes, floods and windstorms (Schuster and Fleming, 1986; Alexander, 1989; Swanston and Schuster, 1989; Olshansky, 1990; Schuster, 1995a; Glade, 1998). Casualties due to slope failures are larger in the developing countries, whereas economic losses are more severe in the industrialized world. Both may be increasing because of the higher value of endangered structures and the greater number of people potentially involved (Schuster and Fleming, 1986).

Third world countries have always had difficulty affording the high costs involved in controlling natural hazards through major engineering works and rational land-use planning. Owing to the economic recession, many industrialized societies are reluctant to invest in structural measures to reduce natural risks. Economic and social considerations suggest that, even if the recurrence of natural disasters remains constant — and it may not be the case — damage caused by catastrophic events is too costly even for industrialized societies. In other words, natural catastrophes occur with higher frequency than our ability to recover from previous events.

The recent trend is towards the development of warning systems and land utilization regulations aimed at minimizing the loss of lives and property damage without investing in long-term, costly projects of slope stabilization (U.S. Geological Survey, 1982; Kockelman, 1986; Schuster and Fleming, 1986; IDNHR, 1987; UNDRO, 1991; Schuster, 1995b). Despite the largely acknowledged need for landslide planning strategies, few attempts have been made to introduce landslide hazard considerations in building codes or civil protection strategies (Brabb and Harrod, 1989). Notable examples are in France (Humbert, 1976, 1977; Antoine, 1977; Godefroy and Humbert, 1983; Leroi, 1996), the San Francisco Bay region (Nilsen and Brabb, 1977; Nilsen et al., 1979; Brabb, 1995) and the Los Angeles area (IDNHR, 1987) in the United States, in Japan (IDNHR, 1987), Sweden (Ahlberg et al., 1988) and Hong Kong (Brand et al., 1982; Brand, 1988; Hansen et al., 1995).

Within this framework, earth sciences, and geomorphology in particular, may play a relevant role in assessing areas at high landslide hazard and in helping to mitigate the associated risk, providing a valuable aid to a sustainable progress. Tools for handling and analyzing spatial data (i.e., GIS) may facilitate the application of quantitative techniques in landslide hazard assessment and mapping.

In this paper, we first introduce the general assumptions, the mapping unit types, and the most commonly used hazard evaluation methods. We then discuss the experience gained from the application of GIS-based models of hazard and risk due to slope-failures over test areas in Central Italy, ranging in size from some tens to some thousands of square kilometers, and outline the potentials and pitfalls of the approach. In the light of the results obtained, data quality, type of terrain-unit and statistical models are critically evaluated. Lastly, general comments on data collection, model production and information transfer are addressed.

2. Definition of landslide hazard

Physical scientists define a natural hazard either as the probability that a reasonably stable condition may change abruptly (Scheidegger, 1994), or as the probability of occurrence of a potentially damaging phenomenon within a given area and in a given period of time (Varnes et al., 1984). The latter remains the most widely accepted definition for natural hazard and for maps portraying its distribution over a region (IDNHR, 1987; Einstein, 1988, 1997; Starosolszky and Melder, 1989; Horlick-Jones et al., 1995; Murck et al., 1997).

The definition incorporates the concepts of *magnitude*, *geographical location* and *time recurrence*. The first refers to the ‘‘dimension’’ or ‘‘intensity’’ of the natural phenomenon which conditions its behavior and destructive power; the second implies the ability to identify the place where the phenomenon may occur; the third refers to the temporal frequency of the event.

Traditionally, earthquake predictive models attempt to define hazard in terms of magnitude (a measure of the energy released by a seismic event), affected area, and time recurrence. Ideally, they largely fulfil the definition of hazard previously mentioned; unfortunately, scientists are generally unable to predict with the required accuracy where and when an earthquake will take place and how severe it will be. Despite the different meanings of the term ''flood'' (Baker, 1994), flood hazard evaluation essentially consists in the temporal prediction of an extreme hydrological event of a given magnitude (peak flow or volume), while, its location and spatial extent (potentially inundated areas) are determined from other sources of information, such as historical records and ground morphology.

For landsliding, a conceptual confusion arises from the use of the same term, *landslide*, to address both the landslide deposit (the failed mass) and the movement of slope material or of an existing landslide mass (Bosi, 1978; Cruden, 1991). Regional landslide predictive models generally attempt to identify *where* landslides may occur over a given region on the basis of a set of relevant environmental characteristics. Under the assumption that slope failures in the future will be more likely to occur under the conditions which led to past and present slope movements (Varnes et al., 1984; Carrara et al., 1991,1995), these models provide information on potentially unstable slopes. Hence they differ from maps of landslide deposits (*landslide inventories*) which consist of a catalogue of the landslide deposits present over a region which formed within a generally unknown (or unspecified) period of time. However, such models do not directly incorporate time and magnitude (i.e., size (Fell, 1994), speed (Cruden and Varnes, 1996), kinetic energy (Hsü, 1975; Sassa, 1988) or momentum of the failed mass), hence, they cannot be correctly defined as hazard models.

Predictive models of landslide movement are generally confined to single slopes where detailed geotechnical site investigations attempt to assess *when* and to what extent the slope-forming material, frequently an existing landslide deposit, will move. Also in this case, the term hazard would be incorrect since the location of the phenomenon under study derives from information acquired from other sources.

Therefore, the application to landsliding of the term ''*natural hazard*'' is difficult and somewhat inadequate.

The wide spectrum of landslide phenomena and the complexity and variability of their interactions with the environment (both natural and human) make the acceptance of a single definition of landslide hazard unsuitable. For example, very large, fast-moving landslides (e.g., rock avalanches) are probably the most destructive and hazardous mass movements. Slow-moving, deep-seated failures rarely claim lives but can cause high property damage. Fast-moving soil-slip–debris flows triggered by intense rainfalls are extremely destructive, causing widespread damage and casualties. Each type of slope movement pose different threats and may require a separate assessment, based on distinct definitions of landslide hazard.

Recurrence, the expected time for the repetition of an event, is evaluated studying historical records. Historical data however are seldom available and difficult to obtain for single landslides or landslide prone areas (Guzzetti et al., 1994; Ibsen and Brunsden, 1996). In addition, for first-time failures (Hutchinson, 1988) recurrence is not applicable. First-time landslides occur at or close to peak strength values, whereas reactivations occur between peak and residual conditions. Thus, first-time landslides provide little information on the behavior of reactivations. Additionally, each time a landslide occurs, the topographic, geological and hydrological settings of the slope change, often dramatically, giving rise to different conditions of instability. These changes allow geomorphologists to identify landslides and understand mechanisms and causes of failures, but limit their ability to forecast reactivations. Despite the lack of consensus on the reliability and usefulness of historic information, some investigators have attempted the reconstruction of historical records for single landslides or landslide prone regions. The results appear to be somewhat encouraging and useful for the evaluation of landslide hazard at various scales (Guzzetti et al., 1994; Ibsen and Brunsden, 1996; Cruden, 1997; Evans, 1997; Glade, 1998). Historical records may be integrated with temporal data derived from dendrocronology and other dating techniques which have been used by some investigators to date landslide deposits (Stout, 1977; DeGraff and Agard, 1984; Trustrum and De Rose, 1988).

Due to the conceptual and operational limitations, most landslide hazard maps could be better defined as landslide susceptibility maps (Brabb, 1984). Unfortunately, terms such as *susceptibility* or *propensity* have long been used with different meanings ranging from landslide-deposits inventory to estimates of landslide incidence based on the subjective judgement of the investigator (Radbruch-Hall and Varnes, 1976; Varnes et al., 1984; van Westen, 1993). In this paper, the term *landslide map* (or landslide inventory map) will be used to indicate a map portraying the distribution of deposition and erosion areas of gravity-induced mass movements which may vary in type, age and activity. The term *landslide hazard map* will refer to a *quantitative* prediction of the spatial distribution of both landslide deposits and slopes which are likely to be site of failures; whose movement (or reactivations) will take place in a way and within a time period defined from information that is not directly incorporated in the model.

3. Landslide hazard mapping

Over the past 25 years, government and research institutions have invested considerable resources in assessing landslide hazard, and in attempting to produce maps portraying its spatial distribution (*landslide hazard zonation*). Several different methods and techniques for evaluating landslide hazard and risk have been proposed or tested. Inspection of the literature reveals that a few reviews of the concepts, principles, techniques and methodologies for landslide hazard evaluation have been proposed (Cotecchia, 1978; Carrara, 1983; Brabb, 1984; Crozier, 1984; Hansen, 1984; Varnes et al., 1984; Crozier, 1986; Einstein, 1988; Hartlén and Viberg, 1988; Mulder, 1991; van Westen, 1993, 1994). Surprisingly, little work has been done on the systematic comparison of different techniques, outlining advantages and limitations of the proposed methods (Carrara et al., 1992, 1995; van Westen, 1993); or to the critical discussion of the basic principles and underlying assumptions of landslide hazard evaluation (Varnes et al., 1984; Carrara et al., 1995; Hutchinson, 1995). Likewise, only few attempts have been made to define, conceptually or operationally, landslide risk (Yong et al., 1977; Ahlberg et al., 1988; Bernknopf et al., 1988; Brand, 1988; Carrara et al., 1991; Fell, 1994; Cruden and Fell, 1997).

The majority of papers discuss specific attempts at the evaluation of landslide hazard in limited areas. Only a few authors report on long-term projects on the evaluation of slope instability conditions, and the related hazard and risk, over large regions. Notable examples are represented by the work carried out in San Mateo County, CA, by the US Geological Survey (Nilsen and Brabb, 1977; Brabb et al., 1978; Mark, 1992; Brabb, 1995); by the proposal made by the French Bureau des Recherches Géologiques et Minières for a geomorphologically based evaluation of landslide hazard (Humbert, 1976, 1977; Antoine, 1977; Delaunay, 1981; Godefroy and Humbert, 1983; Leroi, 1996); by the work carried out at the Geotechnical Engineering Office, in Hong Kong (Brand, 1988; Brand et al., 1982; Burnett et al., 1985; Hansen et al., 1995); and by the application of multivariate statistical techniques in pilot areas of Southern and Central Italy (Carrara, 1983; Carrara et al., 1991, 1995).

At present, there is no agreement either on the methods for or on the scope of producing hazard maps (Brabb, 1984; Carrara, 1989; Nieto, 1989). Operational and conceptual differences include: general underlying assumptions; the type of mapping unit selected for the investigation; and the techniques and tools favored for the analysis and the hazard assessment.

3.1. Basic assumptions

Despite the conflicting views among geomorphologists and engineers, all the proposed methods are based upon a few, widely accepted principles or assumptions (Varnes et al., 1984; Carrara et al., 1991; Hutchinson and Chandler, 1991; Hutchinson, 1995; Turner and Schuster, 1995), namely, the following:

– Slope failures leave discernible morphological features; most of them can be recognized, classified and mapped both in the field or through remote sensing, chiefly aerial photographs (Rib and Liang, 1978; Varnes, 1978; Hansen, 1984; Hutchinson, 1988; Dikau et al., 1996).

– Landsliding is controlled by mechanical laws that can be determined empirically, statistically or in deterministic fashion. Conditions that cause landslides (*instability factors*) directly or indirectly linked to slope failure, can be collected and used to build predictive models of landslide occurrence (Dietrich et al., 1995).

– The past and present are keys to the future (Varnes et al., 1984; Carrara et al., 1991; Hutchinson, 1995). As previously mentioned, the principle, which follows from uniformitarianism, implies that slope failures in the future will be more likely to occur under the conditions which led to past and present instability. Hence, the understanding of past failures is essential in the assessment of landslide hazard.

– Landslide occurrence, in space or time, can be inferred from heuristic investigations, computed through the analysis of environmental information, or inferred from physical models. Therefore, a territory can be zoned into hazard classes ranked according to different probabilities.

Ideally, evaluation of landslide hazard and its mapping should derive from all of these assumptions. Failure to comply to them will limit the applicability of any hazard assessment, regardless of the methodology used or the goal of the investigation. Unfortunately, as will be later discussed, satisfactory application of all of these principles proves difficult, both operationally and conceptually.

3.2. The mapping unit

Evaluation of landslide hazard requires the preliminary selection of a suitable *mapping unit*. The term refers to a portion of the land surface which contains a set of ground conditions which differ from the adjacent units across definable boundaries (Hansen, 1984). At the scale of the analysis, a mapping unit represents domain that maximises internal homogeneity and between-units heterogeneity. Various methods have been proposed to partition the landscape for landslide hazard assessment and mapping (Meijerink, 1988; Carrara et al., 1995). All methods fall into one of the following five groups:

- grid-cells;
- terrain units;
- unique-condition units;
- slope-units; and
- topographic units.

Grid-cells, preferred by raster-based GIS users, divide the territory into regular squares of pre-defined size which become the mapping unit of reference (Carrara, 1983; Bernknopf et al., 1988; Pike, 1988; van Westen, 1993, 1994; Mark and Ellen, 1995). Each grid-cell is assigned a value for each factor (morphological, geological, of land-use, etc.) taken into consideration. Alternatively, a stack of raster layers, each mapping a single instability factor, is prepared.

Terrain units, traditionally favored by geomorphologists, are based on the observation that in natural environments the interrelations between materials, forms and processes result in boundaries which frequently reflect geomorphological and geological differences. Terrain units are the base of the land-system classification approach which has found application in many land resources investigations (Cooke and Doornkamp, 1974; Speight, 1977; Verstappen, 1983; Burnett et al., 1985; Meijerink, 1988; Hansen et al., 1995).

Unique-condition units (Bonham-Carter, 1994; Chung et al., 1995) imply the classification of each slope-instability factor into a few significant classes which are stored into a single map, or layer. By sequentially overlying all the layers, homogeneous domains (*unique conditions*) are singled out whose number, size and nature depend on the criteria used in classifying the input factors.

Slope-units, automatically derived from high-quality DTMs, partition the territory into hydrological regions between drainage and divide lines (Carrara, 1988; Carrara et al., 1991). Depending on the type of instability to be investigated (deep-seated vs. shallow slides or complex slides vs. debris flows) the mapping unit may correspond either to the sub-basin or to the main slope-unit (right/left side of the sub-basin).

Slope-units can be further subdivided into *topographic units* defined by the intersections of contours and flow tube boundaries orthogonal to contours (O'Loughlin, 1986). For each topographic unit, local morphometric variables and the cumulative drainage area of all up-slope elements are computed.

Selection of an appropriate mapping unit depends on a number of factors, namely: the type of landslide phenomena to be studied; the scale of the investigation; the quality, resolution, scale and type of the thematic information required; and the availability of the adequate information management and analysis tools. Each technique for tesselling the territory has advantages and limitations that can be enhanced or reduced choosing the appropriate hazard evaluation method.

3.3. Landslide hazard modelling

Methods for ranking slope instability factors and assigning the different hazard levels can be *qualitative* or *quantitative* and *direct* or *indirect*.

Qualitative methods are subjective and portray the hazard zoning in descriptive (qualitative) terms. Quantitative methods produce numerical estimates (probabilities) of the occurrence of landslide phenomena in any hazard zone. Direct methods consist of the geomorphological mapping of landslide hazard (Verstappen, 1983). Indirect methods for landslide hazard assessment are essentially stepwise. They require first the recognition and mapping of landslides over a target region or a subset of it (*training area*). It follows the identification and mapping of a group of physical factors which are directly or indirectly correlated with slope instability (*instability factors*). They then involve an estimate of the relative contribution of the instability factors in generating slope-failures, and the classification of the land surface into domains of different hazard degree (*hazard zoning*).

The most important methods proposed in the literature can be grouped into few main categories (Carrara et al., 1992; van Westen, 1993; Carrara et al., 1995; Hutchinson, 1995), namely:

- geomorphological hazard mapping;
- analysis of landslide inventories;
- heuristic or index based methods;
- functional, statistically based models;
- geotechnical or physically based models.

Geomorphological mapping of landslide hazard is a direct, qualitative method that relies on the ability of the investigator to estimate actual and potential slope failures (Humbert, 1977; Godefroy and Humbert, 1983; Kienholz et al., 1983, 1984; Bosi et al., 1985; Zimmerman et al., 1986; Seeley and West, 1990; Hansen et al., 1995). The heuristic approach, based on the a priori knowledge of all causes and instability factors of landsliding in the area under investigation, is an indirect, mostly qualitative method, that depends on how well and how much the investigator understands the geomorphological processes acting upon the terrain. Instability factors are ranked and weighted according to their assumed or expected importance in causing mass movements (Nilsen and Brabb, 1977; Amadesi and Vianello, 1978; Hollingsworth and Kovacs, 1981; Neeley and Rice, 1990; Montgomery et al., 1991; Mejía-Navarro et al., 1994).

