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GIS-based landslide hazard assessment: an overview

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Abstract: In recent years, landslide hazard assessment has played an important role in developing land utilization regulations aimed at minimizing the loss of lives and damage to property. A variety of approaches has been used in landslide assessment and these can be classified into qualitative factor overlay, statistical models, geotechnical process models, etc. However, there is little work on the satisfactory integration of these models with geographic information systems (GIS) to support slope management and landslide hazard mitigation. This paper deals with several aspects of landslide hazard assessment by presenting a focused review of GIS-based landslide hazard assessment: it starts with a framework for GIS-based assessment of landslide hazard; continues with a critical review of the state of the art in using GIS and digital elevation models (DEM) for mapping and modelling landslide hazards; and concludes with a description of an integrated system for effective landslide hazard assessment and zonation incorporating artificial intelligence and data mining technology in a GIS-based framework of knowledge discovery.

Key words: GIS modelling, hazard assessment, landslide, the state of the art.

I Introduction

Landslides, defined as the mass movement of rock, debris or earth down a slope (Cruden, 1991), can be triggered by various external stimuli. These include intense rainfall, earthquakes, water-level changes, storm waves or rapid stream erosion which cause a rapid increase in shear stress or decrease in shear strength of slope-forming materials. As one of the major natural hazards, landslides claim peoples lives almost every year and cause huge property damage in mountainous areas (Hansen, 1984; Chung and Fabbri, 1995). It is estimated that, in 1998, about 180 000 geological hazards such as avalanches, landslides and debris flows in different scales

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have occurred in China, resulting in 1573 people dead, more than 10 000 people injured and 500 000 houses destroyed, with up to 3 billion dollars worth of direct economic losses (http://www.mlr.gov.cn/minprice/english.htm).

In recent years, the assessment of landslide hazard has drawn greater attention from geoscientists, engineering professionals, local communities and all levels of government in many parts of the world. Traditionally, susceptibility assessment or probability mapping were laborious and time-consuming because of the time and effort required for the manual handling and processing of the data. Recently, geographic information systems (GIS) have become an important tool for landslide hazard assessment. GIS is a computer-based technology designed to capture, store, manipulate, analyse and display diverse sets of spatial or georeferenced data. There are many published technical papers dealing with this subject, in addition to solid developments in the setup of spatial databases by regional land-planning authorities. The current trends are generally towards the development of early-warning systems and enhancement of land-utilization regulations for minimizing the loss of life and property damage and, in the mean time, avoiding investment in long-term, often expensive, projects of slope stabilization (USGS, 1982; Kockelman, 1986; IDNHR, 1987; UNDRO, 1991; Schuster, 1995). Tools for handling and analysing geospatial data (i.e., GIS) may facilitate the application of quantitative techniques in landslide hazard assessment and mapping (Turrini and Visintainer, 1998; Chung and Fabbri, 1999; Guzzetti *et al.*, 1999; Gokceoglu *et al.*, 2000; Luzi *et al.*, 2000; Lee and Min, 2001), and many assume that a landslide hazard map obtained by systematic data manipulation within a GIS is more objective than a comparable hand-made product derived from the same input data and based on the same conceptual model (Carrara *et al.*, 1999). However, up till now, there has been no general agreement on the methods or even on the scope of these investigations. Despite the methodological and operational difference, all the methods proposed involve an increasing degree of analysis, and rigour, not necessarily an increasing accuracy in the assessment of probability. The application of such methods should include consideration of the following aspects to give realistic outcomes: surface and subsurface geometry, hydrology, variation of porewater pressure with time, material strengths and spatial variation of parameters. Diffusion of GIS technology is, however, still hampered by factors such as the difficulty in acquiring appropriate raw data, the intrinsic complexity of predictive models, the lack of efficient graphical user interfaces, and the high cost of digitization.

In this paper, the state of the art of landslide hazard assessment is focused on, starting with a framework of landslide hazard assessment, which is followed by a critical review of present application of GIS modelling and DEM for landslide mapping and hazard evaluation in different scales. Moreover, a conceptual framework is proposed incorporating data mining and artificial intelligence for landslide zonation, which can produce landslide hazard mapping with high reliability and accuracy.

II Landslide hazard assessment

1 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 that a potential damaging phenomenon may occur within a given area in a given period of time (Varnes, 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; Starosolszky and Melder, 1989; Horlick-Jones *et al.*, 1995). Conceptual confusions often result from using the same term, 'landslide', to address both the existing landslide deposit (the failed mass) and the movement of slope material (Cruden, 1991). Predictive models of regional landslide are generally used to identify where landslides may occur over a given region based on a set of relevant environmental characteristics, assuming that slope failures in the future will be more likely to occur under the conditions which led to past and present slope movements (Varnes, 1984; Carrara *et al.*, 1991; 1995). These models provided information on potentially unstable slopes, but did not directly incorporate time, magnitude and size (Fell, 1994), speed (Cruden and Varnes, 1996), kinetic energy (Hsu, 1975; Sassa, 1988) or momentum of failed masses.

