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GIS in landslide hazard zonation: a review, with examples from the Andes of Colombia

Cees J. van Westen

Introduction

Mass movements in mountainous terrain are natural degradational processes, and one of the most important landscape building factors. Most of the terrain in mountainous areas has been subjected to slope failure at least once, under the influence of a variety of causal factors, and triggered by events such as earthquakes or extreme rainfall.

Mass movements become a problem when they interfere with human activity. The frequency and the magnitude of slope failures can increase due to human activities, such as deforestation or urban expansion (Figures 8.1 and 8.2). In developing countries, this problem is especially great due to rapid non-sustainable development of natural resources. Developing countries suffer some 95 per cent of total disaster-related fatalities, which are estimated to number on the order of 225 000 per year (Hansen, 1984). Economic losses attributable to natural hazards in developing countries may represent as much as 1–2 per cent of gross national product (Fournier D'Albe, 1976). Losses due to mass movements are estimated to be one quarter of the total losses due to natural hazards (Hansen, 1984). These statistics illustrate well the importance of hazard mitigation. Indeed, the decade 1990–2000 has been designated the International Decade for Natural Disaster Reduction by the General Assembly of the United Nations.

Mitigation of landslide disasters can be successful only when detailed knowledge is obtained about the expected frequency, character, and magnitude of mass movement in an area. The zonation of landslide hazard must be the basis for any landslide mitigation project and should supply planners and decision-makers with adequate and understandable information. Analysis of landslide hazard is a complex task, as many factors can play a role in the occurrence of mass movements (see Crozier, 1986 for a comprehensive treatment of causes). The analysis requires a large number of input parameters, and techniques of analysis may be very costly and time-consuming. The

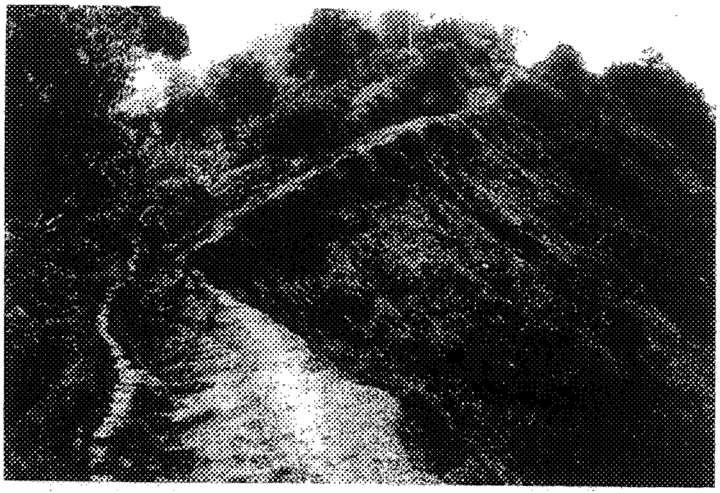


Figure 8.1 Landslide in the Rio Chinchina catchment, Colombia.

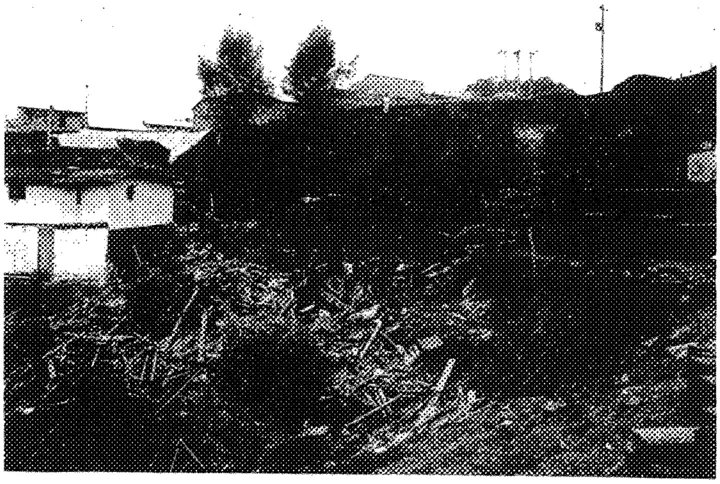


Figure 8.2 Landslide in the city of Manizales, Colombia.

increasing availability of computers during the last decades has created opportunities for a more detailed and rapid analysis of landslide hazard. This chapter describes in a general way the results of an international research project dealing with the application of GIS in landslide hazard zonation. For more information the reader is referred to Soeters *et al.* (1991), Rengers (1992), Rengers *et al.* (1992), Van Asch *et al.* (1992), van Westen and Alzate (1990) and van Westen (1992a, 1992b, 1993).

Definitions

Mass movement is defined as 'the outward or downward gravitational movement of earth material without the aid of running water as a transporting agent' (Crozier, 1986). Although by definition the term landslide is used only for mass movements occurring along a well-defined sliding surface, it has been used as the most general term for all mass movements, including those that involve little or no sliding. In this study the terms mass movement; landslide; slope movement; and slope failure are used synonymously.

To differentiate between the terms hazard; vulnerability; and risk, the following definitions (given by Varnes, 1984) have become generally accepted:

Natural hazard (H):	the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area.
Vulnerability (V):	the degree of loss to a given element or set of elements at risk (see below) resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss).
Specific risk (Rs):	the expected degree of loss due to a particular natural phenomenon. It may be expressed by the product of H and V.
Elements at risk (E):	the population, properties, economic activities, including public services, etc. at risk in a given area.
Total risk (Rt):	the expected number of lives lost, persons injured, damage to property, or disruption of economic activity due to a particular natural phenomenon. It is therefore the product of specific risk (Rs) and elements at risk (E):

$$Rt = (E) * (Rs) = (E) * (H*V).$$

Landslide hazard is commonly shown on maps, which display the spatial distribution of hazard classes (landslide hazard zonation). Zonation refers to 'the division of the land in homogeneous areas or domains and their ranking according to degrees of actual/potential hazard caused by mass movement' (Varnes, 1984). Landslide hazard zonation requires a detailed knowledge of the processes that are or have been active in an area, and of the factors leading to the occurrence of the potentially damaging phenomenon. This is considered the task of earth scientists. Vulnerability analysis requires detailed knowledge of the population density, infrastructure, and economic activities, in addition to the hazard. Therefore, this part of the analysis is done mainly by persons from other disciplines, such as urban planning, social geography, and economics.

Fully-developed examples of risk analysis on a quantitative basis are still scarce in the literature (Einstein, 1988), because of the difficulties in defining quantitatively both hazard and vulnerability. Hazard analysis is seldom executed in accordance with the definition given above, since the probability of occurrence of potentially damaging phenomena is extremely difficult to determine for larger areas. The determination of actual probabilities requires analysis of triggering factors, such as earthquakes or rainfall, or the application of complex models. In most cases, however, there is no clear relationship between these factors and the occurrence of landslides. Therefore, the legend classes used in most hazard maps do not give more information than relative indications, such as high, medium, and low hazard. This study is restricted to the analysis of landslide hazard.

Trends in landslide hazard zonation

A large amount of research on hazard zonation has been done over the last 30 years, as the consequence of an urgent demand for slope instability hazard mapping. Overviews of the various slope instability hazard zonation techniques can be found in Hansen (1984), Varnes (1984), and Hartlén and Viberg (1988). The initial investigations were oriented mainly toward problem solving at the scale of site investigation and development of deterministic models. A wide variety of deterministic slope stability methods is now available to the engineer (Chowdury, 1978; Graham, 1984).