All other approaches are indirect and quantitative. The analysis of landslide inventories attempts to predict future patterns of instability from the past and present distribution of landslide deposits. This is accomplished by preparing landslide density (‘‘*isopleth*’’) maps, i.e., maps showing the number or percent of area covered by landslide deposits over a region (Campbell, 1973; Wright, 1974; Wright and Nilsen, 1974; Wright et al., 1974; DeGraff, 1985; Guzzetti et al., 1994). Statistical, ‘‘black-box’’ approaches are based on the analysis of the functional relationships between instability factors and the past and present distribution of landslides. Various multivariate statistical techniques have been applied on various mapping units. The most favored are discriminant analysis, linear and logistic regression, and neural networks (Neuland, 1976; Carrara, 1983; Carrara et al., 1991; Carrara et al., 1995; Roth, 1983; Yin and Yan, 1988; Neeley and Rice, 1990; Mark, 1992; van Westen, 1993, 1994; Chung et al., 1995). A statistical model of slope instability is built on the assumption that the factors which caused slope-failure in a region are the same as those which will generate landslides in the future. The general linear model assumes the form:

$$L = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + \ldots + B_m X_m + \epsilon$$

where L is the presence/absence (or the area percentage) of landslides in each sampling unit, the X’s are input predictor variables (or instability factors) measured or observed for each mapping unit, the B’s are coefficients estimated from the data through techniques which are dependent on the statistical tool selected (multiple regression, discriminant analysis, etc.), and ϵ represents the model error.

Lastly, process-based (geotechnical) models rely upon the understanding of few physical laws controlling slope instability (Okimura and Kawatani, 1987; Dunne, 1991; Montgomery and Dietrich, 1994; Dietrich et al., 1995; Terlien et al., 1995). These models couple shallow subsurface flow (i.e., the pore pressure spatial distribution), predicted soil thickness, and landsliding of the soil mantle (Dietrich et al., 1995). Stability conditions are generally evaluated by means of a static model, such as the ''infinite slope model'', where the local equilibrium along a potential slip surface is considered.

As previously mentioned, hazard models and mapping units are conceptually and operationally interrelated (Carrara et al., 1995). In the direct hazard mapping the geomorphological unit of reference is implicitly defined by the interpreter that maps those portions of the territory that are subject to different geomorphological hazards (Hansen, 1984). In all other cases (i.e., grid-based modelling, unique-condition units, slope-units, topographic units), the mapping unit is explicitly defined by the operator. In general, grid-cells are preferred for heuristic (Pike, 1988; Mejía-Navarro et al., 1994), statistical (Carrara, 1983; van Westen, 1994) and physical or simulation (Mark, 1992; Terlien et al., 1995) modelling. Unique-condition units have been applied to both heuristic (van Westen, 1993) and statistical methods (Carrara et al., 1995; Chung et al., 1995). Slope-units and topographic units have been used in statistical (Carrara et al., 1991; 1995) and physically based (Montgomery and Dietrich, 1994) models.

4. The Umbria–Marche hazard assessment project

In the Umbria and Marche Regions of Central Italy (Fig. 1) evaluation of landslide hazard was attempted using a variety of techniques pertaining to the realms of geology, geomorphology, statistics, and information technology. Experiments were carried out at the regional scale, for the entire Umbria–Marche territory (18,125 km^2 in size), and at the local scale, in the Tescio (59 km^2) and Carpina (67 km^2) basins (Guzzetti, 1993). The long-term hazard assessment project involved:

- the regional evaluation of landslide occurrence, obtained through the interpretation of medium-scale aerial photographs (Guzzetti and Cardinali, 1989, 1990; Antonini et al., 1993) and the inventory of historical information on slope movements (Guzzetti et al., 1994);
- a reconnaissance estimate of landslide hazard, attempted using the regional landslide inventory and the available, small scale thematic information;
- a set of detailed landslide hazard models in test areas, selected for their lithological, structural and morphological settings representative of large sectors of the Umbria–Marche territory (Carrara et al., 1991, 1995);
- a conceptual model of landslide occurrence (Guzzetti et al., 1996).

Results of these experiments, along with the outcomes of an international workshop on the application of GIS technology in assessing natural hazards (Reichenbach et al., 1993; Carrara and Guzzetti, 1995), encouraged the undertaking of a detailed evaluation of landslide hazard over the upper section of the Tiber River basin (4097 km^2 in size). This experiment, which is still in progress, is requiring a great deal of work in data acquisition, storage and processing and will need a significant amount of time and funds to be completed.

4.1. Regional setting

The Umbria and Marche Regions are located along the Apennines mountain chain (Fig. 1). To the east of the Apennines, the Umbria Region is drained by the Tiber River that flows into the Tyrrhenian sea. The Marche Region, to the west of the Apennines main divide, exhibits a parallel drainage that flows into the Adriatic sea.

The study area has a long history of hydrogeological catastrophes. Reports on landslides go back to Etruscan and Roman periods, but the first documented information on slope movements in the hillsides of Todi and Orvieto dates back to the fourteenth century. Due to the extent and economic

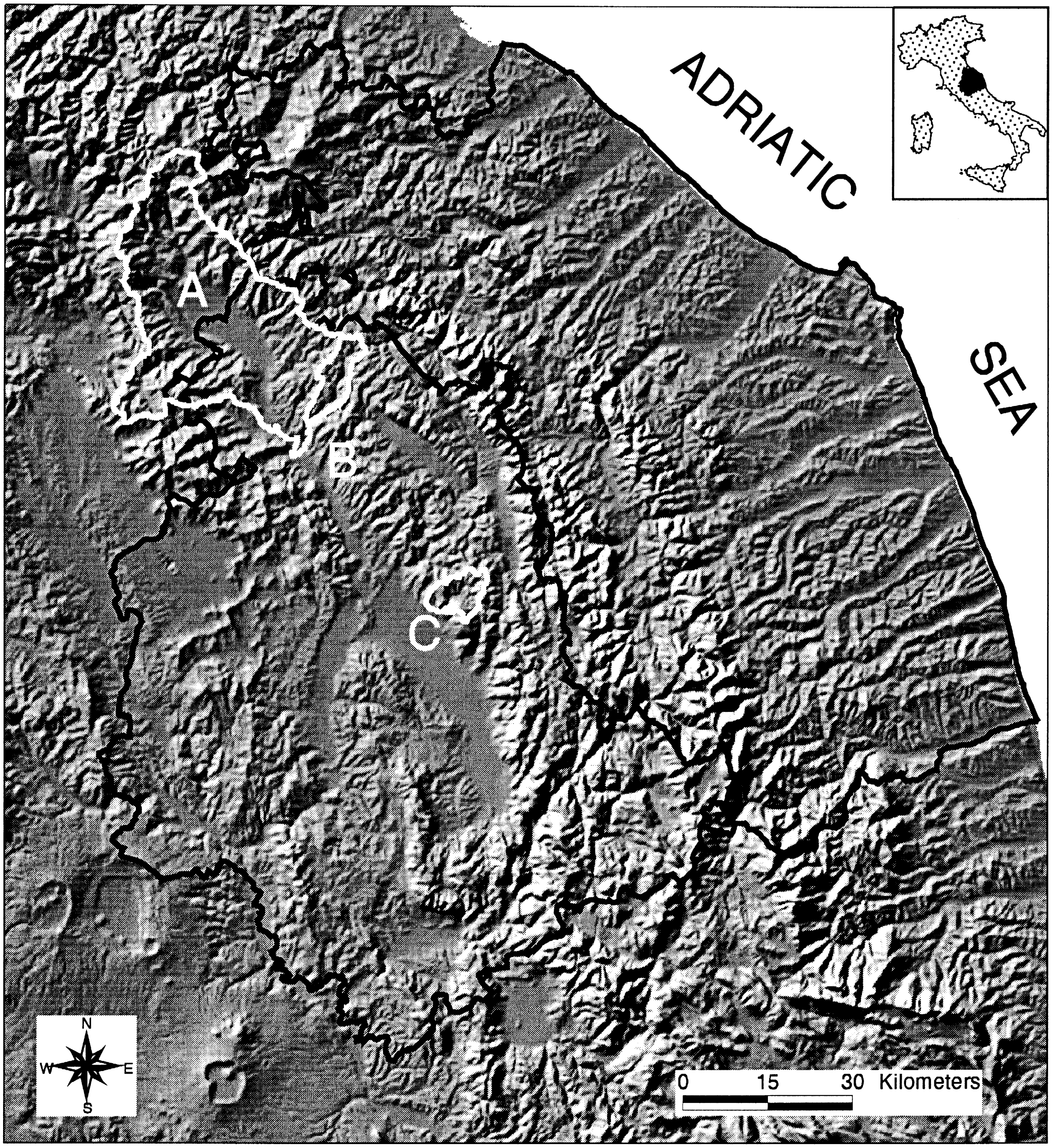

Fig. 1. The Umbria–Marche territory in shaded relief. The image was prepared from the Archive of Mean Elevations of Italy with a ground resolution of 230 × 230 m. Sun azimuth angle is 315°, elevation above the horizon is 45°. No vertical exaggeration. (A) Upper Tiber River basin. (B) Carpina basin. (C) Tescio basin.

significance of landslides, research on slope movements, ranging in scale from site specific investigations to regional studies, is abundant (Guzzetti et al., 1996).

Different rock types crop out in the area, varying in strength from hard to weak and soft rocks, that can be grouped into few lithological domains (Fig. 2A). Hard rocks consist of layered and massive limestone, cherty limestone, sandstone, pyroclastic deposits, travertine and conglomerate. Weak rocks are marl, shale, sand, silty clay and stiff, overconsolidated clay. Soft rocks are marine and continental clay, silty clay and shale. The morphological and structural setting of the area is determined by the superposition of two tectonic phases. A compressive phase, late Miocene to early Pliocene in age, was followed by an extension phase of Pliocene to Recent age. The compressive deformation produced large anticlines, corresponding to major divides, and synclines associated with thrusts and transcurrent faults. The extensional tectonic phase produced normal faults that formed intra-mountain basins and valleys.

The lithological and structural domains are characterized by a prevalent geomorphological setting and by typical geotechnical and hydrogeological properties that control the abundance and pattern of slope failures. Mass movements, ranging in size from less than 1 ha to few square kilometers, include: falls and topples in hard rocks; soil-slips in the colluvial cover mantling slopes in soft or weak rocks; rotational slides in homogeneous, mostly soft rocks; translational slides in well bedded, soft and hard rocks; earth-flows, complex and compound slides where alternating hard and soft rocks crop out (Guzzetti et al., 1996).

4.2. Regional evaluation of landslide occurrence

The regional inventory of landslides can be attempted through the catalogue of existing information on mass movements (*bibliographical or historical catalogue*; cf. Nemcok and Rybár, 1968; Radbruch-Hall et al., 1982; Brabb, 1984) or by means of the systematic interpretation of medium- or small-scale aerial photographs (*reconnaissance inventory*; cf. Brabb, 1984; Hansen, 1984; Wieczorek, 1984). For the Umbria and Marche Regions a reconnaissance inventory of landslide deposits (Guzzetti and Cardinali, 1989, 1990; Antonini et al., 1993) and a catalogue of bibliographical information on landslides (CoGeo, 1994a, 1994b; Guzzetti et al., 1994) were completed in the years 1986–1992.

The reconnaissance mapping was carried out through the systematic analysis of about 2100 black and white vertical aerial photographs, at 1:33,000 scale. Landslides were classified according to a simplified version of Varnes (1978) classification of mass movements. In the Marche Region, landslide relative-age was also estimated. Mapping took 5 man/years and detected about 14,700 landslide deposits. Additionally, 9700 small (less than 1 ha) failures, affecting mostly clay (about 50%) and flysch deposits (about 30%), were identified and mapped as single points. The total mapped landslide area was 1628 km^2, namely, 9% of the Umbria–Marche territory (Fig. 2B). Detailed geomorphological investigations carried out in pilot areas suggest that this is a lower estimate (Guzzetti et al., 1996).

The reconnaissance inventory revealed different types of landslides. Complex failures, covering 40% of the total landslide area, showed the largest extent. Flows were the smallest failures, but in the northern part of the study area flows exceeding 3 km^2 are present. In addition, tectonic melanges (40% of the territory) and flysch deposits (12% of the territory) were the most landslide-prone rocks, followed by all other rock types with less than 10% landslide area.

A catalogue of bibliographical information on slope failures for the Umbria and Marche Regions was completed for the period 1918–1990 through the systematic review of four newspapers, the interview of 24 expert witnesses, and inspection of 180 technical and scientific reports (CoGeo, 1994a, 1994b). The historical investigation revealed 1485 landslide events, at 956 different sites, affecting 89 out of 92 townships in Umbria (97%) and 148 out of 246 townships in the Marche Region (60%) (Fig. 2C). The analysis of the limited number of failures (35% for Umbria and 16% for Marche) for which the date of occurrence was known, showed a higher frequency of events in the winter season (Fig. 3A). Additionally, landslide frequency exhibited a correlation with the general climatic trend (Fig. 3B). Landslide events were found abundant in the period 1950–1969 and rare during the Second World War and the post war period (1940–1949). The latter reflects the incompleteness of the catalogue rather

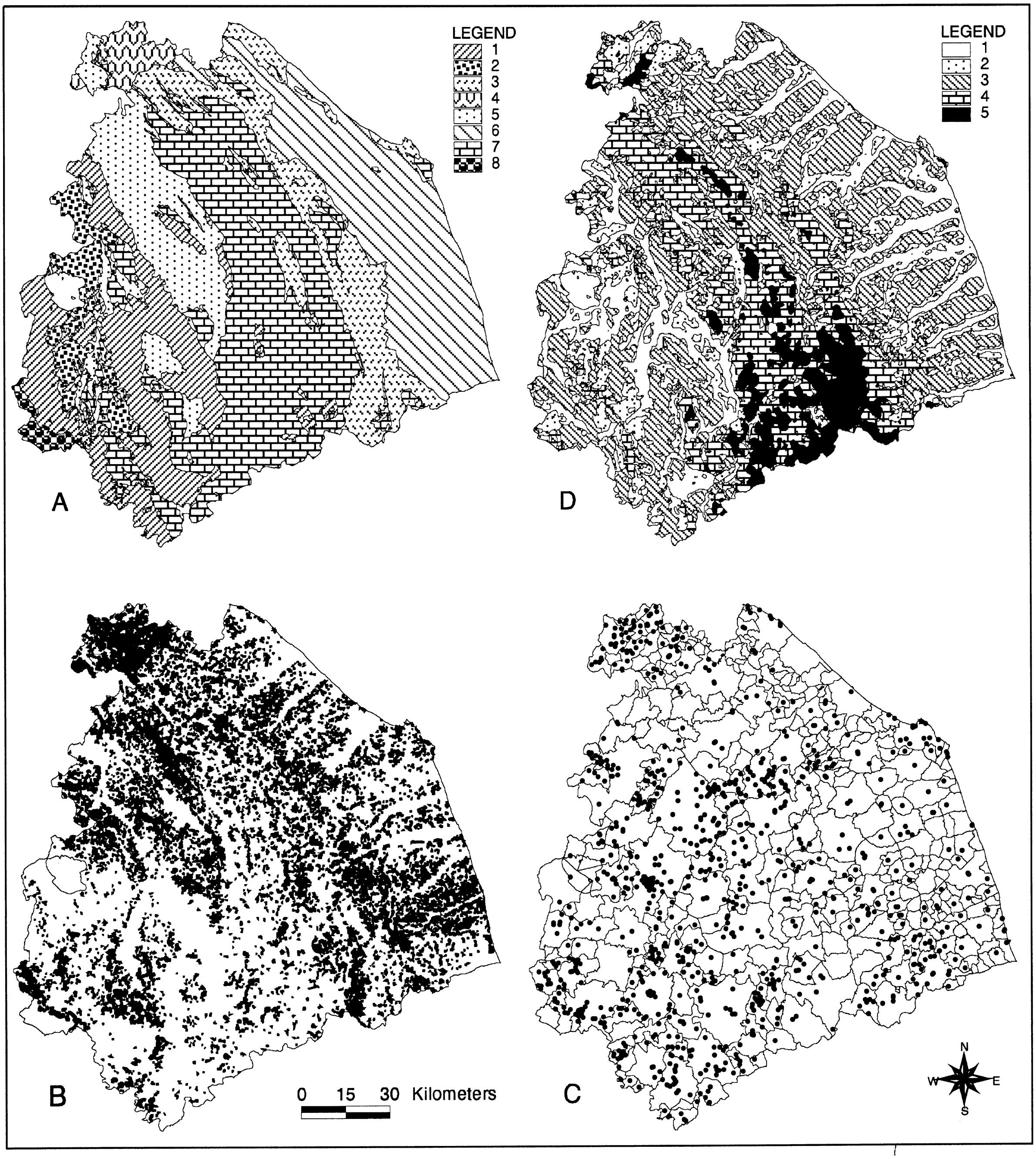

Fig. 2. Umbria and Marche Regions. Geological and morphological setting of the territory. (A) Lithological domains. (1) Lake and alluvial, post-orogenic sediments; (2) Flysch deposits pertaining to the Macigno Fms.; (3) Flysch deposits of the Marche sequence; (4) Ligurian allochtonous complex; (5) Flysch deposits pertaining to the Marnoso–Arenacea Fm.; (6) Plio-Pleistocene marine and continental deposits; (7) Limestone and Marls pertaining to the Umbria–Marche sequence; (8) Volcanic rocks. (B) Distribution of landslide deposits mapped through a reconnaissance survey of medium-scale aerial photographs (after Guzzetti and Cardinali, 1989; Antonini et al., 1993). (C) Administrative boundaries (townships). Dots report the location of 956 sites affected by mass movements cataloged by the historical inventory completed for the period 1918–1990. (D) Morphological classification in terrain types. (1) Lowlands; (2) Low hills; (3) Hills; (4) Mountains; (5) High mountains.

