CHAPTER 2

BACKGROUND INFORMATION ON LANDSLIDE HAZARD AND USE OF REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEMS IN LANDSLIDE HAZARD ASSESSMENT

2.1. Definition of Landslide Hazard and Terminology

Mass movement is defined as "the outward and downward gravitational movement of earth material without the aid of running water as a transporting agent" by Crozier (1986), or "the movement of a mass of rock, debris or earth down a slope" by Cruden (1991). These are the internationally accepted and most widely used definitions of the phenomenon. Although they are slightly different from each other considering beyond the scope of inclusion of water, they both point a mass transportation down the slope in which a hazardous activity for humans can occur.

Rather than dealing with the types, activities and definitions, as they are defined by the IAEG Commission on Landslides in the 1990's, a more relational approach is given by Soeters and van Westen (1996) "Slope instability processes are the product of local geomorphic, hydrologic and geologic conditions; the modification of these by geodynamic processes, vegetation, land use practices and human activities; and the frequency and intensity of precipitation and seismicity".

Mass movement or slope instability or landsliding are natural denudational and degradational processes, unless they are affecting human life. Their interference with ongoing human practices in the terrain makes it a landslide hazard. The general accepted terminology in the world is followed below by Varnes (1984):

Natural hazard (H): The probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area (Figure 2.1).

Vulnerability (V): The degree of loss a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. Scale is 0 (no change) to 1 (total loss) (Figure 2.1).

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.

$$Rs=H*V$$

Elements at Risk (E): The population, properties, economic activities, including public services and 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 (Figure 2.1). It is expressed as

$$Rt=E*Rs$$

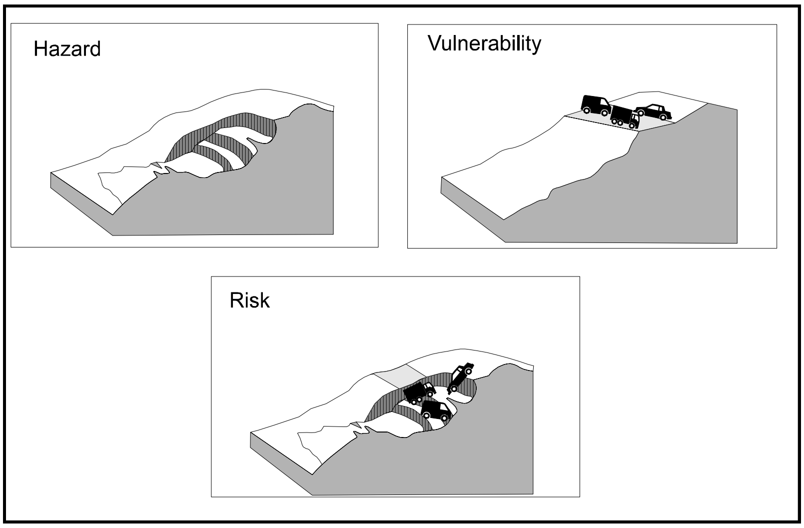

Figure 2.1. Graphical representation of hazard, vulnerability and risk

Based on the above definitions, hazard and risk information are generally represented as discrete maps. The discrete classes represent equal probability classes, which are inturn equal hazard or risk classes. The differentiation of hazard classes and their groupings are called as “zonation”. The formal definition is as follows: “The term zonation refers to the division of land into homogenous areas or user defined domains and the ranking of these areas according to their degrees of actual or potential natural hazards” (Varnes, 1984).

The natural hazard zoning/mapping constitutes the first and major task of the earth scientists in natural hazard analysis (Figure 2.2). The zoning of a natural hazard is the vital part of the study strategy in which the whole strategy will be based on. The zonation activities are mutually dependent over some factors as shown in Figure 2.2.

These factors can be grouped into magnitude properties of the hazard, frequency of the hazard and the spatial location of the hazard. The next step in hazard mapping is to show the mapped hazard and to classify the hazard map into some homogenous areas regarding the equal attributes of the hazard map.

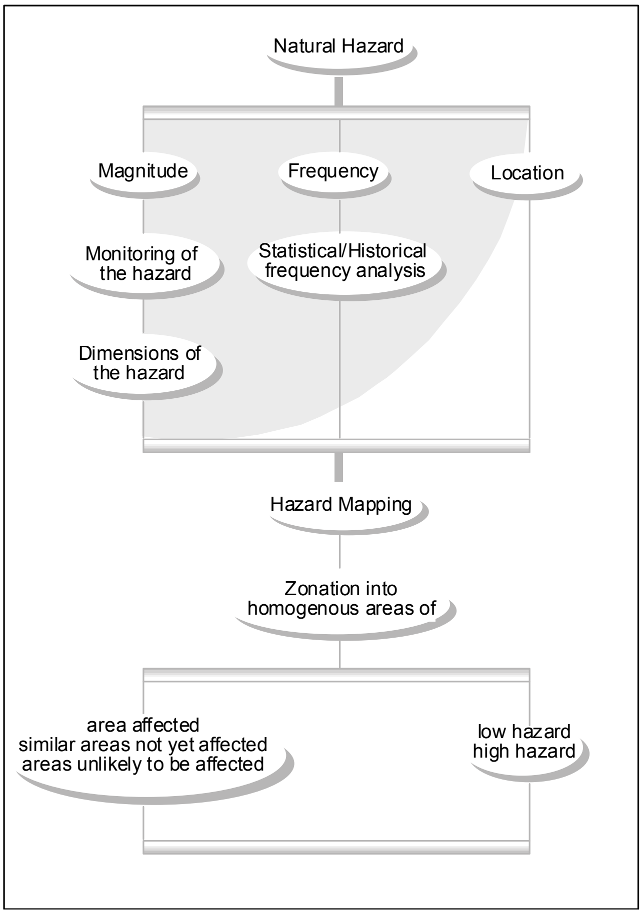

Figure 2.2. An overview of zonation activities

The natural hazard zoning is controlled mainly by two factors, such as: the scale of the zoning or mapping and the knowledge type used in the hazard zoning.

2.1.1. Scale Factor in Analysis

Before starting to any data collection, an earth scientist working on a hazard analysis project should have to answer a number of interrelated questions:

1. What is the aim of the study?
2. What scale and with what degree of precision must the result be presented?
3. What are the available resources in the form of money, data and manpower?

As the aim of the study would be previously defined, the scale and the precision are the first parameters to be defined prior to the start of the project. Hence, the scale factor should have to be determined at the first glance as it controls the type of the input data, nature of the analysis and the output data of the project. The outcome precision is also dependent on the scale chosen. Although the precision is dependent on scale, it is also an independent parameter regarding the nature of the project. The necessary adjustments should be made with the scale until the output precision and the desired precision fulfills the project conditions. The resource analysis will be conducted after the aim and scale is fixed.

The following scales of analysis, which were presented in the International Association of Engineering Geologists (IAEG) Monograph on engineering geological mapping (IAEG, 1976) can also be distinguished in general natural hazard zonation (Figure 2.3).

2.1.1.1. National Scale (<1/1.000.000)

The national scale analysis is used only to outline the problem, give an idea about the hazard types and affected hazard prone areas. They are prepared generally for the entire country and the required map detail is very low, even in the best case giving only data based on records in the form of an inventory. The degree of the hazard is assumed to be uniform. These kinds of maps are generally prepared for agencies dealing with regional (agricultural, urban or infrastructure) planning or national disaster prevention / hazard assessment agencies.