The large regional variability of geotechnical variables, such as cohesion; angle of internal friction; thickness of layers; or depth to groundwater, is inconsistent with the homogeneity of data required in deterministic models. The site investigation approach provides an unacceptable cost/benefit ratio for engineering projects over larger areas during the planning and decision-making phases due to the high cost and time requirements of data collection. Several types of landslide hazard zonation techniques have been developed to tackle such problems encountered in the application of deterministic modelling. A summary of the various trends in the development of techniques is given in Table 8.1. Each of the main groups highlighted in Table 8.1 is described in more detail in the following paragraphs.

Previous landslide studies using GIS

The development of GIS has greatly increased the availability of techniques for landslide hazard assessment and their application. The first applications of simple, self-programmed, prototype GIS in the analysis of landslide hazard zonation date from the late 1970s (Burrough, 1986). Newman *et al.* (1978) reported on the feasibility of producing landslide susceptibility maps using computers. Carrara *et al.* (1978) reported results of multivariate analysis applied

Table 8.1 General trends in landslide hazard methods

Type of landslide hazard analysis	Main characteristic
A. Distribution analysis	Direct mapping of mass movement features resulting in a map which gives information only for those sites where landslides have occurred in the past
B. Qualitative analysis	Direct, or semi-direct, methods in which the geomorphological map is renumbered to a hazard map, or in which several maps are combined into one using subjective decision rules, based on the experience of the earth scientist
C. Statistical analysis	Indirect methods in which statistical analyses are used to obtain predictions of the mass movement hazard from a number of parameter maps
D. Deterministic analysis	Indirect methods in which parameter maps are combined in slope stability calculations
E. Landslide frequency analysis	Indirect methods in which earthquake and/or rainfall records or hydrological models are used for correlation with known landslide dates, to obtain threshold values with a certain frequency

on grid cells with a ground resolution of 200 m × 200 m using approximately 25 variables. Huma and Radulescu (1978) reported an example from Romania of a qualitative hazard analysis including the factors of mass movement occurrence, geology, structural geological conditions, hydrological conditions, vegetation, slope angle, and slope aspect. Radbruch-Hall *et al.* (1979) wrote their own software to produce small-scale (1:7500 000) maps with 6 million pixels showing hazards, unfavourable geological conditions, and areas where construction or land development may exacerbate existing hazards. The maps were made by qualitative overlay of several input maps.

During the 1980s, the use of GIS for slope instability mapping increased sharply due to the development of commercial GIS systems, such as ARC/INFO, Intergraph, SPANS, ILWIS and IDRISI, and the increasing availability of personal computers (PCs). The majority of case studies presented in the literature on this subject deal with qualitative hazard mapping. The importance of geomorphological input data is stressed in the methods used by Kienholz *et al.* (1988), who used a GIS for a qualitative mountain hazard analysis; detailed aerial photo interpretation was used as a basis. The authors state that, due to the lack of good models and geotechnical input data, the use of a relatively simple model based on geomorphology seems to be the most realistic method. Most examples of qualitative hazard analysis with GIS are very recent (Stakenborg, 1986; Mani and Gerber, 1992; Kingsbury *et al.*, 1992). Many examples are presented in the proceedings of the First International Symposium on the use of Remote Sensing and GIS for Natural Risk Assessment, held in Bogotá, Colombia, in March 1992 (Alzate, 1992).

Examples of landslide susceptibility analysis with GIS reported since the 1970s have come mainly from the United States Geological Survey (USGS) in Menlo Park, California, where Brabb and his team have proceeded with their work and extended it, taking into account additional factors besides landslides, geology, and slope (Brabb, 1984; Brabb *et al.*, 1989). Other examples of quantitative univariate statistical analysis with GIS are rather scarce (Lopez and Zinck, 1991; Choubey and Litoria, 1990). This is rather strange, since one of the strong advantages of using a GIS is the capability to test the importance of each factor, or combinations of factors, and assign quantitative weighting values based on mass movement density.

Recent examples of multivariate statistical analysis using GIS have been presented mainly by Carrara and his team. Their work has developed from the use of large rectangular grid cells as the basis for analysis (Carrara *et al.*, 1978; Carrara, 1983, 1988) towards the use of morphometric units (Carrara *et al.*, 1990, 1991). The method itself has not undergone major changes. The statistical model is built-up in a training area, where the spatial distribution of landslides is (or should be) well known (Carrara, 1988). In the next step the model is extended to the whole study area or target area, based on the assumption that the factors that cause slope failure in the training area are the same as in the target area.

Another example of multivariate analysis using a GIS is presented by Bernknopf *et al.* (1988). They applied multiple regression analysis to a data set, using presence/absence of landslides as the dependent variable and the factors used in a slope stability model (soil depth, soil strength, slope angle) as independent variables. Water table data and cohesion data were not taken into account. The resulting regression function is transformed so that landslide probability can be calculated for each pixel.

Deterministic modelling of landslide hazard using GIS has become rather popular. Most examples deal with infinite slope models, since they are simple to use for each pixel separately (Brass *et al.*, 1989; Murphy and Vita-Finzi, 1991). Hammond *et al.* (1992) presented methods in which the variability of the factor of safety is calculated from selected input variables following the Monte Carlo technique. This implies a large number of repeated calculations, which require the use of a GIS.

A relatively new development in the use of GIS for slope instability assessment is the application of so-called neighbourhood analysis. Most of the conventional GIS techniques are based on map overlaying, which allows only for the comparison of different maps at the same pixel locations. Neighbourhood operations also allow evaluation of the neighbouring pixels around a central pixel, and can be used in the automatic extraction from a digital terrain model (DTM) of such morphometric and hydrological features as slope angle; slope aspect; downslope and cross-slope convexity; ridge and valley lines; catchment area; stream ordering, and the contributing area for each pixel. An overview of the algorithms applied in the extraction of morphometric parameters from GTMs is given by Gardner *et al.* (1990). Carrara identified automatically the homogeneous units he used as the basis for a multivariate analysis from a detailed DTM. The morphometric and hydrological parameters used in that analysis were also extracted automatically (Carrara *et al.*, 1990). Niemann and Howes (1991) performed a statistical analysis based on automatically extracted morphometric parameters (slope angle, slope aspect, down-slope and cross-slope convexity and drainage area), which they grouped into homogeneous units using cluster analysis. Van Dijke and van Westen (1990) applied a simple type of neighbourhood analysis to model the runout distances for rockfall blocks.

A recent development in the use of GIS for slope instability zonation is the application of expert systems. Pearson *et al.* (1991) developed an expert system in connection with a GIS in order to 'remove the constraints that the users should have a considerable experience with GIS'. A prototype interface between a GIS (ARC/INFO) and an expert system (Nexpert Object) was developed and applied for translational landslide hazard mapping in an area in Cyprus. The question remains, however, whether the rules used in the expert system apply only to this specific area, or whether they are universally applicable.

Pilot study areas

Selecting the working scale for a slope instability analysis project is determined by the purpose for which it is executed. The following scales of analysis, which were presented in the International Association of Engineering Geologists' monograph on engineering geological mapping (IAEG, 1976), can also be distinguished in landslide hazard zonation:

- Synoptic or regional scale (<1:100 000);
- Medium scale (1:25 000–1:50 000);
- Large scale (1:5000–1:10 000).

Regional-scale hazard analysis is used to outline problem areas with potential slope instability. The maps are mainly intended for agencies dealing with regional (agricultural, urban, or infrastructural) planning. The areas to be investigated are very large, on the order of 1000 km^2 or more, and the required detail of the map is low. The maps indicate regions where severe mass movement problems can be expected to threaten rural, urban, or infrastructural projects. Terrain units with areas of at least several tens of hectares are outlined. Within these units the degree of hazard is assumed to be uniform.