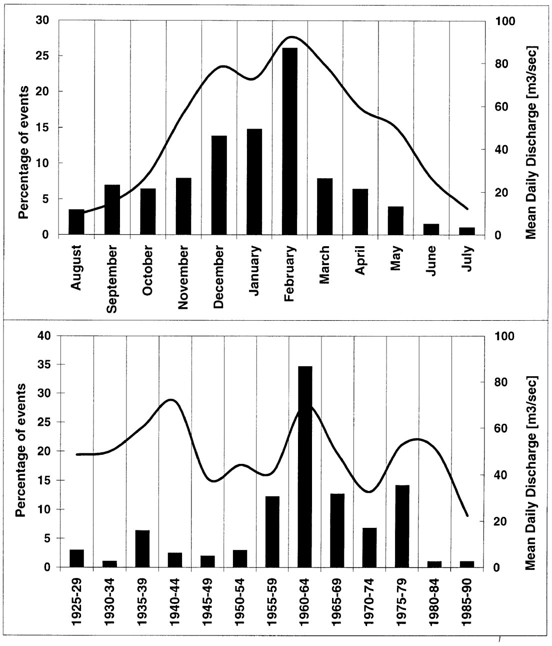

Fig. 3. Umbria and Marche Regions. Frequency of landslide events cataloged for the period 1918–1990, compared with the regional climatic trend, expressed by average mean daily discharge of the Tiber River at the Ponte Nuovo gauging station (Perugia). (A) Average, monthly frequency of landslide events. (B) Frequency of landslide events in 5-year intervals.

than a peculiar climatological condition (a dry period).

As a preliminary assessment of the regional economic impact of landslides in the Umbria–Marche territory, the two inventories (reconnaissance and bibliographical) were compared using the local administrative boundaries (townships) as the reference mapping unit (Fig. 2C). The percentage of landslide area mapped by the reconnaissance inventory and the number of events available in the historical catalogue were counted within the territory of each municipality. Percentage of landslide area was found ranging between nil (0%), in landslide free areas, to 88% (at Carpegna), with an average value of 10%. Forty percent of townships (125), corresponding to about 30% of the territory, exhibit a percentage of landslide area greater than the average. Only 15 townships had a percentage of landslide area less than 1%. Of these, five, due to the local morphological and geological setting (i.e., large plains), were found completely free of landslide deposits. The bibliographical inventory revealed that 237 townships (70%) experienced from one up to a maximum of 88 landslide events in 72 years (1918–1990), with an average of five events. For 101 townships (30%) no information on landslides was reported. Further analysis showed that for only about 10% of the townships, the morphological and geological setting was not landslide-prone. In all other cases the lack of information could not be interpreted as a safety condition, but the result of the incompleteness of the historical record.

An attempt was made to test the consistency of the two regional evaluations of landslide occurrence. Due to the lack of precision in the location of many landslides identified by the historical investigation (Guzzetti et al., 1994), and the uncertainty associated with small scale landslide mapping (Carrara et al., 1992), a direct map overlay was not appropriate. To take care of possible mapping errors a ''*confidence belt*'' (a ''buffer'') was traced around each landslide whose width was proportional (10%) to landslide area. Then the distance between each landslide identified historically to the nearest landslide mapped by the reconnaissance inventory was computed. It was found that the density of events (number of events/km^2) that fall directly on landslides mapped by the reconnaissance inventory (landslide deposit plus 10% confidence belt) or within a distance of 500 m, is twice the density of events that lay at a greater distance. In other words, 70% of historical events lay on, or within a distance of 500 m to the nearest mapped landslide.

4.3. Reconnaissance modelling of landslide hazard

The reconnaissance estimate of landslide hazard for the entire Umbria–Marche territory was attempted in two ways. At first, an isopleth map, showing the distribution of landslide density, was prepared counting the percentage of area affected by landslides within a circular moving window of about 1 km^2 (Fig. 4A). In landslide-prone areas, landslide density varies from 0.01 (1 ha/km^2) up to 1.0, where the whole area is covered by landslide deposits (Guzzetti et al., 1994).

As a second attempt, a statistical model of landslide hazard was developed using the reconnaissance inventory of slope movements and the thematic information available at small scale (Fig. 4B). Geology was obtained from existing maps at 1:100,000 scale by grouping the over 100 formations into eight lithological domains (Fig. 2A). Major lithological boundaries were buffered to capture the instability effect on slopes of contrasting lithologies (Guzzetti et al., 1996).

Morphology was estimated through the computation of geomorphological parameters (i.e., elevation, terrain gradient, curvature, frequency of slope direction changes, and elevation relief ratio) from a coarse (230×230 m) DTM and an unsupervised cluster analysis of such morphometric data. Hence, the territory was simply divided into five terrain types, namely: lowlands, low hills, hills, mountains and high mountains (Fig. 2D).

Regional seismicity was obtained from a synoptic map showing the maximum felt seismic intensity in Italy (Boschi et al., 1995). Intensity levels were grouped into three classes, namely: low (6°–7°), medium (8°–9°), and high (10°–11°) MCS scale intensity.

Regional climatic conditions were estimated by preparing maps of mean annual precipitation and yearly number of rainy days for the period 1921–1950. Mean annual precipitation ranges from 570 to 1880 mm, whereas rainy days are between 62 and 124 mm. Both parameters are correlated to elevation. A simple index expressing the average yearly rainfall intensity was computed as the ratio between mean annual rainfall and the yearly number of rainy days. Index values were ranked into three classes, corresponding to low, medium and high yearly rainfall intensity.

Mapping units for the analysis were obtained by sequentially overlaying the five thematic maps previously listed. Because the thematic variables are spatially correlated, of the 1080 possible unique conditions only 522 actually resulted, for a total of over 50,000 domains (polygons). Each unique condition was classified as stable or unstable depending on the percentage of area affected by any type of landslide deposit. The threshold was selected equal to the mean landslide area of the whole territory (9%), that is, the expected probability to find a landslide deposit by chance.

Logistic regression was then applied to predict stable and unstable terrain units using 17 dummy (0/1) variables corresponding to the classes into which the five input thematic maps were grouped (Table 1). The results of the classification are shown in Table 2, and the probabilities of landslide occurrence, grouped into four classes, are displayed in Fig. 4B. Of the variables entered into the equation, those reflecting rock type (eight) are the most important in classifying stable and unstable units with a success nearly equal to 75%. Conversely, seismic zoning (two) and climatic belts (two) proved to be rather poor predictors of landslide distribution. This might reflect the time-span of the seismic map (few centuries) and of the rainfall map (30 years). Both are much shorter than that of the reconnaissance inventory that portrays the result of 10,000 years (or more) of geomorphological history. The limited predictive power of morphological variables (four) may be due to the strong correlation at regional scale between morphology (Fig. 2D) and lithology (Fig. 2A).

By overlaying the landslide deposits map (Fig. 2B) over the regional hazard model map (Fig. 4B), the belts at lower probability (0%–20% and 20%–40%) were found to have a percentage of landslide area (4.4% and 6.3%, respectively) which is about one third of that featuring the belts at high hazard (60%–100%), namely 14.1%; while in the intermediate hazard region (40%–60%) landslide area is 8.9%.

Lastly, a preliminary attempt was made to rank the territory of each municipality into hazard classes based on the outcome of the reconnaissance hazard model. It was found that 95 townships have more than 75% of their territory classified as landslide

Fig. 4. Umbria and Marche Regions. Reconnaissance assessment of landslide hazard. (A) Landslide density map (‘‘*isopleth map*’’). Shades of grey indicate increasing percentage of landslide area, from less than 1% (white) to 100% (black). (B) Landslide hazard assessment by logistic regression on 522 unique-condition units. Hazard levels are: (1) 0%–20% (very low); (2) 20%–40% (low); (3) 40%–60% (intermediate); and (4) 60%–100% (high).

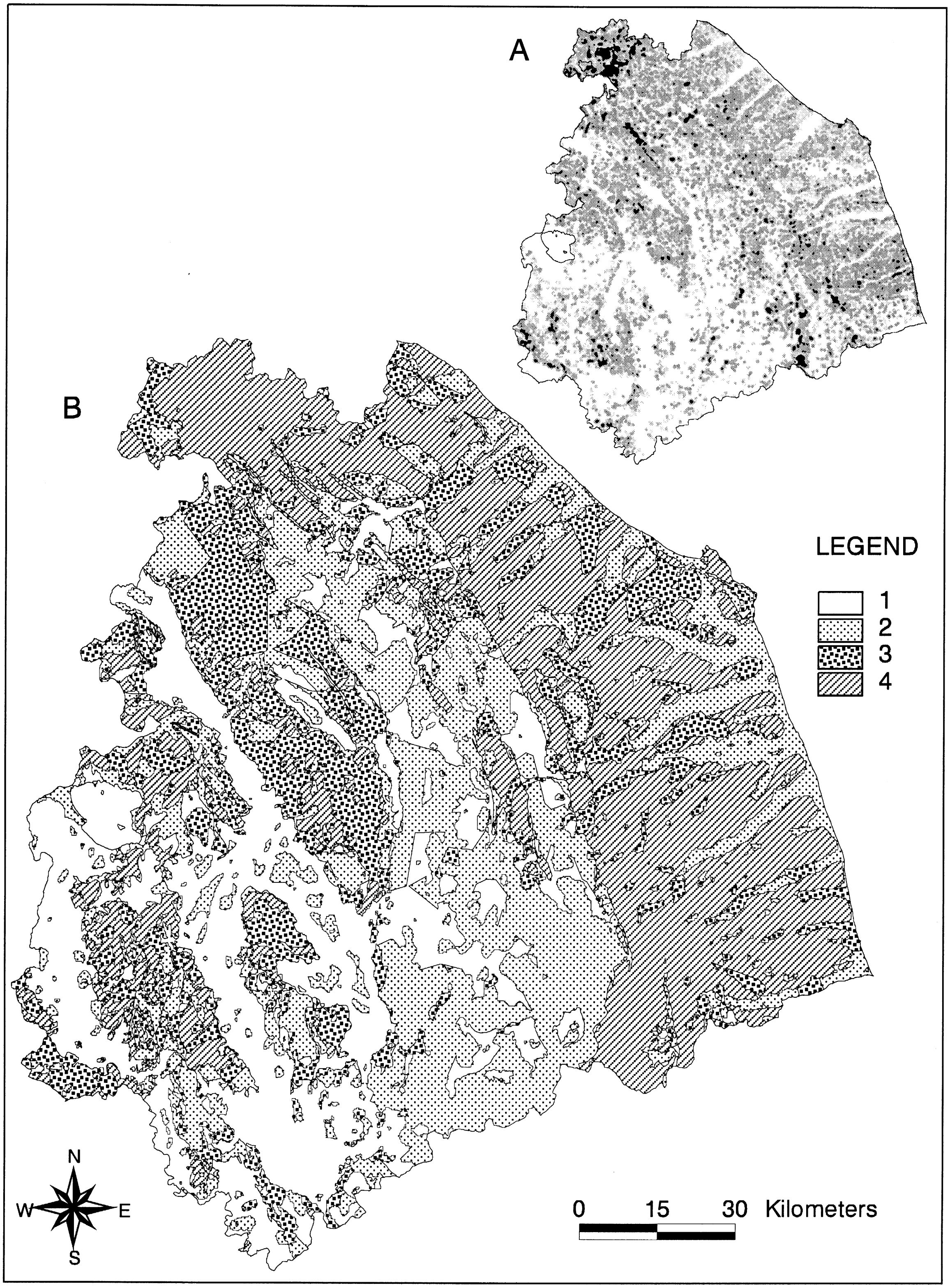
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Table 1
Umbria and Marche Regions. List of 17 dummy variables entered into the logistic regression model, equation coefficients and their standard errors (S.E.). Grouping variable: unique-condition unit free (unstable area $\leq$ 9%) vs. affected (unstable area > 9%) by landslide deposits

Variable	Explanation	Coefficent	S.E.
MAR	Marnoso–Arenacea Fm. Flysch deposits	3.081	1.221
AVAN	marine clay and sand	3.724	1.235
GESSO	Marche flysch deposits	4.225	1.229
UMBRO	Umbria–Marche stratigraphic sequence	2.333	1.218
SINE	lake and alluvial deposits	1.102	1.244
CERVA	Macigno Fms. Flysch deposits	3.244	1.229
VULC	volcanic rocks	2.937	1.257
LIGU	Ligurian allochtonus sediments	4.732	1.313
DD-DD	corridor at the boundary of lithological units	0.919	0.366
MOR-1	lowland	−0.894	0.330
MOR-2	low hills	1.144	2.315
MOR-3	hills	0.401	0.309
MOR-5	high mountains	0.481	0.408
CLIMA-1	low rainfall intensity	−0.465	0.267
CLIMA-3	high rainfall intensity	−0.415	0.251
SEIS-1	low seismicity, 6 to 7 MCS scale	0.403	0.225
SEIS-2	intermediate seismicity, 8 to 9 MCS scale	0.097	0.072
Model		−3.322	1.237

prone (high hazard class). Conversely, only 35 townships have 75% or more of the territory mapped as potentially stable (low hazard class).

4.4. Landslide hazard modelling in pilot areas

In the Tescio and Carpina tributaries of the Tiber River (Fig. 1), detailed hazard evaluations were carried out testing a variety of data acquisition techniques, mapping unit types, and information management and statistical techniques (Carrara et al., 1991, 1995).

Both areas are underlain by rocks belonging to the Umbria–Marche stratigraphic sequence. In the Tescio basin crop out: to the south, thinly bedded limestone, marl and shale Late Jurassic to Cretaceous in age; in the central part, marl and shale Oligocene to Eocene in age; and, to the north, alternating sandstone, calcarenite and marl Miocene in age. The latter cover half of the basin and are affected by numerous landslides, mostly complex, rotational or translational slides with a distinct flow component at the toe. The Carpina basin is underlined by flysch deposits, Eocene to Miocene in age. In the area crop out rhythmic sequences of sandstone, calcarenite and marl in different proportion, marl, shale, and chaotic mixtures (olistostromes) of various rock types. Mass movements comprise large, very old complex slides controlled by the local bedding attitude; old to recent slides are abundant where competent beds (sandstone

Table 2
Umbria and Marche Regions. Classification of stable and unstable unique-condition units by logistic regression
Unique-condition units correctly classified: 74.8%.

Actual group	No. of unique condition units	Predicted group membership	
		Group 1 (stable units)	Group 2 (unstable units)
Group 1 (stable units)	278	214	64
Group 2 (unstable units)	244	68	176

Table 3
Tescio basin. List of variables entered in the discriminant function and their relative importance as expressed by the standardized discriminant function coefficient (SDFC). Grouping variable: slope-unit free of vs. affected by landsliding (after Carrara et al., 1991)

Variable		SDFC
CINE	slope-unit percent of Scaglia Cinerea rock type	−0.202
SCHL	slope-unit percent of Schlier rock type	−0.355
ARCA	slope-unit percent of sandstone-rich rock type	0.331
MAXCA	product of marl-rich and calcarenite-rich rock types	0.693
DENUD	slope-unit percent of uncultivated area	0.314
BOSCO	slope-unit percent of forest	−0.601
AN	slope-unit facing N	0.199
AW	slope-unit facing W	0.293
MAGN	sub-basin magnitude	−0.492
ELV-M	slope-unit mean elevation	−0.295
FORM	slope-unit form perimeter/area	−0.503
RXGR	slope-unit surface roughness index	−0.260
FRA-TR	bedding dipping toward slope-unit free face	0.251
IDR-A	permeable beds (sandstone) capping impermeable ones	0.545
IDR-D	impermeable beds (clay and shale) throughout slope-unit	0.840

and calcarenite) are present within mostly marly rocks; and old to recent shallow soil-slips and flows take place on soil-mantled slopes.

