Chapter 2

LITERATURE REVIEW

2.1 GENERAL

History of landslides in Murree and adjoining areas is old: numerous cases of landslides are regularly reported in the area. Accordingly, efforts are made by the concerned departments, consultants, and contractors to mitigate the problem. Most of the efforts made so far have been directed only to the triggered slide areas for stabilization and rehabilitation works. Geological Survey of Pakistan (GSP) and National Engineering Services of Pakistan (NESPAK) have carried out few project level studies in the area. In order to keep the roads / highways passable in all weather conditions, efforts are also made by the Forest Department, Murree and Galiat Development Authority (MDA / GDA), and Punjab Highway Department (PHD).

The efforts to mitigate landslides in the area are directed towards stabilization and restoration / rehabilitation works only. No efforts has been directed towards a comprehensive landslide hazard mapping of the area that should help in planning, design, and construction / maintenance of infrastructure projects, including management and relief works in case of landslide induced disaster.

The present research aims at developing an understanding of the factors affecting the slope instability, causing risk to the human life and property. The factors affecting the slope stability include the natural environment of the area including relief, geology / seismic activity (history, setting and processes), hydrologic / climatic conditions, and vegetation (type, nature, and density). Therefore, literature search is carried out to gather information regarding the natural environment of the area. Study area description, landslide zoning and the associated risk, including risk modeling concepts, principles, and methods as covered in the literature are explained in the following sections.

2.2 DESCRIPTION OF THE STUDY AREA

Murree is located at a distance of about 65km north-west of Islamabad and 75km south-west of Abbottabad. Murree being one of the busiest hill stations in Northern Pakistan attracts a large number of tourists. It is estimated that there are more than 1000 hotels and guest houses in the Murree urban area. The population of Murree urban area increases approximately from 25,000 to 300,000 during peak summer season. Furthermore, tourist related commercial activities like shops, hotels, motels and residential construction is also growing at a very rapid pace. A number of important strategic and defense installations like Airforce Base and Army Headquarter are located in Murree and its close proximity. Additionally, the road link between Islamabad and Muzaffarabad (Azad Jammu and Kashmir) also traverses through Murree.

The altitude of Murree hills above mean sea level ranges from 1600m at Lawrenace College, Ghora Gali to 2200m at Kashmir Point. These hills form watershed in the form of steep lateral spurs. Geographically, Murree and Galiat area form the southern part of outer or sub Himalayas. Location map of Murree is shown in Fig. 2.1 (GSP, 1999), the layout map in Fig. 2.2 (Survey of Pakistan, 1997), highlights the main highways and roads of urban Murree area.

2.3 GEOLOGIC HISTORY

The geological history of the area reveals that the Galiat hills were formed during the mountain building process (Orogeny) of Himalayas (Mehdiratta, 1989). The modern concept of Himalayan Orogeny is based on "plate tectonic theory". Under this process, the crustal material is supposed to be generated from a deep mantle depth in the mid-oceanic ridges and "spread side-ways". Geological investigations have proved that the crust together with a thickness of the upper mantle down to the "Low Seismic Velocity Layer" (100-150km from the earth surface) – the two together being called the lithosphere. The lithosphere is broken into smaller plates. These plates move and push against each other, converge, diverge or plunge. As a result, trenches are formed; sediments are laid down and folded to form mountains. It is envisaged that India, Africa, Australia, and South Africa were once one big continent lying in the southern hemisphere of the earth (Mehdiratta, 1989). This landmass was separated by Tethys Ocean from another supercontinent in the northern hemisphere consisting of North America, Greenland, and Eurasia. Tethys was a big ocean and existed from Tibet to the Mediterranean Sea. About 130 to 180 millions years ago, the supercontinent in the southern hemisphere got disintegrated into drifting plates which ultimately developed into mid-oceanic ridges (Gohar, 1987). The distance between these ridges increased with time and resulted in the development of Indian Ocean. Further northward advance of African and Indian plates towards Eurasian plates closed down the intervening Tethys and resulted in Himalayan Orogeny.

The upheaval of Himalayas was not a continuous process; it took place in four successive stages (Mehdiratta, 1989). The first rise or push up of sediments of Tethys took place in the upper Eocene period resulting in the breaking up of the continuity of the ocean basin into smaller areas of sedimentation. During the interval that followed were laid the sediments of Murree, Nari, and Ghaj formations.

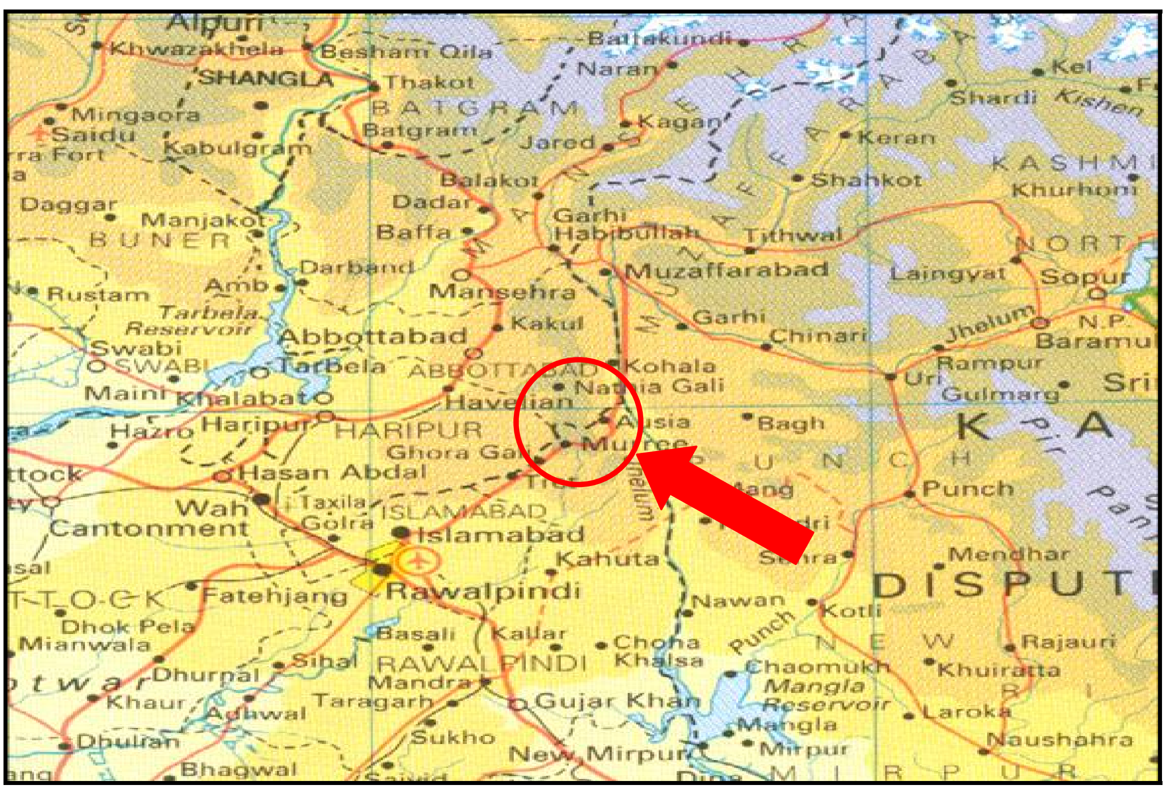

Fig. 2.1. Location Map of Murree Area (GSP, 1999)