Medium-scale hazard maps are made mainly for agencies dealing with inter-municipal planning or companies dealing with feasibility studies for large engineering works (such as dams, roads, railroads). The areas to be investigated will have areas of several hundreds of square kilometres. At this scale considerably more detail is required than at the regional scale. The maps may serve, for example, for the choice of corridors for infrastructural construction or zones for urban development. The detail should be such that adjacent slopes with the same lithology are evaluated separately, which may result in different hazard scores, depending on other characteristics, such as slope angle and land use. Even within a single terrain unit, a distinction should be made between different slope segments, for example a concave part of a slope should receive a different score than an adjacent straight slope.

Large-scale hazard maps are produced mainly for authorities dealing with detailed planning of infrastructural, housing, or industrial projects, or with evaluation of risk within a city. The size of an area under study would be on the order of several tens of square kilometres. The hazard classes on such maps should be absolute, indicating, for example, the probability of failure for each individual unit with an area down to less than a hectare.

Although the selection of the scale of analysis is usually determined by the intended application of its results, the choice of technique for mapping landslide hazard remains open. The choice depends on the type of problem, the availability of geotechnical and other data, the availability of financial resources, and time restrictions, as well as on the knowledge and experience of the research team.

Three pilot study areas for the different working scales, defined above, were selected in the Rio Chinchina catchment in Colombia. The catchment of the Rio Chinchina, with a surface area of 722 km^2 and a perimeter of 159 km, is located on the western slope of the central Andean mountain range (Cordillera Central) in the Caldas Department in Colombia (see Figure 8.3). This area was chosen as the study area to test the methodology developed in this work because of its following characteristics.

1. The severity of natural hazards in the area, combined with intensive industrial and agricultural activity and a high population density, has caused considerable damage and loss of lives in the past. The area is susceptible to mass movement, earthquake, and volcanic hazards. The largest disaster in the Rio Chinchina area took place on 13 November 1985, when a lahar, triggered by an eruption of the glacier-covered Nevado del Ruiz, caused the death of about 2000 persons and destroyed all bridges over the Rio Claro and Rio Chinchina. The last major earthquake, which killed 50 persons in Pereira and Manizales and caused considerable property damage, occurred on 23 November 1979. Landslide casualties and material damage are reported almost annually, in both urban and rural areas. The road network also suffers from severe mass movement problems. The so called *triangulo vial* (road triangle) between Manizales, La Manuela, and

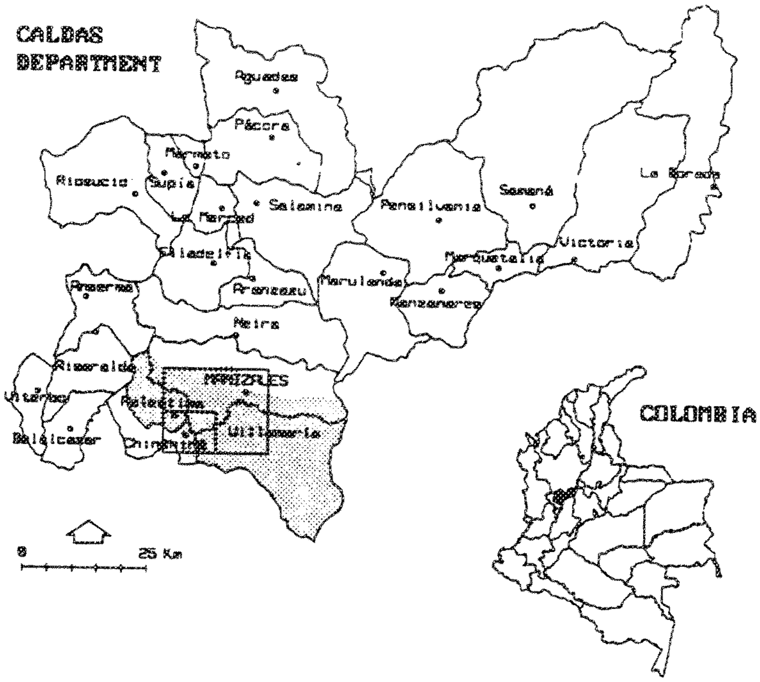


Figure 8.3 The pilot study areas for the three working scales, located in the Rio Chinchina catchment, central Colombia.

Chinchina is considered by the Ministry of Public Works to be one of the main problem areas in the Colombian road network (Baez *et al.*, 1988).

2. The availability of maps, aerial photos, and reports. Imagery and topographic maps, as well as a wide range of thematic maps from different years and at different scales, are available for most parts of the area.

Input data

A list of the various input data needed to assess landslide hazard at the regional, medium, and large scale is given in Table 8.2. The list is extensive, and only in an ideal case will all types of data be available. However, the amount and type of data that can be collected, determine the type of hazard analysis that can be applied, ranging from qualitative assessment to complex statistical methods.

The data layers needed to analyse landslide hazard can be subdivided into five main groups: geomorphological; topographic; engineering geological or geotechnical; land use; and hydrological data. A data layer in a GIS can be seen as one digital map, containing one type of data, composed of one

Table 8.2 Overview of input data needed for landslide hazard analysis

Data types	Summary of data collection techniques	Feasibility of data collection		
		Regional scale	Medium scale	Large scale
GEOMORPHOLOGY				
1. Terrain mapping units (TMUs)	Satellite image interpretation + walk over study	High	Moderate	Low
2. Geomorphological units	Aerial photo interpretation and field check	Moderate	High	High
3. Geomorphological subunits	Aerial photo interpretation and field check	Low	High	High
4. Landslides (recent)	Aerial photo interpretation and field descriptions	Low	High	High
5. Landslides (older period)	Aerial photo interpretation + collection of landslide records from newspapers, fire brigades, or church archives	Low	High	High
TOPOGRAPHY				
6. Digital terrain model (DTM)	Collection of existing contour maps	Moderate	High	High
7. Slope map (degrees or percentage)	Made from a (DTM)	Moderate	High	High
8. Slope direction map	Made from a DTM, no extra data collection required	Moderate	High	High
9. Breaks of slope	Aerial photo interpretation	Low	Moderate	High
10. Concavities/convexities	Made from a DTM, or detailed photo interpretation	Low	Low	High
ENGINEERING GEOLOGY				
11. Lithologies	Checking of existing geological maps, or by mapping if no data are available	Moderate	High	High
12. Material sequences	Made by a combination of other maps (geomorphological, geology, slope and DTM)	Low	Moderate	High
13. Sampling points	Field descriptions of soil and rock outcrops, and laboratory analysis of selected samples to characterize material types	Moderate	High	High

14. Faults & lineaments	Satellite image interpretation, aerial photo interpretation, and fieldwork	High	High	High
15. Seismic events	Collection of existing seismic records	High	High	High
16. Isolines of seismic intensity	Questionnaires on the observed damage from earthquake(s)	Low	Moderate	High
LAND USE				
17. Infrastructure (recent)	Aerial photo interpretation and topographic map	Moderate	High	High
18. Infrastructure (older)	Aerial photo interpretation and topographic map	High	High	High
19. Land use map (recent)	Aerial photo interpretation and classification of satellite images and field check	Moderate	High	High
20. Land use map (older)	Aerial photo interpretation	Moderate	High	High
21. Cadastral blocks	Collection of existing cadastral maps and database	Low	Low	High
HYDROLOGY				
22. Drainage	Aerial photo interpretation and topographic map	High	High	High
23. Catchment areas	Aerial photo interpretation and topographic map or modelling from a DTM	Moderate	High	High
24. Meteorological data	Collection of existing meteorological stations	High	High	High
25. Water table	Field measurements of Ksat and modelling	Low	Low	Moderate

type of element (points, lines, units), and having one or more accompanying tables. Of course, the layers that have to be taken into account vary for different environments. Tectonic data, for example, are not needed in an area that is seismically inactive, and in some areas it may be necessary to include types of data not listed in the Table.