Detailed thematic data were derived from existing topographic maps, aerial photographs and field surveys. Landslide deposits, classified according to relative age, degree of activity, movement type, estimated depth and velocity, type of material, and mapping certainty, were determined by interpreting aerial photographs of different dates and scales (1:33,000 and 1:13,000), and by systematic field investigations.

Using high-fidelity DTMs (20×20 or 25×25 m), drainage-divide networks were automatically identified and basins were partitioned into sub-basins and slope-units, each characterized by a wide set of morphometric and hydrological parameters (Carrara, 1988; Carrara et al., 1991, 1995).

Geological data were obtained by field mapping at 1:10,000 scale, aided by photo-geological techniques. Bedding and structural measurements (joints, cleavage and faults) were taken as uniformly as possible throughout the study areas. This allowed partitioning of the terrain into structural domains (i.e., anticline, thrust, graben, etc.) as well as in constant bedding (strike and dip) areas. By comparing bedding attitude and slope orientation (aspect and steepness), slope-units were classified in structural and bedding attitude classes. To estimate the hydrological conditions of slopes, the stratigraphic relations between permeable and impermeable rocks were estimated in the field and from the lithological maps. Land-use data were obtained from existing maps at 1:10,000 scale and through the interpretation of large scale, color aerial photographs.

In the Tescio basin, for each slope-unit the percentage of unstable area was derived as the weighted summation of the landslide area existing in the unit. Slope-units were defined as landslide-free and landslide-bearing when the percentage of failed area was

Table 4
Tescio basin. Classification of stable and unstable slope-units by discriminant analysis (after Carrara et al., 1991)
Slope-units correctly classified: 83.8%.

Actual group	No. of slope-units	Predicted group membership	
		Group 1 (stable slopes)	Group 2 (unstable slopes)
Group 1 (stable slopes)	148	128	20
Group 2 (unstable slopes)	118	23	95

Table 5
Carpina basin. List of variables entered in the discriminant function and their relative importance as expressed by the standardized discriminant function coefficient (SDFC). Grouping variable: slope-unit free of vs. affected by *old to recent slides* (after Carrara et al., 1995)

Variable		SDFC
CAM	slope-unit percent of marly–calcareous sandstone	0.253
ALL-COL	slope-unit percent of alluvial–colluvial deposits	−0.209
D3	slope-unit percent of N monocline domain	0.215
D11	slope-unit percent of NE transcurrent fault domain	0.122
D12	slope-unit percent of graben domain	0.173
TRR	bedding dipping obliquely into the slope	−0.217
TFP	bedding dipping toward slope free face	0.245
CATA	slope-unit percent of cataclastic rocks	0.105
RX	variability of across-slope profile	−0.338
COC-COV	concave–convex slope-unit profile	−0.170
IRR	irregular slope-unit profile	−0.109
MOR-A1	PC reflecting slope length and width	0.354
MOR-B1	PC reflecting slope steepness	−0.264
PALEO	slope-unit profile inherited from old landsliding	0.268
AC-TM	permeable beds capping impermeable ones	0.115
AC-A	acquifer in alluvial–colluvial deposits	−0.232
S-BO	slope-unit percent of forest area	−0.204
S-PP	slope-unit percent of pasture area	0.126
S-DN	slope-unit percent of barren area	−0.264
S-SAP	slope-unit percent of cultivated area	0.254

less or greater than 2%, respectively. This threshold was derived from an estimate of average drafting and digitising errors. Using classified slope-units as the grouping variable and almost 40 factors as input predictor variables, stepwise discriminant analysis was applied in order to predict stable or unstable slope-units, on the basis of their morphological, geological and land-use characteristics. The variables (factors) entered into the discriminant function are listed in Table 3, while the results of the classification are summarized in Table 4. A test of the statistical reliability of the model showed that the discriminant function was able to classify correctly (from 75% to 82%) stable and unstable slopes belonging to the test set.

In the Carpina basin large, very old complex slides; old to recent slides; and old to recent, shallow flows or soil-slips were processed separately. For the area, three drainage-divide networks of increasing detail were prepared, partitioning the basin into a different number of slope-units, namely: 66, 414 and 750 which correspond to an average size of 1.109, 0.162 and 0.090 km^2, respectively. These values were selected in agreement with the average size of each landslide group.

Because of the large number of variables available (over 60) and their high interrelations, selected subsets were replaced with their most significant principal components (PC), through standard principal components analysis (PCA), to reduce redundancy and to improve numerical stability in the subsequent analyses. Stepwise discriminant analysis was performed on each set of 66, 414 and 750 slope-units, setting as grouping variable the presence/absence of slope failures belonging to either the large, very old landslides, or slides, or flows. Since slope-units are very unequal in size in each map and uncertainty in the input data is expected to

Fig. 5. Carpina basin. Evaluation of landslide hazard. Hazard levels are: (1) 0%–40% (low); (2) 40%–60% (intermediate); and (3) 60%–100% (high); (4) are landslide deposits. (A) Landslide hazard assessment by discriminant analysis on 414 slope-units. (B) Landslide hazard assessment by discriminant analysis on 2092 unique-condition units.

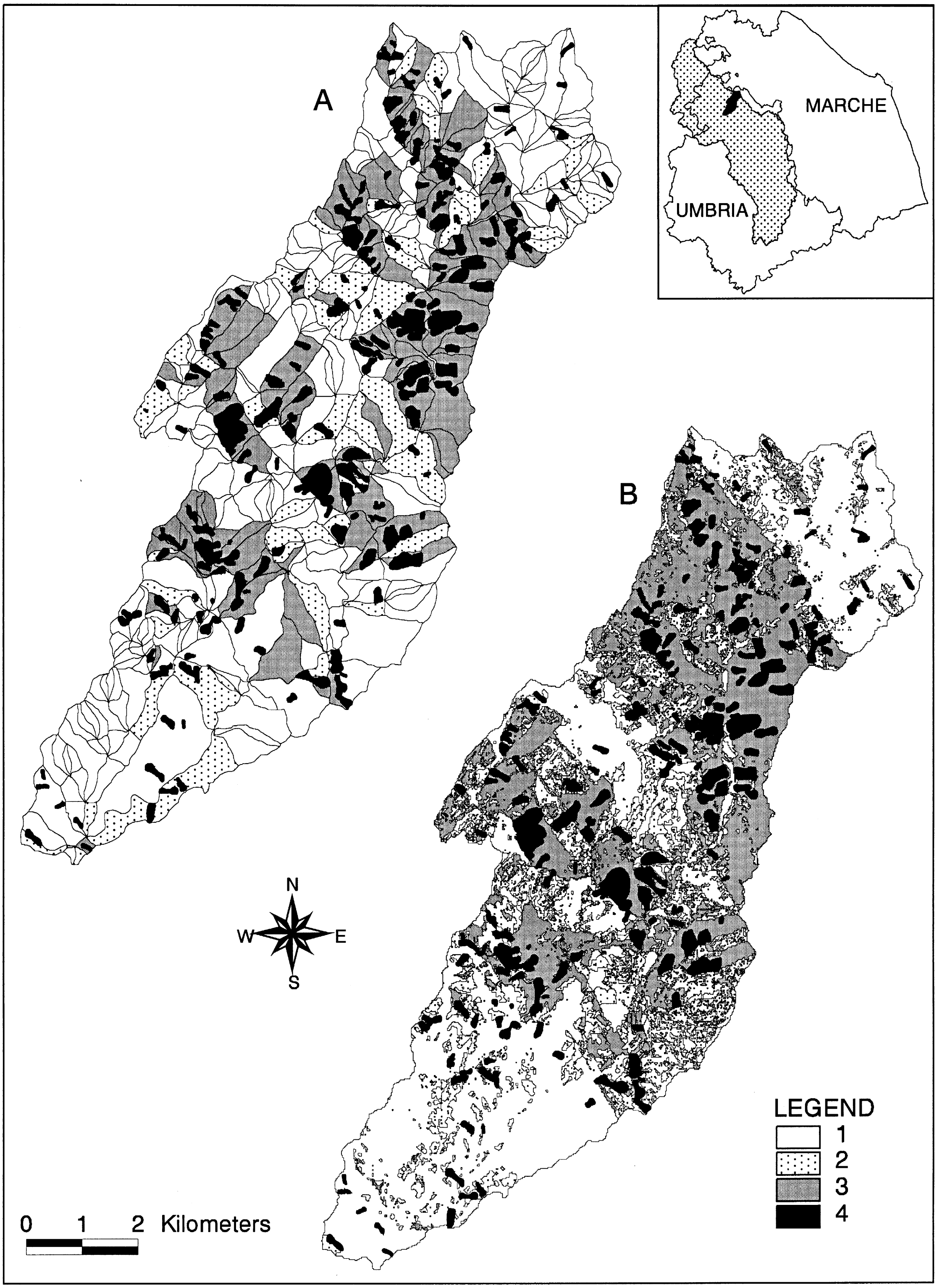
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Table 6
Carpina basin. Classification of stable and unstable slope-units by discriminant analysis (after Carrara et al., 1995)
Slope-units correctly classified: 80.7%.

Actual Group	No. of slope-units	Predicted group membership	
		Group 1 (stable slopes)	Group 2 (unstable slopes)
Group 1 (stable slopes)	278	228	50
Group 2 (unstable slopes)	136	30	106

decrease with slope-unit size, all analyses were weighted by the log of the slope-unit area. The results of this threefold analysis can be summarized as follows.

To predict successfully (at the 92% level) the occurrence of the few large, very old slides, 12 variables entered into the model. They equally reflect rock composition, structural setting, slope morphometry and ground water conditions.

In the second analysis carried out on the statistically more significant group of the old to recent slides, a wider spectrum of variables entered into the model (Table 5), namely: rock type (two), structure (six), morphometry (six), water conditions (two) and land-use (four). In Fig. 5A, the probabilities of slide occurrence, grouped into three classes, are displayed along with the slide deposits. Although the classification power of the model is rather good (over 80%, Table 6), too many predictors were needed to obtain this result. Indeed, an intrinsic limitation of any multivariate analysis is that as the number of variables increases the reliability of the model decreases to some extent.

To predict at the 75% level slope-units affected by shallow landslides, 20 variables entered into the discriminant function, of which two regard slope

Table 7
Carpina basin. List of dummy variables entered into the discriminant function and their relative importance as expressed by the standardized discriminant function coefficient (SDFC). Grouping variable: unique-condition unit free of (unstable area $< 4.39\%$) vs. affected by old to recent slides (after Carrara et al., 1995)

Variable		SDFC
CALC	calcareous sandstone and marl	−0.195
ARP	sandstone and marl	−0.141
CAM	marly–calcareous sandstone	0.419
PELC	marl and calcareous sandstone	−0.100
OLI	tectonic clayey melange	0.075
ALL-COL	alluvial–colluvial deposits	−0.216
D3	northern monocline domain	0.307
D7	southern thrust fault domain	−0.201
D10	central transcurrent fault domain	0.171
D11	northeastern transcurrent fault domain	0.160
SLO10	slope angle $< 10°$	−0.194
SLO25	slope angle between 20°–25°	−0.151
SLO90	slope angle $> 25°$	−0.262
PROF1	concave down-slope profile	−0.205
PROF2	rectilinear down-slope profile	−0.071
CATA	cataclastic rock	0.157
LEN200	slope length < 200 m	−0.112
LEN400	slope length between 200–400 m	0.286
REG-T	bedding dipping into the slope	−0.192
FRP-T	bedding dipping toward the slope free face	0.231
S-BO	forested area	0.220
S-PP	pasture area	0.479

Table 8
Carpina basin. Classification of stable and unstable unique-condition units by discriminant analysis (after Carrara et al., 1995)
Unique-condition units correctly classified: 72.7%.

Actual group	No. of unique condition units	Predicted group membership	
		Group 1 (stable units)	Group 2 (unstable units)
Group 1 (stable units)	1213	893	320
Group 2 (unstable units)	879	252	627

material, nine the structure, six the morphometry and three the land-use type. The rather low percentage of slope-units correctly classified indicates that input variables were unable to predict adequately the spatial distribution of flows in the area. This is not surprising; a test of randomness of their distribution proved that in a large portion of the basin shallow failures were nearly randomly distributed with respect to the available thematic information (Cardinali et al., 1994).

In the Carpina basin, an attempt was also made to assess landslide hazard due to old to recent slides using unique-conditions as mapping unit. In order to apply a multivariate statistical analysis to such an approach, all input variables were grouped into a few meaningful classes. For categorical data, such as rock type and land-use, this operation did not involve any subjective judgement. For continuous variables, such as slope angle or length, the selection of the number of classes and class limits (*break points*) required a significant amount of guess work guided by previous knowledge of the causal relationships between slope failures and instability factors. As a result, from eight input dummy (0/1) variables, namely: rock type (eight classes), structural domains (12 classes), fault zones (two classes), bedding attitude vs. slope aspect/angle (four classes), slope angle (five classes), down-slope profile (three classes), slope length (four classes) and land-use (three classes) a total of 41 classes were derived. To limit the number of statistically meaningless unique-conditions, filtering techniques were applied after each map overlay step. As a result, the final map had only 2092 unique-conditions, out of 138,240 possible cases.

Stepwise discriminant analysis was then applied using, as the grouping variable, unique-condition units having a percentage of sliding area lower or greater than 4.39%, that is half the average instability percentage of the basin, and, as predictors, the dummy variables corresponding to the classes into which the eight input layers were grouped. Under the assumption that both the errors and uncertainty decrease with the size of the ground domain, all the analyses were weighted by the log of the domain area.

Model results are listed in Table 7 and the probabilities of slide occurrence, grouped into three classes, are displayed in Fig. 5B. Of the 22 dummy (0/1) variables entered into the function, five are lithological, seven structural, seven morphometrical, and two concern land-use. The presence/absence of pasture, marly–calcareous sandstone, northern monocline domain, and slope length are the most important in classifying stable and unstable units with a success equal to 73% (Table 8).

The outcome of the two hazard assessments, on slope-units (model A) and on unique-condition units

Table 9
Carpina basin. Comparison of percentages of area predicted as unstable, intermediate (‘‘*unclassified*’’) and stable, based on discriminant membership probabilities greater than 60%, between 40%–60% and less than 40%. Model A (slope-units) refers to Tables 5 and 6 and Fig. 5A. Model B (*unique-condition units*) refers to Tables 7 and 8 and Fig. 5B (after Carrara et al., 1995)

	Model A (*slope-units*)	Model B (*unique-condition units*)
Unstable area	31.5%	34.0%
Intermediate area	18.7%	21.1%
Stable area	49.8%	44.8%

(model B), can be compared. The lists of variables entered into the discriminant functions for slope-units (Table 5) and unique-condition units (Table 7) show that several predictors are in common, albeit with