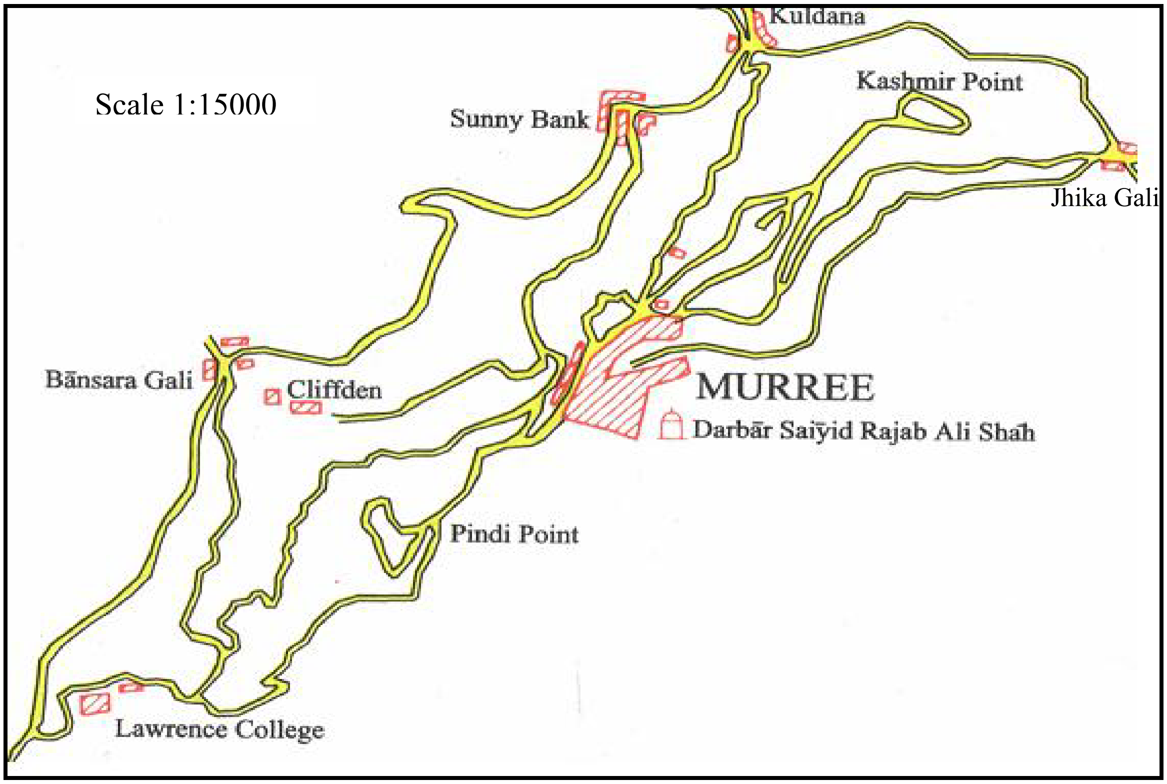

Fig. 2.2. Layout Map of the Study Area (Murree Guide Map, Survey of Pakistan, 1997)

The second upheaval took place during the middle Miocene times, resulting in the laying of Siwalik sediments. The third phase came off in upper Pliocene period and this gave rise to Siwalik Hills. The fourth period commenced in Pleistocene period when the soft and incoherent sediments were pushed upto their existing positions. The last phase of Himalayan Orogeny is not believed to have died out and the mountains are getting higher and all the Himalayan streams as a result of upheaval are very active and are excavating steep-sided or U-shaped valleys.

2.4 TECTONICS / SEISMICITY OF STUDY AREA

Himalayan system is classified into three longitudinal portions differing from one another, in well marked orographic boundaries (Gohar, 1987):

- Outer or Sub Himalayas
- Central or Middle or Lesser Himalayas
- Northern or Tibetan Zone

The study area is tectonically placed on the southward extension of the Garhi HabibUllah syncline located in the outer Himalaya (Gohar, 1987). Indian subcontinent is moving northward at a rate of about 4cm/year and colliding with the Eurasian continent. This collision is causing uplift that produces the highest mountain peaks in the world including the Himalayas, the Karakoram, the Pamir and the Hindu Kush ranges. As the Indian plate moves northward, it is being subducted or pushed beneath the Eurasian plate much of the compressional motion between these two colliding plates has been and continues to be accommodated by the slip on a suite of major thrust faults that dip northward beneath these mountain ranges. These include the Main Frontal Thrust (MFT), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Mantle Thrust (MMT).

There are three main thrust zones recognized in the study area, the southern most part of these thrust zones is generally designated as Main Boundary Thrust (MBT) (Gohar, 1987). MBT is the result of the folding and thrusting of the Murree formation rocks against the Paleozoic rocks in the foreland of the Himalayan zone. The other faults are Panjal and Zankasar Thrust faults. Tectonic map of the Northern Pakistan is shown in Fig. 2.3 (GSP, 1999).

2.5 GEOLOGIC STRATIFICATION

As explained earlier, the geological history reveals that the Galiat hills were formed during the mountain building process (Orogeny) of Himalayas. Himalayan orogeny is the result of the subduction of the Indian Plate beneath the Eurasian Plate at a constant rate of 4cm/year. The result is the formation of several thrust faults among which Main Boundary Thrust (MBT) have traces near the study area. MBT is resulting in the thrusting of Murree Formation with the Paleozoic rocks (Gohar, 1987). MBT can be traced at Darya Gali, located about 8km from Murree on Murree-Nathiagali Road. The geologic map of the study area is shown in Fig. 2.4 (GSP, Sheet No. 1, 2000).

The rock units on the southern side of MBT consist of Miocene age Murree Formation, while rocks units exposed on the northern side of MBT (Darya Gali to Abbotabad) consist of several Formations ranging from pre-Cambrian to Eocene age. The study area entirely consists of Murree Formation (Tmm): Murree Formation is alternate sequences of sandstone, siltstone, and shale with occasional intraformational conglomerate (GSP, 2000).