The second column of Table 8.2 gives a summary of the method by which each data layer is collected, referring to the three phases of data collection (image interpretation, fieldwork, and laboratory analysis). The last three columns in Table 8.2 give an indication of the relative feasibility (high, moderate, or low) of collecting a certain data type at each of the three scales under consideration.

Due to the large size of areas to be studied at the regional scale (on the order of 500–2000 km^2), and because of the objectives of hazard assessment at this scale, detailed data collection for individual variables is not a cost-effective approach. Data gathered at this scale is limited to the delineation of homogeneous terrain mapping units, and collection of regional seismic data. At the medium scale, nearly all of the data layers given in Table 8.2 can be gathered for areas smaller than 200 km^2, with exception of detailed soil and groundwater information. At the large scale, where the study area is generally smaller than 50 km^2, all of the proposed data layers can be collected.

Methods of analysis

The following subsections systematically present the techniques for landslide hazard zonation for their use in a GIS. An overview of the required input data is given and the various steps using GIS are mentioned briefly. A recommendation is also given regarding the most appropriate working scale.

Landslide distribution analysis

The most straightforward approach to landslide hazard mapping is a landslide inventory map, based on aerial photo interpretation, ground survey, and/or a database of historical occurrences of landslides in an area. The final product gives the spatial distribution of mass movements, represented either at scale or as points. The maps can be used as an elementary form of hazard map, because they display the location of a particular type of slope movement in an area. They provide information only for the period shortly preceding the date the aerial photos were taken or the fieldwork was conducted. They provide no insight into the temporal changes in mass movement distribution. Many landslides that occurred some time before the photographs were taken may have become undetectable.

In most of the methodologies for landslide hazard assessment, a mass movement distribution map is the most important input map, as it shows the distribution of the phenomena that one wants to predict. The input consists of a field-checked photo-interpretation map of landslides for which recent, relatively large-scale, aerial photographs have been used, combined with a table containing landslide parameters, obtained from a checklist. GIS can perform an important task in transferring the digitized photo-interpretation to the topographic basemap projection using a series of control points and camera information.

The GIS procedure followed is:

- digitizing of the mass movement phenomena, each with its own unique label and a six-digit code containing information on the landslide type, subtype, activity, depth, and site vegetation, and on whether the unit is a landslide scarp or body;
- recoding of the landslide map with the parameters for type or subtype into maps displaying only one type of process.

The method is most appropriate at medium or large scales. At the regional scale, the construction of a mass movement distribution map is very time-consuming and too detailed for procedures of general regional zoning. Nevertheless, when possible it is advisable to prepare such a map also for the regional scale, although with less detail.

Two important considerations arise in this method.

- The accuracy of interpretation of mass movement phenomena from aerial photographs depends on the skill of the interpreter, and the interpretation is subjective. Detailed fieldwork is very important.
- GIS in this technique is used only to store the information and to display maps in different forms (e.g. only the scarps, only slides, only active slides). Although the actual analysis is very simple, the use of a GIS is of great advantage in this method. The user can select specific combinations of mass movement parameters and obtain a better insight into the spatial distribution of the various landslide types.

Landslide activity analysis

A refinement of landslide distribution mapping is the construction of landslide activity maps, based on multi-temporal aerial photo-interpretation. To study the effects of the temporal variation of a variable such as land use, landslide activity maps are indispensable.

The code for mass movement activity which is given to each mass movement phenomenon can also be used in combination with mass movement distribution maps from earlier dates to analyze mass movement activity. Depending on the type of terrain which is studied, time intervals of 5–20 years can be selected. This method of interval analysis offers numbers or percentages of reactivated, new, or stabilized landslides. The following GIS procedures are used.

- The digitized map of recent mass movements is used as the basis for the digitizing of maps from earlier dates. This is done in order to make sure that the landslides which were already present at earlier dates are digitized in the same position.
- Calculation of the differences in activity between two different dates, by comparison of the data from the checklists combined with the map data.
- Calculation of all landslides which were initiated or reactivated in the period between the two photo-coverages.

The most appropriate scales are the medium and the large scales, because of the required detail of input maps, as discussed earlier. The main problems with the landslide activity method are that it is very time-consuming, and that it is difficult to prevent inconsistencies between interpretations from the various dates. The information derived from aerial photos from earlier dates cannot be checked in the field, and will result in greater inaccuracies. The method is represented schematically in Figure 8.4, and an example of the use of the methodology is shown for the large-scale area in Plate 4.

Landslide density analysis

Landslide distribution can also be shown in the form of a density map, showing the percentage cover within mapping units. These mapping units may be terrain mapping units (TMUs), geomorphological units, geological units, etc. This method is also used to test the importance of each parameter individually for the occurrence of mass movements. The required input data consist of a mass movement distribution map, and a land-unit map. If the method is used to test the importance of specific parameter classes, the user decides, on the basis of his field experience, which individual parameter maps, or combination of parameter maps will be used. The following GIS procedures are used for mass movement density analysis.

- Calculation of a bit map (presence/absence) for the specific mass movement type for which the analysis is carried out.
- Combination of the selected parameter map with the bit map through map overlay.
- Calculation of the area percentage per parameter class occupied by landslides.

With a small modification, the number of landslides can be calculated instead of the areal density. In that case a bit map is not made, and the mass