The factors that determine the landslide hazard of an area may be grouped into two categories: intrinsic variables, such as geological conditions and slope structures, and extrinsic variables, such as rainfall and human activities. A landslide hazard zonation consists of two different aspects: assessing the susceptibility of the terrain for a slope failure, and determining the probability of a specific triggering event occurring. Obviously, the probability of landslide occurrence depends on both the intrinsic and extrinsic variables. The spatial distribution of the intrinsic variables within a given area determines the spatial distribution of relative landslide susceptibility in that region (Carrara *et al.*, 1995). Due to the conceptual and operational limitations, most landslide hazard maps could be better defined as landslide susceptibility maps (Brabb, 1984). Terms like susceptibility, hazard, vulnerability and risk are popularly used in the slope instability and landslide literatures, but with different definitions which can be referenced to many technical papers (Yong *et al.*, 1977; Brabb, 1984; Brand, 1988; Carrara *et al.*, 1991; van Westen, 1993; Fell, 1994; Guzzetti *et al.*, 1994; Ibsen and Brunsden, 1996; Leone *et al.*, 1996; Cruden and Fell, 1997; Wong *et al.*, 1997; Glade, 1998; Aleotti and Chowdhury, 1999; Dai and Lee, 2002). Susceptibility or propensity has long been used with different meanings ranging from landslide-deposits inventory to estimates of landslide incidence based on the subjective judgement of the investigator (van Westen, 1993). Only by knowing where and how the landslides will occur in what type of failures can one define the landslide susceptibility in the area under investigation. For a comprehensive landslide hazard assessment, however, the questions of both when the landslides will occur and the frequency with which they will occur over time must be addressed (Aleotti and Chowdhury, 1999).

When assessing landslide hazard within a specified period and within a given area, recognition of the conditions that caused or may cause the slope to become unstable and the processes or events that triggered or may trigger the mass movement is of primary importance. The factors that are responsible for creating a landslide on a particular slope or in a particular area may be grouped into two categories: preparatory and triggering. The occurrence of landsliding depends on both the preparatory and triggering factors. If triggering factors are not taken into account, the term ‘susceptibility’ may be employed to define the likelihood of occurrence of a landslide event. At present, when assessing landslide hazard on the regional scale, it might be feasible to consider landslide susceptibility as the probability of landsliding based on the assumption that long-term historic landslide records tend to smooth out the spatiotemporal effect of triggering events on landslide occurrence (Dai and Lee, 2002).

2 Methods of assessment

Different methods and techniques for evaluating landslide hazard have been proposed or practised, and up to now no agreement has been reached either on the procedure or scope of producing landslide hazard maps (Brabb, 1984). All the proposed methods are based upon a few widely accepted principles or assumptions (Varnes, 1984; Carrara *et al.*, 1991; Hutchinson *et al.*, 1991; Hutchinson, 1995a; Turner and Schuster, 1995), particularly the well-known and widely applied principle ‘the past and present are keys to the future’.

Careful inspection of reviews of the concepts, principles, techniques and methodologies for landslide hazard evaluation (Cotecchia, 1978; Carrara, 1983; Brabb, 1984; Varnes, 1984; Crozier, 1986; Einstein, 1988; Hartlen and Viberg, 1988; Mulder, 1991; van Westen, 1993; 1994; IUGS, 1997; Cross, 1998; Miles and Ho, 1999; Baeza and Corominas, 2000; Wu and Abdel-Latif, 2000; Clerici *et al.*, 2002) reveals that: (1) the most commonly used methods are geomorphological hazard mapping, analysis of landslide inventories, heuristic or index-based methods, functional, statistically based models and geotechnical or physically based models; (2) there is hardly any systematic comparison of different techniques, in terms of respective strength and limitations (Carrara *et al.*, 1992; 1995; van Westen, 1993) or critical discussions of the basic principles and underlying assumptions of landslide hazard evaluation (Varnes, 1984; Carrara *et al.*, 1995; Hutchinson, 1995b); and (3) no real attempts have been made to define and distinguish, conceptually or operationally, landslide hazard and risk (Yong *et al.*, 1977; Ahlberg *et al.*, 1988; Brand, 1988; Carrara *et al.*, 1991; Fell, 1994; Cruden and Fell, 1997).

3 Landslide analysis scale

The work scale could be chosen on the basis of three factors, such as the purpose of assessment, the extent of the studied areas and data availability (Aleotti and Chowdhury, 1999). The landslide analysis can be grouped in the input map scale: detailed scale (>1:5000), large scale (<1:5000–1:10 000), medium scale (1:25 000–1:50 000) and regional scale (<1:250 000) (Luzi and Pergalani, 1996), whereas some planners and engineers use another scales of analysis for landslide hazard zonation (CEOS, 2001): national scale (<1:1 000 000), regional scale (1:100 000–1:500 000), medium scale (1:25 000–1:50 000) and large scale (1:5000–1:15 000).

Whatever the analysis scale mentioned above is, different work scale affects the selection of the approach: thus, a statistical approach may not be suitable for studies concerning individual slopes or small areas while a geotechnical engineering approach based on the calculations of safety factor and/or associated failure probability would not be suitable at the regional scale. Generally, landslide susceptibility analysis methods used consist of landslide distribution analysis, landslide density analysis, landslide activity analysis, geomorphologic analysis, qualitative map combination and safety factor analysis. At a regional scale, landslide distribution analysis, landslide density analysis, geomorphologic analysis and qualitative map combination are used. At a medium scale, the relationship between the landslide and contributing factors is analysed statistically. Other methods used are landslide distribution analysis, landslide activity analysis, geomorphologic analysis and qualitative map combination. At a large scale, safety factors analysis is chosen for one main method to assess the landslide hazard after the analysis of landslide distribution, landslide activity and geomorphologic features. At a detailed scale, only safety factor analysis is suitable to the landslide hazard evaluation.

