3. RESEARCH REVIEWS, APPROACHES EMPLOYED AND ISSUES

3-1 DEFINITION AND CLASSIFICATION OF LANDSLIDES

Landslide is widely used as an all-inclusive term for almost all varieties of slope movements, and terms like slope movements, mass movements, and slope failures are often synonymously used for landslides (Varnes, 1978). The Special report 29, Highway research board USA, (Schuster, 1978) defines landslide as the downward and outward movement of slope forming materials; natural rocks, soils, artificial fills or combinations of these materials. Coates (1977) defines landslide as abrupt, short-lived, geomorphic events constituting the rapid motion end of the mass movement spectrum. Crozier (1986) defines mass movement as the outward and downward gravitational movement of earth material without the aid of running water as a transporting agent.

More than two dozen of partial or complete classifications of landslides have appeared in many languages (Varnes, 1978). Varnes (1978) suggests the use of terminology "slope movement" as a general for various processes of slope failures. Slope movements may be classified in many ways, each having some usefulness in emphasizing features pertinent to recognition, avoidance, control, correction or an other purpose for the classification (Varnes, 1978). The various attributes that have been used as criterion for classification are; 1) type of movement, 2) kind of material, 3) rate of movement, 4) geometry of the area of failure and the resulting deposits, 5) age, 6) causes, 7) degree of disruption of the displaced mass, 8) relation or lack of relation of slide geometry to geologic structure, 9) degree of development, 10) geographic location, and 11) state of activity. Among them the chief criteria in the classification are primarily, type of movement and secondarily, type of material. Table 3-1 and Figure 3-1 describe the simplified classification of slope movement based on type of movement and type of material (Varnes, 1978).

3–2 CAUSES OF LANDSLIDES

The assessment of causes associated with landsliding for an area is the landslide hazard assessment for that area. The stability of slope in soil mechanics is expressed by the safety factor. The safety factor is defined as the ratio of forces tending to inhibit or

Table 3-1 Simplified classification of slope movements (after Varnes, 1978).

Type of movement		Type of Material		
		Bed Rock	Engineering soil	
			Predominantly coarse	Fine
Falls		Rock Falls	Debris Falls	Earth Falls
Topples		Rock Topples	Debris Topples	Earth Topples
Slides	Rotational	Rock Slump	Debris Slump	Earth Slump
	Translational	Rock Block Slide Rock Slide	Debris Block Slide Debris Slide	Earth Block Slide Earth Slide
Lateral Spreads		Rock Spreads	Debris Spreads	Earth Spreads
Flows		Rock Flows	Debris Flows	Earth Flows
Complex		Combination of two or more principal type of movements.		