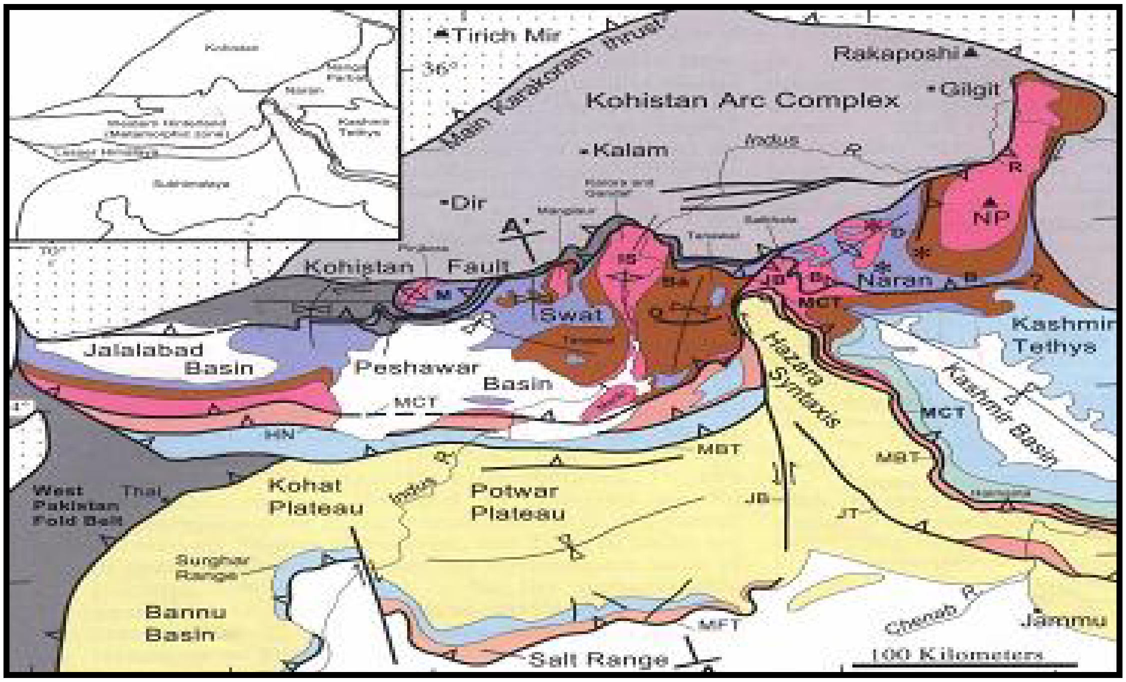

Fig. 2.3. Tectonic Map of Northern Pakistan (GSP, 1999)

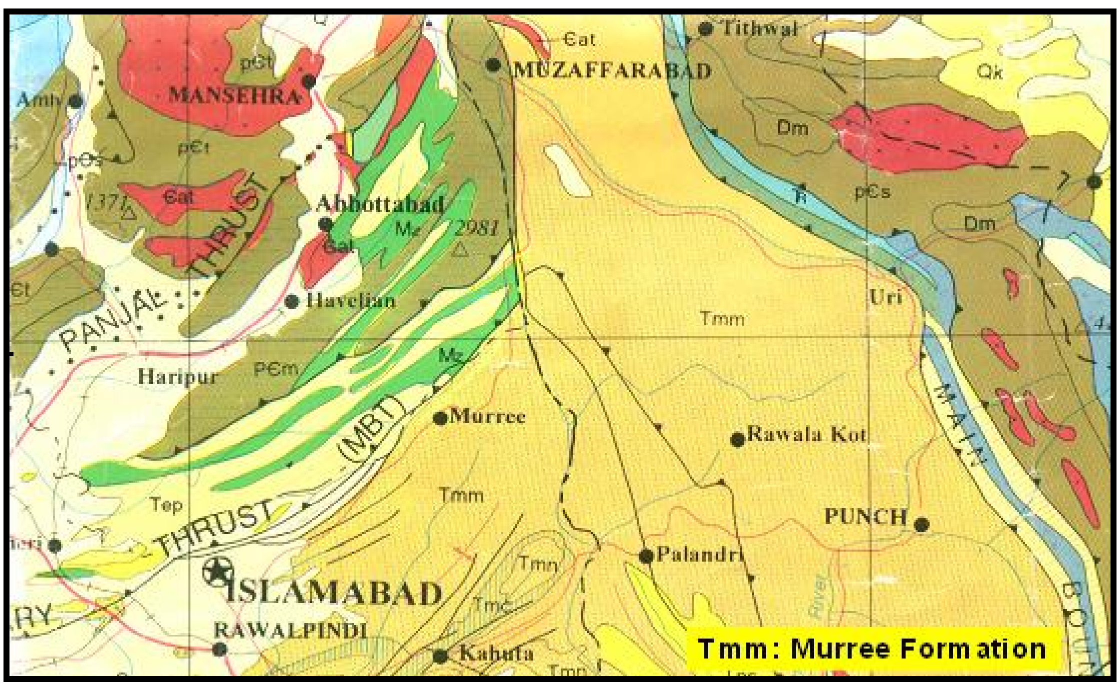

Fig. 2.4. Geological Map of the Study Area (GSP, 2000)

2.6 CLIMATIC AND VEGETATION CONDITIONS

The study area is characterized by both diurnal and seasonal variations in weather and climate (Khan et al., 1987). Generally, the climate is tropical but, at higher altitudes, the winters are very cold. According to Gohar (1987), the study area falls in Maritime climatic zone, characterized by high rainfall and warmer temperatures. The area receives most of the rainfall from July to September, known as Monsoon rains. Most of the precipitation is in the form of snowfall. The area receives winter rains in the month of March accompanied by thawing of snow. Average annual rainfall in the area is from 1200 to 1400mm (Khan et al., 1987 and Gohar, 1987). The summer temperatures in Murree and Galiat vary between 25^o to 30^{o}C, and the humidity ranges between 50% and 60% (Khan et al., 1987). The hills around Murree and their southern slopes have a fairly thick growth of Pine trees.

2.7 TYPES OF SLOPE FAILURES IN STUDY AREA

Slopes in the mountainous areas may fail in a variety of ways, depending on the slope configuration, the type, nature, and saturation level of the strata, land use, and local environmental factors such as extent and type of vegetation, intensity and variation of temperature and precipitation, weathering extent etc. Mass movements (landslides, mass wasting) may take place suddenly and catastrophically, resulting in debris and snow avalanches, rock falls and slides, flows (debris, quick clay, loess, and dry or wet sand and silt). Slower movements result in slides (debris, rock blocks), topples, slumps (rock, soil), complex landslides and creep.

Based on the literature review, the study area is characterized by the following types of slope failures / landslides:

- Rotational Slope Failures
- Boulder Falls
- Road Settlements / Failures

2.8 LANDSLIDE STABILIZATION / REHABILITATION WORKS IN THE STUDY AREA

Investigation, stabilization, and rehabilitation efforts carried out on the landslides in the area by various agencies are highlighted in the following sections.

2.8.1 Geological Survey of Pakistan (GSP)

Khan et. al. (1987) conducted a study of various chronic landslides locations along Rawalpindi-Murree-Kohala Highway (Kashmir Highway). The investigations were carried out during the rainy season (July-August) of 1984 and 1985. Surface geologic observation / mapping method were used for investigating the landslides. Out of total thirteen landslides locations in the study area four were investigated.

2.8.2 National Engineering Services of Pakistan (NESPAK)

Several project level studies have been performed by NESPAK in the study area. Some of the investigated locations were Shi Fang, Shawala, Chitta Morrr, and Kuldanna. Photographic views of landslide rehabilitation works supervised by NESPAK at Chitta Morrr and Shawala Landslides are shown in Fig. 2.5 and Fig. 2.6 respectively. In all the studies, extensive investigations were only concentrated to the chronic landslides areas. Investigations resulted in determining the probable failure reasons specific to selected locations only. Based on the probable reasons of instability at the investigated locations, recommendations were furnished for short-term and long-term treatment of the investigated areas.