2.1.1.2. Regional/Synoptic Scale (< 1/100.000)

The scale is still so small to use in any quantitative method, but these maps are used for regional planning and in early stages of region wise planning activities. The areas to be investigated are still large in the order of thousands of square kilometers and the map detail is low again. Only simple methods are used with qualitative data combination and the zoning is primarily based on regional geomorphological Terrain Mapping Units / Complexes (TMU) or dependent on regional geological units.

2.1.1.3. Medium Scale (1/25.000 - 1/50.000)

These hazard maps are made mainly for agencies dealing with intermunicipal planning or companies dealing with feasibility studies for large engineering works. The areas to be investigated will have areas of several hundreds of square kilometers. At this scale considerably more detail is required than at the regional scale. These maps do serve especially for the choice of corridors for infrastructure construction or zones for urban development. Statistical techniques are dominantly used in this scale.

Figure 2.3. The scales of analysis and minor details

2.1.1.4. Large Scale (> 1/10.000)

These hazard maps are produced generally for authorities dealing with detailed planning of infrastructure, housing or industrial projects or with evaluation of risk within a city or within a specified project area. They cover very small areas hence the deterministic hazard analyses become available to be used. The detail level of the maps is set into maximum. They are based on physical numerical models that require extensive data collection in the field and laboratory surveys.

2.1.2. Knowledge Type Used

Prediction of landslide hazard for areas not currently subject to landslide hazard is based on the assumption that hazardous phenomena that have occurred in the past can provide useful information for prediction of future occurrences. Unlike general educational geological phrases in this case "present is not key to the past but present and past are the keys of future", of which the real value of engineering and its futuristic approaches are represented. Therefore, mapping these phenomena and the factors thought to be of influence is very important in hazard zonation. In relation to the analysis of the terrain conditions leading to slope instability, two basic methodologies can be recognized (van Westen, 1993):

1. The first mapping methodology is the experience-driven applied-geomorphic approach, by which the earth scientist evaluates direct relationships between landslides and their geomorphic and geologic settings by employing direct observations during a survey of as many existing landslide sites as possible. This is also known as direct mapping technology.

2. The opposite of this experience-based, or heuristic approach is the indirect mapping methodology, which consists of mapping a large number of parameters considered to potentially affect landsliding and subsequently analyzing (statistically) all these possible contributing factors with respect to the occurrence of slope instability phenomena. In this way the relationships between the terrain conditions and the occurrence of the landslides may be identified. On the basis of the result of this analysis, statements are made regarding the conditions under which slope failures occur.

Another division of techniques for assessment of slope instability hazard was given by Hartlen and Viberg (1988), who differentiated between relative and absolute hazard assessment techniques.

1. Relative hazard assessment techniques differentiate the likelihood of occurrence of mass movements for different areas on the map without giving exact values.
2. Absolute hazard maps display an absolute value for the hazard such as a factor of safety or a probability of occurrence.

Furthermore the hazard assessment techniques can also be divided into three broad classes based on use of statistical methods (Carrara, 1983; Hartlen and Viberg, 1988; Soeters and van Westen, 1996).

1. White box models: based on physical models (slope stability and hydrologic models), also referred to as deterministic models
2. Black box models: not based on physical models but strictly on statistical analysis
3. Gray box models: partly based on physical models and factual data and partly on statistics.

2.2. Use of Remote Sensing in Landslide Hazard Assessment

The phenomenon, landslide is affecting the earth’s surface, hence it also falls in to the research and application areas of both aerial and space born remote sensing. The nature of this phenomenon as it is occurring at the surface of earth lets earth scientists to exploit this fact using remotely sensed data. On the other hand, again the nature of this phenomenon limits the applications, as being dynamic and sometimes being quite small in terms of conservative remote sensing language. Furthermore they reveal very small information when they are observed in planar 2-D, however, they contain large amounts of data when explored in 3-D. Basing on this fact the use of stereo-remote sensing products seems to be indispensable, which reveals the true morphodynamical features of the landslides. These information are providing the diagnostic information regarding the type of the movement (Crozier, 1973). The general application fields of remote sensing in landslide business are monitoring the change of landslide activities through time (change detection) and mapping out where the hazard occurs.

Plenty of researchers have tested the usage of remote sensing products through the last 30 years. Two major groupings could be made upon the investigation of these researches. These are aerial photography and space-born sensor images.

Numerous applications have been carried out which generally define the landslide areas. Chandler and Moore (1989), Chandler and Brunsden (1995) and Fookes et al. (1991) give excellent applications for photogrammetry. For single landslides and for smaller areas, a monitoring scheme is best applied with this technique with large accuracies. In opposition, the applicability of this technique limits the extents of the interest area as the larger areas could be accomplished by classical aerial photographical studies easily. For stereographical aerial photography Rengers (1986), Sissakian (1986) and Mollard (1986) could be counted as single application manuscripts. However, studies with landslides and aerial photographs are as old as the applications of first stereographical aerial photographs, resulting in plenty of textbooks and textbook sections.

The landslide information extracted from the remotely sensed products is mainly related with the morphology, vegetation and the hydrological conditions of the slope. The slope morphology is best examined with stereographical coverages. Generally the identification of the slope instabilities are indirect, they are identified by associated elements with slope instability process. The advantages of aerial photographs can be listed as:

1. They provide quite older coverages before digital world starts
2. The flight coverages are flexible for new missions
3. The spatial and temporal resolution are very high
4. Stereoscopic coverage
5. Most of the geoscientist are familiar
6. Every country have at least one full coverage of their land due to military reasons

The disadvantages are as follows:

1. Low spectral resolution
2. The nature of photograph as hardcopy
3. Presence of distortions in the images
4. Absence of coordinate information
5. Orthorectification is needed to remove distortion and add coordinate information
6. The resultant map is dependent to the experience of interpreter

The applications with space born images are quite new compared to the others. Furthermore, they are generally defining the landslides indirectly by mapping out other parameters such as land cover. Some examples from the literature could be said of Gagon (1975); Mc Donalds and Grubbs (1975); Sauchyn and Trench (1978); Stephens (1988); Huang and Chen (1991) and Vargas (1992).

In comparison to the aerial photographs, the advantages of satellite images are:

1. Getting the bigger picture
2. Larger spectral range
3. Easily accessible
4. No distortion
5. Only georeference is needed to transfer the coordinates

The disadvantages are:

1. Low spatial resolution
2. More expensive than aerial photographs of the same resolution
3. Limited stereo capability
4. Limited number geoscientists are familiar

Although there are plenty of disadvantages of aerial photographs, they are the most frequently used medium in landslide projects as they have cheaper high-resolution images. The spatial resolution nearly controls everything in landslide hazard assessment. The comparison of spatial resolution of photographic and non-photographic remote sensing product requires the concept of Ground Resolution Cell (GRC) defined by Strandberg (1967) and introduced to landslides first by Rengers et al. (1992). Strandberg (1967) suggested that the formula for GRC is in relation to scale as:

$$GRC=S/1000R$$

Where GRC is ground resolution cell in meters, S in the scale number of photograph and R is the resolution of photographic system (line pairs/mm, normally 40 in conventional systems)

Soeters and van Westen (1996) figured out the necessary minimum number of GRC's namely the pixels in the images, in order to identify and interpret the landslides, which is presented in Table 2.1. They also exploited this information and created a comparison table of photographic images with non-photographic ones that is also presented in Table 2.2.