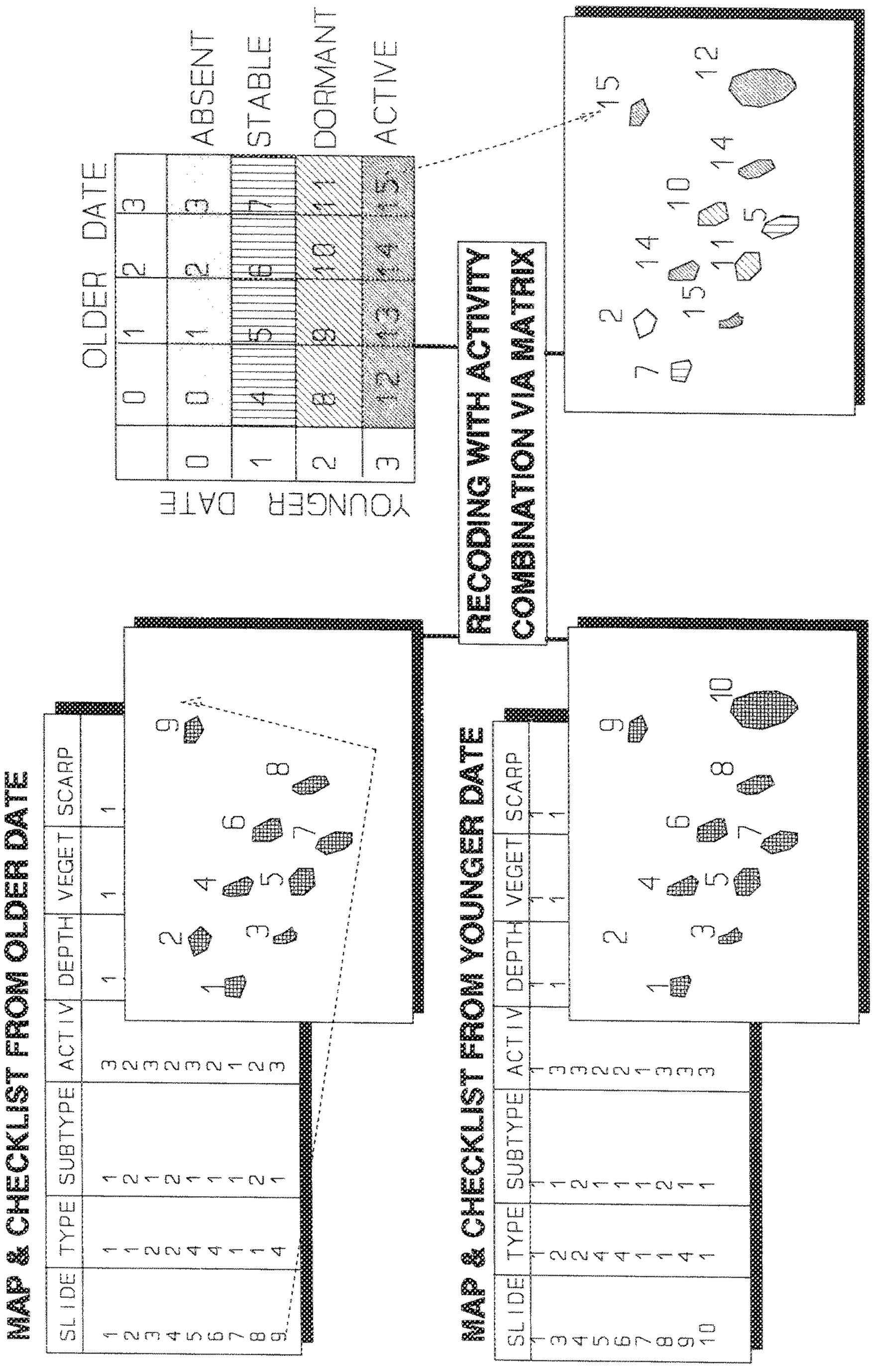


Figure 8.4 Schematic representation of the use of GIS for landslide activity analysis.

movement map itself, in which each polygon has a unique code, is overlaid with the parameter map.

A special form of mass movement density mapping is isopleth mapping (Wright *et al.*, 1974). The method uses a large, moving, counting circle which calculates the landslide density for each circle centre. The result is a contour map of landslide density. The size of the pixels and the size of the filter used define the values in the resulting density map. Except for the creation of a bit map, the procedure for landslide isopleth mapping is rather different.

The method is most appropriate on the medium and large scales for the reasons discussed in the previous section. An example of a series of density maps for the regional-scale area is shown in Figure 8.5.

Geomorphological landslide hazard analysis

In geomorphological methods, mapping of mass movements and their geomorphological setting is the main input factor for hazard determination. The basis for this approach was outlined by Kienholz (1977), who developed a method to produce a combined hazard map based on the mapping of 'silent witnesses (*Stumme Zeugen*)'. In this method, the degree of hazard is evaluated at each site in the terrain. The decision rules are therefore difficult to formulate, as they vary from place to place. Because the hazard analysis is in fact accomplished in the mind of the geomorphologist, geomorphological methods are considered subjective. In this study the terms objective and subjective are used to indicate whether the various steps taken in the determination of the degree of hazard are verifiable and reproducible by other researchers, or whether they depend upon the personal judgment of the researcher. The term subjective is not intended as a disqualification. Subjective analysis may result in a very reliable map when it is executed by an experienced geomorphologist and objective analysis may result in an unreliable map when it is based on an oversimplification of the real situation. Some examples of geomorphological hazard maps can be found in Rupke *et al.* (1988) and Seijmonsbergen *et al.* (1989).

GIS can be used in this type of work as a drawing tool, allowing rapid recoding of units, and correction of units which were coded erroneously. GIS is not used as a tool for the analysis of the important parameters related to the occurrence of mass movements. The method can be applied at regional, medium, or large scales in a relatively short time period. It does not require the digitizing of many different maps. However, the detailed fieldwork requires a considerable amount of time as well. The accuracy of the resulting hazard map will depend completely on the skill and experience of the geomorphologist. Geomorphological maps of the same area made by different geomorphologists may vary considerably, as was tested in this study (van Westen, 1993).

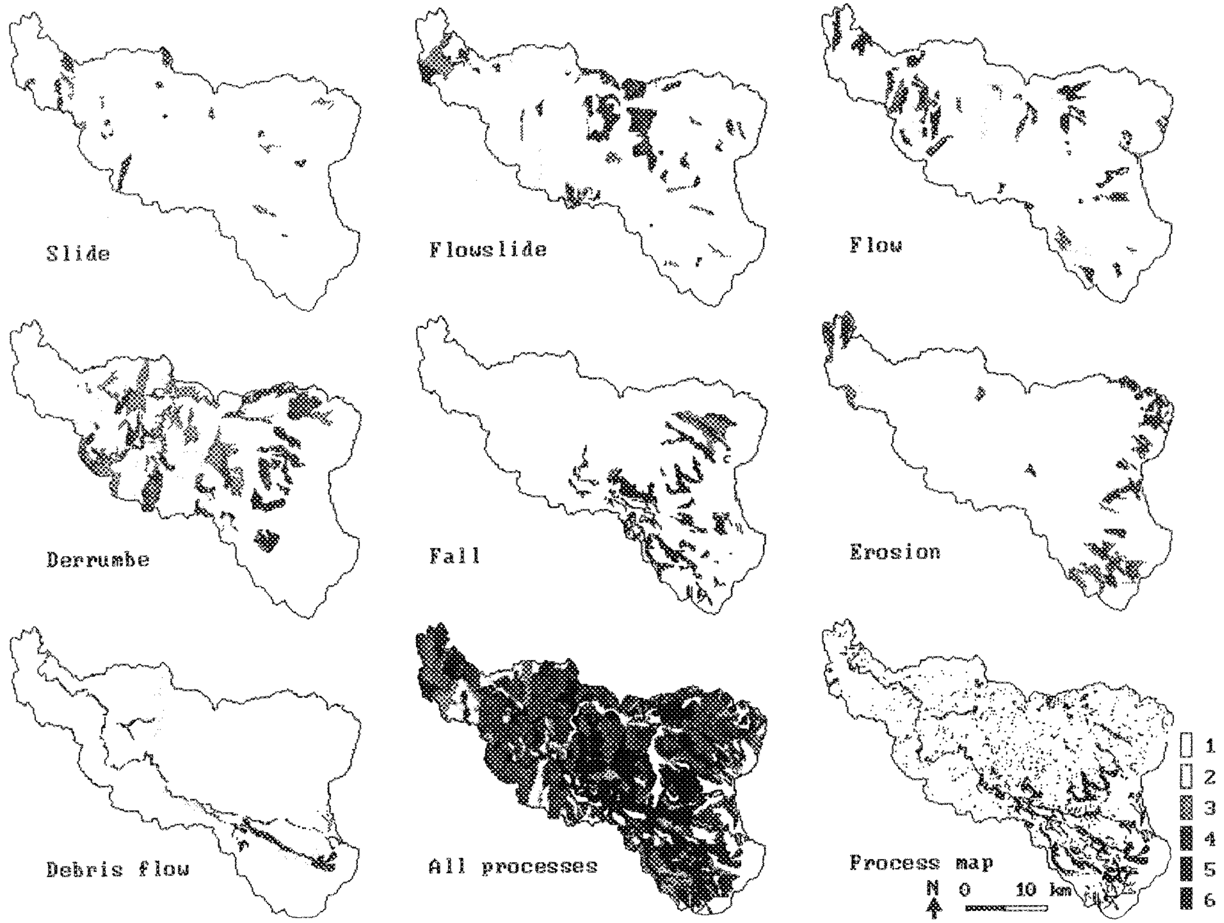


Figure 8.5 Classified density values for several denudational processes calculated per terrain mapping subunit (regional-scale area). Legend: 1 = 0‰, 2 = 0–5‰, 3 = 5–10‰, 4 = 10–50‰, 5 = >50‰, and 6 = all processes.