2.8.3 Other Responsible Departments

MDA, GDA, Forest Department, and PHD are responsible to keep the roads open in all weather conditions in their respective areas of responsibility. The literature search and reconnaissance visits of the study area indicate that mostly rehabilitative works and minor stabilization works are undertaken by these departments.

Fig. 2.5. Stabilization Work at Chitta Morr Landslide by NESPAK

Fig. 2.6. Stabilization Work at Shawala Landslide by NESPAK

2.9 LANDSLIDES HAZARD ZONATION TECHNIQUES

Hazard is defined as the probability of occurrence of a potential phenomenon within a specified period of time and within a given area (Varnes, 1984). Zonation is the division of land into homogeneous areas or domains and their ranking according to degrees of actual / potential hazard caused by mass movements (Varnes, 1984).

Landslides hazard is typically depicted on maps which show spatial distribution of hazard classes, or "landslide hazard zonation."

Slope instability processes are the product of local geomorphic, hydrologic, and geologic conditions; the modification of these conditions by geodynamic processes, vegetation, land use practices, and human activities; and the frequency and intensity of precipitation and seismicity (Soesters and Westen, 1996). The development of the zonation requires knowledge of the processes active in the area being analyzed, and factors (conditioning and triggering) leading to the occurrence of landslides. Considering the many terrain factors involved in slope instability, the practice of landslide hazard zonation requires (Soesters and Westen, 1996):

- A detailed inventory of slope instability processes.
- The study of these processes in relation to their environmental setting.
- The analysis of conditioning and triggering factors.
- Representation of the spatial distribution of these factors.

The engineering approach to landslide studies is focused on analysis of individual slope failures and their remedial measures. The techniques used in these studies are in accordance to size and type of individual landslide, thereby; do not incorporate zonation of extensive areas according to their susceptibility to slope instability phenomena. The need for area zonation has increased with the understanding that proper planning will decrease considerably the costs of construction and maintenance of engineering structures. In this regard, landslides hazard mapping concepts, techniques, and methods are explained in the subsequent sections.

2.9.1 Direct and Indirect Hazard Mapping Techniques

Prediction of landslide hazard for areas not currently subject to landsliding is based on the assumption that hazardous phenomena that have occurred in the past can provide useful information for prediction of future occurrences. 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:

- **Direct Hazard Mapping Technique**

  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 the direct mapping methodology.

- **Indirect Hazard Mapping Technique**

  The opposite of 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. Typical landslide hazard mapping parameters are shown in Table 2.1 (Soesters and Westen, 1996).

2.9.2 White, Black, and Grey Box Models

Another useful division of techniques for assessment of slope instability hazard was given by Harden and Viberg (1988); they differentiated between relative-hazard assessment and absolute-hazard assessment techniques. Relative-hazard assessment techniques differentiate the likelihood of occurrence of mass movements for different areas on the map without giving exact values. Absolute-hazard maps display an absolute value for the hazard, such as a factor of safety or a probability of occurrence. Hazard assessment techniques can also be divided into three main groups (Carrara 1983; Harden and Viberg, 1988). These groups are defined below and the approaches being used to develop such models are explained in the following sections:

- **White Box Models**
  Based on physical models (slope stability and hydrologic models), also referred to as deterministic models.

- **Black Box Models**
  Not based on physical models but strictly on statistical analysis.
- **Grey Box Models**
  Based partly on physical models and partly on statistics.

Table 2.1. Overview of Input Data in Landslide Hazard Analysis (Soesters and Westen, 1996)

DATA LAYERS FOR SLOPE INSTABILITY HAZARD ZONATION	ACCOMPANYING DATA IN TABLES	SCALE OF ANALYSIS METHOD USED	REGIONAL	MEDIUM	LARGE
GEOMORPHOLOGY					
1. Terrain mapping units	Terrain mapping units	SII + walk-over survey	3	3	3
2. Geomorphological (sub)units	Geomorphological description	API + fieldwork	2	3	3
3. Landslides (recent)	Type, activity, depth, dimension etc.	API + API checklist + fieldwork + field checklist	1	3	3
4. Landslides (older period)	Type, activity, depth, dimension, date, etc.	API + API checklist + landslide archives	1	3	3
TOPOGRAPHY					
5. Digital terrain model	Altitude classes	With GIS from topographic map	2	3	3
6. Slope map	Slope angle classes	With GIS from DTM	2	3	3
7. Slope direction map	Slope direction classes	With GIS from DTM	2	3	3
8. Slope length	Slope length classes	With GIS from DTM	2	3	3
9. Concavities/convexities	Concavity /convexity	With GIS from DTM	1	1	3
ENGINEERING GEOLOGY					
10. Lithologies	Lithology, rock strength, discontinuity spacing	Existing maps + API + fieldwork, field and laboratory testing	2	3	3
11. Material sequences	Material types, depth, USCS classification, grain-size distribution, bulk density, *c* and cp	Modeling from lithological map + geomorphological map + slope map, field descriptions, field and laboratory testing	1	2	3
12. Structural geological map	Fault type, length, dip, dip direction, fold axis, etc.	SII + API + fieldwork	3	3	3
13. Seismic accelerations	Maximum seismic acceleration	Seismic data + engineering geological data + modeling	3	3	3
LANDUSE					
14- Infrastructure (recent)	Road types, railway lines, urban extension, etc.	API + topographical map + fieldwork + classification of satellite imagery	3	3	3
15. Infrastructure (older)	Road types, railway lines, urban extension, etc.	API + topographical map	3	3	3
16. Land use map (recent)	Land use types, tree density, root depth	API + classification of satellite imagery + fieldwork	2	3	3
17. Land use map (older)	Land use types	API	2	3	3
HYDROLOGY					
18. Drainage	Type, order, length	API + topographical maps	3	3	3
19. Catchment areas	Order, size	API + topographical maps	2	3	3
20. Rainfall	Rainfall in time	From meteorological stations	2	3	3
21. Temperature	Temperature in time	From meteorological stations	2	3	3
22. Evapo-transpiration	Evapo-transpiration in time	From meteorological stations and modeling	2	3	3
23. Water table maps	Depth of water table in time	Field measurements of *K* + hydrological model	1	1	2

NOTE: The last three columns indicate the possibility for data collection for the three scales of analysis: 3 = good, 2 = moderate, and 1 = poor. Abbreviations used: SII = satellite image interpretation, API = aerial photo-interpretation, DTM = digital terrain model, GIS = geographic information system, K_{sat} = saturated conductivity testing.

2.9.2.1 Heuristic Approach

In heuristic methods the expert opinion of the geomorphologist 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. Two types of heuristic analysis can be distinguished: geomorphic analysis and qualitative map combination. The concept of heuristic approach is highlighted in Fig. 2.7 (Soesters and Westen, 1996).