Table 2.1. The number of GRC needed to identify and interpret object of varying contrast in relation to its background (Soeters and van Westen, 1996).

	The number of GRC	
	For identification	For interpretation
Extreme contrast	20-30	40-50
High contrast	80-100	120-140
Low Contrast	1000-1200	1600-2000

Table 2.2. Minimum object size needed for landslide Identification or Interpretation (Soeters and van Westen, 1996).

		Size m^2 needed for			
		High Contrast		Low Contrast	
	GRC size (m)	Identification	Interpretation	Identification	Interpretation
Landsat MSS	~80	160000	288000	7040000	11520000
Landsat 5 TM	30	22500	40500	990000	1620000
Spot Multispectral	20	10000	18000	440000	720000
Spot Panchromatic	10	2500	4500	110000	180000
Aerial Photographs					
1:50000	1	25	45	1100	1800
1:15000	0,3	6,5	11,5	300	450

Basing on the above facts, aerial photography is still indispensable in the landslide hazard zonation activities. However, remote sensing is depicting an important role in landslide hazard assessment, though, this role is not the primary role in the game.

2.3. Geographical Information Systems and Landslide Hazard Assessment

A GIS is defined as a "powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for particular set of purposes" (Burrough, 1986). A more specific definition is given by Bonham-Carter (1996) as follows: "a geographic information system, or simply GIS, is a computer system for managing spatial data. The word *geographic* implies that the locations of the data items are known, or can be calculated, in terms of geographical coordinates. The word *information* implies that the data in GIS are organized to yield useful knowledge, often as colored maps and images, but as also statistical graphics, tables and various on-screen responses to interactive queries. The word *system* implies that a GIS is made up from several interrelated and linked components with different functions. Thus, GIS has functional capabilities for data capture, input, manipulation, transformation, visualization, combination, query, analysis, modeling and output."

These international valid definitions of GIS directly oppose to the belief that GIS is only a CAD software or only a drawing tool. CAD can only constitute a small portion of the whole integrated system, in which an ideal GIS and its possible components are shown in Figure 2.4.

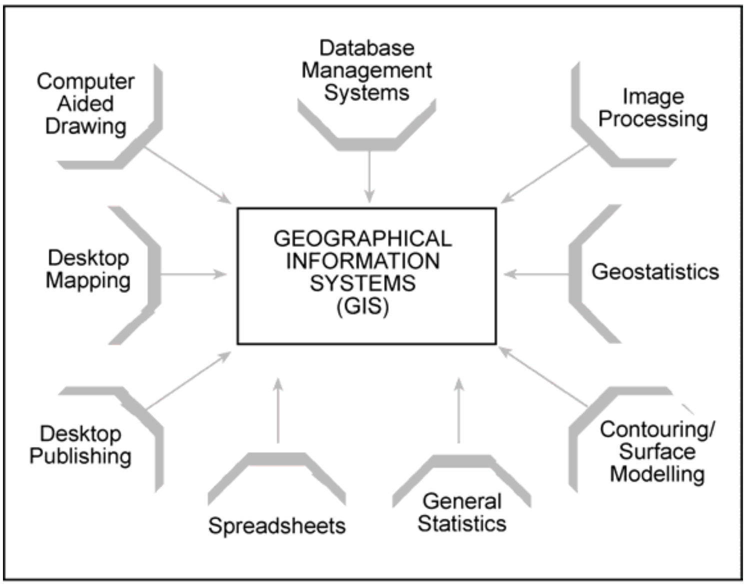

Figure 2.4. GIS and its related software systems as components of GIS (modified from Bonham-Carter, 1996)

Generally a GIS consists of the following phases (Figure 2.5).

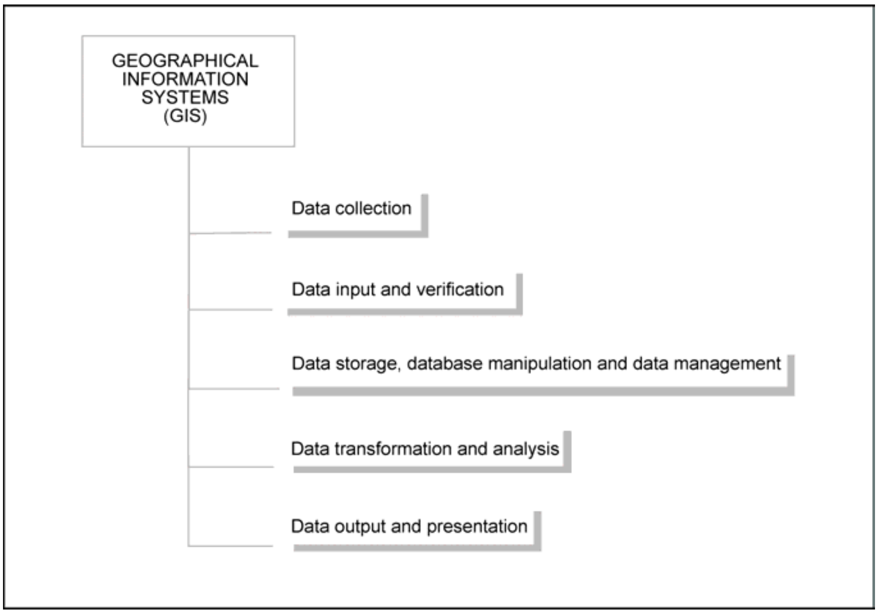

Figure 2.5. The phases of a GIS

A GIS if based over the former components should answer the following questions (Figure 2.6):

More and more the products of mapping and inventory are being stored in data banks for their ultimate retrieval or combination with data from other sources. Often they are incorporated is GIS or LIS (Land Information Systems) which serve as a base for programmable data manipulation and selective information extraction for planning and project assessment.

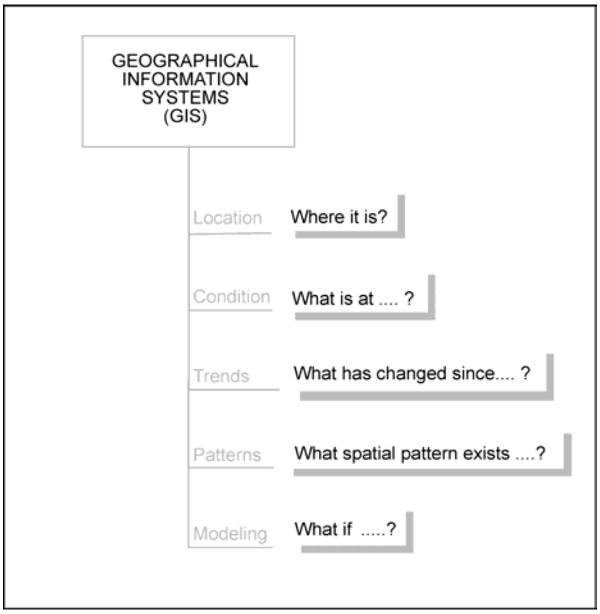

Figure 2.6. The questions of a well-built GIS should answer.

The development of GIS and LIS systems is of considerable interest in the context of satellite surveying, change detection and monitoring. The flexibility of digital data processing, combined with quick input of new data (possible from updating on the basis of satellite remote sensing records) offers new possibilities to the surveyor, cartographer and planner.

It is clear that in a rapidly developing society, change detection is of great importance. In modern society, mapping suffers from high rate of change: change in land use in rural and urban areas; change in requirements for maps and inventories; change in concepts in the various disciplines of earth and social sciences, leading to different interpretations of the same data and change in the economical and technical factors on which mapping methods were based.