Qualitative landslide hazard analysis

To overcome the problem of the hidden rules in geomorphological mapping, other qualitative methods have been developed based on qualitative map combination. Stevenson (1977) developed an empirical hazard rating system for an area in Tasmania. On the basis of his expert knowledge on the causal factors of slope instability, he assigned weighting values to different classes in a number of parameter maps. This method of qualitative map combination has become very popular in slope instability zonation. The problem with this method is that the exact weighting of the various parameter maps is often based on insufficient field knowledge of the important factors, which leads to unacceptable generalizations.

The basis for this method of hazard mapping is the field knowledge of the earth scientist who decides which parameters are important for the occurrence of mass movements. Qualitative weighting values are assigned to each class of a parameter map, and each parameter map receives a different weight. Depending on the detail of the study, several input maps can be used, among which the most important are geomorphology, mass movement occurrences, slope angle, geology, land use, and distance to faults, roads, and drainage lines.

The following GIS procedures are used.

- Classification of each parameter map into a number of relevant classes.
- Assignment of weight values to each of the parameter classes (e.g. on a scale of 1–10).
- Assignment of weight values to each of the parameter maps.
- Calculation of weights for each pixel and classification in a few hazard classes.

The method is applicable on all three scales. Each scale has its own requirements as to the required detail of the input maps.

Bivariate statistical landslide hazard analysis

Aiming at a higher degree of objectivity and better reproducibility of the hazard zonation, which is important for legal reasons, statistical techniques have been developed for the assessment of landslide hazard. These quantitative methods have benefited strongly from the availability of computers. Brabb *et al.* (1972) presented a method for quantitative landslide susceptibility analysis at a regional scale, which is based on landslide occurrence, substrate material type, and slope angle. Geological units are grouped according to their landslide density and relative susceptibility values are assigned. Combining these values with a slope map produces final susceptibility classes. The method is easy to use, although it is usually not sufficient to use only the factors of rock type and slope angle.

In this method, overlay of parameter maps and calculation of landslide densities form the core of the analysis. The importance of each parameter, or specific combinations of parameters, can be analyzed individually. Using normalized values (landslide density per parameter class in relation to the landslide density over the whole area), a total hazard map can be made by addition of the weights for individual parameters. The weight values can also be used to design decision rules, which are based on the experience of the earth scientist. It is also possible to combine various parameter maps into a map of homogeneous units, which is then overlaid with the landslide map to give a density per unique combination of input parameters.

GIS is very suitable for use with this method, which involves a large number of map overlays and manipulation of attribute data. This method requires the same input data as the qualitative method discussed in the previous section.

It should be stressed that the selection of parameters has also an important subjective element in this method. The following GIS procedures are used.

- Classification of each parameter map into a number of relevant classes.
- Combination of the selected parameter maps with the landslide map via map overlay.
- Calculation of weighting values based on the cross table data.
- Assignment of weighting values to the various parameter maps, or design of decision rules to be applied to the maps, and classification of the resulting scores in a few hazard classes.

The medium scale is most appropriate for this type of analysis. The method is not detailed enough to apply at the large scale, and at the regional scale the necessary landslide occurrence map is difficult to obtain.

Several specific bivariate statistical methods exist which are based on the same principles, but use different indexes, of which two are briefly described here. The 'information value method' (Yin and Yan, 1988) is a statistical technique that requires a database of parameters collected for different land units. The analysis is based on the presence (1) or absence (0) of landslides at a certain location or within a land unit. It can be used for both alphanumeric and numeric data. The presence or absence of parameters is also calculated. The relative importance for the occurrence of landslides of each parameter is calculated in terms of an information value, which is the log of the landslide density per parameter, as compared to the overall landslide density. In the 'weights of evidence method' (Bonham-Carter *et al.*, 1990), point phenomena (landslides) are regarded along with several terrain factors. These factors are translated into binary input maps. Weights are assigned to the binary maps using Bayes rules for conditional probability. These weights are added to the log of the odds of the prior probability, to give the log of the odds of the posterior probability. The final product of this analysis is a predictor map giving the posterior probability of the occurrence of landslides for each pixel, which is based upon the unique overlap of all binary input pattern maps.

An example of a landslide probability map produced with the weights of evidence method is given in Figure 8.6.

Multivariate statistical landslide hazard analysis

Multivariate statistical analyses of important factors related to landslide occurrence may give the relative contribution of each of these factors to the total hazard within a defined land unit. Carrara *et al.* (1977, 1978) introduced methods for multivariate statistical analysis of mass movement data. Two main approaches of multivariate analysis exist:

1. Statistical analysis of point data obtained from checklists of causal factors associated with individual landslide occurrences (Neuland, 1976; Carrara *et al.*, 1977).
2. Statistical analysis performed on terrain units covering the whole study area. For each of the units, data on a number of geological, geomorphological, hydrological, and morphometrical factors is collected and analyzed using multiple regression or discriminant analysis (Carrara *et al.*, 1978, 1990, 1991; Carrara, 1983, 1988, 1992).

These methods are rather time-consuming, for both data collection and data processing. The analyses are based on the presence or absence of mass movement phenomena within these land units, which may be catchment areas, interpreted geomorphological units or other kinds of terrain units.

Several multivariate methods have been proposed in the literature. Most of these, such as discriminant analysis or multiple regression, require the use of external statistical packages. GIS is used to sample parameters for each land unit. However, with PC-based GIS systems, the large volume of data may become problematic. The method requires a landslide distribution map and a land unit map. A large number of parameters is used, comparable to those mentioned in the previous section. The different classes of a parameter map are considered as individual parameters, resulting in a large matrix. The following GIS procedures are used.

- Determination of the list of factors that will be included in the analysis. As many input maps (such as geology) are of an alpha-numeric type, they must be converted to numerical maps. These maps can be converted to presence/absence values for each land-unit, or presented as percentage cover, or the parameter classes can be ranked according to increasing mass movement density. By overlaying the parameter maps with the land-unit map, a large matrix is created.