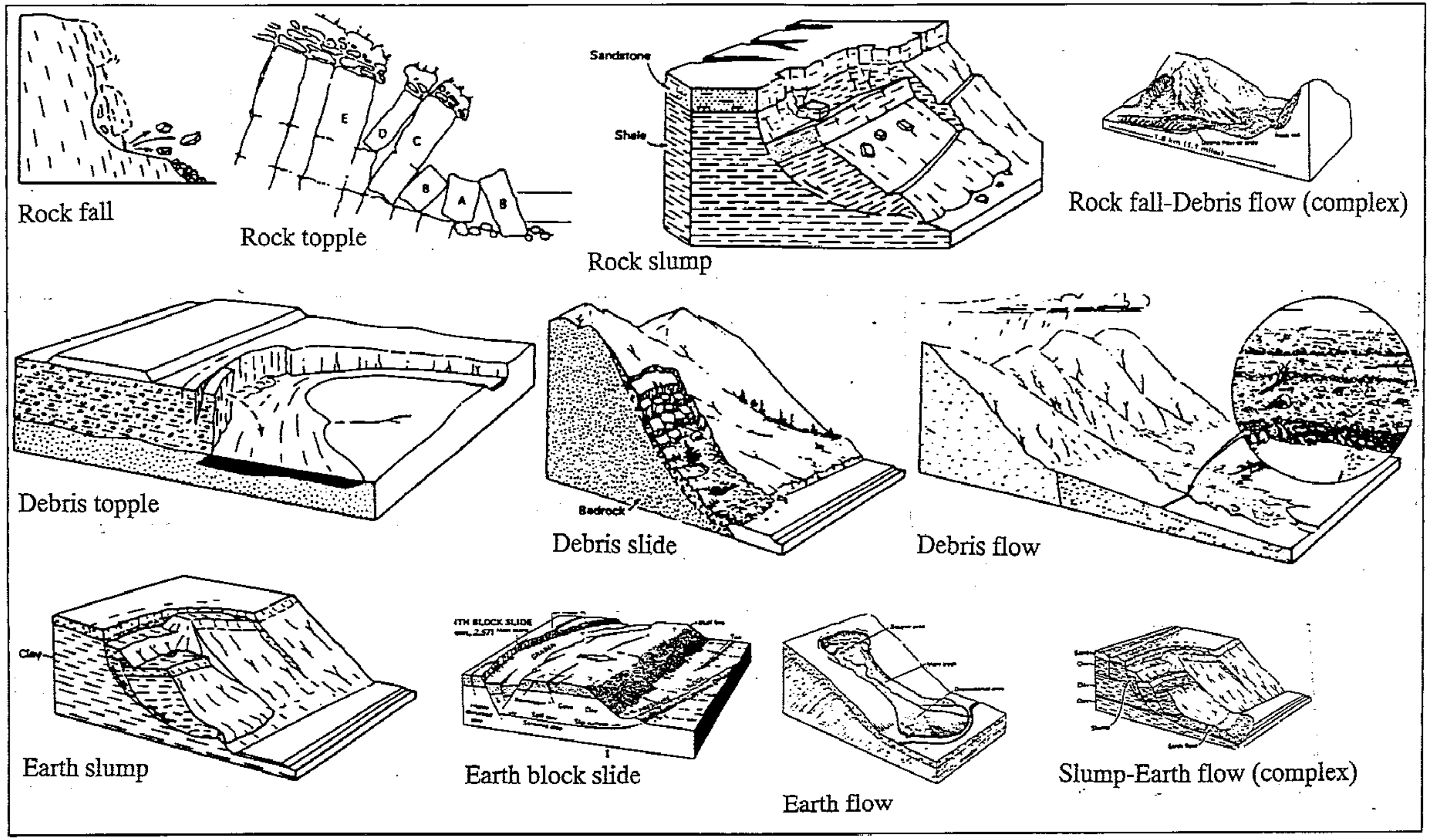

Figure 3-1 Simplified sketches of different types of slope movements (modified after Varnes, 1978).

resist slope movement, to those tending to initiate or drive that movement. The former one is called shear resistance and the later one is called shear stress. The safety factor of 1 represents the moment when the movement occurs. Higher values represent progressively more stable conditions. The safety factor can be expressed as follows (Terzaghi *et al.*, 1967).

Safety factor = Shear resistance / Shear stress

$$= C + (\sigma - u) \tan\phi / T$$

$$= C + (W/A \cos\beta - u) \tan\phi / (W/A \sin\beta) \quad \text{------------------------} (1)$$

where, T = Shear stress

C = cohesion with respect to effective normal stress

σ = Total normal stress

u = Pore water pressure

ϕ = Angle of internal friction

W = Weight of material

A = Area of shear plane

β = Angle of surface on which movement occurs

The factors contributing to shear resistance are cohesion, internal angle of friction, bulk density of slope material, the slope geometry, the distribution of pore-water pressure within the soil mass and the geometry of potential slip surface. Factors related to shear stress are slope geometry and bulk densities of slope material. Some other factors are to be incorporated when the slope is subjected to earthquake shaking.

The assessment of slope instability from equation 1 is called "limiting equilibrium analysis". In this method the strength parameters and hydrological conditions in the slope have to be determined from field or laboratory tests (Crozier, 1986). The application of this form of analysis is fraught with difficulties for large areas. The slope stability analysis in this manner would be feasible only on a specific site because most of the factors in equation (1) are difficult to accurately quantify on a regional basis. Variations in pore-pressure distribution, bulk density, and slip surface geometry are great throughout the area, both between and within the geologic units, and accurate measurement of these properties at sites enough to permit the quantification of their regional variation is not feasible.

The factors associated with topography, geology, and vegetation, however, can be considered as indexes of parameters included for safety factor and can be quantified to some extent from univariate statistical analysis or from multivariate statistical analysis to assess the relative contributions to landsliding, with the assumption that the slope failure will be more likely to occur under those circumstances which in the past have led to slope failure. This is the approach employed in this study (see also section 3-4-4). For example, slope gradient and slope aspect can be an index for slip surface geometry and ground water condition. Geology can be related to bulk density, porosity and ground water condition. Land use/cover such as vegetation can be linked to shear resistance, as a well spread root system increases the shearing resistance of the slope.

3-3 HAZARD AND RISK

Hazards themselves are not disaster but rather a factor in causing a disaster (Cuny, 1983). Hazards are natural agents that transform a vulnerable condition into a disaster. Terminology related to hazards and disasters have numerous definitions depending on the particular nature or special interest of the person or organization concerned. It should therefore be a great value if a more general and internationally accepted definition could be applied to these terms. The definitions of Varnes (1984) which have been accepted internationally are as follows;

Natural Hazards :	The probability of occurrence of potentially damaging phenomena within a specified period of time and within a given area.
Vulnerability :	The degree of loss to a given element or set of elements at risk resulting from the occurrence of natural phenomenon of a given magnitude.
Specific risk :	The expected degree of loss to a particular natural phenomenon. It may be expressed by the product of hazard and vulnerability.
Elements at risk :	The population, properties, economic activities, including public services etc. at risk in a given area.