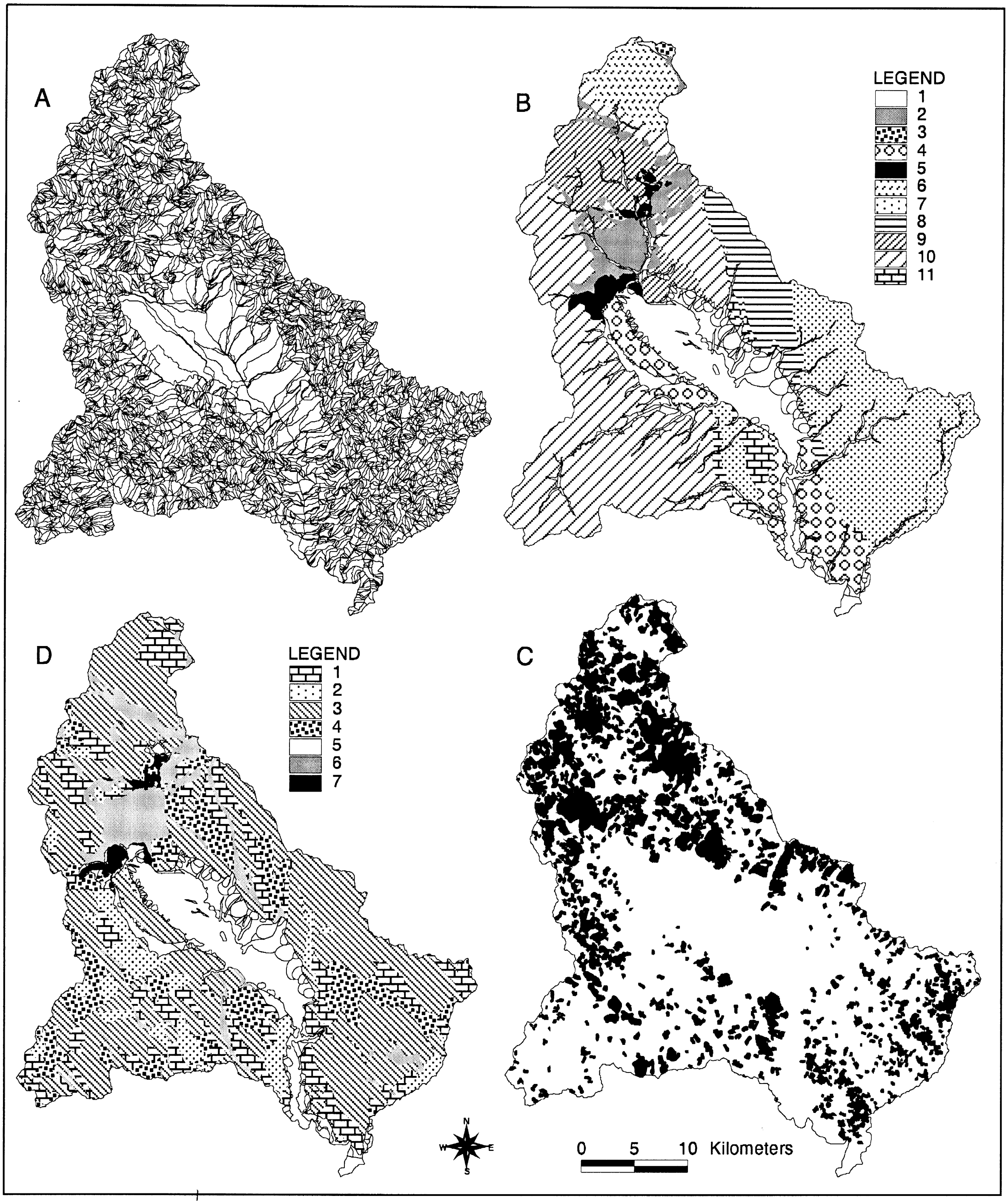

Table 10
Upper Tiber River basin. List of 40 variables entered into the discriminant function and their relative importance as expressed by the standardized discriminant function coefficient (SDFC). Grouping variable: slope-unit free vs. slope-unit affected by deep-seated landslides

Variable		SDFC
SAPM	Alberese Fm. Limestone and marls	0.345
MAUH	Marnoso–Arenacea Fm. Flysch deposits	0.163
ASS	Chaotic lithological complex	0.166
FADT	alluvial deposits, fans and detritus	−0.335
STS	Macigno del Mugello Fm. Marly flysch	0.235
STH	Macigno del Chianti Fm. Sandy flysch	0.092
MNS	Monte Nero Fm. Marl and shale	0.073
LIGH	Ligurian allochtonus complex. Ophiolite suite	0.231
MARS	Marnoso–Arenacea Fm. Marly, flysch deposits	0.219
DFLS	lake deposits, clay and silt	0.082
DFLM	lake deposits, silt and sand	0.296
DFLH	lake deposits, gravel and cobbles	−0.049
LINK_LEN	channel link length	−0.131
LINK_ANG	channel link slope	0.164
ANG_STD	dispersion of channel link slope	−0.129
SLO_ARE	slope-unit area	0.153
R	variability of slope profile	−0.106
ELEV_STD	dispersion of elevation	0.588
SLO_LEN	slope-unit length	0.422
COV_COC	convex–concave slope-unit profile	−0.173
COC_COV	concave–convex slope-unit profile	0.040
MOR_A1	PC reflecting slope-unit hydrologic position	0.300
MOR_A2	PC reflecting slope-unit hydrologic position	0.189
MOR_B1	PC reflecting slope steepness	−0.475
IRR	irregular slope-unit profile	−0.064
TR1	slope-unit facing N or NW	0.036
TR2	slope-unit facing NE or E	0.095
STRU1	PC reflecting rock structure and attitude	−0.427
STRU3	PC reflecting rock structure and attitude	−0.453
REG	bedding dipping into the slope	−0.389
FRAM	bedding dipping toward slope free face	0.537
TRA	bedding dipping at right angle to the slope	−0.049
CAO	chaotic bedding	0.122
NONE	undefined bedding	−0.116
MASS	massive rock types	−0.160
AE	slope-unit percent of built up area	−0.077
SA	slope-unit percent of culture with orchard area	0.033
PA	slope-unit percent of pasture area	0.275
SS	slope-unit percent of cultivated area	0.162
AN	slope-unit percent of denuded and unclassified area	−0.083

similar of different coefficients (SDCF). Of the 20 variables entered into the slope-unit model, nine, equally distributed between lithology (two), structure (two) bedding attitude (three) and land-use (two),

Fig. 6. Upper Tiber River basin. (A) Subdivision of the basin into 5598 slope-units. (B) Lithological map. (1) Alluvial deposits, fans and detritus; (2) Chaotic lithological complex; (3) Limestone and sandstone of the San Marino sequence; (4) Lake deposits; (5) Ligurian allochtonous complex; (6) Flysch deposits of the Marnoso–Arenacea Romagnola sequence; (7) Flysch deposits of the Marnoso–Arenacea Umbra sequence; (8) Marl and shale of the Monte Nero Fm.; (9) Limestone and marl of the Alberese Fm.; (10) Flysch deposits of the Macigno Fms.; (11) Schlier Fm. (C) Landslide inventory map, only deep-seated landslides are reported. (D) Bedding attitude map. (1) N–NE; (2) E–SE; (3) S–SW; (4) W–NW; (5) chaotic; (6) undefined; (7) massive.

entered directly into the unique-condition model. Other variables are comparable, namely: MOR_B1, a proxy for terrain gradient, incorporates much of the information of SLO10, SLO25 and SLO90. Likewise, MOR_A1, a proxy for slope length, includes LEN200 and LEN400.

The total areas predicted by the two models as unstable, intermediate (''unclassified'') and stable are comparable (Table 9). In terms of predictive power, model A (slope-units) is significantly superior for the higher percentage of classes correctly classified (80.7 vs. 72.7) and for the lower proportion of area ''unclassified'' (18.7% vs. 21.1%); however, its spatial resolution is lower than that of model B (unique-condition units). The average size of a slope-unit (0.13 km^2) is five times larger the average size of a unique-condition unit (0.03 km^2).

4.5. *Predictive model of landslide hazard for the upper Tiber river basin*

A detailed estimation of landslide hazard over a large area is currently being attempted in the Upper Tiber River Basin (Fig. 1). The long-term experiment involves: the generation of a high-fidelity DTM; the production of a revised, 1:25,000 scale landslide inventory map; the acquisition of lithological, hydrological, structural and land-use data at 1:25,000 or 1:10,000 scale.

A detailed digital representation of terrain was generated from contour lines obtained from 1:25,000 scale topographic maps. From a 25 × 25 m DTM (totalling 6.5 million heights), nearly 20,000 slope-units were generated (Fig. 6A). For each slope-unit, 24 morphometric parameters were automatically computed or subsequently derived.

Lithological, bedding-plane, and landslide inventory maps were prepared through an extensive interpretation of 1:33,000 scale, black and white, aerial photographs and, limited to the outcrop of lake and continental deposits, of 1:13,000 scale color aerial photographs (Fig. 6B). Landslides were classified into shallow failures and deep-seated movements, of certain or uncertain identification (Fig. 6C). The lithological map was obtained updating the available geological maps, at 1:100,000 scale or larger. Attention was paid to the identification of rock types particularly prone to landslides, differentiating clay rich units from more competent rocks. Bedding attitude, an important factor in controlling landslide types and pattern in the region (Guzzetti et al., 1996), was mapped identifying areas of constant bedding attitude with respect to the local slope (Fig. 6D). The lithological, bedding attitude and landslide maps were locally checked against detailed surveys (Carrara et al., 1991; Barchi et al., 1993; Toppi, 1993; Cardinali et al., 1994; Lambrugo and Lattuada; 1996). Land-use was obtained assembling the existing maps at 1:10,000 and 1:25,000 scale.

Lithological, geological, structural, geomorphological and land-use data are available for the entire area. However, only for the northernmost part of the basin, covering about 1132 km^2, thematic data are validated. For each of the 5598 slope-units pertaining to this portion of the basin, the percentage of unstable area was computed adding all deep-seated landslide area existing in each unit. Area of uncertain landslides was weighted by a factor of 0.7. Shallow failures were not taken into consideration.

Small slope-units (less than 10 ha) were considered stable if the total landslide area was less than 10%. Large slope-units (larger than 40 ha) were classified as landslide-bearing if landslide deposits exceeded 2.5% of the area. For slope-units of intermediate size (10–40 ha), the threshold value was set to 5%.

As for the Carpina basin, selected subsets of the 60 input variables were replaced by their most signif-

Table 11
Upper Tiber River basin. Classification of stable and unstable slope-units by discriminant analysis
Slope-units correctly classified: 72.0%.

Actual Group	No. of unique condition units	Predicted group membership	
		Group 1 (stable units)	Group 2 (unstable units)
Group 1 (stable units)	3502	2522	980
Group 2 (unstable units)	2096	587	1509

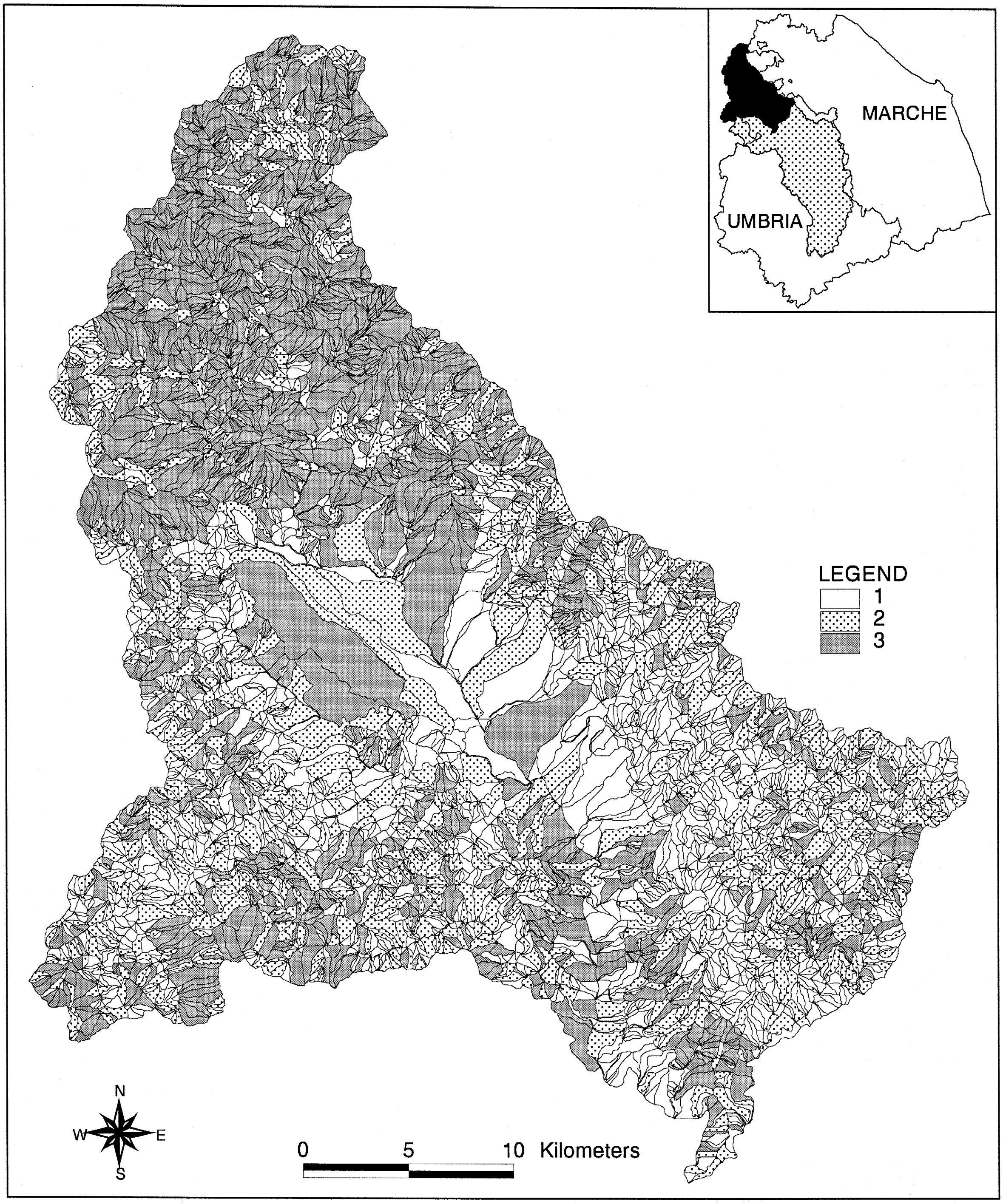

Fig. 7. Upper Tiber River basin. Landslide hazard assessment by discriminant analysis on 5598 slope-units. Hazard levels are: (1) 0%–40% (low); (2) 40%–60% (intermediate); and (3) 60%–100% (high).

icant principal components (PC). Factors were computed for morphometrical and structural/bedding attitude variables.

Using the presence/absence of landslides as the grouping variable, stepwise discriminant function was applied to the 5598 slope-units. For a preliminary prediction of deep-seated landslide hazard, 40 variables entered the discriminant function (Table 10). Of these, 12 are lithological, 15 morphometrical, eight express structure or bedding plane attitude, and five refer to land-use. Variables reflecting slope morphometry and attitude of bedding were the most powerful in classifying stable and unstable units with a success equal to 72% (Table 11). The probability of slide occurrence, grouped into three classes, is displayed in Fig. 7.

The preliminary hazard assessment assigned 42% of the territory of the Upper Tiber River basin to the high probability class, 28% to the intermediate (''undefined'') class, and 30% to the low hazard class. Frequencies of landslide area in each class are 28%, 11% and 4%, respectively.

5. Discussion

Landslide hazard evaluation and mapping rely on a rather complex body of knowledge of slope movements and on few basic assumptions, widely accepted among earth scientists. Ideally, such assumptions form the conceptual framework within which the ''*rationale*'' on slope movements is applied, regardless of the hazard evaluation method, the mapping unit, the scale of the analysis, or the goal of the investigation. Unfortunately, due to operational and conceptual constraints, the task is not always feasible or possible.

Major constraints include: systematically identifying landslide deposits; correctly understanding the causes and triggering mechanisms of slope-failures; obtaining adequate information on the relevant geological, geomorphological, hydrological, climatological, etc. instability factors; selecting the most suitable mapping unit and predictive model; and acquiring appropriate techniques and tools for data analysis and modelling.

These constraints pose severe limitations on the evaluation of landslide hazard. Lack of understanding and recognition of the main causes of landsliding prevents any successful hazard evaluation. Deficiency of adequate information on the instability factors affects the reliability and effectiveness of the forecast. Selection of a mapping unit and of a modelling method affect the way uncertainties in the input data are dealt with, as well as the model fit and its reliability. Inadequacy of GIS and modelling software limits the reliability of the forecast and jeopardize the practical application of any model.

Some of these limitations can be overcome; others pose more severe conceptual constraints. The conceptual limitations and the operational difficulties will now be discussed in the light of the experience gained from the Umbria–Marche project.

5.1. Constraints in the application of basic principles

Geomorphological information remains largely descriptive. Its subjectivity makes it somewhat unsuitable for engineers, policy makers or developers in planning land resources, when mitigating the effects of geological hazards. In the past two decades, countless landslide maps were produced by geomorphologists. The reliability of these maps is poorly documented. This introduces a factor of uncertainty that cannot readily be evaluated and incorporated in the subsequent phases of data modelling and in the transfer and use of this information.

Identification and mapping of landslide deposition–erosional areas, the first step in any landslide hazard assessment (Brabb, 1984; Hansen, 1984), are indeed difficult, error prone, and subject to uncertainties largely untested (Fookes et al., 1991; Carrara et al., 1992; van Westen, 1993). This is particularly true for old or inactive slope movements, for landslides that leave faint morphological signs, for failures in forested areas, on slopes intensively ploughed, and in recently urbanized areas (Brabb, 1984; Guzzetti and Cardinali, 1989; Brabb, 1995; Hutchinson, 1995). Inadequacy in mapping the full extent of slope movement limits the reliability of any hazard assessment, particularly, if errors are systematic in recognizing some types of slope processes (Brabb, 1995).

Reconnaissance inventories provide a fairly unbiased spatial coverage but generally lack information on the time of occurrence of failures (Cotecchia, 1978). This information is available only where a reconnaissance inventory is completed shortly after a particularly damaging meteorological or seismic event. Attempts at evaluating the ‘‘goodness’’ of reconnaissance inventories at different scales proved that errors can be large and related to the experience of the interpreter, the scale of the inventory and of the aerial photographs, and the time available for the study (Carrara et al., 1992; van Westen, 1993).