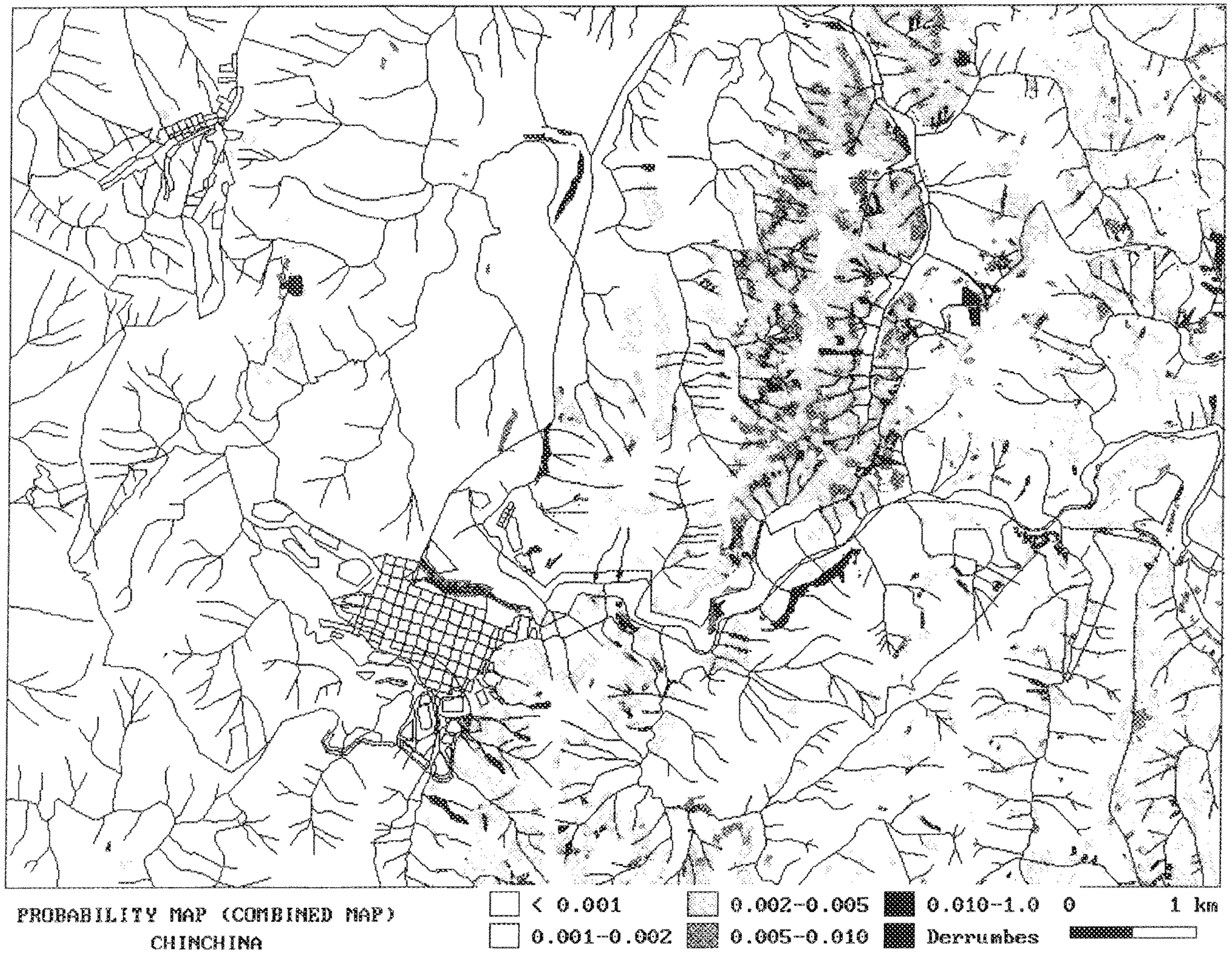


Figure 8.6 *Classified probablity values for the occurrence of derrumbes (local term for debris avalanches) in the medium-scale study area made from a map with unique combinations of variable classes.*

- Combination of the land-unit map with the mass movement map via map overlay and dividing the stable and the unstable units into two groups.
- Exportation of the matrix to a statistical package for subsequent analysis.
- Importation of the results per land-unit into the GIS and recoding of the land-units. The frequency distribution of stable and unstable classified units is checked to see whether the two groups are separated correctly.
- Classification of the map into a few hazard classes.

Although these techniques can be applied at different scales, their use becomes quite restricted at the regional scale, where an accurate input map of landslide occurrences may not be available, and where most of the important parameters cannot be collected with satisfactory accuracy. At large scales, different factors will have to be used (such as water-table depth, soil layer sequences and thicknesses). These data are very difficult to obtain even for relatively small areas. Therefore the medium scale is considered most appropriate for this technique.

Deterministic landslide hazard analysis

Despite problems related to collection of sufficient and reliable input data, deterministic models are increasingly used in hazard analysis over larger areas. They are applicable only when the geomorphological and geological conditions are fairly homogeneous over the entire study area and the landslide types are simple. The advantage of these 'white box models' is that they have a physical basis. Their main problem is the high degree of oversimplification. This method is usually applied for translational landslides using the infinite slope model (Brass *et al.*, 1989; Murphy and Vita-Finzi, 1991). The methods generally require the use of groundwater simulation models (Okimura and Kawatani, 1986). Stochastic methods are sometimes used for selection of input parameters (Mulder and van Asch, 1988; Mulder, 1991; Hammond *et al.*, 1992).

Slope stability models require input data on: soil layer thickness; soil strength; depth below the terrain surface of potential sliding surfaces; slope angle; and pore pressure conditions to be expected on the slip surfaces.

The following parameter maps should be available in order to be able to use such models.

- a material map, showing both the distribution at ground surface as in the vertical profile, with accompanying data on soil characteristics;
- a groundwater level map, based on a groundwater model or on field measurements; and
- a detailed slope angle map, derived from a very detailed DTM.

For the application of GIS in deterministic modelling, several approaches can be followed:

- the use of an infinite slope model, which calculates the safety factor for each pixel;
- selection of a number of profiles from the DTM and the other parameter maps which are exported to external slope stability models; and
- sampling of data at predefined grid-points, and exportation of these data to a three-dimensional slope stability model.

The method is applicable only at large scales and over small areas. At regional and medium scale, the detail of the input data, especially concerning groundwater levels, soil-profile, and geotechnical descriptions is insufficient. The variability of the input data can be used to calculate the probability of failure in connection with the return period of triggering events.

The resulting safety factors should never be used as absolute values. They are only indicative and can be used to test different scenarios of slip surfaces and groundwater depths. An example of a landslide probability map is given in Plate 5. This map indicates the probability that the safety factor is lower than 1 when a rainfall event occurs with a return period of 25 years.

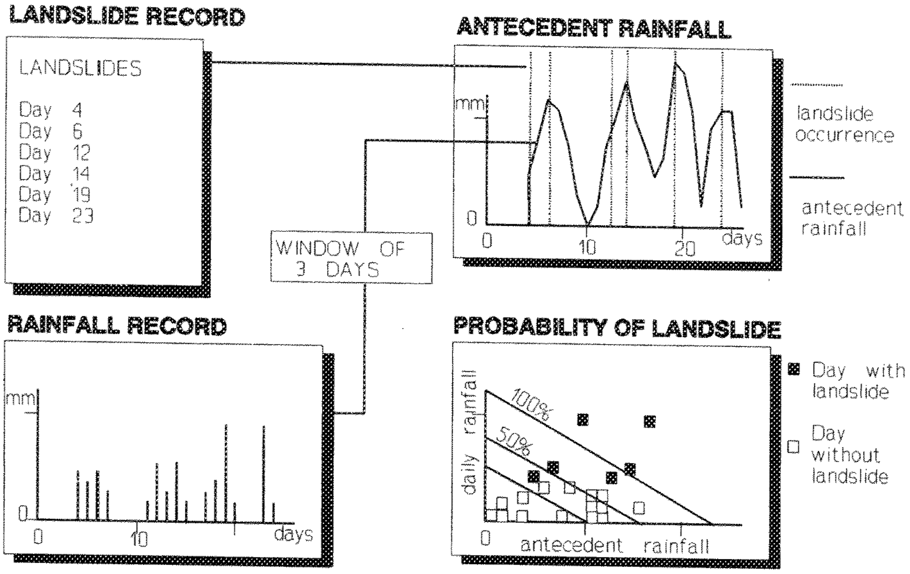
Landslide frequency analysis

Most of the methods mentioned so far do not result in real hazard maps as defined by Varnes (1984). Assessing the probability of occurrence at a specific location within a certain time period is possible only when a relationship can be found between the occurrence of landslides and the frequency of triggering factors, such as rainfall or earthquakes. Especially for rainfall-related landslides, various techniques have been developed which determine threshold values of antecedent rainfall (Crozier, 1986; Keefer *et al.*, 1987; Capecchi and Focardi, 1988). Antecedent rainfall is the accumulated amount of precipitation over a specified number of days preceding the day on which a landslide occurred. This permits the calculation of a rainfall threshold value.