Total risk :	The expected number of lives lost, person injured, damage to property or disruption of economic activity due to particular natural phenomenon. It is the product of specific risk and element at risk.

3-4 Remote Sensing, GIS, and Landslide Hazard Assessment and Mapping

Airborne and satellite remote sensing techniques such as photography and multispectral scanning , provide imagerey of the Earth's surface and is a valuable means of landslide hazard assessment and mapping. When this imagery is visually interpreted or processed by the computer based systems spatially distributed data can be obtained. When the interpreted data is combined with the layers of other digital terrain factors derived from original analogue form in computer based Geographic Information Systems (GIS), the data can be analyzed in GIS to determine the influence of terrain factors upon the landslide hazard.

The integration of remote sensing and GIS offers greater opportunity in the field of landslide hazard assessment. Figure 3-1 shows the relationship between remote sensing and GIS and describes the work flow in this study in which remote sensing serves as one of the several types of data input into a GIS. Both remote sensing and GIS are based on assigning numerical values to well-defined areas of the Earth's surface in order to produce a numerical image of this surface. Through a process of image correction and resampling , the remote sensing data can be matched with the raster layers of GIS. This opens many possibilities for correlation studies between basic remote sensing data and the thematic information derived from the introduction of maps digitized in GIS.

The subsequent sections discusses more about remote sensing, GIS and then about the approaches employed and issues of using remote sensing and GIS in the landslide hazard studies.

3-4-1 Remote Sensing and Remotely Sensed Data

Remote sensing is the measurement or acquisition of data about an object or scene by a satellite or other instrument above or far from the object (Colwell, 1984). Aerial photography, satellite imagery are all forms of remotely sensed data. Though