Historical records (*landslide time-series*) constitute the main source for every estimate of landslide recurrence. Drawbacks of the historical analysis include: lack of spatial completeness, resolution and precision; and an undefined over-estimate of events which caused damage to human structures as opposed to an under-estimate of failures, even large, which took place in unpopulated areas (Guzzetti et al., 1994; Ibsen and Brunsden, 1996). The Umbria–Marche archive inventory largely confirms such biases.

Identification and mapping of a suitable set of instability factors (*thematic mapping*) bearing a relationship with slope failures — such as surface and bedrock lithology and structure, bedding attitude, seismicity, slope steepness and morphology, stream evolution, groundwater conditions, climate, vegetation cover, land-use and human activity (Carrara et al., 1995; Hutchinson, 1995) — require an a priori knowledge of the main causes of landsliding (Schuster and Krizek, 1978; Crozier, 1986). The availability of thematic data largely varies depending on the type, scale, and technique for data acquisition. As for landslide maps, the quality of this information remains largely undefined. Where thematic data are gathered manually, by field survey or through the interpretation of remote sensing data (aerial photographs or satellite images), mismatch between different interpreters can be large (Carrara et al., 1992). Recent visual estimates of the mismatch between geological maps at different scale and of different dates in the Umbria Region revealed large discrepancies. Attempts to evaluate the quality of digital terrain models, widely used in describing landscape morphology for slope stability (Carrara, 1983; Carrara et al., 1991, 1995; Pike, 1988; van Westen, 1993; Dietrich et al., 1995; Mark and Ellen, 1995), proved that even where data are gathered and manipulated automatically or semi-automatically, errors and uncertainties can be greater than commonly expected (Carrara et al., 1997).

As previously pointed out, predictive hazard models assume that landslides in the future will take place under the conditions which led to past and present instability. This assumption holds true for factors, such as bedrock lithology, structure and morphology, which are time-invariant within the temporal framework of the model. Conversely, it cannot be extended to environmental factors which vary with time, such as land-use, human activity and even climate. Climatological conditions that triggered mass movements in the past may differ from present climate, in a way and for an amount that is usually unknown in quantitative terms. Information on land-use and human activity can be obtained for both historical and modern time; however, such instability factors may vary rapidly in response to environmental changes or economical needs. Thus, the use of past environmental settings exhibiting large temporal variability may lead to erroneous predictions.

The estimate of the relative contribution of each physical factor in generating slope-failures, and the classification of the land surface into domains of different hazard degree (*hazard zoning*) are a crucial step. When the main instability factors leading to slope failure are identified, the understanding of their complex interactions becomes the next difficult issue to be accomplished, particularly over large regions (Hutchinson, 1995; Guzzetti et al., 1996). Additionally, the role played by factors leading to (i.e., rock type, clay content, bedding attitude, etc.) or bearing (i.e., land-use, vegetation cover, etc.) a functional relationship to landslide occurrence in one area may turn out to be very different in other areas (Guzzetti et al., 1996).

Quite surprisingly, investigators have invested little time in the acquisition of terrain information and in testing innovative mapping techniques. Likewise, few attempts have been made at the ‘‘regionalization’’ of site specific information and models. This has limited the use of geotechnical and site specific data on regional hazard modelling (Nieto, 1989; Hutchinson, 1995).

5.2. Selection of a mapping unit

As previously mentioned, various methods (grid-cells, terrain units, unique-condition units, slope-units and topographic units) have been proposed and tested to partition the landscape into mapping units. Each method has advantages and drawbacks which can be either enhanced or controlled depending on the hazard assessment approach used.

Automated cartography and GIS-based spatial operations have demonstrated their usefulness in partitioning a territory into mapping units according to various criteria without the constraints due to traditional, time-consuming manual work. When appropriate software is available, the investigator can readily choose among grid-cells, unique-conditions, slope-units or other terrain subdivisions without investing a great deal of time and tedious work. Hence, the major issue is no longer how to create the sampling unit, but which unit is the most suitable for the type of problem to be investigated. Actually, as it was demonstrated in the Carpina basin, more than one mapping unit can be tried and the most suitable for the problem at hand can be used.

Advantages and limitations of grid-cells are known. Owing to the matrix form of the grid data, computer implementation is simple and processing is fast. Since data are regularly spaced, sampling constraints are relaxed. Drawbacks lay in the absence of any relation between grid-cells and geological, geomorphological, or any other terrain information. The tendency to use smaller and smaller grid-cells appears unjustified. Spatial inaccuracy is partially reduced but to cover even small areas an overwhelming number of grid-cells is required, leading to unmanageable computer problems and numerical instability when data have to be processed by statistical techniques.

Terrain units, which have long been applied in many land resources investigations on a wide range of scales, fully exploit the investigator skill in detecting in the field or on aerial photographs the complex relations existing between slope-failure and the geomorphological context. The approach, emphasizing cataloging, provides much information about the land but it does little to measure the functional relationships between instability factors. The main drawback lays in the intrinsic subjectivity of the method. Different investigators may classify any given region in different ways. To partition the landscape into geomorphological-units, maps portraying all the different forms and processes are used. These maps use a variety of classification schemes which are always complex and frequently inconsistent; conceptually or spatially.

Unique-condition units are appropriately applied where it is conceptually or operationally difficult or impossible to pre-define a physically based mapping unit or domain. They perform well where thematic information (layers) completely ‘‘fill’’ the territory. Problems arise where linear features (i.e., fault lines or lithological boundaries) are used in the analysis. The problem arose in the Umbria–Marche experiment, where lithological boundaries were buffered to capture the instability effect of contrasting lithology. Another weakness is the inherent subjectivity in factor classification that has to be performed prior to map overlay. Additionally, by overlying more than just few maps (five to seven), each with a relatively small number of factors (3–10), thousands of small domains are generated. Most of these areas result from errors in data collection and digitisation and are statistically meaningless. They can be cancelled out by applying some filtering technique, however loosing in objectivity in the process. Other areas may reflect rare (small in size) but physically meaningful conditions (‘‘*outliers*’’) that cannot be eliminated. Since some of the factors into which each input layer is classified may turn out to be not very significant, it would be wise to restart the whole map overlay operation after the reclassification of such layers. This makes the procedure rather cumbersome.

Since a clear physical relationship exists between landsliding and the fundamental morphological elements of a hilly or mountain region, namely drainage and divide lines, the slope-unit technique seems appropriate for landslide hazard assessment. In the Upper Tiber River basin, it was observed that problems arise where intra-mountain basins or large open valleys are present. In these areas, slope-units do not match with the local geomorphological setting bearing on slope instability. Slope-units can be resized according to the prevailing failure type and dimension, partitioning a river basin into nested subdivisions, coarser for larger landslides and finer for smaller failures (cf. Carpina basin). Despite this capability, the tendency of slope-units to identify relatively large areas into stability types rather than resolve fine-scale patterns of instability conditions, limits the applicability of this approach for small, shallow landslides such as soil-slips and debris flows (Montgomery and Dietrich, 1994).

To overcome this limitation, slope-units can be further subdivided into topographic units. Due to the physical relationship between topography and surface and sub-surface hydrology, the approach appears most appropriate to predict surface saturation and the occurrence of topographically controlled landslides, such as soil-slip–debris flows, in soil mantled topography (Montgomery and Dietrich, 1994). Limitations refer to: the availability of detailed contour lines that accurately portray topography, seldom available over large areas; the assumption that sub-surface hydrology is directly related to surface topography; and the related inadequacy to investigate deep-seated, complex slope failures.

It should be pointed out that too often, the selection of the mapping unit appears guided more by the type of software available (i.e., raster vs. vector GIS, DTM modelling software, etc.), rather than by the specific requirements of the geomorphological data to be analysed.

5.3. Landslide hazard modelling

As previously discussed, all methods proposed and tested to evaluate landslide hazard fall into a few main categories, namely: direct geomorphological mapping; analysis of landslide inventories; heuristic or index based models; functional or statistical models; and geotechnical or physically based models.

The goodness of direct methods for landslide hazard mapping relies on the ability of the investigator to estimate actual and potential slope failures, taking into account a large number of instability factors detected in the field or on aerial photographs (Verstappen, 1983). In addition, local or peculiar slope instability conditions can be identified and assessed. Drawbacks concern the high subjectivity that characterizes all phases of the geomorphological investigation. Moreover, the degree of uncertainty can not be readily evaluated, making it difficult, or impossible, to compare landslide hazard maps produced by different investigators, even if they applied the same ranking criteria (Godefroy and Humbert, 1983).

Isopleth maps can be readily produced for large areas; they provide a general overview of landslide occurrence and may be useful when portraying the distribution of many failures triggered by severe storms or seismic events. However, such fairly popular maps are founded upon the wrong assumption that landslide presence/absence is a spatially continuous variable. Thus, isopleth maps do not incorporate any relation between slope-failure and landscape, namely, stable areas, such as flat terrain, can be ranked as unstable, or isolated outcrops of landslide-prone clayey rocks may well be classified as stable.

The reliability of heuristic methods depends largely on how well and how much the investigator understands the geomorphological processes acting upon the terrain. Since this knowledge can be formalized into rules, the method could take into account local geomorphological variability or specific conditions leading to slope failures. Major limitations refer to the fact that in most cases the body of knowledge available on the causal relations between environmental factors and landslides is inadequate and, most importantly, is essentially dependent on the experience of the investigator. At present, maps obtained by this method cannot be readily evaluated in terms of reliability or certainty. Additionally, landslide hazard is not directly expressed in terms of probability, limiting the use for risk evaluation and economic estimates.

Statistical or probabilistic approaches are based on the observed relationships between each factor and the distribution of landslides. Since the instability determinants and their interrelations are evaluated on a statistical basis, hazard evaluation becomes an operation as objective as possible. Black-box models are conceptually simple but, due to the great complexity in identifying the slope-failure processes and the difficulty in systematically collecting the different factors related to landsliding, the task of creating a geomorphological predictive model enabling actual/potential unstable slopes to be identified over large areas, is difficult operationally. Errors in mapping past and present landslides will exert a large and not readily predictable influence on statistical models, particularly if errors are systematic in not recognizing specific landslide types (Brabb, 1995). Additionally, being data-driven, a statistical model built up for one region cannot readily be extrapolated to the neighboring areas.

Physically based models, being process-driven, may provide significant insight on the causes and triggering factors of landslide movements. Their limitations include: the use of too simple models of instability evaluation; the fact that very few geotechnical data can be collected over even small regions at reasonable cost (Mulder, 1991; Hutchinson, 1995); and the spatial variability of geotechnical factors that is not controlled for. Additionally, reliable mechanical models are not yet available for several types of structurally complex rock units (Esu, 1977; Nieto, 1989). Despite such limitations, physically based models show promise for investigating, in quantitative terms, the influence of instability factors on landslides (Okimura and Kawatani, 1987; Montgomery and Dietrich, 1994; Dietrich et al., 1995), for modelling topographically controlled, shallow slope failures, for predicting (simulate) the potential run out path of debris flows (Ikeya, 1981; Takahashi et al., 1981; Mark and Ellen, 1995), or where the elements at stake justify extensive, site-specific investigations, over limited areas.

5.4. GIS-based statistical modelling

The experience gained from the application, at various scales, of GIS-based statistical models to landslide hazard assessment in the Umbria and Marche Regions allows a few considerations to be made.

Nowadays, owing to the ever-increasing capabilities of hardware and software technologies, electronic geographical data processing is becoming a common tool in a wide range of research activities related to the assessment and control of landsliding or other natural catastrophes (Wadge, 1988; Soeters et al., 1991; van Driel, 1991; Carrara, 1993; Carrara and Guzzetti, 1995; van Westen, 1993; Bonham-Carter, 1994; Kovar and Nachtnebel, 1994).

A crucial issue in hazard assessment remains that of the input data, which are fundamentally inadequate in quantity and quality for the task to be accomplished. With the diffusion of GIS-driven techniques the basic data did not change significantly. The most relevant progress refer to the morphometric variables derived from DTMs, which in the future might allow simulating the visual recognition of the topographic form, the latter being a fundamental element in any geomorphologic analysis of landslide identification (Ollier, 1977; Rib and Liang, 1978; Pike, 1988; Carrara, 1993; Carrara et al., 1995; Howard, 1994; Montgomery and Dietrich; 1994). Empirical and process-based models for estimating the spatial variation in soil attributes (chiefly thickness) from DTMs proved efficient for predicting shallow slope instability (soil-slip) (Moore et al., 1993; Dietrich et al., 1995). Attempts at automatically combining lithological and bedding attitude data with morphometric parameters (terrain gradient and aspect) to classify the territory into structural or hydrogeological domains, proved quite satisfactory for detailed investigations (cf. Tescio and Carpina basins), but performed less efficiently at the regional scale (cf. Upper Tiber River basin). Also, the application of remote sensing techniques to aerial photographs and satellite imagery to obtain significant and cost-effective information on instability factors, remains a future resource, whose potential, yet to be determined and exploited, appears more promising in unpopulated areas of developing countries (Brunsden, 1993).

Besides this task, which should constitute a major research effort in the coming years, more attention should be paid to the many sources of errors and uncertainties associated with data acquisition and manipulation. It has clearly been demonstrated that landslide mapping is the most error-prone phase of the whole operation (Carrara et al., 1992; van Westen, 1993). Likewise, virtually all the instability factors collected in the field or derived in laboratory through GIS manipulation, are affected by inaccuracies or errors whose magnitude cannot readily be estimated or controlled during the subsequent phase of data analysis or modelling (Walsh et al., 1987).

Environmental processes are highly non-linear and most environmental thematic information is spatially correlated. Additionally, environmental variables exhibit large variances, and peculiar (rare or small), but significant values (outliers). Thus, hazard models based on the statistical analysis of environment variables may be affected by large errors and wrong assumptions, or generate questionable or equivocal outcomes. Discriminant and regression analyses would require data derived from a normally distributed population, an assumption frequently violated. In addition, a mixture of continuous (i.e., elevation) and categorical (i.e., presence/absence of a rock type) variables leads to a solution which is generally not optimal, namely, it does not minimize the probability of incorrect predictions. Most importantly, when the variable set includes good and poor predictors, that is, some of the input variables do not bear a clear physical relationship with mass movement, a statistical stepwise procedure may generate a linear combination of both types of variables whose interpretation will eventually give difficult, unreliable or even meaningless results. Better results could be obtained by entering into the model only the variables that the investigator assumes to be the most significant. However, in general different investigators will not select the same variables; so the model becomes dependent on the skill and experience of the analyst. Since input factors are invariably correlated, the technique of entering all the available variables can produce even worse outcomes with some variables characterized by meaningless coefficients (Carrara et al., 1995). Hence, correlation between variables should always be carefully checked (Bonham-Carter, 1994). Additionally, variables correlated to instability conditions in one area may give rise to stability conditions in a different physiographic environment. In the Umbria–Marche project this was found to be the case for land-use data. Thus, experience on factors bearing a functional relationship on slope instability should be used with care.

Where input information is highly generalized, the reliability and usefulness of any predictive model may be limited. The reconnaissance evaluation carried out for the Umbria and Marche Regions (Fig. 4B; Tables 1 and 2) indicates that a statistical model based on a set of broad factors which do not reflect the great variability of conditions leading to slope failures over a wide region may be fairly successful in terms of predictive power, but lack adequate spatial resolution for planning purposes. In addition, by grouping very different landslide types into a single class, the model may become physically unreliable.

In discriminant analysis and logistic regression, high and low values of membership probability indicate hazardous and safe mapping units, respectively. Values close to 0.5 do not provide any additional information with respect to the input landslide map. If this is the case for many sampling units: a large portion of the region under study will turn out to be ‘‘*unclassified*’’. Hence, the model could be statistically sound, but of limited application. In the Umbria–Marche project, models prepared at various scales, classified in the intermediate hazard class (40%–60% probability) between 15% and 28% of the territory.

Any model is unable to correctly classify all mapping units. If this should occur, the model, once again, would not provide more information than the input inventory map. However, misclassifications have very different meanings, namely: (a) a mapping unit is predicted as *unstable*, but no landslides were found on it by the surveyor; (b) a mapping unit is predicted as *stable*, but slope-failures were mapped on it. Under the hypothesis that the model is reliable, the first case is the result of inaccurate mapping or of a failed mass concealed by erosion or farming activity. The second case indicates either wrong mapping or a model which lacks the factors that caused a landslide in that specific or unique environmental setting. Regardless of the causes, the first type of mismatch indicates a mapping unit that has to be interpreted as hazardous, with a high probability of failure in the future; while the second is equivocal and requires further investigation. Ideally, a good model should minimize the latter type of misclassification. Conversely, all multivariate procedures yield an approximately equal proportion of the two types of incorrect predictions (cf. Carpina basin; Tables 6 and 8).