In order to refine the discussion around landslide hazard one can say that, the occurrence of slope failure depends generally on complex interactions among a large number of partially interrelated factors. Analysis of landslide hazard requires evaluation of the relationships between various terrain conditions and landslide occurrences. An experienced earth scientist has the capability to mentally assess the overall slope conditions and to extract the critical parameters. However, an objective procedure is often desired to quantitatively support the slope instability assessment. This procedure requires the evaluation of the spatially varying terrain conditions as well as the spatial representation of landslides. A GIS allows for the storage and manipulation of information concerning the different terrain factors as distinct data layers and thus provides an excellent tool for slope stability hazard zonation.

The advantages of GIS for assessing landslide hazard include the followings:

1. A much larger variety of hazard analysis techniques become attainable. Because of the speed of calculation, complex techniques requiring a large number of map overlays and table calculations become feasible.
2. It is possible to improve models by evaluating their results and adjusting the input variables. Users can achieve maximum results by a process of trial and error, running the models several times, whereas it is difficult to use these models even once in the conventional manner. Therefore, more accurate results can be expected.

The disadvantages of GIS for assessing landslide hazard include the followings:

1. A large amount of time is needed for data entry. Digitizing is especially time consuming
2. There is a danger in placing too much emphasis on data analysis as much as the expense of data collection and manipulation based on professional experience. A number of different techniques of analysis are theoretically possible, but often the necessary data are missing. In other words, the tools are available but cannot be used because of the lack or uncertainty of the data.

2.3.1. Phases of Natural Hazard Analysis in GIS

The following phases can be distinguished in the process of a hazard analysis using GIS (van Westen, 1993); there is a logical order in the sequence though sometimes they may be overlapping. The time schedule of these phases is listed in Table 2.3.

1. Choice of the working scale and the methods of analysis which will be applied
2. Collection of existing maps and reports with relevant data
3. Interpretation of images and creation of new input maps
4. Design of the database and definition of the way in which the data will be collected and stored.

5. Fieldwork to verify the photo-interpretation and to collect relevant quantitative data
6. Digitizing of maps and attribute data
7. Validation of the entered data
8. Manipulation and transformation of the raw data to a form which can be used in the analysis
9. Analysis of data for preparation of hazard maps.
10. Evaluation of the reliability of the input maps and inventory of the errors which may have occurred during the previous phases
11. Final production of hazard maps and adjoining report

Table 2.3. Time schedule comparison of phases of landslide hazard assessment of conventional methods and GIS based methods based on scale (numbers are in percents of the total project time) (van Westen, 1993).

PHASES	Regional Scale		Medium Scale		Large Scale	
	Conventional Methods	GIS Based Methods	Conventional Methods	GIS Based Methods	Conventional Methods	GIS Based Methods
1. Choice of scale and methods	<5	<5	<5	<5	<1	<5
2 Collection of existing data	<5	<5	<5	<5	8	8
3. Image Interpretation	50	50	30	30	10	20
4. Database design	0	<5	0	<5	0	<5
5. Fieldwork	<5	<5	7	7	10	20
6. Data Entry	0	20	0	30	0	15
7. Data Validation	0	<5	0	5	0	5
8. Data Manipulation	0	<5	0	5	0	5
9. Data Analysis	30	10	48	10	61	10
10. Error Analysis	0	<5	0	<5	0	<5
11. Final Map Production	10	<5	10	<5	10	<5

2.3.2. GIS Based Landslide Hazard Zoning Techniques

An ideal map of slope instability hazard should provide information on the spatial probability, temporal probability, type, magnitude, velocity, runout distance and retrogression limit of the mass movements predicted in a certain area (Hartlen and Viberg, 1988). A reliable landslide inventory defining the type and activity of all landslides, as well as their spatial distribution, is essential before any analysis of the occurrence of landslides and their relationship to environmental conditions are undertaken. Even the inventory of historical periods are of great use in the final analyses. The differentiation of slope instability according to type of movement is important, not only because different types of mass movement will occur under different terrain conditions, but also because the impact of slope failures on the environment has to be evaluated according to type of failure.

2.3.2.1. Trends in Landslide Hazard Zonation

A large amount of research on hazard zonation has been done in 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), Hartlen and Viberg (1988). The general trends in landslide hazard zonation are given in Table 2.4. The distribution analyses and qualitative analyses are generally used for very large areas with very low detail such as national hazard maps. The deterministic and frequency analyses are used generally for very small areas such as specific large engineering projects like dams, nuclear power plants, highway strips, open pit mine slopes and spoils. Monitoring and laboratory analyses are indispensable for these analyses. Good reviews of these initial deterministic methods can be found in Lambe and Whitman (1969), Hoek and Bray (1981), Graham (1984), Bromhead (1986) and Anderson and Richards (1987). The limited GIS examples of these methods could be cited as Ward et al. (1982), Okimura and Kawatani (1986), Mulder and van Asch (1988), Mulder (1991) and Hammond et al. (1992). The statistical analyses have the most flexibility in scale and in data type and will be investigated in detail in the following sections.

Table 2.4. The trends in landslide hazard zonation (van Westen, 1993).

Type of landslide hazard analysis	Main characteristics
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 re-numbered 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.

2.3.2.2 Direct Mapping in Landslide Hazard Analysis

2.3.2.2.1 Landslide Distribution Analysis

The most straightforward approach to landslide hazard zonation is a landslide inventory, based on any or all of the following; aerial photo interpretation, ground survey, and a database of historical occurrences of landslides in an area. The final product gives the spatial distribution of mass movements, which may be represented on a map either as affected areas to scale or point symbols (Wieczorek, 1984).

Such mass movement inventory maps are the basis for most other landslide hazard zonation techniques. However, they can be used as an elementary form of hazard map because they display the location of a particular type of slope movement. They provide only information for the period shortly preceding the date that aerial photographs are taken or the fieldwork conducted. They provide no insight into temporal changes in mass movement distribution. Many landslides occurred some time before photographs are taken my have become undetectable. Therefore, a refinement is the construction of landslide activity maps, which are based on multitemporal aerial photo interpretation (Canuti et al., 1979, 1985, 1986). Landslide activity maps are indispensable to study the effects of temporal variation of a factor such as land use on landsliding. Landslide distribution can also be shown in the form of a density map (Wright et al, 1974). The resulting density values are interpolated and used as landslide isopleths. They can also be used to cite out the current situation of the landslide density per terrain mapping unit or catchment or a predefined geological unit. This method may also be used to test the importance of each individual parameter for predicting the occurrence of mass movements. If the method is used to test the importance of specific parameter classes, the user decides, on the basis of his/her field experience, which individual maps or combination of parameter maps will be used. The method is most appropriate at medium or large scales. At the regional scale the construction of a mass movement distribution or activity map is very time consuming and too detailed for procedures of general zoning.

However, the selection of terrain mapping unit and the conversion of continuous parameter maps into discrete parameter maps involve a quite large subjectivity into the analysis. Furthermore, this analysis should have to be done for each parameter map and for different parameter classes. The effects of the separate parameters with respect to each other are not implemented, hence it is still expert dependent who will be on the charge to define the parameter classes and the parameter maps to be used. The analysis is similar to general bivariate analyses, but does not end up with a hazard score of any sampling frame in the area. Basically, a simple density per kilometer or per sample area will provide much more objective results about the factual data.