For the geographic scale considering the purpose of landslide assessment (Luzi and Pergalani, 1996), the detailed scale is mainly for the companies or municipal agencies dealing with hazards on individual sites with a maximum area of several hectares. The large-scale maps are used for problems of local slope instability, for planning of infrastructure, housing and industrial projects. The size of the evaluation area is several tens of square kilometres. In the detailed and large-scale maps, the slope stability model was applied or the physically processed model used. Using this model, a safety factor is calculated, and the index is calculated using the score table. The medium-scale map is principally for agencies dealing with intermunicipal planning and studies for local engineering works. At the medium scale, the relationship between the landslide and contributing factors is analysed statistically. The regional-scale map is used to identify broad areas affected by landslide problems; the maps produced are for agencies that deal with planning of regional land use. At the regional scale, a qualitative map-combination method was used. An expert opinion about the weight and ratio of factors is applied, to assess the susceptibility. However, it should be noted that the complexity of failure process means that any evaluation of stability contains a considerable amount of uncertainty because of different work scales. At the medium-scale assessment of landslide hazard, for example, the 1:20 000-scale topographic map cannot fully reflect the microtopographic conditions prerequisite for the occurrence of landslide, because in some study areas landslide occurrence is characterized by small volumes, and a slight change in microscale landform may have a strong influence on the occurrence of landslides. The uncertainty with different sources of data in scale, to some extent, will reflect the reliability of hazard assessment.

III GIS application on landslide hazard zonation

Geographic information systems (GIS) offer a technological framework for supporting efficient and effective data capture, storage, management, retrieval, analysis, integration and display, and have already shown great benefits to the study and mapping of landslide distributions and hazard potential (Carrara *et al.*, 1995; Guzzetti *et al.*, 1999). Since the early 1970s, hundreds of technical papers have been published proposing a variety of different GIS-based methods for the assessment of future landslide probability. Surprisingly, little work has been done on the systematic comparison of different modelling in GIS-based landslide zonation, outlining advantages and limitations of the proposed methods. An excellent review of the methodological aspects, together with examples and extensive reference lists, can be found in Guzzetti *et al.* (1999) and Aleotti and Chowdhury (1999).

All the methods share a common conceptual model of landslide mapping, the mapping of a set of environmental factors, which are supposed to be directly or indirectly correlated with slope instability. Based on the detected relationships between these factors and the instability phenomena, the land surface is partitioned into area units of different landslide potential.

1 Landslide mapping units

Landslide hazards are site-specific, situation-sensible and spatially heterogeneous. An important step in any landslide hazard assessment is the preparation of landslide maps. Landslide maps can be loosely grouped into the three classes mentioned before: inventory, density and hazard maps. Inventory maps simply show the location of known landslides from direct mapping (Hansen, 1984). Density maps attempt to portray the spatial abundance of landslides through indirect mapping. Hazard maps show the inferred or computed degree of landslide hazard obtained by modelling or by indirect mapping (Carrara *et al.*, 1995; Guzzetti *et al.*, 1999; Parise, 2001). In discussing the advantages and limitations of the available maps, and outlining possible applications for decision-makers, land-developers and environmental and civil defence agencies, Guzzetti *et al.* (2000) have shown that GIS technology makes it easy to prepare landslide density maps from landslide inventories in a research project carried out in the Upper Tiber River basin in central Italy.

Landslide hazard mapping and assessment require a preliminary selection of a suitable mapping unit that refers to a portion of the land surface. Each unit has a set of ground conditions that are different in a definable manner from those if its adjacent units (Hansen, 1984). At the scale of the analysis, a mapping unit represents a region that maximizes intra-unit homogeneity and inter-unit heterogeneity for specific condition(s). Various methods have been proposed to partition the landscape for the purpose of landslide hazard assessment and zonation mapping (Meijerink, 1988; Carrara *et al.*, 1995; Leroi, 1996), including grid cells, terrain units, unique-condition units, slope units and topographic units (Carrara, 1983; Meijerink, 1988; Pike, 1988; Carrara *et al.*, 1991; van Westen, 1993; 1994; Bonham-Carter, 1994; Chung and Fabbri, 1995; Hearn and Griffiths, 2001; Lee and Min, 2001). Hazard models and mapping units are conceptually and operationally interrelated. In general, grid cells are preferred for heuristic (Pike, 1988), statistical (Carrara, 1983; van Westen, 1994) and physical or simulation modelling (Mark, 1992; Terlien *et al.*, 1995). Unique-condition units have been applied to both heuristic and statistical methods (van Westen, 1993; Carrara *et al.*, 1995; Chung and Fabbri, 1995). Slope units and topographic and terrain units have been used in statistical and physical models (Meijerink, 1988; Carrara *et al.*, 1991; 1995; Hansen *et al.*, 1995; Dai and Lee, 2001).

As previously mentioned, various methods have been proposed and tested to partition the landscape into mapping units. 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 (Guzzetti *et al.*, 1999).

Owing to the matrix form of the grid data, computer implementation is simple and processing is fast. Drawbacks lie in the absence of any relation between grid cells and geological, geomorphological or any other terrain information. Spatial inaccuracy is partially reduced, but to cover even small areas an overwhelming number of grid cells are required, leading to unmanageable computer problems and numerical instability when data have to be processed by statistical techniques.

Terrain units, emphasizing cataloguing, provide much information about the land but do little to measure the functional relationships between instability factors. The main drawback lies in the intrinsic subjectivity of the method. Different investigators may then classify any given region in different ways.