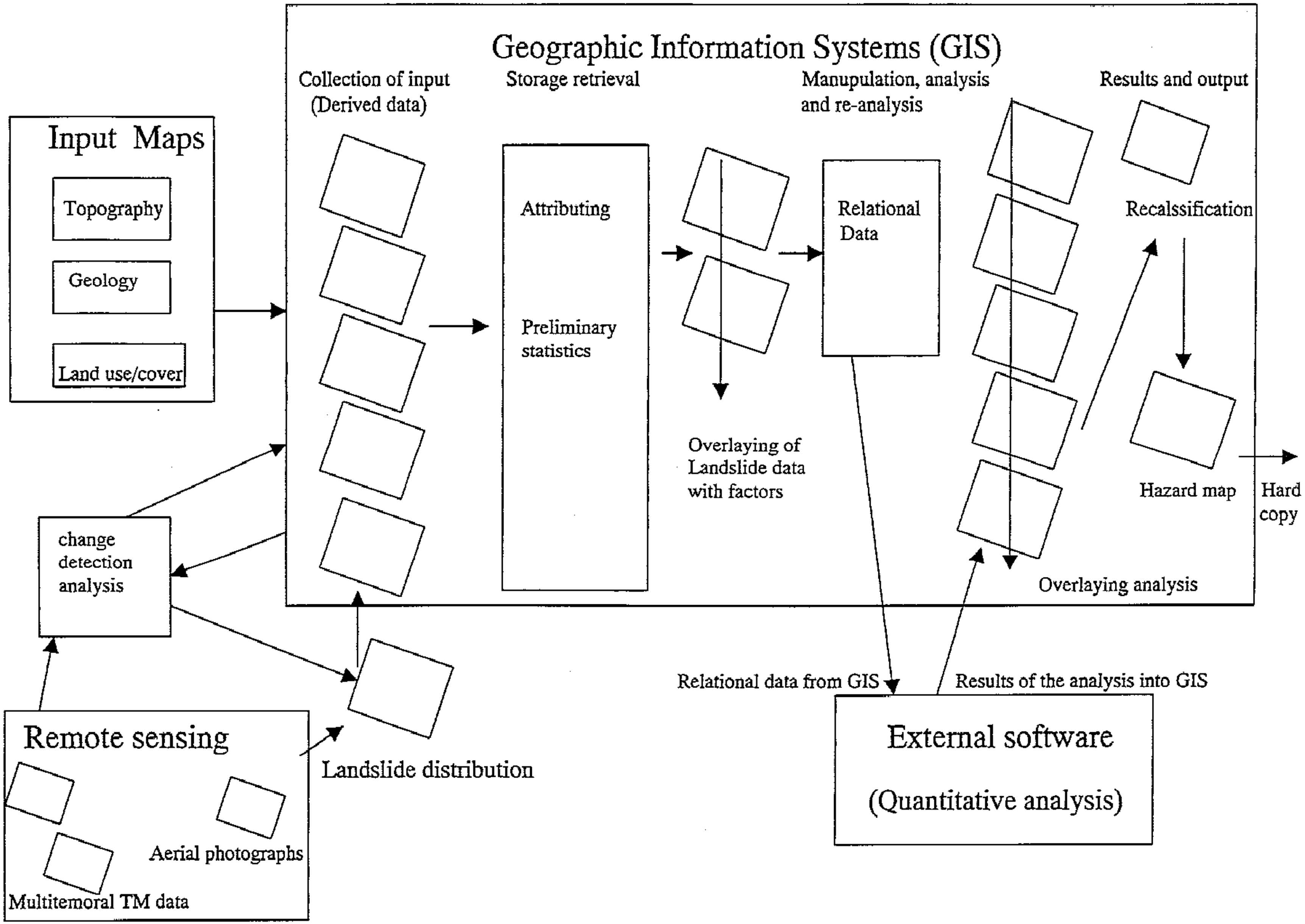

Figure 3-2 Schematic illustration of relationship between Remote sensing and GIS employed for landslide hazard assessment.

there are many ways to classify remotely sensed data, the subsequent two sections discuss the analogue remotely sensed data focusing conventional aerial photographs, and satellite digital data focusing Landsat thematic mapper (TM) data. These are the two kinds of remotely sensed data used in this study.

3-4-1.1 Analogue remotely sensed data

Aerial photography is the oldest development in remote sensing. It has become the most essential data at any level of study in most of the field. In addition to the conventional photography such as black and white and color, the non-conventional photography such as multispectral, infrared and ultraviolet have also become popular. Non photographic sensors such as laser systems and luminescence systems have also been in a use to capture the information through the electromagnetic radiation outside of the narrow visible spectral region.

Image interpretation is one of the most important tasks while working with photographs as well as digital remotely sensed data. It can be defined as the act of examining photographs for the purposes of identifying objects and phenomena and judging their significance (Reeves *et al.*, 1975). The interpretation process requires the interpreter to have at his command the knowledge derived not only from the images themselves but also from the relevant field or field of study.

Black and white images consist of variation in tone by means of which the shapes of objects are perceived. Basic image interpretation is essential to the efficient and effective use of data transmitted into the image. The basic elements in aerial photographs may include size, shape, shadow, site, association and resolution.

Various instruments are used for viewing, measuring and transferring of the detail. Viewing instruments often provide three-dimensional (stereoscopic) views. The measuring instruments may be used on single imagery or stereoscopic pairs; instruments that record or transfer the detail do so through the principle of projection or by means of a pantograph. Stereoscopic vision is the ability to appreciate depth. It provides the three dimensional view of the photographic image. A lot of instruments can be used to transfer the photo interpretation onto the base map, e.g., stereoplotter, zoom transferscope, sketchmaster, and mapmaster. The zoom transfer equipment, used for this study, for aerial photographs interpretation provides binocular viewing, variable magnification, image rotation, and scale correction to transfer detail from the aerial photographs to a reference map.

3-4-1.2 Satellite system and digital remotely sensed data

NASA initiated a program for Earth Resources Technology Satellites in 1967 and the first satellite, ERTS-1 was launched in 1972. This was later renamed Landsat. To date, this was then followed by series of seven satellites. The first three satellites launched in 1972, 1976, and 1980 carried only multispectral sensor (MSS). The Landsat-4 and Landsat-5 were launched on 1985 and 1988 respectively, and carried much improved sensor called Thematic Mapper (TM) in addition to the MSS. The mishap of Landsat-6, which was launched on 1995, is a real tragedy. However, Landsat-7 has been successfully launched in 1999. The data from Landsat-7 are emerging, and at present Landsat-7 and Landsat-5 are Landsat satellite systems in the operation. Landsat program is the most successful satellite program. The SPOT satellite system, Marine Observation Satellite (MOS), National Oceanic and Atmospheric Administration (NOAA), Japanese Earth Resources Satellite (JERS), European Earth Remote Sensing System (ERS), and Indian Remote Sensing (IRS) satellites are some other satellites carrying different sensors to capture data of earth at different wavelength bands. The Earth Observation Systems (EOS) satellite, which is supposed to carry different sensors to capture data in visible, infrared, thermal and microwave region of the wavelength, is the most promising satellite system of the future.

Landsat TM data is one of the most commonly and widely used remotely sensed data in remote sensing research because of its high radiometric, spatial and temporal resolutions. This is also the satellite data used in this study. TM sensor collects data in three visible bands, one near infrared band, two mid infrared bands, and one thermal infrared band (Table 3-2). The spatial resolution except for thermal infrared band is 30 m. The thermal infrared has the spatial resolution of 120 m. Table 3-2 depicts the basic characteristics of the TM sensor and the common understanding of usefulness of various bands. This study uses the ERDAS Imagine raster based software for digital image analysis.

Table 3-2 General characteristics of seven bands of TM sensor on board of LANDSAT –4, -5 (Altitude 705 km, repeat cycle 16 days).