2.3.2.2.2 Heuristic Approach (Geomorphic Analysis)

In heuristic methods the expert opinion of the earth scientist making the survey is used to classify the hazard. These methods combine the mapping of mass movements and their geomorphologic setting as the main input factor for hazard determination.

The basis of geomorphic analysis was outlined by Kienholz (1977), who developed a method for producing a combined hazard map based on the mapping of "silent witnesses" (Stumme Zeugen). The geomorphic method is also known as the direct mapping method. The hazard is determined directly either in the field or by photo or satellite image interpretation by the earth scientist. The process is based on individual experience and the use of reasoning by analogy. The decision rules are, therefore, difficult to formulate because they vary from place to place, yielding as unformalized applicable rules that vary from polygon to polygon. This method is totally subjective and dependent on the skill and experience of the earth scientist. However, GIS serves as an undeniable tool for reproduction and querying the entered data. This method can be applied at all scales in a relatively short period. Some examples of geomorphic analyses can be found in Carrara and Merenda (1974), Brunsden et.al. (1975), Stevenson (1977), Malgot and Mahr (1979), Kienholz (1977,1978,1980,1984), Kienholz et al. (1983,1988), Grunder (1980), Ives and Messerli (1981), Rupke et al. (1987,1988), Perrot (1988), Hermelin (1990,1992), Hearn (1992) and Seijmonsbergen (1992). A weighting scheme is also present in this type of analysis, however this weighting scheme is also quite subjective and "blind weighting" is suggested for this type of weighting by Gee (1992).

2.3.2.3. Indirect Mapping in Landslide Hazard Analysis

2.3.2.3.1. Statistical Methods in 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 assessment of landslide hazard.

In statistical landslide hazard analysis the combinations of factors that have led to landslides in the past are determined statistically, and quantitative predictions are made for areas currently free of landslides but where similar conditions exist. Furthermore, overlying of parameter maps and calculation of landslide densities form the core of the analysis. Most of the analyses are based on the relationship between the landslide densities per parameter class compared with the landslide density over the entire area. Each method has its own specific rules for data integration required to produce the total hazard map. Two different statistical approaches are used in landslide analyses: bivariate and multivariate approaches.

Although the statistical 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 parameter cannot be collected with appropriate 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.

2.3.2.3.1.1. Bivariate Statistical Methods in Landslide Hazard Analysis

In this method, overlay of parameter maps and calculations of landslide densities form the core of the analysis, the importance of each parameter, or specific combinations of parameter 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 for 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 homogenous units, which is then overlaid by the landslide map to give a density per unique combination of input parameters.

It should be stressed that the selection of parameters has also an important subjective element in this method. The following GIS procedures are used (van Westen, 1993).

1. Classification of each parameter map into a number of relevant classes.
2. Combination of the selected parameter maps with landslide map via map overlay
3. Calculation of weighting values based on the cross table data
4. 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.

As it is seen from the procedure list the first and the last item contains quite large subjectivity, it is not clear to how to divide the parameter maps into classes and how many classes should there be? Furthermore, the division of the final hazard map into hazard classes inherits the same problem. This problem limits these methods, as the start and the end directly depends on the expert, which means a degradation in the final hazard map and also limits the reproducibility of the hazard maps under different conditions.

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.

Bivariate statistical analysis deals with one dependent variable (in this case the occurrence of mass movements) and one independent variable. The importance of each factor is analyzed separately. Specific combinations of variables can also be tested by treating the combination map as a new variable. The methods are based on the assumption that the important factors leading to mass movements can be quantified by calculating the density of mass movements for each variable class. However, the new parameter map production as crossing the available parameter maps in fact carries this bivariate analysis procedure into somewhat multivariate domain; as the factor analysis in the multivariate domain also bases its core on new parameter maps with different factor loadings from the initial parameter maps.

In bivariate statistical analysis, each factor map is combined with the landslide distribution map, and weighting values based on landslide densities are calculated for each parameter class. Several statistical methods have been applied to calculate weighting values; these have been termed the *landslide susceptibility method* (Brabb, 1984; van Westen, 1992, 1993), *Information value method* (Kobashi and Suzuki, 1988; Yin and Yan, 1988), *weight of evidence modeling method* (Spiegelhalter, 1986; Bonham-Carter, 1996). Furthermore, there still exist not enough exploited methods as Bayesian combination rules, certainty factors, Dempster and Shafer belief method and fuzzy logic. The three of the methods will be further investigated in the following sections, which are landslide susceptibility analyses, information value analyses and weights of evidence methods. The first two of them depend on the density of landslides in parameter classes; even though they result in approximately same hazard maps, the calculation schemes are different from each other. The weights of evidence method utilize the usage of binary dumb variables, and again based on the probability of occurrence of landslides in parameter classes. However, the usage of binary dumb variables turns a simple GIS in to a small scale chaos especially in landslide hazard projects. As this method is first created to assess the locations of ore deposits, the variables of its initial version were well defined and directly depend on factual data, where all of the answers of “what if?” questions were known.

2.3.2.3.1.1.1. Landslide Susceptibility Analysis

A simple and useful method in statistical analysis to determine the importance of different variables for the occurrence of mass movements is the use of pair wise map crossing. In order to evaluate the importance of the individual maps, a cross between these maps and a landslide occurrence map is prepared. For each variable class and landslide type, two types of densities can be calculated.

1. Area density: the density expressed as the number of pixels with landslides divided by the total number of pixels within the variable class. This can be displayed as a percentage or permillage contents.

$$D_{area} = 1000 \frac{Npix(SX_i)}{Npix(X_i)}$$

where D_{area}: Areal density per millage

$Npix(SX_i)$: number of pixels with mass movements within variable class X_i.

$Npix(X_i)$: number of pixels within variable class X_i.

2. Number density: the density expressed as the number of landslide occurrences per square kilometer of the area of the variable class.

$$D_{number} = \frac{1*10^6}{Area(X_i)} Number(SX_i)$$

where D_{Number} : Number Density (Number/km^2)

$Area(X_i)$: Area in square meters of variable class X_i.

$Number(SX_i)$: Number of mass movements within variable class X_i.

To evaluate the influence of each variable, weighting factors should have to be introduced, which compare the calculated density with the overall density in the area. The formula for the density-based area is:

$$W_{area} = 1000 \frac{Npix(SX_i)}{Npix(X_i)} - 1000 \frac{\sum Npix(SX_i)}{\sum Npix(X_i)}$$

and for the density based on number/km^2

$$W_{number} = \frac{1*10^6}{Area(X_i)} Number(SX_i) - \frac{1*10^6}{\sum Area(X_i)} \sum Number(SX_i)$$

2.3.2.3.1.1.1.1. Production of the Susceptibility Map

The weight values for the variable classes are added to produce a hazard map. With the number of input maps and different combinations of type and activity, a number of different susceptibility maps can be made. The optimal combination of variables is generally a problem, however selection of a small set of maps incorporate the most relevant variables. Two methods have been applied in literature. First method is selection of maps based on field experience in which the variables that are considered, on the basis of field experience, to be relevant for the occurrence of mass movements are selected and summed. The other method is called the stepwise map combination, adding the various input maps one by one. After the addition of another map, the resulting scores are analyzed by crossing with the map showing active landslides. The percentage of pixels with landslides and a total score larger than zero is calculated (correctly classified pixels). If this percentage decreases after the addition of another map, such a map is rejected. If the percentage increases, the map is included (van Westen, 1993). However, the sequence of this summation changes everything which is a major drawback of this method and needs to be justified.