The following input data are required:

- daily rainfall records; and
- landslide records (taken from insurance companies, newspapers, or fire/rescue departments).

The method is most appropriate at medium and large scales. At the regional scale, it may be difficult to correlate known landslides at one location with rainfall records from a different location in the area. The spatial component is usually not taken into account in this analysis, and therefore the use of a GIS is not crucial. GIS can be used to analyze the spatial distribution of



rainfall, however. A schematic representation of the method is given in Figure 8.7.

Discussion and conclusions

Any hazard evaluation involves a large degree of uncertainty. Prediction of natural hazards such as landslides, which are caused by the interaction of factors which are not always fully understood and are sometimes unknown, confronts earth scientists with especially large problems. For large areas and at small, not detailed, scales it is possible to make general predictions: the number of landslides that have occurred in the past within a land unit is a good indication of what can be expected to occur in the near future. It is, however, much more difficult when predictions need to be made in more detail for areas presently free of landslides. In this situation, the earth scientist must rely on models based on the assumption that landslides are more likely to occur in places where a combination of conditions exists which has led to landslides in the past. Most methods presented in the literature and evaluated in this study are based on this principle. This implies knowledge of causal factors, and the ability to represent these on a map, as well as detailed knowledge about past mass movements.

Since hazard maps are used to make predictions over relatively large areas, collection of data for and preparation of these factor maps is a time-consuming operation, and cannot be based solely on factual, measured, field data. During the preparation of these factor maps, the subjective evaluation of field conditions by the earth scientist will play an important role. Since all earth scientists are not equally experienced, these maps will normally contain a considerable degree of uncertainty. It is clear that hazard maps prepared by very experienced geomorphologists will have the highest reliability, with or without the use of GIS. However, solutions must be found to upgrade the reliability of hazard maps in studies where less experienced earth scientists are responsible for the collection of basic data and subsequent analysis. For those cases, it is important to give recommendations as to how the reliability of the end product can be increased, by reducing the uncertainty of the input factors as much as possible. This should be achieved by clear definition of criteria for the interpretation of landslides and their controlling factors, as well as by thorough fieldwork. Instead of making a map by photo-interpretation followed by a field check, input maps for a hazard zonation should be prepared after fieldwork preceded by photo-interpretation.

The use of GIS confronts the earth scientist with the need to provide quantitative values for many uncertainties encountered in the input data, and can serve as an important tool in analyzing the sources of error. It can also help in reducing the errors occurring in the phase of transfer of the photo-information to a topographic map, and in the correct positioning of the various input layers. Apart from the large subjectivity present in the input factors, some of the methods for landslide hazard zonation, evaluated in this study, also contain a considerable subjectivity in the subsequent analytical phase.

GIS offers map overlaying possibilities and calculation facilities far superior to conventional techniques. One of the major contributions of GIS may be the reduction of the subjective element during the analysis phase, allowing the user to concentrate more on reducing errors stemming from the input data. It is especially useful in those situations where the causal factors for mass movements are not fully understood. The user can test hypotheses rapidly, and select the most important combination of factors by trial and error. The result will be optimal when field knowledge is combined with the calculation facilities of GIS. GIS should not be used to throw a large group of variables into a 'black box', to see what comes out, since such an approach is not based on a clear understanding of the causal mechanisms of slope failures. Standard calculation methods are presented, but the user is fully responsible for the selection of relevant input data and the analytical model.

The methods presented in this study cannot be executed at each scale of analysis. Before starting a hazard evaluation study, an earth scientist should be aware of the desired degree of detail of the hazard map, given the requirements of the study. When a degree of detail and a working scale have been defined, the cost-effectiveness of obtaining input data must be considered. This chapter provides recommendations as to which kind of data can be collected at each working scale (regional, medium, and large scale). The availability of data determines the type of analysis that can be executed. Table 8.3 gives a summary of the author's conclusions on the feasibility and

Table 8.3 Summary of the feasibility and usefulness of applying GIS-based techniques for landslide hazard zonation on the three scales under consideration

Method	Regional scale	Medium scale	Large scale	Usefulness of GIS in the analysis
Landslide distribution analysis	2–3	3–3	3–3	Intermediate
Landslide density analysis	2–3	3–2	3–1	Intermediate/high
Landslide activity analysis	1–3	3–3	3–3	Intermediate/high
Landslide isopleth analysis	2–3	3–2	3–1	High
Geomorphological landslide hazard analysis	3–3	3–3	3–3	Very low
Qualitative landslide hazard analysis	3–3	3–2	3–1	Low/intermediate
Landslide susceptibility analysis	1–3	3–3	3–2	High
Information value method	1–1	3–3	3–2	High
Weights of evidence method	1–1	3–3	3–2	High
Multivariate statistical analysis	1–2	3–2	3–2	High
Deterministic landslide hazard analysis	1–1	1–2	2–3	High
Antecedent rainfall analysis	2–2	3–3	3–2	Very low

The first number indicates the feasibility (1 = low: it would take too much time and money to gather sufficient information in relation to the expected output; 2 = moderate: a considerable investment would be needed, which only moderately justifies the output; 3 = good: the necessary input data can be gathered with a reasonable investment related to the expected output). The second number indicates the usefulness (1 = of no use: the method does not result in very useful maps at the particular scale; 2 = of limited use: other techniques would be better, 3 = useful).

usefulness of applying the methods discussed in this chapter for the various scales under consideration, and of the usefulness of GIS. The following recommendations are given.

- For very large areas at the regional scale, the best method is the use of terrain classification based on satellite imagery, followed by qualitative hazard analysis using relative weight values obtained from brief field visits.
- For moderately large areas at the regional scale, it is advisable to use terrain classification based on satellite imagery and interpretation of landslides from aerial photos, followed by a density calculation of landslides per mapping unit.
- At the medium scale, the most useful method consists of the collection of important factors related to mass movement occurrence, followed by reclassification and combination into homogeneous units and calculation of quantitative weight values.
- For geomorphologically homogeneous areas, at the large scale the best method is the application of simple slope stability models.

- For geomorphologically heterogeneous terrain at the large scale, the use of detailed geomorphological mapping is considered the best solution.

GIS will play an increasingly important role in the analysis of landslide hazards. It is an important tool in evaluating the accuracy of the input data. With a good database structure and standardized methods of data gathering, the input maps can be greatly improved during the course of a project by the entry of newly collected data. In this way, GIS will not only serve inexperienced earth scientists in the analysis of unknown causal factors of slope instability within a region, but will also enable experienced professionals to create a detailed database which can be useful for many more engineering geological applications other than landslide hazard assessment alone.

GIS is very important in analysing the complex combination of factors leading to slope instability. It allows the use of models which were previously available, but which could not be used because of the large amounts of time involved in their application. One of the most promising applications of GIS in landslide hazard assessment could be the further development of detailed slope instability models, in combination with groundwater models, applied over relatively small areas. Provided that it is used in combination with detailed field knowledge, GIS will enhance the reliability and objectivity of the hazard maps, which therefore will become increasingly important in the decision-making process.

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