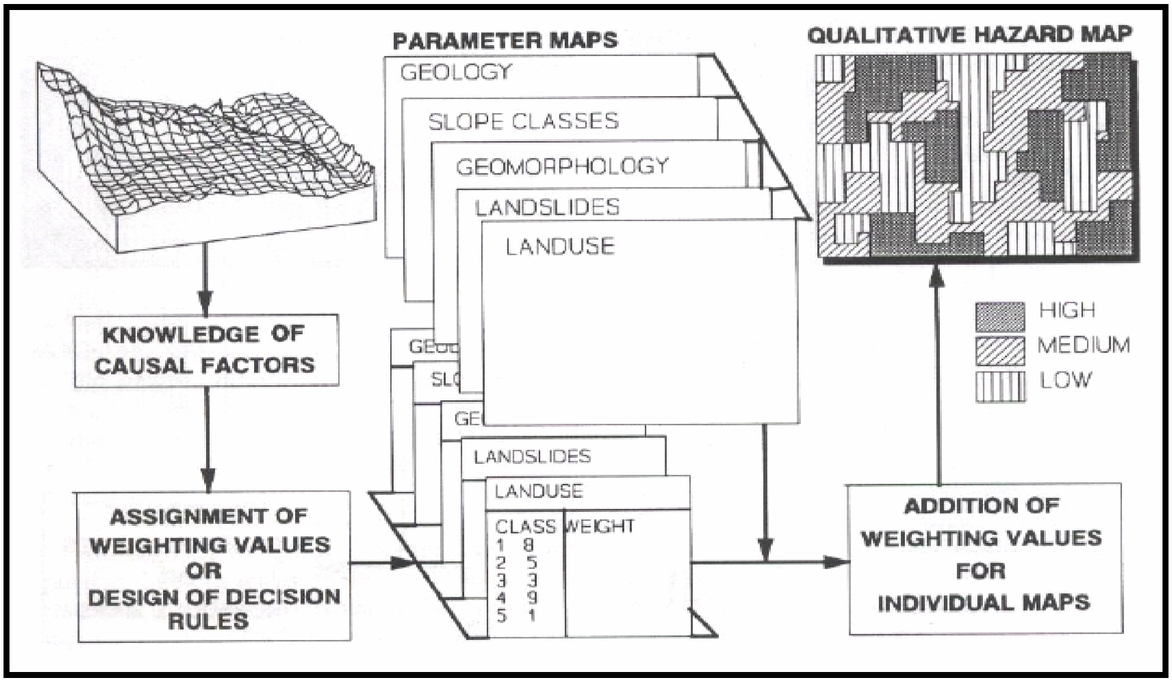

Fig. 2.7. Heuristical Approach in Landslide Hazard Zoning (Soesters and Westen, 1996)

2.9.2.2 Statistical Approach

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. Two different statistical approaches are used in landslide hazard analysis: Bivariate and multivariate.

2.9.2.3 Deterministic Approach

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 types are 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 their high degree of oversimplification. A deterministic method that is usually applied for translational landslides is the infinite slope model. These deterministic methods generally require the use of groundwater simulation models. Stochastic methods are sometimes used to select input parameters for the deterministic models (Mulder and van Asch, 1988; Mulder, 1991). The flowchart of activities in a deterministic model is shown in Fig. 2.8 (Soesters and Westen, 1996).

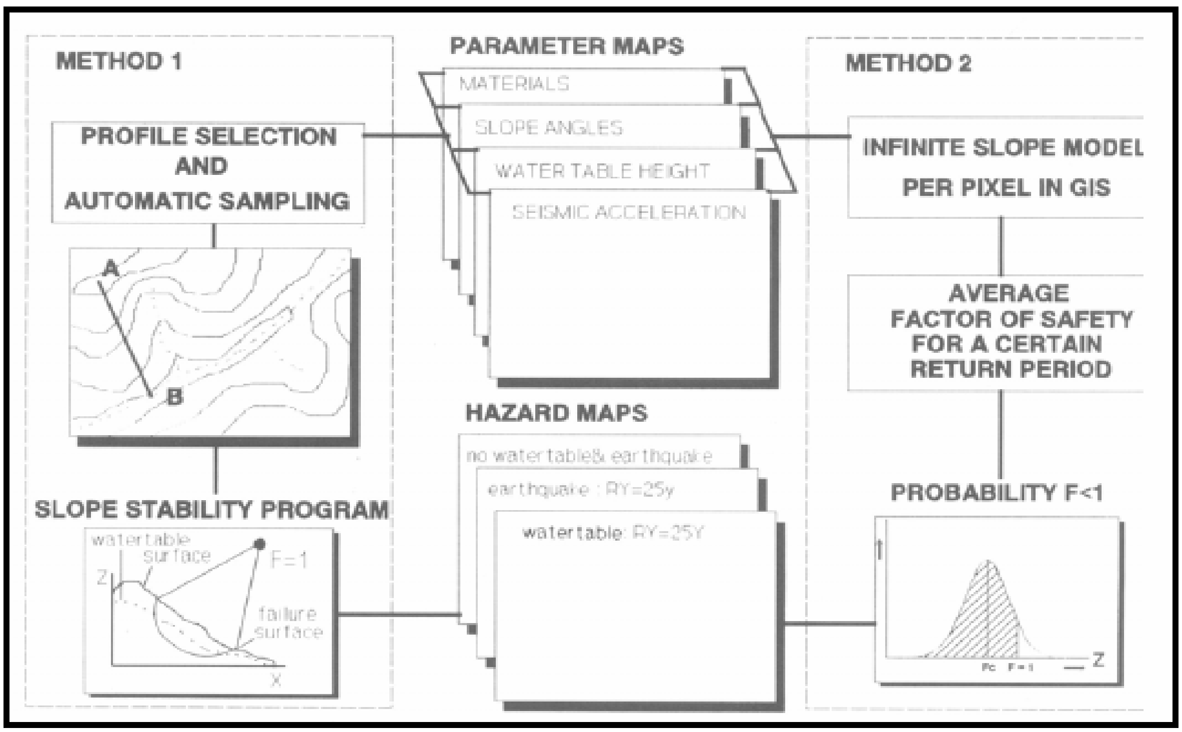

Fig 2.8. Deterministic Approach for Landslide Hazard Zoning (Soesters and Westen, 1996)

2.9.3 Fuzzy Set Theory and Logic

Statistical techniques aim at a higher degree of objectivity and better reproducibility of hazard zonation. There are many statistical methods used in this field.

All the available methods for regional landslide assessment have some uncertainties arising from lack of knowledge and variability. This is because regional landslide assessments require some generalizations and simplifications, although these assessments are complex. For this reason, a perfect assessment method for landslide susceptibility does not exist. The fuzzy logic introduced by Zadeh (1965) is one of the tools to solve these complex problems. Problems in the real world quite often turn out to be complex owing to an element of uncertainty either in the parameters which define the problem or in the situations in which the problem occurs (Rajasekaran and Vijayalakshami, 2004). Although probability theory has been classically used since long time to handle uncertainness, it can be applied only to those problems where the occurrence of events takes place only by chance. However, in reality, there turn out to be problems, a large class of them whose uncertainty is characterized by a nonrandom process. In such problems, uncertainty may arise from partial information about the problem or due to information which is not fully reliable, or due to inherent imprecision in the language with which the problem is defined, or due to receipt of information from more than one source about the problem which is conflicting (Rajasekaran and Vijayalakshami, 2004). It is under such situations that Fuzzy Set Theory exhibits immense potential for effective solving of the uncertainty in the problem. Fuzzy set theory is an excellent mathematical tool to handle the uncertainty arising due to vagueness.