Unique-condition units are appropriately applied where it is conceptually or operationally difficult or impossible to predefine 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. Another weakness is the inherent subjectivity in factor classification that has to be performed prior to map overlay. Additionally, by overlaying more than just few maps (5–7), each with a relatively small number of classes (3–10), thousands of small unique-condition units are usually generated. Most of these areas result from errors in data collection and digitization, e.g., the same boundary has been digitized slightly differently on different maps, and are statistically distracting (Guzzetti *et al.*, 1999).

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. 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. 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 subsurface 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 subsurface 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 versus. vector GIS, DEM/ DTM modelling software, etc., rather than by the specific requirements of the geomorphological data to be analysed.

2 DEM application

Due to the influence of relief in landslide-prone areas, construction of an accurate model of the terrain surface is fundamental to the successful development of computer-based modelling tools for landslide hazard assessment in mountainous areas.

Digital elevation models (DEMs), or digital terrain models (DTMs), are digital representations of the topographic surface of the Earth, in the form of a raster or regular grid of spot heights. DEMs are being increasingly used in landslide assessment for estimating slope gradient, aspect and shaded relief information, for analysing the hydrological flow paths on the surface, and so on. The morphometric variables derived from DEMs can enhance the visual recognition of various topographic forms. Topographic form is a fundamental element in any geomorphologic analysis for landslide identification (Carrara, 1993; Montgomery and Dietrich, 1994; Carrara *et al.*, 1995). The DEM's spatial solution, or the horizontal distance between adjacent elevation points, and vertical resolution are critical parameters indicating if the DEM is suitable for the intended application. From elevation values at regularly distributed points stored in a DEM, morphometric parameters and characteristics of the land surface can be estimated automatically in a consistent and efficient manner using computer programs. These morphometric parameters have been widely used in geomorphological and hydrological modelling. Using 25 m grid DEMs, for example, 'stable slope', 'landslide mass', 'landslide scarp', 'collapse scarp' and 'crack' have been mapped (Jwahashi *et al.*, 2001). A landslide susceptibility model, employing a DEM and geological data, was used in a GIS to predict slope stability (Murillo and Hunter, 1997; Iwahashi *et al.*, 2001). In addition to the commonly used grid-cell approach, David and Douglas (1998) also explore alternative approach based on geomorphometrically significant terrain units.

Attempts at automatically combining lithological and bedding altitude data with morphometric parameters of terrain gradient and aspect to classify the territory into structural or hydrogeological domains proved quite satisfactory for detailed investigations, but performed less efficiently at the regional scale (Guzzetti *et al.*, 1999). However, the present potential for use of readily available DEMs, often derived from national mapping agency data, is limited by the insufficient accuracy if such models and inadequate knowledge about these inaccuracies exist.

The sources of inaccuracy in the creation of DEMs can be classed under the two headings of digital elevation data production and interpolation. The former results in inaccuracy from parallax error in the aerial photography, subjectivity of the stereo plotter, liner generalization and displacement during cartographic production, distortion in cartographic print process, etc., whereas the latter generates the inaccuracy from the unavailability of more advanced algorithms for the more widespread application to calculate gradient and aspect due to a unique heterogeneity of altitude. Skidmore (1989) demonstrated that general linear regression models and the third-order finite difference methods were the most accurate based on the comparison of six algorithms for calculating gradient and aspect using a regular 30 grid-spacing data. In the study of the impact of DEM resolution on the accuracy of terrain representation and of the gradient determined, Gao (1995) found that the representation accuracy decreases moderately at an intermediate resolution, but sharply at coarse resolutions for all different terrain types, and resolution reduction profoundly affects the gradient determined from DEMs. It is also found that increasing the grid size resulted in an increased mean topographic index because of increased contributing area and decreased slopes (Zhang and Montgomery, 1994), and a 10 m grid size presented a rational compromise between increasing resolution and data volume for simulating geomorphologic and hydrologic processes.

Digital elevation data and their derivatives, however, may well be affected by a great deal of uncertainty or errors which are dependent on the quality of, for example, the digitized source contour lines and on the algorithms employed for interpolating elevation values or calculating morphometric parameters. Sensitivity analysis may be performed to evaluate the contribution of errors in elevation to the uncertainty of the final output of the landslide model (Niemann and Howes, 1992); several different, but equally probable, versions of the input DEM may be realized through simulation. These simulated versions differ only to a degree consistent with known errors. Error has been simulated using a model designed to replicate the known error properties of the DEMs – the distribution of error magnitude, and the spatial autocorrelation between errors. In that case, the discrepancy between the morphological stability DEM-based map and the multifactor slope stability map is a product of factors and variability of the hazard class criteria used to develop the two stability classifications, and of the spatial resolution of the original derivation data used in the DEM. The multifactor slope stability systems rely on a greater number of factors in defining slope stability than does the DEM-based classification based on combination of slope angle, shape and position. The spatial resolution of the elevation data used to create the morphological DEM-based stability map is insufficient to identify the steep sloping escarpments of unconsolidated materials as a high stability hazard. It is suggested that the use of finer-resolution elevation data may reduce this problem.

However, grid DEMs have several disadvantages: (1) they cannot easily handle discontinuities in elevation; (2) the resolution of the mesh effects the results and computational efficiency; (3) grid spacing needs to be based on the roughest terrain in the catchment, resulting in redundancy in smoother areas; (4) the computed flow paths tend to zigzag, not following drainage lines, and are systematically too long (Moore *et al.*, 1991). Grid size, production styles and interpolation algorithms of DEMs, therefore, vary from different geomorphological regions to obtain the reliable data for the calculation of slope and aspect. Whatever the DEM/DTM is used for, both geometric and semantic aspects of terrain representation should be emphasized with information concerning the quality provided to reliable digital terrain models. Reliable terrain modelling involves the producer as well as the user of the DEM/DTM by presuming that the former is able to specify requirements for the DEM/DTM, and that the latter makes available a quality report of his/her products.