2.3.2.3.1.1.2. Information Value Method

The use of a combination of numerical variables (such as slope angle values) and alphanumerical variables (such as lithological variables) in a statistical analysis is generally problematic. This can be solved by treating each variable class as a separate variable, which can only one of the two states: present (1) or absent (0). It can be determined whether a variable class is present or absent. The information value method can be applied both to land units as well as on a pixel basis. The hazard information method, developed by Yin and Yan (1988) is based on the following simple formula for calculating the information value I_i for variable X_i:

$$I_i = \log \frac{S_i / N_i}{S / N}$$

where:

S_i: the number of land units or pixels with mass movements and the presence of variable X_i,

N_i: The number of land units or pixels with variable X_i

S: The total number of land units or pixels with mass movements

N: The total number of land units or pixels.

The degree of a hazard for a land unit or pixel j is calculated by the total information value $\mathbf{I}_j$

$$I_j = \sum_{i=0}^{m} X_{ij} I_j$$

where:

m : number of variables,

X_{ij} : 0, if the variable X_i is not present in the land unit or pixel j and 1, if the variable is present.

For the assessment of precision of the classification, Yin and Yan (1988) presented the following equation

$$A = \frac{M_i}{N_i} \sqrt[3]{\left(1 - \frac{M - M_i}{N - N_i}\right)}$$

in which:

A: precision of the predicted result

N: total number of terrain units (catchments in this case) in this area

N_i: total number of units with landslides

M: number of terrain units predicted as unstable

M_i: number of terrain units predicted as unstable which have landslides.

The information value method applied on a pixel basis is in fact very similar to the susceptibility determination. The only difference is that in the information value method the log value of the quotient of class density over map density is entered, whereas in the susceptibility method the difference in densities was used. The information values are always smaller than the weight values.

2.3.2.3.1.1.3. Weights of Evidence Modelling

This method was developed at the Canadian Geological Survey (Agterberg et al., 1990; Bonham-Carter et al, 1990) and was applied to the mapping of mineral potential. Sabto (1991) applied the method for landslide hazard analysis. The method consists of reducing each set of landslide-related factors on a map to a pattern of a few discrete states. In its simplest form, the pattern for a feature is binary, representing its presence or absence within a pixel. According to Bonham-Carter et al. (1990), the first step is determining the prior probability of landslides, which is given by the density of pixels with landslides within the study area.

$$P_{prior} = \frac{Npix(slide)}{Npix(total)}$$

in which

P_{prior}	: prior probability,
Npix (slide)	: the number of pixels with a landslide occurrence,
Npix (total)	: the total number of pixels in the map

for mathematical reasons it is more convenient to use the odds (O):

$$O_{prior} = \frac{P_{prior}}{1 - P_{prior}} = \frac{Npix(slides)}{Npix(total) - Npix(slides)}$$

Considering the relationship between a binary variable map (b_i) and a landslide map (S), the following combinations are possible:

$$B_i : \quad Npix(B_i) \big/ Npix(total)$$

$$\overline{B_i} : \quad Npix(total) - Npix(B_i) \big/ Npix(total)$$

four combinations of B_i and S are possible in the map: $B_i \cap S$, $\overline{B_i} \cap S$, $B_i \cap \overline{S}$, $\overline{B_i} \cap \overline{S}$.

The conditional probability of choosing a pixel with a landslide, given that the cell contains pattern B_i, is:

$$P\{S|B_i\} = \frac{B_i \cap S}{B_i}$$

and the three other conditional probabilities are:

$$P\{\overline{S}|B_i\} = \frac{B_i \cap \overline{S}}{B_i} \qquad P\{S|\overline{B_i}\} = \frac{\overline{B_i} \cap S}{\overline{B_i}} \qquad P\{\overline{S}|\overline{B_i}\} = \frac{\overline{B_i} \cap \overline{S}}{\overline{B_i}}$$

According to Bayes rule:

$$P\{S|B_i\} = \frac{P\{B_i|S\}P\{S\}}{P\{B_i\}}, \; P\{S|\overline{B_i}\} = \frac{P\{\overline{B_i}|S\}P\{S\}}{P\{\overline{B_i}\}}$$

Bonham-Carter et al. (1990) defined positive and negative weights (W_i^+ and W_i^-), which combine these conditional probabilities:

$$W_i^+ = \log_e \frac{P\{B_i|S\}}{P\{B_i|\overline{S}\}} \quad \text{and} \quad W_i^- = \log_e \frac{P\{\overline{B_i}|S\}}{P\{\overline{B_i}|\overline{S}\}}$$

In GIS the method can be implemented rather easily. It is considered as the simple crossing of a binary landslide map with a binary variable map. The four possible resulting combinations are given Table 2.5.below.

Table 2.5. The possible combinations after map crossing

LANDSLIDES	Variable Class represented as binary pattern	
	1 (present)	0 (absent)
Present 1	$Npix_1$	$Npix_2$
Absent 0	$Npix_3$	$Npix_4$

The weights of evidence can be written in numbers of pixels as follows:

$$W_i^+ = log_e \frac{\dfrac{Npix_1}{Npix_1 + Npix_2}}{\dfrac{Npix_3}{Npix_3 + Npix_4}} \qquad W_i^- = log_e \frac{\dfrac{Npix_2}{Npix_1 + Npix_2}}{\dfrac{Npix_4}{Npix_3 + Npix_4}}$$

If more binary maps are used, the weights can be added, provided that the variable maps are conditionally independent with respect to landslide occurrence. The logarithm of the posterior odds can be calculated as follows:

$$\log_e O\left\{S \middle| B_1^k \cap B_2^k \cap B_3^k \ldots\ldots B_n^k\right\} = \sum_{i=1}^{n} W_i^k + \log_e O_{prior}\{S\}$$

and the posterior probability as:

$$P\{S\} = \frac{O}{(1+O)}$$

The contrast $C=W^+ - W^-$ gives a useful measure of the correlation between the variable map and the landslide occurrence. C becomes zero when a map has a distribution which is spatially independent of the points.

The main assumption for univariate statistical methods is that the maps should be conditionally independent. To test this independence a pairwise test can be executed (Bonham-Carter et al, 1990). All possible pairs of variable maps should be evaluated separately. The pairwise test includes the calculation of observed and expected frequencies of landslides. Therefore, the maps are crossed pairwise, and the resulting cross map is then crossed again with the mass movement map. The combinations obtained from crossing two binary maps and a landslide map is given in the Table 2.6.