The idea of fuzzy logic is to consider the spatial objects on a map as members of a set. In classical set theory, an object is a member of a set if it has a membership value of 1, or not a member if it has a membership value of 0. In fuzzy set theory, membership can take on any value between 0 and 1 reflecting the degree of certainty of membership. Fuzzy set theory employs the idea of a membership function that expresses the degree of membership with respect to some attribute of interest. With maps, generally the attribute of interest is measured over discrete intervals, and the membership function can be expressed as a table relating map classes to membership values.

2.9.4 Use of Fuzzy Set Theory and Logic in Landslides Studies

The idea of using fuzzy logic in landslide susceptibility mapping is to consider the spatial objects on a map as members of a set (Tangestani, 2000). For example, the spatial objects could be areas on an evidence map and the set defined as "areas susceptible to landslide". Fuzzy membership values must lie in the range between 0 - 1, but there are no practical constraints on the choice of fuzzy membership values. Values are simply chosen to reflect the degree of membership of a set, based on subjective judgment.

Lee and Juang (1992) carried out failure potential mapping in mudstone slopes in Taiwan using Fuzzy Sets. They developed a qualitative evaluation technique for assessing the slope failure potential. The main thrust of the evaluation scheme is an evaluation tree consisting of two levels of factors that are known by experts to affect stability of slopes. The concept of evaluation-tree is shown in Fig. 2.9 (Lee and Juang, 1992). Selection of these factors and weights among them are based on results of a survey of expert opinions on slope failures in the Southwestern Taiwan mudstone area. Finally, a slope failure potential map was prepared for the studied area.

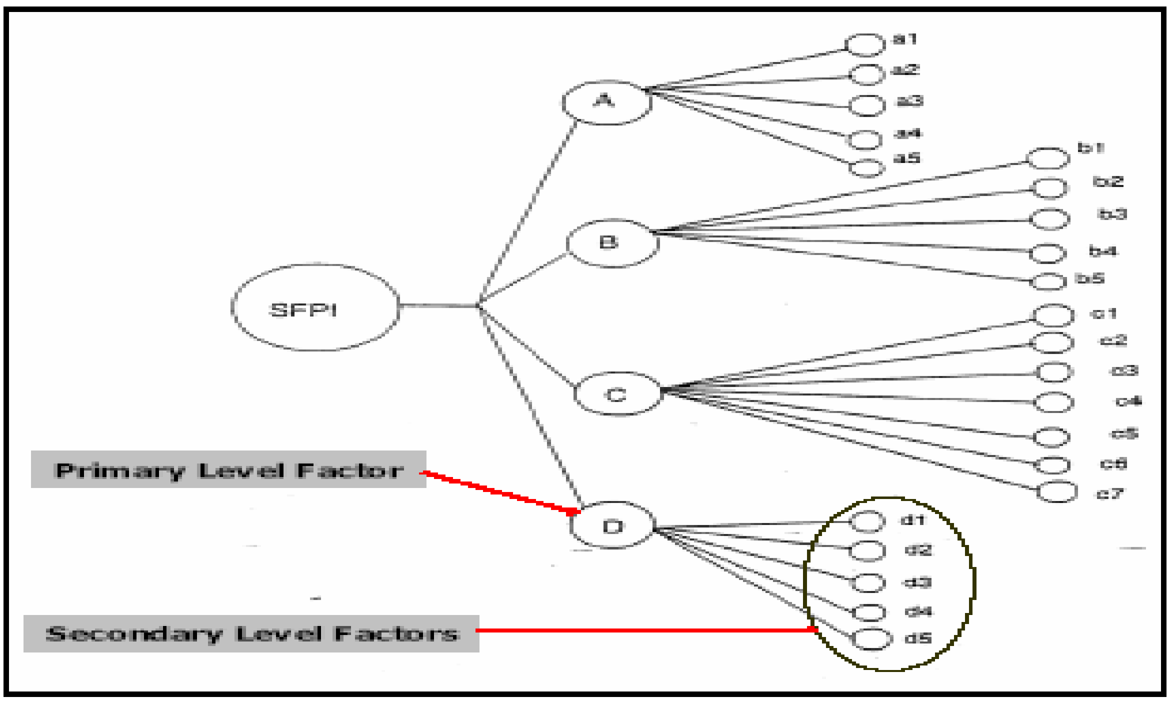

Fig. 2.9. Slope Failure Potential Factors Tree (Lee and Juang, 1992)

Jawaid (2000) studied the use of Fuzzy Theory for the hazard assessment of landslides. He prepared a low cost quantitative landslides potential evaluation scheme using Fuzzy Set Theory. He used an evaluation tree similar to the one proposed by Lee and Juang (1992). In this study, Topography, Geology, Environment, and Metrology were considered as the primary factors affecting the slope stability. Chi et al., (2002) studied the effectiveness of the fuzzy set theory for landslide hazard mapping using spatial data from Boeun in Korea. In this study, they collected several data sets related to landslides occurrences in Boeun, Korea, and then digitally represented as the fuzzy membership functions. The data was integrated using fuzzy inference networks through a variety of different fuzzy operators. The results show that the fuzzy set theory can integrate effectively various spatial data for landslide hazard mapping.

2.9.5 Use of GIS in Analysis and Prediction of Landslides

A large database is necessary for the analysis and prediction of slope failures. It needs to be able to store, manipulate, and apply the data collected in first two stages (recognition and monitoring). A Geographical Information System (GIS) is ideal for this stage in a landslide investigation because it is capable of handling large amounts of past, present and future data and integrating this data with predictions. It is capable of data storage and visualization, it is cheaper and easier to use than a manual map production and overlay, and it can have regional databases, and therefore perform both local and regional modeling. There are many types of GIS packages which differ in terms of hardware requirements, potential of spatial functions, efficiency of the data-base, and internal data structure.

2.10 LANDSLIDES HAZARD MAPPING WORKS IN STUDY AREA

In the Murree and Galiat area, Ishfaq (2005) carried out landslide hazard zonation of Murree to Kohala area using remote sensing (satellite imageries) and GIS techniques. In this study, a number of parameter maps were prepared by collecting information from various sources and converted to GIS maps. The susceptibility assessment was based on multivariate statistical techniques also authenticated on ground. The minor inaccuracies in susceptibility assessment were due to non-availability of accurate maps for deriving the Digital Elevation Model (DEM) and other factor maps. The result of the study concluded that the inherent vulnerability of the study area is because of both natural and man induced activities. Typical Digital Elevation Model (DEM) and the hazard map prepared by Ishfaq (2005) are shown in Fig. 2.10.