3 GIS-based modelling of landslide hazard

Of particular interest are discussions and applications of GIS to landslide hazard and general slope instability research (Carrara, 1983; Wadge, 1988; Gupta and Joshi, 1989; Niemann and Howes, 1992; Kingsbury *et al.*, 1992; Wang and Unwin, 1992; van Westen, 1993; Carrara *et al.*, 1995; Clouatre *et al.*, 1996; Dhakal *et al.*, 1999; Cavallo and Norese, 2000; Carrasco *et al.*, 2000; Corominas, 2000; Barredo *et al.*, 2000; C.F. Lee *et al.*, 2001). One of the crucial issues in GIS-based hazard assessment is the availability of suitable input data, which remain fundamentally inadequate in quantity and quality for the intended task. Another issue is related to many sources of errors and uncertainties associated with data representation, acquisition and manipulation. It has been demonstrated clearly that landslide mapping is the most error-prone phase of the whole landslide assessment effort (Carrara, *et al.*, 1992; van Westen, 1993). Virtually all the instability factors collected in the field or derived in laboratory are affected by inaccuracies or errors whose magnitude cannot readily be estimated or controlled during the subsequent phase of data analysis or modelling (Carrara *et al.*, 1995).

In data collection and selection, all available information and data could be collected considering the size of the study area, the work scale, the technique adopted and the type of landslides. However, this is undoubtedly one of the most burdensome operations in the task of hazard assessment, regardless of the particular approach adopted and the extent of the study area. On the scope of GIS enhancing the achievement of effective data management, two fundamental rules must be observed when creating a database (Leroi, 1996): the information must be homogeneous, i.e., it must have the same work scale and the same geographic projection system, and the database must be organized into basic monothematic layers, each of which contains homogeneous data.

In addition, a database should include at least the following basic information: a census of existing landslides including their nature, size, location and history, a reliable site reference code, any information available from previous site investigation (aerial photo interpretation, laboratory testing, field analyses including back analyses of failures), any remedial or preventive measures installed and their effectiveness and data from any installed instrumentation.

Another aspect which should be mentioned is the reliability and accuracy of data during collection and storage. Nevertheless, its reliability and accuracy should subsequently be reviewed from time to time. Hazard assessment should be an ongoing process which can be updated as frequently as required. Additional information often becomes available with the discovery of new historical sources or as a result of additional investigation. For example, data on frequency and spatial distribution of past landsliding must always remain open to revision and expansion. The occurrence of new instabilities or the reactivation of old landslides may provide detailed information on the failure mechanisms or further details of the relationship between rainfall and landsliding may become available. Every effort should be made to continually increase the accuracy and reliability of the data, checking the validity of assumed mechanisms of failure and further refining the relationships between causative and influencing factors and on the landsliding phenomena themselves. It will therefore be necessary to develop procedures and methods for updating of data concerning both currently stable areas and areas which have already been subject to landsliding. Accurate information on geological details, geotechnical parameters and porewater pressures is of paramount importance for detailed studies concerning individual sites. The target or desirable level of detail and reliability concerning all this information will be determined not only by the purpose and importance of the project but also by the availability of the financial and other resources to carry out the relevant tasks.

Apart from considering the reliability and accuracy of data collected and used, the model integrated in GIS will also be vital to pose the subjective and reliable result of landslide assessment. Commonly, all methods used for ranking slope instability factors and assigning the different hazard levels in GIS-based landslide hazard assessment are overlaying of index maps, statistical model, deterministic model, and other technology (Table 1).

GIS-based overlay functions have been used extensively for the production of landslide hazard maps (Wagner *et al.*, 1988; Gupta and Joshi, 1989). As one of the qualitative methods through appropriate use of GIS, the combination or overlaying of index maps with or without weighting considerably reduces the problem of the hidden rules and enables total automation of the operations,

Table 1 Comparisons of main methods to assess landslide hazard based on GIS technology

Type of analysis	Technique	Scale of use recommended			Advantages	Disadvantages
		Regional	Medium	Large		
Heuristic analysis	Qualititative map combination	Yes	Yes	No	The degree of hazard is determined rapidly after the fieldwork on the basis of a detailed geomorphological map taking into account a large number of factors as attribute database	The length of operations involved The problem of subjectivity in attributing weighted values
Statistical analysis	Bivariate statistical analysis	No	Yes	No	To map out in detail the occurrence of past landslides	Difficult to prepare data Under no consideration of trigger factor
	Multivariate statistical analysis	No	Yes	Restricted use	To collect sufficient information on the variables that are considered to be relevant to the occurrence of landslides Objective in methodology	Just susceptibility assessment Not readily be extrapolated to the neighbouring areas
Deterministic analysis	Safety factor analysis	No	No	Yes	To permit quantitative factors of safety to be calculated	Data requirements for deterministic models can be prohibitive, and frequently it is impossible to acquire the input data necessary to use the models effectively
	Probability of failure	No	No	Yes	External existing models can be used without losing time in programming the model algorithms in a GIS Encourage investigation and measurement of geotechnical parameters in detail	

such as subdivision of each parameter into a number of relevant classes, attribution of a weighted value to each class, attribution of weighted values to each of the parameters, overlay mapping of weighted maps and development of a final map showing hazard classes. Furthermore, it enables the standardization of data management techniques, from acquisition through to final analysis. This method can be utilized at any scale to assess landslide hazard using GIS technology. The major disadvantage is the lengthy operations involved, especially where large areas are concerned. The problem of subjectivity in attributing weighted values to each parameter and to the different factors also remains, as well as the difficulty of extrapolating a model developed in a particular area to other sites or zones (Carrara, 1983).