Bands	Wave length (μm)	Resolution (Spatial / Radiometric)	Applications
Band 1	0.45-0.52 (Blue)	30 m /8 bit	Mapping Coastal water area, differentiating between soil and vegetation, forest type mapping, and detecting cultural features.
Band 2	0.52-0.60 (Green)	30 m /8 bit	Corresponds to the green reflectance of healthy vegetation, also useful for cultural feature identification.
Band 3	0.63-0.69 (Red)	30 m /8 bit	Useful for discriminating between plant species, also useful for soil and geology boundary delineation as well as cultural features.
Band 4	0.76-0.9 (Near –Infrared)	30 m /8 bit	Especially responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification and emphasizes soil/crop and land/water contrast.
Band 5	1.55-1.75 (Mid-infrared)	30 m /8 bit	Sensitive to the amount of water in plants, which is useful in crop drought studies and plant health analyses. Useful to discriminate between clouds, snow and ice.
Band 6	10.4-12.5 (Thermal infrared)	120 m /8 bit	Useful for vegetation and crop stress detection. heat intensity, insecticide applications, and for locating thermal pollution.
Band 7	2.08-2.35 (Mid-Infrared)	30 m /8 bit	Useful for discrimination of geologic rock formations and soil boundaries, as well as soil moisture content.

8-bit radiometric resolution gives each pixel a possible range of data values from 0 to 255 (i.e. 2^8 possible range)

3-4-2 Geographic Information Systems (GIS)

A Geographic Information System (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 a particular set of purposes (Burrough, 1986)". The followings are the major reasons of importance of GIS and its rapid development in the last two decades (Aronoff, 1989).

i) Difficulty to handle large volumes of data in thematic maps.

ii) Availability of suitable digital computers.

iii) Development in aerial photography and satellite based remote sensing.

iv) Difficulty in retrieving large amount of information from maps.

v) Difficulty in combining information from several maps.

The GIS comprise a sophisticated computers software which contains the following major components (Marble, 1990).

i) A data input subsystem which collects and /or processes spatial data derived from existing maps, remote sensors, etc.

ii) A data storage and retrieval subsystem which organizes the spatial data in a form which permits it to be quickly retrieved by the user for subsequent analysis, updates and corrections.

iii) A data manipulation and analysis subsystem, which performs a variety of analytical tasks.

iv) A data reporting subsystem, which is capable of displaying, output from spatial models in tabular or map form.

GIS works with two types of data structures; raster and vector. In a raster structure data is stored in an array of grid-cells referenced by a set of row and column numbers and each cell can be independently addressed with the value of an attribute.
A vector data is a set of graphic data that can be ultimately decomposed into point locations generally described by coordinates; it comprises of points, lines or polygon.

ARC/INFO, used in this study for most of the GIS analysis, is a commercially developed GIS software. ADS, ARCEDIT, ARCPLOT, LIBRARIAN are various sub systems of ARC/INFO. Network, Triangulated Irregular Network (TIN), COGO, GRID are the complementary software modules of ARC/INFO.

3-4-3 Assessment of Landslide Affected Areas Using Satellite Digital Data: the Approaches Employed and Issues

The disturbances such as flooding or landsliding causes abrupt changes in spectral characteristics exhibited by land covers, both in the visible and infrared parts of the spectrum. Hence the digital images obtained by satellite remote sensors at different time can detect these changes. The process of determining these changes can be termed change detection (Nelson 1987; Singh, 1989). It is the process of identifying differences in the object of phenomenon by observing at different times. Hence, one of the major applications of remotely sensed data obtained from Earth-orbiting satellites is the change detection because of the availability of repetitive coverage at short intervals and consistent image quality of satellite remotely sensed data. It should be useful in such diverse applications as land use change analysis, monitoring of shifting cultivation, assessment of deforestation, study of changes in vegetation phenology, seasonal changes in pasture production, damage assessment, crop stress detection, disaster monitoring, and snow-melt measurements.

Change detection analyses, employing satellite data obtained prior to and following a disturbance, have been used to assess vegetation responses to draught (Peters *et al.*, 1993; Jacobberger and Jellison, 1994), insect outbreaks (Muchoney and Haack, 1994), dust storms (Chavez and Mackinnon, 1994), highwinds (Cablk *et al.* 1994; Johnson 1994), and deforestation (Foody and Curran, 1994). Michener and Houhoulis (1998) study the vegetation responses to flooding in a forested ecosystem. It is, however, interesting to note that studies on change detection techniques applied to flooding/landsliding remain very much limited. The full capabilities of remote sensing data have not been fully exploited in the damage assessment associated with landsliding and flooding despite the fact that such assessment has a great practical value. The damage due to landsliding often covers large areas and investigations based on field survey alone is difficult and costly.