Table 2.6. The possible combinations after crossing of two binary maps

Landslides	possible combinations of binary maps			
	$B_i \cap B_2$	$B_1 \cap \overline{B_2}$	$\overline{B_i} \cap B_2$	$\overline{B_i} \cap \overline{B_2}$
Present	$Npix_1$	$Npix_2$	$Npix_3$	$Npix_4$
Absent	$Npix_5$	$Npix_6$	$Npix_7$	$Npix_8$

Using the weight of evidence modeling, the logarithm of the odds for each unique overlap of two variable classes, is calculated by:

$$\log_e O\left(S \middle| B_1 B_2\right) = W_1^+ + W_2^+ + \log_e O(S)$$

$$\log_e O\left(S \middle| B_1 \overline{B_2}\right) = W_1^+ + W_2^- + \log_e O(S)$$

$$\log_e O\left(S \middle| \overline{B_1} B_2\right) = W_1^- + W_2^+ + \log_e O(S)$$

$$\log_e O\left(S \middle| \overline{B_1 B_2}\right) = W_1^- + W_2^- + \log_e O(S)$$

The predicted number of pixels in each unique overlap can be calculated using:

$$m_i = P_i \; Npix_i$$

in which :

m_i : the number of predicted landslides for the overlap of two classes

P_i : The calculated probability for the overlap of the two classes

$Npix_i$: The number of pixels in each overlap (for $B_i \cap B_2$ this will be $Npix_1$ + $Npix_5$)

The conditional independence is tested with the following formula:

$$G^2 = -2\sum_{i=1}^{8} X_i \log \frac{m_i}{x_i}$$

in which

x_i: the number of mass movement occurrences for the overlap of two classes (for $B_i \cap B_2$ this will be Npix1)

The function G^2 has a χ^2 distribution with 2 degrees of freedom (Bonham-Carter et al., 1990). On the basis of the result of the χ^2 test the selection of the variable maps is made. The weight of evidence values are added and the posterior probability is calculated. After classification of the posterior probability, the expected number of landslide occurrences per probability class is calculated for each class and compared with the observed number of occurrences per probability class. The expected frequency per class is given by:

$$f_{i(e)} = P_i Npix_i$$

in which

$f_{i(e)}$: expected number of occurrences per probability class i

P_i : the probability per class i

$Npix_i$:the area (in pixels) of probability class i.

By crossing the predictor map with the mass movement map the actual number of mass movements can be calculated, and the χ^2 test can be applied

$$\chi^2 = \sum \frac{\left(f_{i(0)} - f_{i(e)}\right)^2}{f_{i(e)}}$$

where, $f_{i(0)}$ is the observed frequency of landslides.

2.3.2.3.1.2. Multivariate Statistical Methods in Landslide Hazard Analysis

Multivariate statistical analyses of important causal factors controlling landslide occurrence may indicate the relative contribution of each of these factors to the degree of hazard within a defined land unit. The analyses are based on the presence or absence of stability phenomena within these units (van Westen, 1993).

Multivariate statistical analysis models for landslide hazard zonation were developed in Italy, mainly by Carrara (1983, 1988) and his colleagues (Carrara et al., 1990, 1991, 1992). In their applications, all relevant factors are sampled either on a large-grid basis or in morphometric units. For each of the sampling units, the presence or absence of landslides is also determined. The resulting matrix is then analyzed using multiple regression or discriminant analysis. With these techniques good results can be expected in homogenous zones or areas with only a few types of slope instability processes. When complex statistics are applied, as was done by Carrara (1983, 1988) and his colleagues (Carrara et al., 1990, 1991, 1992) or by Neuland (1976) or by Kobashi and Suzuki (1988), subdivision of the data according to the type of the landslide should be also made as well. Therefore, large data sets are needed to obtain enough cases to produce reliable results. The use of complex statistics implies laborious efforts in collecting large amounts of data, because these methods do not use selective criteria based on professional experience. Multivariate statistical analyses of important factors related to landslide occurrence give the relative contribution of each of these factors to the total hazard within a defined land unit. The analyses are based on the presence or absence of mass movement phenomena within these land units, which may be catchment areas, interpreted geomorphic units, or other kinds of terrain units.

The following GIS procedures are used to evaluate multivariate statistics in landslide hazard zonation:

1. Determination of the list of factors that will be included in the analysis. As many input maps are of alphanumeric type, they must be converted into numerical maps. These maps can be converted to presence/absence values for each landunit 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.
2. Combination of the land unit map with the mass movement map via map overlay and dividing the stable and unstable units into two groups.
3. Export of the matrix to a statistical package for subsequent analysis.
4. 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.
5. Classification of the map into a few hazard classes.

Two types of multivariate analyses have been conducted in the literature extensively, multiple regression and discriminant analyses. There exists plenty of other statistical methods, such as logistic regression or analysis of the parameter maps prior to bivariate analyses by factor analyses. However, these methods require more than entry level statistics and the data manipulation should be done very carefully, as within these methods data manipulation is not a speculative event. Although the multiple regression and discriminant analyses constitute some part of the landslide hazard analysis literature some real big drawbacks are introduced, as the data used for these analyses should have to be distributed normally, which is quite impossible when dealing with natural data. Especially when the data sets of distance to some object is used. Several normality conversion tables could have been used in order to convert the data into normal distribution such as log-log or log-normal coversions, however, these conversions do inherit some critical biases to the natural distribution of the data. Some authors have tried to exploit the data via using dummy binary variables but this had increased the complexity of the data structure and limits the flexibility of the statistical system. Examples of these dummy variables could be seen in Carrara et al. (1990, 1991, 1992) and in Chung et al. (1993). On the other hand, the use of binary logical regression, which is free of data distribution issues, are not so well exploited in the literature only few examples in the last few years are observed, such as: Atkinson and Massari (1998), Dai et al. (2001) and Lee and Min (2001). It is also seen from this fact that logical regression is quite new in this area. In the next sections, only multiple regression and discriminant analyses will be introduced, the application of logical regression and tidbits will be explained in the application chapters.

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 thickness). These data are very difficult to obtain even for relatively small areas. Therefore, the medium scale is considered most appropriate for these sets of techniques.

2.3.2.3.1.2.1. Multiple Regression

The most common and well-known multivariate statistical method used in earth sciences is multiple regression. It is used to correlate landscape factors and mass movements, according to the following linear equation.

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots\ldots\ldots + b_n X_n$$

The dependent variable Y represents the presence (1) or absence (0) of a mass movement. It can also be expressed as the percentage of a terrain unit covered by landslides. The variables X_1-X_n are the independent variables, such as slope class, geological units, etc. the symbols b_0-b_n are the partial regression coefficients. The standardized partial regression coefficients, which are the partial regression coefficients expressed in units of standard deviation, indicate the relative contribution of the independent variables to the occurrence of landslides (Davis, 1986). The following statistics are used to evaluate the result of a calculation.

R^2 : amount of variance accounted for by the model. It adjusts for the number of independent variables in the regression

SE: standard error of estimate. The square root of the residual mean square error. It measures the unexplained variability in the dependent variable.

MEA: absolute mean error. The average of the absolute values of the residuals, which is the average error one can expect in a prediction.

The use of terrain units for the sampling of variables in multiple regression analysis is welcomed with a number of problems.

1. Sampling method
2. Size of terrain unit
3. Resultant maps
4. Sample areas / Prediction areas
5. Complexity of the study areas

In order to avoid these cited problems, generally a pixel based approach is used, even in this approach the data requirements of normal distribution could not be achieved. A series of assumptions are made about the assumption of the data normality which in fact degrades the efficiency of the whole system.

2.3.2.3.1.2.2. Discriminant Analyses

A second type of multivariate analysis is discriminant analysis. The objective of the analysis is to find the best discrimination between two groups: units or pixels with and those without mass movements. The analysis results in a discriminant function:

$$D_s = B_0 + B_1 X_1 + B_2 X_2 + \dots\dots B_n X_n$$

where X_i are the values of the variables and B_i the calculated coefficients. Before any further analysis can be performed, the success of the formula in separating the two groups must be tested. For this purpose three tests can be used.