Statistical techniques are generally considered the most appropriate approach for landslide susceptibility mapping at scales of 1:20 000 to 1:50 000 because, on these scales, it is possible to map out in detail the occurrence of past landslides, and to collect sufficient information on the variables that are considered to be relevant to the occurrence of landslides. Statistical models involve statistical determination of the combinations of variables that have led to landslide occurrence in the past. Quantitative or semi-quantitative estimates are then made for areas currently free of landslides, but where similar conditions exist. Statistical approaches are based on the observed relationships between each factor and distribution of landslides. Since instability determinants and their interrelations are evaluated on a statistical basis, hazard evaluation becomes an operation as objective as possible. 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. Additionally, being data-driven, a statistical model built up for one region cannot readily be extrapolated to the neighbouring areas.

Various statistical techniques have been tested by different researchers, almost exclusively using regular grid cells as the basic analytical unit. In addition to multivariate statistics, bivariate statistical analysis, whereby each explanatory variable is represented as a separate thematic data layer in a GIS, has also gained popularity (van Westen, 1993; Dhakal *et al.*, 2000; Donati and Turini, 2002). Within the methods adopted, 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 or 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. Compared with other multivariate statistical techniques including multiple regression analysis and discriminant analysis, logistic regression allows one to form a multivariate regression relation between a dependent variable and several independent variables. The advantages of logistic regression over simple regression is that, through the addition of an appropriate link function to the usual linear regression model, the variables may be either continuous or categorical, or any combination of both types variable representing the presence or absence of landslides. Where the dependent variable is binary, the logistic link function is appropriate.

As a drawback, statistical models of landslide hazard are difficult to prepare. They require large efforts to collect and validate input data that are often not readily available. They also need interaction between expert geomorphologists and statisticians in order to process data in such a way as to avoid statistically sound but geomorphologically unrealistic or erroneous results. All the techniques, however, produce maps which are often hard to comprehend and assess for nonspecialists in the field of statistics like planners or policymakers. Lastly, they are negatively influenced by the extent of the investigated area, which makes it difficult to compare hazard classes from different locations (Carrara *et al.*, 1991; 1995; Guzzetti *et al.*, 1999).

Moreover, some of the key data may not be available in many instances, or it may not be possible to acquire the data necessary for using the models effectively over large areas. As defined by Varnes (1984), natural hazard is the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area. In this sense, landslide hazard assessment should be conducted on both spatial and temporal probabilities of landsliding in a certain area. Many studies using statistical methods have focused on landslide susceptibility mapping without due consideration for factors that trigger the landsliding, rather than hazard mapping in a spatiotemporal context. Hence, Dai and Lee (2003) developed a logistic regression model based on both quasi-static and dynamic variables, using lithology, slope gradient, slope aspect, elevation, slope shape, land cover and rolling 24 h rainfall as independent variables. In the case of North Lantau, Hong Kong, this model achieved an overall accuracy of 87.2%, with 89.5% of landslide grid cells correctly classified and found to be performing satisfactorily, and was then applied to rainfalls of a variety of periods of return, to predict the probability of landsliding on natural slopes in space and time.

However, due to slope geological complexity and self-organized system, many variables are involved in a slope stability evaluation, and these variables have been a highly nonlinear relation with the evaluation results. Artificial neural networks have been introduced to produce the landslide hazard maps under the consideration of the nonlinear characteristics of sliding process. The main characteristics of artificial neural networks (ANNs) dealing with quantitative and qualitative indexes include large-scale parallel distributed processing, continuously nonlinear dynamics, collective computation, high fault-tolerance, self-organization, self-learning and real-time treatment (Rumelhart *et al.*, 1986). It is worth pointing out that a neural network system is a processing device, implemented as an algorithm or in hardware, whose design was motivated by the design and the function of mammalian brains; they react to training data input in such a way as to alter their initial state, and they can learn with unconventional algorithm. Neural networks integrated with GIS may represent an effective approach when dealing with landslide hazard assessments where meaningful outcomes are difficult to achieve by means of standard mathematical models; because artificial neural network models are adaptive and capable of generalization, they can handle imperfect or incomplete data, and they can capture nonlinear and complex interactions among variables of a system (Lee and Min, 2001).

Compared with the statistical methods that have no consideration of mechanism meaning, deterministic approaches are based on slope stability analyses, and are only applicable when the ground conditions are fairly uniform across the study area and the landslide types are known and relatively easy to analyse. The infinite slope stability model has been widely used in landslide zonation in small areas (Terlien *et al.*, 1995; van Westen *et al.*, 1997). Presently, many more researches on integrating GIS and various deterministic models for slope failure zonation have been conducted, including GIS-based infinite slope stability models (Pack *et al.*, 1998; 2001), GIS-infinite-slope-seepage model (Montgomery *et al.*, 1991; Dietrich *et al.*, 1993; Montgomery and Dietrich, 1994), GIS-probabilistic-infinite-slope models (Fannin and Wilkinson, 1995; Fannin *et al.*, 1996) and GIS-infinite-slope-probabilistic seismic landslide models

(Jibson *et al.*, 1999; Khazai and Sitar, 2000). Particular attention was also devoted to the error evaluation due to spatial variability of the geotechnical, geometric and hydrologic parameters using the Monte Carlo procedure and the First-Order-Second-Moment method (Luzi *et al.*, 2000; Zhou *et al.*, 2003).