The basic premise in using remote sensing data for change detection is that changes in land cover must result in changes in radiance values. The changes in radiance due to land cover change must be large with respect to changes caused by other factors. The other factors include 1) difference in atmospheric condition, 2) differences in sun angle, and 3) differences in soil moisture. The impact of these factors may be partially reduced by selecting the appropriate data. For example, Landsat data belonging to the same time of the year may reduce problems from sun angle differences and vegetation phenological changes.

Though the fundamental aspect in change detection is to detect changes based on change in brightness value (BV) at a particular wavelength, variety of change detection methods can be applied. It is also interesting to note that depending on the type of change we aim to detect, different change detection algorithms may behave differently. Hence, finding out the change detection algorithm that is most suited to solve the particular problem is the most important aspect of the change detection analysis. The selection of a single change detection method to address a specific problem may not be a straightforward task (Collins and Woodcock, 1996). For example, vegetation and related spectral responses to a disturbance may vary markedly by type and intensity of disturbance, ecosystem type, and other environmental types. Furthermore, change detection techniques are often not well developed or widely applied in variety of ecosystem types and algorithms are not well tested (Cohen, *et al.*, 1996). Consequently, there is a need to employ and compare a variety of techniques for their applicability to a particular problem (Dobson *et al.*, 1995). In this study various change detection techniques were developed and compared to determine the best technique in the assessment of landslide affected areas.

3-4-4 Landslide Hazard Assessment and Mapping: the Approaches Employed and Issues

The major concept of landslide hazard assessment is to determine the characteristics of unstable and stable slopes, and that of hazard mapping is to differentiate between the stable slope and unstable slope and depict them in a map. Selections of scale of the analysis, the hazard assessment method, and analysis unit can be considered as items to be decided primarily before the initiation of hazard assessment. These three components are interrelated with each other and should basically be decided by the objective of a hazard map, nature of a hazard map required, type of data available for the analysis, type of method of analysis, and time and funds available for the analysis. The various decision components and their elements necessary to be considered primarily before the initiation of landslide hazard assessment are described in Figure 3-3 and Table 3-3. The first decision by any means before the initiation of hazard assessment would be to select the working scale. The scale of the analysis is often guided by the purpose of the hazard maps, availability of data, and fund. It is much better to say that the selection of the scale of analysis is usually determined by the intended application of its results, the choice of assessment technique of landslide hazard, and its analysis unit depends on the availability of kinds of data and financial resources. Table 3-4 shows the objectives of the hazard maps at different scales. The selection of analysis unit is another important aspect of hazard assessment. I have chosen the use of grid-cells unit in the landsldie hazard assessment because in raster based GIS we can choose the gird size according to our need and depending on the data detailed hazard assessment can be done. However there are also authors (Carrara *et al.*, 1991), who prefer the use of other unit such as catchment units or slope sections. The hazard maps produced with these units are overly generalized. Table 3-5 shows the advantages and disadvantages of using different units in the landslide hazard assessment. The selection of unit may also be guided by the type of data and type of hazard assessment technique employed.

Among many useful classifications of assessment techniques for landslide hazard, the classifications given by Mantovani *et al.* (1996), and Hartle'n and Viberg (1988) cover the majority (Table 3-6). The methods of Mantovani *et al.* are for analysis methods (distribution analysis, qualitative analysis, deterministic analysis, landslide frequency analysis, and statistical analysis). The approach of Hartle'n and Viberg describes hazard types (absolute hazard, monitored hazard, empirical hazard, and relative hazard). Distribution analysis results in a map, which gives information pertaining only to those sites where landslides have occurred in the past. In qualitative analysis, which is also called geomorphological (Kienholz *et al.*, 1984, Mckean *et al.*, 1991), several characteristics of terrain are used to define landforms. The degree of hazard is then evaluated at each site of the terrain based on subjective decision rules. The deterministic approach (e.g., Skempton and Delory, 1957; Okimura, 1982; Sidle, 1992; Wu and Sidle, 1995; Mostyn and Fell, 1997) expresses the stability of slopes in terms of the safety factor (absolute hazard). For large areas, the variations in parameters included in the analysis of the safety factor are too large to accurately quantify (Jibson and Keefer, 1989; Mulder, 1991). In landslide frequency analysis (e.g., Capecchi and