1. the variability between the two groups and within the groups, and the total variability of the data, are calculated. The ratio of the variability between the two groups and the variability within the groups is called the eigenvalue. It should be maximized for a good discriminant function.
2. the ratio of the variability between the two groups and the total variability is called "Wilk's λ". A small value indicates strong variation between groups and less variation within groups. A Wilk's λ of 1 indicates that there is equally great

variation within groups as between groups (i.e. that the function does not discriminate)

3. the χ^2 test to determine if the two groups are significantly different.

Furthermore, as the slope stability depends on several factors acting at the same time, some efforts have been directed towards the acquisition of simply and quickly determined parameters. Stevenson (1977) using scored factors proposed a method to evaluate relative landslide risk in clayey slopes.

Discriminant analysis provides a more accurate stability assessment. A classical work using statistical techniques is that from Jones et al. (1961) on landslides in Pleistocene terrace deposits of Colombia river. A total of 160 slump-earthflow movement and additional 160 stable slopes were considered. Qualitative and quantitative factors influencing sliding were searched. A final analysis using the discriminant - function method was performed considering as influencing factors: original slope (X1), submergence percentage (X2), terrace height (X3) and groundwater (X4).

2.3.2.3.2. Knowledge Driven Methods in Landslide Hazard Analysis

2.3.2.3.2.1. Qualitative Map Combination

To overcome the problem of the "hidden rules" in geomorphic mapping, other qualitative methods based on qualitative map combination have been developed. In qualitative map combination, the earth scientist uses the expert knowledge of an individual to assign weighting values to a series of parameter maps. The terrain conditions at a large number of locations are summed according to these weights, leading to hazard values that can be grouped into hazard classes. The problem with this method is in determining the exact weighting of the various parameter maps. Often insufficient field knowledge of the important factors prevents the proper establishment of the factor weights, leading to unacceptable generalizations (Soeters and van Westen, 1996).

2.3.2.3.2.2 Favourability Functions

In order to achieve the minimum common factors of expert knowledge dependency and the information derived from the original data, the geographical database is designed under the envelope of some data and expert knowledge dependent functions. This is also used to decrease the subjectivity of expert knowledge and not to deal with the redundant information yielding from pure statistical analyses. In favourability analyses, the data layers are first divided into a number of expert designed classes such as geological, geomorphological or slope classes and etc. For data integration (numeric and alphanumeric databases) each layer is transformed into a number between α and β, where α and β are known constants such as 0 and 1 or -1 and +1. This transformation is the basic step of forming a probabilistic favourability function from a class to the interval α and β. After completion of this stage, some previously defined decision rules are applied to let the expert earth scientist decide about the factor probability and favourability of the current situation such as standard probability measures, certainty factor, Dempster-Shafer belief method and fuzzy logic interpretation (Soeters and van Westen, 1996; van Westen, 1993).

2.3.2.3.3. Deterministic Modeling in Landslide Hazard Analysis

The methods described so far give no information on the stability of a slope as expressed in terms of its factor of safety, in order to obtain this information these kinds of slope stability deterministic models are necessary.

Despite problems related to collection of sufficient and reliable input data, deterministic models are increasingly used in hazard analysis of larger areas, especially with the aid of GIS techniques, which can handle the large number of calculations involved in determination of safety factors over large areas. Deterministic methods are applicable only when the geomorphic and geologic conditions are fairly homogeneous over the entire study area and the landslide type is simple. The advantage of these white box models is that they are based on slope stability models, allowing the calculation of quantitative values of stability (safety factors). The main problem with these methods is the degree of simplification which is required in the acceptance limits of the assumptions. A deterministic method, usually applied for translational slides is the infinite slope model. These deterministic models generally require the use of ground water simulation models. Stochastic methods are sometimes used to select input parameters for the deterministic models (Mulder and van Asch, 1988; Mulder, 1991; Hammond et al. 1992).

The result is a map showing the average safety factor for a given magnitude of groundwater depth and seismic acceleration. The variability of the input data can be used to calculate the probability of failure in connection with the return period of triggering events. Generally the resulting safety factors and probability factors should not be used as absolute values unless the analysis is done in a small area where all the parameters are well known. Normally they are only indicative and can be used to test different scenarios of slip surfaces and groundwater depths. The method is applicable only at large scales over small areas. At regional and medium scales, the required detailed input data, especially concerning groundwater levels, soil profile, and geotechnical descriptions, usually cannot be provided.

2.3.2.3.4 Landslide Frequency Analysis

The probability of mass movement occurrence at a certain place within a certain time period can only be determined when a relationship can be found between the occurrence of landslides and the frequency of triggering factors, such as rainfall or earthquakes. The most promising technique is the calculation of antecedent rainfall, which is the accumulated amount of precipitation over a specified number of days preceding the day on which a landslide occurred (Crozier, 1986).

The method is most appropriate at medium and large scales. At 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 GIS is not crucial, however GIS can be used to analyze the spatial distribution of rainfall.

2.3.2.4. Accuracy and Objectivity

The most important question to be asked in each landslide hazard study relates to its degree of accuracy. The terms accuracy and reliability are used to indicate whether the hazard map makes a correct distinction between landslide free and landslide prone areas. The accuracy of landslide prediction depends on a large number of factors the most important of which are:

1. accuracy of the models
2. accuracy of the input data
3. experience of the earth scientist
4. size of the study area

The context of accuracy is a fatal section in disaster management, as the wrong decision of landslide free areas will cause loss of lives, which discloses to the aim of hazard and risk assessment. This fatal section can be checked out by some statistical analyses and trying to find out the possible error component, furthermore the error component should have to be put in all of the maps produced and the knowledge that are made public accessible.

Related to the problem of assessing the accuracy of hazard maps is the question of their objectivity. 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 on the personal judgement of the earth scientist in charge of the hazard assessment.

Objectivity in the assessment of landslide hazard does not necessarily result in an accurate hazard map. For example, if a very simple but verifiable model is used or if only a few parameters are taken into account, the procedure may be highly objective but produce an inaccurate map. On the other hand, subjective studies, such as detailed geomorphic slope stability analyses, when made by experienced geomorphologists may result in very accurate hazard maps. Yet, such a good, but subjective assessment may have a relatively low objectivity because its reproducibility will be low. This means the same evaluation made by an other expert will probably yield another result, which can have clearly undesirable legal effects (Soeters and van Westen, 1996; van Westen, 1993).

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2.3.2.5. Evaluation of Methods via Scale Factor

Any hazard evaluation involves a large degree of uncertainty. Prediction of natural hazards such as landslides, which are caused by interaction of factors which are not always fully understood and sometimes unknown, confronts earth scientists with especially large problems. However, the use of statistics indeed will increase the accuracy of the input data, this minor improvement will reduce the degree of uncertainty in the assessment. On the other hand the use of multivariate statistics in GIS will yield in assembling factor maps, that could not be done only on statistical packages. This assemblage is routing the earth scientists, to use GIS which confronts the user to more complex and more variable dominated platforms. More onwards, the used models have to be improved by the availability of huge amount of data and availability of adequate type and method of handling. Based on this knowledge, the available methodologies in landslide hazard zonation can be classified and rated as follows in correspondence to the analysis of scale factor (Table 2.7).

Table 2.7. Classification of Methods based on scale factor (Soeters and van Westen, 1996, van Westen, 1993).(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, 2: of limited use, 3: useful).

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	3/3	High
Geomorphological Landslide Hazard analysis	3/3	3/3	3/3	very low
Qualitative Landslide Hazard Analysis	3/3	3/2	3/1	high
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