Calculated probabilities of failure based on a geotechnical model may be regarded as conditional probabilities as these calculations are valid for the chosen values of geotechnical material parameters and for a chosen distributions of porewater pressures along the relevant potential slip surfaces. The frequency of occurrence of the assumed conditions should be estimated using other appropriate methods. For example, selected porewater pressures would relate to specified seepage conditions or groundwater levels which may correspond to rainstorms of a particular return period or frequency. Unless analyses concerning intensity, duration and frequency of rainfall have been carried out, the temporal aspect of rainfall-induced landslide hazard will not be clear even if a fully quantitative geotechnical analysis has been performed within either a deterministic or a probabilistic framework.

The use of deterministic models in landslide hazard analyses has no pretension to calculate in an absolute and precise way the safety factor at each site in the terrain. This is not realistic because the amount of data necessary to assess the spatial distribution of parameters needs a tremendous amount of effort (Mulder, 1991). However hazard zonation in a quantitative way can be done using a probabilistic approach: the probability of failure can be assessed in landslide prone areas by using distribution functions of parameters (van Asch *et al.*, 1993). Deterministic, i.e., process-based, models explicitly incorporate the physical processes promoting landsliding and, therefore, can often better pinpoint causes of mass movement (Miller, 1995). In addition, process-based models commonly use site-specific data and therefore they are able to generate more detailed spatial patterns on fine-scale gradations of instability than most statistical or weighted ranking hazard maps. Data requirements for process-based GIS landslide models, however, can be prohibitive; and to acquire the suitable input data is a real operational challenge. GIS-based analyses of slope stability and landslide hazard for improving predictive ability may be achieved by exploring more explanatory variables and appropriate spatial and statistical modelling techniques.

In general, the advantage of the deterministic models is that they permit quantitative factors of safety to be calculated, whereas the main problem is the high degree of simplification that is usually necessary for the use of such models. Another problem that limits the applicability of the deterministic models is that data requirements for deterministic models can be prohibitive, and frequently it is impossible to acquire the input data necessary to use the models effectively.

Validation is a vital process during landslide hazard assessment. After the results of landslide hazard or susceptibility has been assessed using statistical or process-based model, the model or data used should be checked for accuracy and reliability. Commonly, there are two methods adopted to validate the prediction results: time robustness and space robustness. In the validation of time robustness, occurrences of landslide are divided into two time periods, 'past' and 'future', to construct the prediction model based on the past occurrences and then validate the results with respect to 'future' occurrences. One year usually is selected so that approximately half the events occur during or before it. Assuming that year is the current one, these events in the model are used to see how well the rest are predicted. For space robustness, the occurrences are divided into two groups randomly: group 1 and group 2. The prediction maps are constructed based on group 1 only to validate the results with respect to group 2 occurrences. It can be done to repeat the procedure in reverse order to validate the prediction results. Sometimes using a combination at random, space robustness and time robustness validation procedures are useful.

IV Discussions

GIS has raised great expectations as useful means of coping with natural disasters, such as landslides. The most fundamental aspect is to construct useful geospatial database in support of GIS applications (Dikau *et al.*, 1996). Once the geospatial database has been developed, it can be deployed for evaluating what will happen in certain situations.

GIS-based map overlaying allows the spatial comparison of different maps at common locations, with results helpful for the local government and community to make correct decision on land use. The overlay operation of the GIS coupled with heuristic and statistical approaches allows us to combine factor maps of site characteristics in a variety of ways to produce susceptibility maps (e.g., Gupta and Joshi, 1989; van Westen *et al.*, 1997; Luzi *et al.*, 2000; Dai and Lee, 2002). Temporal database information can be correlated with historical triggering factors to calculate temporal probabilities for landslide forecasting. However, these specific capabilities for performing risk analysis, assessment and management in a spatial domain are not all available in a standard off-the-shelf GIS. It is desirable to design a system for landslide hazard assessment that would integrate these required capabilities. At large and site-specific scales, process models can be implemented to simulate the spatial distribution of the factor of safety using slope stability models (van Westen *et al.*, 1997).

Meanwhile, landslides are phenomena with complex feedback varying in scale from local to regional. Their geomorphological and economic impact ranges from a very short to a 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 remain a novel problem to the earth scientists. Knowledge on slope processes appears insufficient for a comprehensive and exhaustive evaluation of landslide hazard. 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 cannot be readily tested by traditional scientific methods. Indeed, the only way a landslide predictive map can be validated is through time (Hutchinson, 1995b). 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.

Although GIS is widely applied in landslide hazard assessment, there are some difficulties to extract latent information from data collected for evaluating landslide susceptibility. For landslide investigation and management, vast amounts of data have been collected on geology, engineering geology, geomorphology, hydrology, etc., which contain valuable information. The difficulties in uncovering useful information buried in these 'data mountains' are partly due to the various detailed classification schemes imposed on these data sets, which are somewhat subjective and dependent upon the choice of the disciplinary aspect/s to be emphasized (Aleotti and Chowdhury, 1999). The selection of data that could or should be used for the assessment of a given area depends essentially on the size of the study area, the work-scale, the technique adopted and the type of landslide under investigation. Using various analysis and modelling tools with diverse data sources in combination, however, often leads to the following problems: (1) weak integration of data sets, (2) weak documentation of data sets and data sources, and (3) missing links between the data sets (Jochen *et al.*, 1999). More significantly, these problems lead to the risk of losing data or misinterpreting data. If the hidden information behind data sets can be made explicitly, it can be valuable for improving landslide hazard assessment including mapping or zonation. Data integration is therefore clearly an important research task, particularly in landslide hazard assessment and, generally, in geosciences research. Object-orientated data modelling techniques can be used to model geospatial data in an integrative way. This approach could lead to the development of new types of information systems capable of facilitating the integration of multiple data structures and complementing analytical methods. Data integration can enforce a standardized documentation of specific data handling and data representation in a multidisciplinary environment. The effectiveness and efficiency in revealing the hidden information and combining updated indexes in a timely manner are vital for enhanced assessment of every landscape location's susceptibility to landslide hazard. Hence, methods and techniques for more effective data management, analysis and information generation, such as interoperable databases, suitable data mining techniques and related expert systems, should be incorporated into GIS-based landslide hazard assessment (Figure 1).