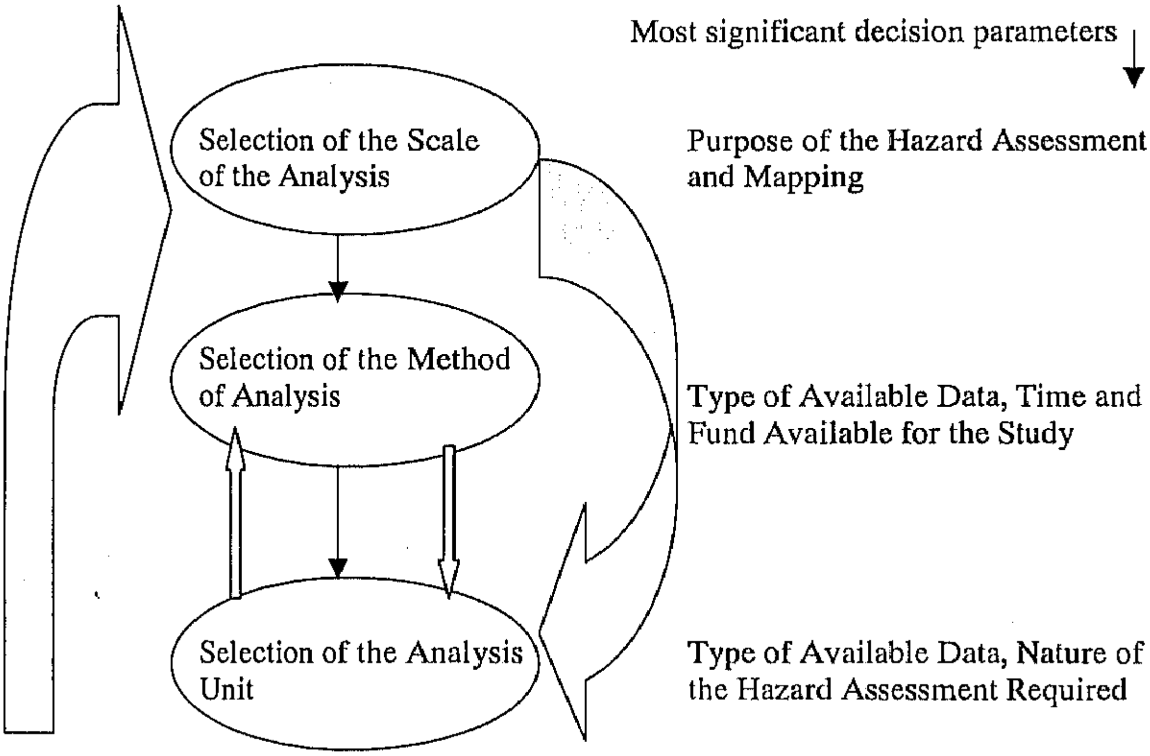

Figure 3-3 Phases of preliminary decision and confirmation during the initiation of landslide hazard assessment.

Table 3-3 Various decision components and their elements necessary to be considered primarily before the initiation of landslide hazard assessment.

Decision Components	Elements to be considered
Selection of the scale of analysis	1. Purpose of the hazard map. 2. Stage of the project for hazard assessment. 3. Availability of funds and nature of data.
Selection of the method of analysis	1. Scale of the analysis. 2. Availability of nature of data 3. Time and tool available for the analysis
Selection of the unit of the analysis	1. Nature of hazard assessment (detailed or generalized) 2. Precision of available data

Table 3-4 Scale of the analysis and objectives of hazard maps at different scales.

Scales of analysis	Purpose of analysis	Objective of hazard maps	Unit of analysis
Regional Scale (< 1:,100,000)	To outline problem areas with potential slope instability. Regional urban or infrastructural planning. The areas to be investigated are large (1000 km^2 or more)	The maps indicate regions where severe mass movement problems can be expected to threaten rural, urban or infrastructural projects.	Terrain units of several tens of hectares are outlined. Within these unit the degree of hazard is assumed to be uniform.
Medium Scale (1:25,000 - 1:50,000)	Sediment modeling at watershed level. Prioritization of sub-watershed for watershed management. Feasibility studies of engineering projects such as roads, and dam. The areas to be investigated are about several tens of km^2 to several hundreds of km^2.	More details are required at this scale. Details should be such that adjacent slopes in the same lithology are evaluated separately depending on other characteristics, such as slope angle and land use. The maps indicate either relative or absolute values of hazard.	Analysis can be based on grid-cell or slope sections or catchment sections depending on the nature of hazard map required and the type of data available.
Large Scale (> 1:10,000)	Detail planning of infrastructural housing, or industrial projects or for evaluation of risk within a city or town. Size of an area under study would be in the order of several tens of square kilometers.	The hazard class in this scale generally indicate absolute value such as probability of failures for each individual unit, or safety factor.	Analysis can be based on grid-cell or slope sections or catchment sections depending on the type of data to be used.

Table 3-5 Grid-cell vs. slope/catchment analysis unit: advantages and disadvantages.

Analysis unit	Advantages	Disadvantages
Grid-cells	1. Factors and classes do not have to be generalized or aggregated for a terrain unit.	1. Due to large number of grid-cells, sampling scheme of the grid-cells for the statistical analysis should be appropriate.
	2. The relationship between the occurrence of landslides and its causing factors can be evaluated at the same location of the landslide phenomena.	2. The errors in factor maps and landslide distribution map affect the results.
	3. The resulting hazard map is more detailed in nature.	3. Grid-cells do not bear any relation to the geomorphological and other environmental characteristics on which landslide occur.
	4. Analysis is relatively easy to perform within the raster based GIS.	
Slope/ Catchment unit	1. The physical relationship that exists between fundamental morphological elements of a mountain terrain and landsliding is preserved.	1. The resulting hazard map is rather very generalized and may not fulfil requirements at the medium scale.
	2. The errors in input factor maps basically landslide distribution map are reduced because of aggregation.	2. Results of the statistical analysis may be affected due to aggregation of data, and how to aggregate input factors is often a problem
	3. The units can be derived from DEM semi-automatically.	3. Generating drainage-divide networks from DEM is prone to errors if enough caution is not taken.