Owing to these pitfalls, hazard assessment and mapping by statistical modelling are intrinsically uncertain operations which nowadays are taking advantage of the opportunities provided by new technologies, such as GIS, but are still requiring new efforts for improving both data quality and model reliability.

Lastly, after a ‘‘black-box’’ model has been built up and tested, results have to be interpreted in the light of the local geomorphological setting. This is a crucial step that often represents one of the most difficult phases of landslide hazard evaluation.

5.5. Model combination and application

Where various types of landslides take place, distinct hazard evaluations should be prepared. This was attempted in the Carpina basin, where different hazard models for the three prevailing types of slope failures were prepared, and in the Upper Tiber River basin, where provisional hazard modelling was confined to deep-seated failures. Unfortunately, even if all hazards can be singled out, assessed and mapped separately — and this may not always be feasible — it remains to be understood how to combine them into a singe hazard/risk map portraying the spatial distribution of all endangered areas. At present, it is not even clear if this is appropriate.

Two conflicting approaches can be followed. Maps portraying different types of hazard are kept separate and no attempt is made to compile a general, holistic hazard evaluation. Alternatively, the different forecasts are ranked and portrayed in a single map. Both approaches have advantages and limitations. The former is preferred where multiple hazard evaluations (landslide as well as others) are available (Seely and West, 1990; Brabb, 1995). The benefit lays in presenting ‘‘simple’’ evaluations, allowing for various interpretations by decision-makers and planners, some of which may not be known to the author of each single hazard assessment. The later is favored where direct geomorphological hazard evaluation is attempted. Its main advantage refers to the possibility of incorporating into a generalized hazard model or map some of the complex interactions existing among single hazard evaluations (Humbert, 1977; Godefroy and Humbert, 1983; Kienholz et al., 1983, 1984; Zimmerman et al., 1986).

A related problem of models combination arises when more than a single landslide hazard evaluation is available for the same area, as in the Carpina basin, where two hazard models based on slope-units (Fig. 6A) and unique-condition units (Fig. 6B) were prepared. This is conceptually equivalent to the situation where two or more experts are asked for their opinion on a technical or scientific problem. The question of which model to prefer or how to combine different forecasts remains largely unsolved. Taking the ‘‘worst-case approach’’, that is, choosing for each site or mapping unit the most catastrophic forecast, may be too conservative. Also, the choice of the ‘‘simplest’’ and cheapest estimate (Hutchinson, 1995) may not be appropriate. A more sensible approach would consist in the critical analysis of the underlying assumptions of each hazard assessment — if these are clearly stated — and in the evaluation of external sources of information, such as economical or other practical constrains.

A still different problem is related to the aggregation of the results of a landslide hazard evaluation (one or more hazard models or maps) prepared using some sort of mapping unit (grid-cells, slope-units, unique-condition units, etc.) into a different partition of the territory, most commonly an administrative or political subdivision. This step, requested by decision makers for regional planning purposes, may be subjective and conceptually troublesome.

Despite the largely acknowledged need of new tools for planning and policy making, no general agreement has been reached among earth scientists and decision makers on the goals and possible use of landslide hazard evaluations. This may explain why, despite the fact that numerous models have been proposed and tested in a variety of physiographic environments, only in a few cases has knowledge on landslide hazard become an integral part of building codes, planning policies, or civil protection regulations.

To limit the discussion to functional models, such as those presented for the Umbria–Marche territory, models for the evaluation of landslide hazard can be prepared with two distinct goals. The first is ‘‘scientific’’ (explanatory) and aims to explain landslide phenomena. In the hope of producing more reliable predictions, it considers a landslide hazard assessment as a scientific theory, and makes all efforts to prove it faulty (Popper, 1959). In this view, uncertainties and the analysis of errors and residuals represent useful tools for model refinement and calibration and for a better understanding of slope phenomena. The second is an ‘‘engineering’’ (pragmatic) approach that, based on the available information on local slope failures, aims at producing the ‘‘best’’ possible predictive model. Little effort is made to improve the understanding on landsliding. Uncertainties, errors and peculiar conditions, that make any model somewhat unsuitable for planners and decision makers, are dealt with pragmatically by introducing a safety factor. Ideally, both approaches are needed for a comprehensive evaluation of landslide hazard. Unfortunately, as has been discussed, due to practical constraints and conceptual limitations, this is not often the case.

6. Concluding remarks

Landslides are among the most hazardous natural disasters. Government and research institutions worldwide have attempted for years to assess landslide hazard and risk and to portray its spatial distribution. Several different methods have been proposed and tested in a variety of physiographic environments, with different results. In the Umbria and Marche Regions, attempts at testing the proficiency and limitations of multivariate statistical techniques and of different methodologies for dividing the territory into suitable terrain units have been completed, or are in progress, at various scales. These experiments showed that, despite the operational and conceptual limitations, landslide hazard assessment may indeed constitute a suitable, cost-effective aid to land-use planning, an aid to a sustainable development both in developed and developing countries.

Evaluation of landslide hazard aims at the solution of a complex, ''multi-dimensional'' problem that requires expertise pertaining to the earth sciences (specifically geomorphology and engineering geology), statistics, computer science, physics, information technology and economics.

The definition of landslide hazard remains a largely open, ill-formalized question. Landslides are phenomena with complex feedback varying in scale from the local to the regional. Their geomorphological and economic impact ranges from the very short to the very long term. Despite efforts, landslide phenomena are still poorly understood, particularly at the regional scale. Additionally, their interactions with the economic and human sphere remains a novel problem to the earth scientists. Knowledge on slope processes appears insufficient for a comprehensive and exhaustive evaluation of landslide hazard.

Industrialized societies and developing countries face increasingly complex problems of planning and policy making. These are different from the traditional problems of both pure and applied science (Funtowicz and Ravetz, 1995; Murck et al., 1997). As regards to landslide hazard evaluation, on one side geomorphology is unable to provide well-founded theories for hazard assessment, and on the other side, environmental issues and policy decisions challenge geomorphologists with difficult issues. Due to the uncertainties in data acquisition and handling, and in model selection and calibration, landslide hazard evaluation and land-zoning appear out of the reach of the traditional puzzle-solving scientific approach, based on experiments and on a generalized consensus among experts. In general, predictive models of landslide hazard can not be readily tested by traditional scientific methods. Indeed, the only way a landslide predictive map can be validated is through time (Hutchinson, 1995). Additionally, as previously discussed, no general agreement has been reached on the scope, techniques and methodologies for landslide hazard evaluation.

Solutions to these challenging problems may come from a new scientific practice enabling to cope with large uncertainties, varying experts judgements, and societal issues risen by hazard evaluation. Within this framework engineering geomorphology will play an important role in the future, particularly if geomorphologists will be able to better formalize and extend their knowledge on slope processes at different scales and in different physiographic environments.

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References

Ahlberg, P., Stigler, B., Viberg, L., 1988. Experiences of landslide risk considerations in land use planning in Sweden. 5th International Symposium on Landslides, Lausanne 2, 1091–1096.

Alexander, E.D., 1989. Urban landslides. Progress in Physical Geography 13, 157–191.

Alexander, E.D., 1995. A survey of the field of natural hazards and disaster studies. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 1–19.

Amadesi, E., Vianello, G., 1978. Nuova guida alla realizzazione di una carta di stabilità dei versanti. Memorie Società Geologica Italiana 19, 53–60, (in Italian).

Antoine, P., 1977. Rèflextions sur la cartographie ZERMOS et bilan des esperiences en cours. Bulletin Bureau des Recherches Géologiques et Minières 3 (2), 9–20, (in French).

Antonini, G., Cardinali, M., Guzzetti, F., Reichenbach, P., Sorrentino, A., 1993. Carta Inventario dei Fenomeni Franosi della Regione Marche ed aree limitrofe. CNR-GNDCI, Publication no. 580, 2 sheets, scale 1:100,000. (in Italian).

Baker, V.R., 1994. Geomorphological understanding of floods. Geomorphology 10, 139–156.

Barchi, M., Cardinali, M., Guzzetti, F., Lemmi, M., 1993. Relazioni fra movimenti di versante e fenomeni tettonici nell'area del M. Coscerno–M. di Civitella, Valnerina, Umbria. Bollettino Società Geologica Italiana 112, 83–111, (in Italian).

Bernknopf, R.L., Campbell, R.H., Brookshire, D.S., Shapiro, C.D., 1988. A probabilitic approach to landslide hazard mapping in Cincinnati, Ohio, with applications for economic evaluation. Bulletin American Association of Engineering Geologists 25 (1), 39–56.

Bonham-Carter, G.F., 1994. Geographic Information Systems for Geoscientists: Modelling with GIS. Pergamon, Ottawa, 398 pp.

Boschi, E., Favali, P., Frugoni, F., Scalera, G., Smaziglio, G., 1995. Maximum felt intensity in Italy. Istituto Nazionale di Geofisica. Map at 1:1,500,000 scale.

Bosi, C., 1978. Considerazioni e proposte metodologiche sulla elaborazione di carte della stabilità. Geologia Applicata ed Idrogeologia, Bari, 13, 246–281, (in Italian).

Bosi, C., Dramis, F., Gentili, B., 1985. Carte geomorfologiche di dettaglio ad indirizzo applicativo e carte di stabilità a base geomorfologica. Geologia Applicata ed Idrogeologia, Bari, 20 (2), 53–62, (in Italian).

Brabb, E.E., 1984. Innovative approaches to landslide hazard mapping. 4th International Symposium on Landslides, Toronto 1, 307–324.

Brabb, E.E., 1995. The San Mateo County California GIS project for predicting the consequences of hazardous geologic processes. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 234–299.

Brabb, E.E., Harrod, B.L. (Eds.), Landslides: Extent and Economic Significance. Balkema Publisher, Rotterdam, 385 pp.

Brabb, E.E., Pampeyan, E.H., Bonilla, M.G., 1978. Landslide susceptibility in San Mateo County, California. US Geological Survey Misc. Field Studies Map, MF-360, map at 1:62,500 scale.

Brand, E.W., 1988. Special lecture: landslide risk assessment in Hong Kong. 5th International Symposium on Landslides, Lausanne 2, 1059–1074.

Brand, E.W., Styles, K.A., Burnett, A.D., 1982. Geotechnical land use maps for planning in Hong Kong. 4th Congress International Association Engineering Geologists, New Delhi, 1, 145–153.

Brunsden, D., 1993. Mass movements; the research frontier and beyond: a geomorphological approach. Geomorphology 7, 85–128.

Burnett, A.D., Brand, E.W., Styles, K.A., 1985. Terrain classification mapping for a landslide inventory in Hong Kong. 4th International Conference and Field Workshop on Landslides, Tokyo, 63–68.

Campbell, R., 1973. Isopleth map of landslide deposits, Point Dume Quadrangle, Los Angeles County, California; an experiment in generalising and quantifying areal distribution of landslides. US Geological Survey Miscellaneous Field Studies Map, MF-535 (Scale 1:24,000).

Cardinali, M., Galli, M., Guzzetti, F., Reichenbach, P., Borri, G., 1994. Relazioni fra movimenti di versante e fenomeni tettonici nel bacino del Torrente Carpina. Geografia Fisica e Dinamica Quaternaria 17, 3–18, (in Italian).

Carrara, A., 1983. A multivariate model for landslide hazard evaluation. Mathematical Geology 15, 403–426.

Carrara, A., 1988. Drainage and divide networks derived from high-fidelity digital terrain models. In: Chung, C.F. (Ed.), Quantitative Analysis of Mineral and Energy Resources. Reidel, Dordrecht, pp. 581–597, (NATO-ASI Series).

Carrara, A. et al., 1989. Landslide hazard mapping by statistical methods: a ''black-box'' model approach. In: Siccardi, F., Brass, R. (Eds.), International Workshop on Natural Disasters in European–Mediterranean Countries, Perugia, 27 June–1 July 1989. CNR-US NFS, pp. 427–445.

Carrara, A., 1993. Potentials and pitfalls of GIS technology in assessing natural hazards. In: Reichenbach, P., Guzzetti, F., Carrara, A. (Eds.), Geographical Information Systems in Assessing Natural Hazards — Abstracts. CNR, Perugia, pp. 128–137, September 20–22, 1993.

Carrara, A., Guzzetti, F. (Eds.), 1995. Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, 353 pp.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., Reichenbach, P., 1991. GIS Techniques and statistical models in evaluating landslide hazard. Earth Surface Processes and Landform 16, 427–445.

Carrara, A., Cardinali, M., Guzzetti, F., 1992. Uncertainty in assessing landslide hazard and risk. ITC Journal, The Netherlands 2, 172–183.

Carrara, A., Cardinali, M., Guzzetti, F., Reichenbach, P., 1995. GIS technology in mapping landslide hazard. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 135–175.

Carrara, A., Bitelli, G., Carlà, R., 1997. Comparison of techniques for generating digital terrain models from contour lines. International Journal Geographical Information System 11, (in press).

Chung, Ch.F., Fabbri, A.G., 1995. Multivariate regression analysis for landslide hazard zonation. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 107–142.

CoGeo, 1994. Progetto AVI — Rapporto di Sintesi: Umbria: CNR-GNDCI, 49 pp. (in Italian).

CoGeo, 1994. Progetto AVI — Rapporto di Sintesi: Marche: CNR-GNDCI, 38 pp. (in Italian).

Cooke, R.U., Doornkamp, J.C., 1974. Geomorphology in environmental management. Clarendon Press, Oxford, 413 pp.

Cotecchia, V., 1978. Systematic reconnaissance mapping and registration of slope movements. Bulletin International Association Engineering Geology 17, 5–37.

Crozier, M.J., 1984. Field assessment of slope instability. In: Brunsden, D., Prior, D.B. (Eds.), Slope Instability. Wiley, Chichester, pp. 103–142, Chap. 4.

Crozier, M.J., 1986. Landslides: Causes, Consequences and Environment. Croom Helm Pub, London.

Cruden, D.M., 1991. A simple definition of a landslide. Bulletin International Association of Engineering Geology 43, 27–29.

Cruden, D.M., 1997. Estimating the risk from landslide historical data. In: Cruden, D.M., Fell, R. (Eds.), Landslide Risk Assessment. Proc. Inter. Workshop on Landslide Risk Assessment, Honolulu, 19–21 February 1997 Balkema, Rotterdam, pp. 177–184.

Cruden, D.M., Fell, R., 1997. Landslide Risk Assessment. Proceedings International Workshop on Landslide Risk Assessment, Honolulu, 19–21 February 1997 Balkema, Rotterdam, 371 pp.

DeGraff, J.V., 1985. Using isopleth maps of landslides deposits as a tool in timber sale planning. Bulletin American Association of Engineering Geologists 22, 445–453.

Degraff, J.V., Agard, S.S., 1984. Defining geologic hazards for natural resources management using tree-ring analysis. Environmental Geology and Water Sciences 6 (3), 147–155.

Delaunay, J. 1981. Carte de France des zones vulnèrables a des glissements, écroulements, affaissements et effrondrements de terrain. Bureau de Recherches Géologiques et Minières. 81 SGN 567 GEG, 23 pp. (in French).

Dietrich, E.W., Reiss, R., Hsu, M.-L., Montgomery, D.R., 1995. A process-based model for colluvial soil depth and shallow landsliding using digital elevation data. Hydrological Process 9, 383–400.

Dikau, R., Brunsden, D., Schrott, L., Ibsen, M.-L., 1996. Landslide recognition. Identification, movements and causes. Wiley, Chichester, England, 251 pp.

Dunne, T., 1991. Stochastic aspects of the relations between climate, hydrology and landform evolution. Transaction Japanese Geomorphological Union 12, 1–24.

Einstein, H.H., 1988. Special lecture: landslide risk assessment procedure. Proceedings 5th International Symposium on Landslides, Lausanne 2, 1075–1090.

Einstein, H.H., 1997. Landslide risk — systematic approaches to assessment and management. In: Cruden, D.M., Fell, R. (Eds.), Landslide Risk Assessment. Proc. Inter. Workshop on Landslide Risk Assessment, Honolulu, 19–21 February 1997 Balkema, Rotterdam, pp. 25–50.

Esu, F., 1977. Behavior of slopes in structurally complex formations. International Symposium on the Geotechnics of Structurally Complex Formations, Capri 2, 292–304.

Evans, S.G., 1997. Fatal landslides and landslide risk in Canada. In: Cruden, D.M., Fell, R. (Eds.), Landslide Risk Assessment. Proc. Inter. Workshop on Landslide Risk Assessment, Honolulu, 19–21 February 1997 Balkema, Rotterdam, pp. 185–196.