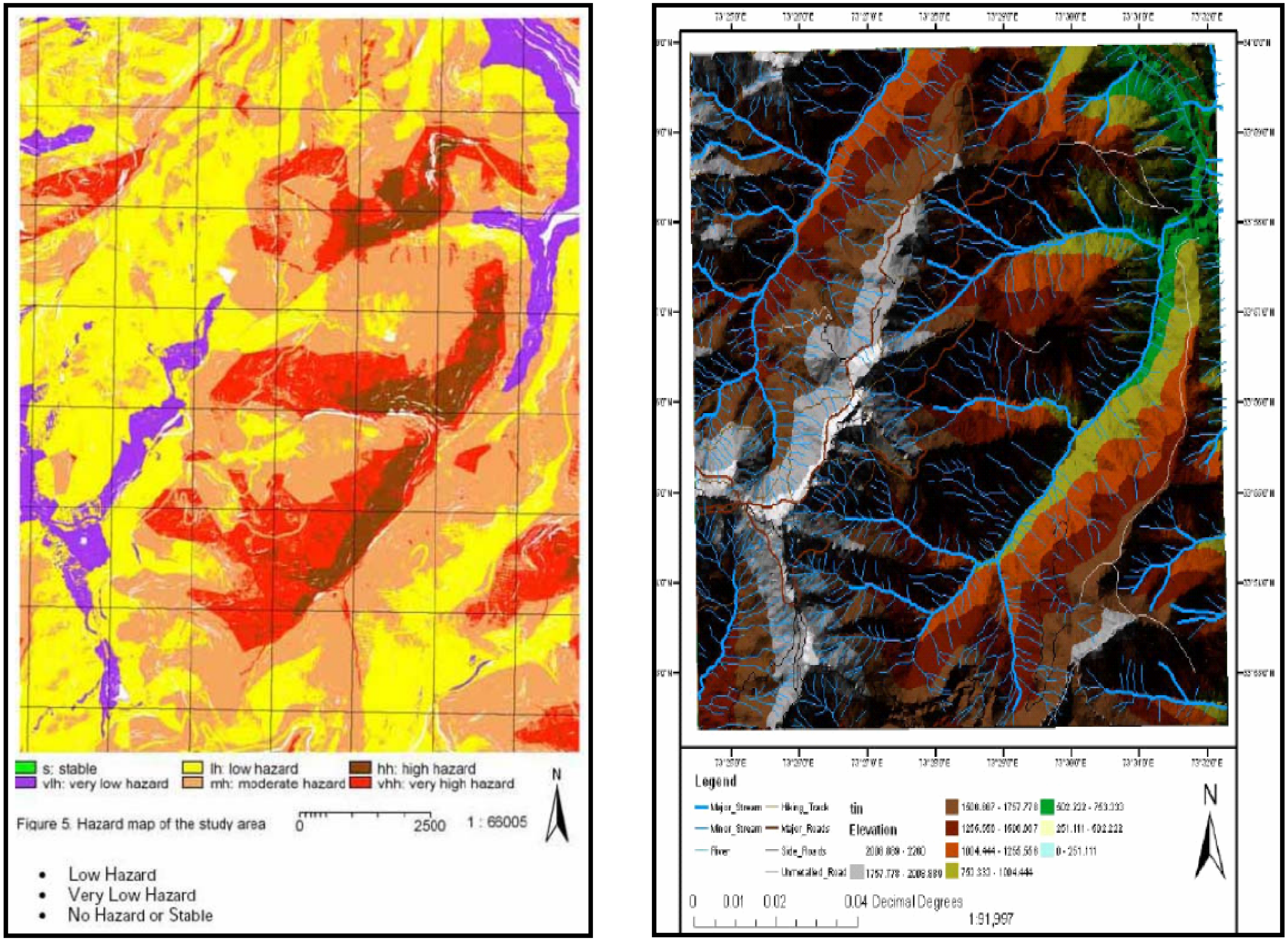

Fig. 2.10: Digital Elevation Model (DEM) and Landslide Hazard Map of Northern Murree Area (Ishfaq, 2005)

2.11 LANDSLIDES RISK MAPPING TECHNIQUES

The likelihood of adverse consequences arising from the occurrence of an event, such as a landslide, is termed as risk (Lee and Jones, 2004). Slope inspections and landslide studies have always involved some simple form of risk assessment. Informal assessments of risk have generally relied on the judgment and skill of experienced engineers, geologists and geomorphologist. Recognition of hazard, mapping of areas of current or past instability and development of an understanding of the causes and mechanisms of failure, are essential for making judgments about the significance of landslide problem within an area. As a consequence, decision-makers have often been able to act on specialists' advice without having quantified risk.

In this section methods of quantitative risk assessment are described as found in literature. However, on many occasions an estimate of risk in terms of economic impact or loss of life cannot either be realistically achieved because of constraints of time, resources and availability of data, or is simply not required (Lee and Jones, 2004). A variety of qualitative or semi-quantitative risk assessment methods have been developed to address these issues, including:

- Relative risk scoring
- Risk ranking matrices
- Relative risk rating
- Failure modes, effects and criticality analysis (FMECA)

These methods have the following common points:

- The sub-division of the area of interest into sub-units, often on the basis of geomorphology, geology or the dominant observed landslide process. This require mapping as a pre-requisite for risk assessment.
- Assessment of the likely magnitude, frequency and impact potential of landsliding within each identified units during defined period of time, using scoring or ranking schemes.

- The use of expert judgment. It is vital that effort is directed towards ensuring that all judgments can be justified through adequate documentation, allowing any reviewer to be able to know the reasoning behind particular scores or ranking.

2.11.1 Relative Risk Scoring

In many insatnces it is not possible (or atleast very difficult) to evaluate risk in absolute terms because of the difficulties in assigning meaningful values for the hazard, the assets or elements at risk and possible adverse consequences (Chowdhury, R.N. et al., 2001). In such situation, it can be useful to assess the relative levels of the threat, or relative risk, to different sites exposed to the particular hazard, based on both factual data and subjective assessment. The value of relative risk aassessment is that it can enable sites to be compared quickly and hence allow early decisions to be made about where limited financial resources should be directed (Clark, A. R. et al., 1993).

The relative risk scoring approach utilises the basic definition of risk (Lee and Jones, 2004).

$$\text{Risk} = (\text{Probability of Hazard}) \times (\text{Adverse Consequences}) \qquad (2.1)$$

However, the hazard probablitity (i.e. landsliding) and adverse consequences, elements in Eq. (2.1) are all represented by relative scores or rank values, with the risk being the product of these scores.

The probability of landsliding of a particular magnitude can be represented by a hazard number:

$$\text{Hazard Number} = (\text{Hazard Score}) \times (\text{Probability Score}) \qquad (2.2)$$

Similarly, the adverse consequences can be represented by a risk value (i.e. the relative value of the assets or elements at risk) and the vulnerability of the assets or elements at risk:

$$\text{Adverse Consequences} = (\text{Risk Value}) \times (\text{Vulnerability}) \qquad (2.3)$$

The risk, expressed as number, is calculated as follows:

$$R_N = (H) \times (P) \times (R) \times (V) \qquad (2.4)$$

Where:

R_N = Risk Number

H = Hazard Score

P = Probability Score

R = Risk Value

V = Vulnerability

The risk numbers produced can be used to place each site within an arbitirarily defined class that allows comparision between sites and provide basis for management decisions.