Table 3-6 Various methods of landslide hazard analysis [Developed from the concept of Hartle'n and Viberg (1988) and Mantovani *et al.* (1996)].

	Method		Methods of analysis	Type of Hazard	Type of data required	Most appropriate analysis scale
1	Geomorpho-logical		Descriptive statistics from fields, qualitative map combination etc.	Relative hazard	Maps, aerial photographs, and extensive field works	All scale
2	Statistical	Univariate Statistical Analysis	Susceptibility analysis Information value method	Relative hazard	Maps, aerial photographs, considerable field work.	Medium
		Multivariate statistical Analysis	Discriminant Analysis Multiple Regression Analysis	Relative hazard	"	Medium
3	Deterministic		Safety factor	Absolute hazard	Detailed soil properties, pore pressure	Large
4	Empirical		Empirical curves	Empirical hazard	Data pertaining to past landslides.	Medium / Large
5	Monitored	Deformation	Monitoring	Monitored hazard	Detail information on triggering factor and landslidng.	Medium
		Precipitation	Monitoring	Monitored hazard		

Focardi, 1988), earthquake and rainfall records are compared with landslide dates to obtain a threshold value for certain frequency levels (monitored hazard). The empirical hazard is assessed from earlier and active landslide data by examining relationships such as those between slope angle and relief (e.g., Zika *et al.*, 1988). The empirical and monitored hazards require continuous, long-term data on the landslides and their causative factors under similar environmental conditions. These data are often unavailable. In statistical analysis, the factors associated with topography, geology, and vegetation which can be considered as indices of the parameters of safety factor are quantified to assess their contributions to landsliding (relative hazard (Yin and Yan, 1988; Wang and Unwin, 1992; Pachauri and Pant, 1992; Sarkar *et al.*, 1995, Mark and Ellen, 1995)). This approach is based on the assumption that the landslides will be more likely to occur under conditions similar to those of previous landslides (Varnes, 1984; Brabb, 1984).

Statistical methods of hazard assessment are particularly appropriate for large areas. The benefit of a statistical model is that landslide assessment can be made rapidly, and site investigation cost is minimized. Moreover, the use of GIS has made this an effective method. A multivariate statistical approach, such as discriminant analysis (Davis, 1986) is considered better than the univariate statistical approach, because the former takes into account the interrelationships between the factors. The need to handle nominal data in discriminant analysis can be overcome by employing Quantification Scaling Type II (Q-S II) analysis (Hayashi, 1952, 1980, 1987), which can incorporate nominal data into the model. Two groups of sample data, the landslide and the non-landslide, are required for discriminant analysis. The critical assumption would be that the sampled data truly represent the population. It is usually stipulated that the two groups are similar in size (Klecka, 1980). Therefore, sampling for a non-landslide group is required due to a very large number of non-landslide data as compared to the number of landslide data, even if all landslide data are to be utilized. Hence, in hazard assessment based on a small grid-cell, the outcome of the analysis may depend on the sample of landslide and non-landslide data used in the analysis (Aniya 1985, Van Westen, 1993; Chung *et al.*, 1995).

Selecting a representative landslide group that occupies a very small area is not a difficult task whereas selecting a non-landslide group that occupies a large area is difficult because a 100-km^2 area consisting of 25 m x 25 m grid-cells results in a total of 160,000 grid-cells. The use of large grid-cell size (e.g., Cararra, 1983) or a land unit based on the catchment area or slope sections (e.g., Carrara *et al.*, 1991) may result in a hazard map that is overly generalized. The aggregation of data in a unit causes a generalization of the input variables, and the relationship between landslide and non-landslide group can not be evaluated at the location of the phenomena themselves (Van Westen, 1993, Chung *et al.*, 1995). Although sampling schemes have been shown to be crucial in the small grid-cell based statistical hazard models, no study exists which has attempted to clarify the problem.

A simple random sampling may be suitable for landslide cells. This approach, however, is not practical for obtaining non-landslide cells, because some parts of the area may be over sampled or under sampled. To overcome this problem for a non-landslide group, either a stratified random or systematic sampling may be effective. GIS is then applied to an examination of the effect of different landslide and non-landslide groups on the outcome of the critical factors and classes, from which hazard maps are produced. With GIS we can evaluate the classified grid-cells at the same location on different hazard maps, a process resulting in what I refer to hereafter as "spatial agreement".