Fell, R., 1994. Landslide risk assessment and acceptable risk. Canadian Geotechnical Journal 31 (2), 261–272.

Fookes, P.G., Dale, S.G., Land, J.M., 1991. Some observations on a comparative aerial photography interpretation of a landslipped area. Quarterly Journal of Engineering Geology 24, 249–265.

Funtowicz, S.O., Ravetz, J.R., 1995. Planning and decision-making in an uncertain world: the challenge of post-normal science. In: Horlick-Jones (Ed.), Natural Risk and Civil Protection. Commission of the European Communities, E&FN Spon, London, pp. 415–423.

Glade, T., 1998. Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. Environmental Geology 35, 2–3.

Godefroy, P., Humbert, M., 1983. La cartographie des risques naturales liés aux movements de terrain et aux séismes. Hydrogéologie — Géologie de l'Ingénieur 2, 69–90, (in French).

Guzzetti, F., 1993. Landslide hazard and risk by GIS-based multivariate models. In: Reichenbach, P., Guzzetti, F., Carrara, A. (Eds.), Geographical Information Systems in Assessing Natural Hazards–Abstracts, CNR, Perugia, September 20–22, 1993. pp. 83–91.

Guzzetti, F., Cardinali, M., 1989. Carta Inventario dei Fenomeni Franosi della Regione dell'Umbria ed aree limitrofe. CNR–GNDCI, Publication no. 204, 2 sheets, scale 1:100,000 (in Italian).

Guzzetti, F., Cardinali, M., 1990. Landslide inventory map of the Umbria region, Central Italy. In: Cancelli, Andrea (Ed.), ALPS 90, 6th International Conference and Field Workshop on Landslides, Milano. pp. 273–284.

Guzzetti, F., Cardinali, M., Reichenbach, P., 1994. The AVI Project: A bibliographical and archive inventory of landslides and floods in Italy. Environmental Management 18 (4), 623–633.

Guzzetti, F., Cardinali, M., Reichenbach, P., 1996. The influence of structural setting an lithology on landslide type and pattern. Environmental and Engineering Geology 2 (4), 531–555.

Hansen, A., 1984. Landslide hazard analysis. In: Brunsden, D., Prior, D.B. (Eds.), Slope Instability. Wiley, New York, pp. 523–602.

Hansen, A., Franks, C.A.M., Kirk, P.A., Brimicombe, A.J., Tung, F., 1995. Application of GIS to hazard assessment, with particular reference to landslides in Hong Kong. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 135–175.

Hartlén, J., Viberg, L., 1988. Evaluation of landslide hazard. 5th International Symposium on Landslides, Lausanne 2, 1037–1058.

Helmore, K., 1996. Cities on the brink try new tactics. Choices 5 (1), 18–21.

Hollingsworth, R., Kovacs, G.S., 1981. Soil slumps and debris flows: prediction and protection. Bulletin American Association of Engineering Geologists 18 (1), 17–28.

Horlick-Jones, T., Amendola, A., Casale, R. (Eds.), Natural risk and civil protection. Commission of the European Communities, E&FN Spon, London, 554 pp.

Howard, A.D., 1994. A detachment-limited model of drainage basin evolution. Water Resources Research 30 (7), 2261–2285.

Hsü, K., 1975. Catastrophic debris stream (Sturzstorm) generated by rockfalls. Geological Society of America Bulletin 86, 129–140.

Humbert, M., 1976. La cartographie en France des zones exposées a des risques liés aux mouvements du sols. Cartes ZERMOS.

International Association Engineering Geology Bulletin 16, 80–82, (in French).

Humbert, M., 1977. La cartographie ZERMOS. Modalités d'établissement des cartes des zones exposées à des risques liés aux mouvements du sol et du sous-sol. Bulletin Bureau Recherche Geologique et Mineraire 3, 5–8, (in French).

Hutchinson, J.N., 1988. General report: morphological and geotechnical parameters of landslides in relation to geology and hydrology. 5th International Symposium on Landslides, Lausanne 1, 3–35.

Hutchinson, J.N., 1995. Keynote paper: landslide hazard assessment. In: Bell (Ed.), Landslides. Balkema, Rotterdam, pp. 1805–1841.

Hutchinson, J.N., Chandler, M.P., 1991. A preliminary landslide hazard zonation of the Undercliff of the Isle of Wight. In: Slope Stability Engineering. Thomas Telford, London, pp. 197–205.

Ibsen, M.-L., Brunsden, D., 1996. The nature, use and problems of historical archives for the temporal occurrence of landslides, with specific reference to the south coast of Britain, Ventnor, Isle of Wight. Geomorphology 15, 241–258.

IDNHR, Advisory Committee, 1987. Confronting Natural Disasters. An International Decade for Natural Hazard Reduction. National Academy Press, WA, 60 pp.

Ikeya, H., 1981. A method for designation for areas in danger of debris flows. Erosion and Sediment Transport in the Pacific Rim Steeplands. IAHS Special Pub. 132, 576–588.

Kienholz, H., Hafner, H., Schneider, G., Tamrakar, R., 1983. Mountain hazards mapping in Nepal's Middle Mountains. Maps of land use and geomorphic damages (Kathmandu–Kakani area). Mountain Research and Development 3 (3), 195–220.

Kienholz, H., Schneider, G., Bichsel, M., Grunder, M., Mool, P., 1984. Mapping of mountain hazards and slope stability. Mountain Research and Development 4, 247–266.

Kockelman, W.J., 1986. Some techniques for reducing landslide hazards. Bulletin American Association Engineering Geologists 23 (1), 29–52.

Kovar, K., Nachtnebel, H.P. (Eds.), 1994. Application of Geographycal Information Systems in hydrology and water resource management. HydroGIS 93, Vienna, April 19–22, 1994, IAHS Publ. 211, 694 pp.

Lambrugo, B., Lattuada, S., 1996. Relazione fra assetto geologico–morfologico e distrubuzione dei movimenti franosi nell'area di Mercatale (Arezzo). Caratterizzazione geotecnica delle Argille Varicolori. Unpublished Thesis. Dipartimento di Scienze della Terra, University of Milano. 152 pp. (in Italian).

Leroi, E., 1996. Landslide hazard-risk maps at different scales: objectives, tools and developments. In: Senneset (Ed.), Landslides. Balkema, Rotterdam, pp. 35–51.

Mark, R.K., 1992. Map of debris flow probability, San Mateo County, California, scale 1:62,500, US Geological Survey Miscellaneous Investigation Map, I-1257-M.

Mark, R.K., Ellen, S.D., 1995. Statistical and simulation models for mapping debris-flows hazard. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 93–106.

Meijerink, A.M.J., 1988. Data acquisition and data capture through terrain mapping unit. ITC Journal 1, 23–44.

Mejía-Navarro, M., Wohl, E.E., Oaks, S.D., 1994. Geological hazards, vulnerability and risk assessment using GIS: model for Glenwood Springs, Colorado. Geomorphology 10, 331–354.

Montgomery, D.R., Dietrich, W.E., 1994. A physically based model for the topographic control of shallow landsliding. Water Resources Research 30 (4), 1153–1171.

Montgomery, D.R., Wright, R.H., Booth, T., 1991. Debris flow hazard mitigation for colluvium-filled swales. Bulletin Association of Engineering Geologists 28 (3), 303–323.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A., 1993. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal 57, 443–452.

Mulder, HFHM, 1991. Assessment of landslide hazard. Profschrift ter Verkrijging van Graad van Doctor an de Rijkuniversiteit te Utrecht, University of Utrecht, 150 pp.

Murck, B.W., Skinner, B.J., Porter, S.C., 1997. Dangerous Earth. An Introduction to Geological Hazards. Wiley, New York, 300 pp.

Neeley, M.K., Rice, R.M., 1990. Estimating risk of debris slides after timber harvest in northwestern California. Bulletin American Association of Engineering Geologists 27 (3), 281–289.

Nemcok, A., Rybár, J., 1968. Synoptic Map of Czechoslovak Landslide Areas. Geol. Ustar Ceskoslovachia Akademia, Praha.

Neuland, H., 1976. A prediction model of landslips. Catena 3, 215–230.

Nieto, A.S., 1989. Mechanical models and geological observations: closing the prediction gap. In: Siccardi, F., Brass, R. (Eds.), International Workshop on Natural Disasters in European–Mediterranean Countries, Perugia, 27 June–1 July 1989. CNR-US NFS, pp. 145–164.

Nilsen, T.H., Brabb, E.E., 1977. Slope stability studies in the San Francisco Bay region, California. Geological Society of America, Reviews in Engineering Geology 3, 235–243.

Nilsen, T.H., Wright, R.H., Vlasic, C., Spangle, W.E., 1979. Relative slope stability and land-use planning in the San Francisco Bay region, California. US Geological Survey Professional Paper 944, 104 pp.

Okimura, T., Kawatani, T., 1987. Mapping of the potential surface-failure sites on granite slopes. In: Gardiner, E. (Ed.), International Geomorphology 1986, Part I. Wiley, Chichester, pp. 121–138.

Ollier, C.D., 1977. Terrain classification: methods, applications and principles. In: Hails, J.R. (Ed.), Applied Geomorphology. Elsevier, Amsterdam, pp. 277–316.

O'Loughlin, E.M., 1986. Prediction of surface saturation zones in natural catchments by topographic analysis. Water Resources Research 22 (5), 794–804.

Olshansky, R., 1990. Landslide hazard in the United States. Case studies in planning and policy development. Garland Publishing, New York, 178 pp.

Pike, R.J., 1988. The geometric signature: quantifying landslide-terrain types from digital elevation models. Mathematical Geology 20 (5), 491–511.

Popper, K.R., 1959. The Logic of Scientific Discovery. Basic Books, New York, 480 pp.

Radbruch-Hall, D.H., Varnes, D.J., 1976. Landslides: causes and effect. International Association Engineering Geologist Bulletin 14, 205–216.

Radbruch-Hall, D.H., Colton, R.B., Davies, W.E., Lucchitta, I., Skipp, B.A., Varnes, D.J., 1982. Landslide overview map of the conterminous United States. US Geological Survey Professional Paper 1183, 25 pp.

Reichenbach, P., Guzzetti, F., Carrara, A. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Abstracts volume, CNR-IRPI, Perugia, September, 20–22, 1993. 140 pp.

Rib, H.T., Liang, T., 1978. Recognition and identification. In: Schuster, R.L., Krizek, R.J. (Eds.), Landslides analysis and control. Washington Transportation Research Board, Special Report 176. National Academy of Sciences, WA, pp. 34–80.

Rosenfeld, C.L., 1994. The geomorphological dimensions of natural disasters. Geomorphology 10, 27–36.

Roth, R.A., 1983. Factors affecting landslide susceptibility in San Mateo County, California. Association of Engineering Geologists Bulletin 20 (4), 353–372.

Sassa, K., 1988. Special lecture: geotechnical model for the motion of landslides. 5th International Symposium on Landslides, Lausanne 1, 37–55.

Scheidegger, A.E., 1994. Hazards: singularities in geomorphic systems. Geomorphology 10, 19–25.

Schuster, R.L., 1995a. Socioeconomic significance of landslides. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides, Investigation and Mitigation. Transportation Research Board Special Report 247. National Academy Press, WA, pp. 12–35.

Schuster, R.L., 1995b. Keynote paper: recent advances in slope stabilization. In: Bell (Ed.), Landslides. Balkema, Rotterdam, pp. 1715–1745.

Schuster, R.L., Fleming, R.W., 1986. Economic losses and fatalities due to landslides. Bulletin American Association Engineering Geologists 23 (1), 11–28.

Schuster, R.L., Krizek, R.J., 1978. Landslides Analysis and Control. Washington Transportation Research Board, Special Report 176. National Academy of Sciences, WA, 234 pp.

Seeley, M.W., West, D.O., 1990. Approach to geologic hazard zoning for regional planning, Inyo National Forest, California and Nevada. Bulletin American Association of Engineering Geologists 27 (1), 23–35.

Soeters, R., Rengers, N., van Westen, C.J., 1991. Remote sensing and geographical information systems as applied to mountain hazard analysis and environmental monitoring. 8th Thematic Conference Geology Remote Sensing (ERIM), April, 29–May, 2 1991, Denver 2, 1389–1402.

Speight, J.G., 1977. Landform pattern description from aerial photographs. Photogrammetry 32, 161–182.

Starosolszky, O., Melder, O.M., 1989. Hydrology of disasters. World Meteorological Organisation Technical conference, Geneva, November 1988. James and James, London, 319 pp.

Stout, M.L., 1977. Radiocarbon dating of landslides in Southern California. California Geology, 99–105, January 1977.

Swanston, D.N., Schuster, R.L., 1989. Long-term landslide hazard mitigation programs: structure and experience from other countries. Bulletin American Association of Engineering Geologists 26 (1), 109–113.

Takahashi, T., Aschida, K., Sawai, K., 1981. Delineation of debris flow hazard areas. Erosion and Sediment Transport in the Pacific Rim Steeplands. IAHS Special Pub. 132, 589–603.

Terlien, M.T.J., van Westen, C.J., van Asch, Th.W.J., 1995. Deterministic modelling in GIS-based landslide hazard assessment. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazards. Kluwer Academic Publisher, Dordrecht, The Netherlands, pp. 57–77.

Toppi, A., 1993. Studio geologico–tecnico sullo stato di dissesto del bacino idrografico del F.sso Bianco–T. Caldaro in Provincia di Terni. Unpublished Thesis, Dipartimento di Scienze della Terra, University of Perugia, Perugia, 103 pp. (in Italian).

Trustrum, N.A., De Rose, R.C., 1988. Soil depth–age relationship of landslides on deforested hillslopes, Taranaki, New Zealand. Geomorphology 1, 143–160.

Turner, A.K., Schuster, R.L. (Eds.), 1995. Landslides, investigation and mitigation. Transportation Research Board Special Report 247. National Academy Press, WA, 673 pp.

UNDRO, 1991. Mitigating Natural Disasters. Phenomena, Effects and Options. United Nations, New York, 164 pp.

U.S. Geological Survey, 1982. Goals and tasks of the landslide part of a ground failure hazard reduction program. US Geological Survey Circular 880, 44 pp.

van Driel, N., 1991. Geographic information systems for earth science applications. 4th International Conference on Seismic Zonation, Stanford 1, 469–485.

van Westen, C.J., 1993. Application of Geographical Information System to landslide hazard zonation. ITC Publication no. 15, ITC, Enschede, The Netherlands, 245 pp.

van Westen, C.J., 1994. GIS in landslide hazard zonation: a review with examples from the Colombian Andes. In: Price, M.F., Heywood, D.I. (Eds.), Taylor and Francis, London, pp. 135–165.

Varnes, D.J., 1978. Slope movements, type and processes. In: Schuster, R.L., Krizek, R.J. (Eds.), Landslide Analysis and Control. Transportation Research Board, National Academy Sciences, Washington, DC, pp. 11–33, Special report 176.

IAEG Commission on Landslides and other Mass-Movements, Varnes, D.J., 1984. Landslide hazard zonation: a review of principles and practice. UNESCO Press, Paris, 63 pp.

Verstappen, H.T., 1983. Applied Geomorphology: Geomorphological Survey for Environmental Development. Elsevier, Amsterdam.

Wadge, G., 1988. The potential of GIS modelling of gravity flows and slope instabilities. International Journal of Geographical Information Systems 2, 143–152.

Walsh, J.S., Lightfoot, D.R., Butler, D.R., 1987. Recognition and assessment of error in Geographic Information Systems. Photogrammetric Engineering and Remote Sensing 53 (10), 1423–1430.

Wieczorek, G.F., 1984. Preparing a detailed landslide-inventory map for hazard evaluation and reduction. Bulletin Association of Engineering Geologists 21 (3), 337–342.

Wright, R.H., Nilsen, T.H., 1974. Isopleth map of landslide deposits, Southern San Francisco Bay Region, California. US Geological Survey Miscellaneous Field Studies Map, MF-550 (scale 1:250,000).

Wright, R.H., Campbell, R.H., Nilsen, T.H., 1974. Preparation and use of isopleth maps of landslide deposits. Geological Society of America, Geology 2, 483–485.

Yin, K.L., Yan, T.Z., 1988. Statistical prediction model for slope instability of metamorphosed rocks. 5th International Symposium on Landslides, Lausanne 2, 1269–1272.

Yong, R.N., Alonso, E., Tabba, M.M., Fransham, P.B., 1977. Application of risk analysis to the prediction of slope instability. Canadian Geotechnical Journal 14 (3), 540–543.

Zimmerman, M., Bichsel, M., Kienholz, H., 1986. Mountain hazards mapping in the Khumbu Himal, Nepal, with prototype map, scale 1:50,000. Mountain Research and Development 6 (1), 29–40.