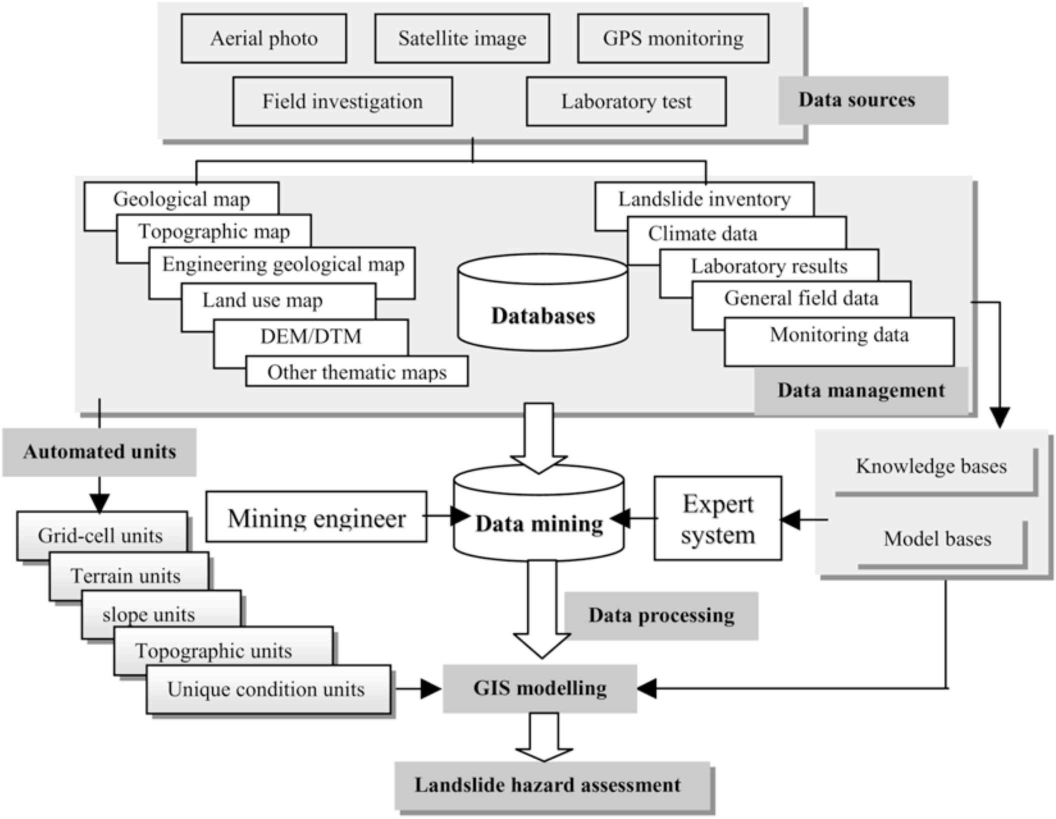

Figure 1 A GIS-based conceptual system integrated with data mining for landslide hazard assessment

Integrated databases should be specifically designed and constructed for the purpose of landslide hazard assessment using the GIS platform. Data mining, as an intersection of statistics, machine learning, database management and data visualization, is an exploratory and iterative process for knowledge discovery in databases, which usually consists of six steps in data processing, including problem definition, acquisition of background knowledge, selection of data, pro-processing of data, analysis and interpretation as well as reporting and use (Feelders *et al.*, 2000).

Data mining requires knowledge of the processes data represent. This knowledge is required to (1) determine useful questions for analysis, (2) select potentially relevant data to answer these questions, (3) help with the construction of useful features from the raw data, (4) interpret (intermediate) results of the analysis, and (5) suggest possible courses of action. A successful data mining project, therefore, requires a collaborative effort in a number of areas of expertise. With regard to data mining and analysis for landslide hazard assessment, various professional experts are needed, including a geologist, an engineering geologist, an experienced civil engineer, a geomophologist, etc., for interpreting intermediate results and indicating what should be further explored.

V Conclusion

Significant progress has been made in the field of landslide hazard assessment using GIS technology. However, landslide phenomena are still poorly understood, particularly at the regional scale. Evaluation of landslide hazard is a complex, multidimensional problem, which requires expertise pertaining to earth science, statistics, computer science, information technology and economics, depends on the effectiveness of finding the hidden information and deriving indexes to predict landslide susceptibility in a timely manner, and calls for a new scientific practice capable of coping with large uncertainties, varying experts' judgements and social issues associated with landslide hazard evaluation. Within this framework, better-quality historic landslide databases could be constructed as the basis for all components of landslide hazard assessment, and the potential to effectively evaluate the landslide posterior to data mining and expert system should be explored in future research of regional landslide zonation.

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