2.11.2 Risk Ranking Matrices

This is another technique for risk scoring which involves the development of a risk matrix. In this approach measure of the likelihood of a hazard occuring is matched against the rising severity of consequences to provide a ranking of risk levels as explained in Fig. 2.11 (Lee and Jones, 2004). Even though ranking are value judgments, experienced landslide specialists should be able to reallistically assess the likelihood of events and consequences, based on an appreciation of the landslide environment and knowledge of particular site (Chowdhury, R.N. et al., 2001 and Lee et al., 2004).

	Consequences			
Probability	**Severe**	**Moderate**	**Mild**	**Negligible**
High	High	High	Medium / Low	Near Zero
Medium	High	Medium	Low	Near Zero
Low	High / Medium	Medium / Low	Low	Near Zero
Negligible	High / Medium / Low	Medium / Low	Low	Near Zero

Fig. 2.11. Example of a Risk Matrix (Lee and Jones, 2004)

Table 2.2a and 2.2b (Australian Geomechanics Society, 2000) present typical scales of hazard likelihood and consequences that could be adapted to particular circumstanses. Relative risk levels can then be assigned to different combinations of hazard and consequences as shown in Table 2.2c (Australian Geomechanics Society, 2000). Each relative risk level should mark a step-up in the degree of threat and a change in the acceptibility or tolerability of the risk as described in Table 2.2d (Australian Geomechanics Society, 2000).

Table 2.2a. Indicative Measures of landslide likelihood (Australian Geomechanics Society, 2000)

Level	**Descriptor**	**Description**	**Indicative Annual Probability**
A	Almost certain	The event is expected to occur	$> \approx 10^{-1}$
B	Likely	The event will probably occur under adverse conditions	$\approx 10^{-2}$
C	Possible	The event could occur under adverse conditions	$\approx 10^{-3}$
D	Unlikely	The event might occur under very adverse circumstances	$\approx 10^{-4}$
E	Rare	The event is conceivable but only under exceptional circumstances	$\approx 10^{-5}$
F	Not credible	The event is inconceivable or fanciful	$<10^{-6}$
Note. '≈' means that the indicative value may vary by say ± half of an order of magnitude, or more			

Table 2.2b. Indicative Measures of Consequences (Australian Geomechanics Society, 2000)

Level	Descriptor	Description
1	Catastrophic	Structure completely destroyed or large-scale damage requiring major engineering works for stabilization
2	Major	Extensive damage to most of structure, or extending beyond site boundaries, requiring significant stabilization works
3	Medium	Moderate damage to some of structure, or significant part of site, requiring large stabilization works
4	Minor	Limited damage to part of structure, or part of site, requiring some reinstatement / stabilization works
5	Insignificant	Little damage

Table 2.2c. Qualitative Risk Assessment Matrix: Levels of Risk to Property (Australian Geomechanics Society, 2000)

Likelihood	Consequences to Property				
	1 Catastrophic	**2 Major**	**3 Medium**	**4 Minor**	**5 Insignificant**
A (almost certain)	VH	VH	H	H	M
B (likely)	VH	H	H	M	L-M
C (possible)	H	H	M	L-M	VL-L
D (unlikely)	M-H	M	L-M	VL-L	VL
E (rare)	L-M	L-M	VL-L	VL	VL
F (not possible)	VL	VL	VL	VL	VL

Table 2. 2d. Indicative Risk Implications (Australian Geomechanics Society, 2000)

Risk Level		**Example Implications**
VH	Very high risk	Extensive detailed investigation and research, planning and implementation of treatment options essential to reduce risk to acceptable levels; may be too expensive and not practical
H	High risk	Detailed investigations, planning and implementation of treatment options required to reduce risk to acceptable levels
M	Moderate risk	Tolerable provided that treatment plan is implemented to maintain or reduce risks. May be accepted. May require investigation and planning of treatment options
L	Low risk	Usually accepted. Treatment requirements and responsibility to be defined to maintain or reduce risk
VL	Very low risk	Acceptable. Manage by normal slope maintenance procedures

2.11.3 Relative Risk Rating

This approach is based on similar principles as used in risk scoring and rsik matrices. It is a descriptive approach in which a range of risk categories are defined, each with a charecteristic degree of hazard and level of consequences. The approach has proved useful in situations where the elements at risk are uniform, or broadly similar, throughout an area such as a pipeline, highway or cliff foot walkway, but are exposed to spatial variation in the degree of hazard (Lee and Jones, 2004). The method provides a means of identifying the relative risk in an area in which a range of risk categories are defined, each with a characteristic degree.

The study area is sub-divided into units, generally on the basis of geomorphology and geology. Information is then gathered about the distribution, nature and frequency of landsliding, the assets at risk and likely levels of adverse consequences within each unit. Risk categories are then developed that summarises the range of hazard and consequence conditions within the area of interest. Each unit is then assigned a risk category.

2.11.4 The FMECA Approach

Failure mode, effects and criticality analysis (FMECA) is a systematic approach for analysing how a system, such as a slope, may fail (the failure mode). The FMECA approach provides a structured framework for the qualitative analysis of various components of a system, using engineering judgment to generate scores or rankings, rather than probabilities.

The approach involves the development and analysis of an LCI diagram (location, cause, indicator) for each slope as shown in Fig. 2.12 (Lee, 2003). An LCI diagram sets out the individual constructed components of each man-made slope and how their lack of integrity might contribute to the overall failure of the slope. Failure through a range of possible causes and with different indicators is considered by means of indicator-cause pathways. The level of detail presented in an LCI diagram should reflect the available knowledge about any potential indicator-cause pathway.

The assessment procedure involves scoring three key factors on a range of 1 to 5, for each indicator-cause pathway:

- The consequence expressed in terms of how directly is failure of an element related to complete failure of the slope:

  1 = failure of element is unlikely to lead to failure of the slope;
  5 = failure of element is highly likely to lead to failure of the slope.

- The likelihood of failure of an element, ranging from 1 (low) to 5 (high).

- The practitioner's confidence in the reliability of his / her predictions of the consequence and likelihood factors.

The confidence score ranges from 1 (very confident) to 5 (no or little confidence). This score allows a measure of uncertainty to be included within the assessment. Table 2.3a (Hughes et al., 2000) presents a range of factors that should be considered when determining the confidence score.

Considerable experience is required to develop and use an LCI diagram. It is important that the scores are the product of careful scrutiny, ideally by a group or panel of experts. It is recommended that the process should be 'transparent' and the reasoning behind the allocation of each value should be clearly documented (Hughes et al., 2000). The results of the LCI diagram analysis are used to identify those structural elements that contribute most to the overall risk. A number of measures may be defined, including:

Element Score = (Consequence of Failure) x (Likelihood of Failure) (2.5)

This provides a measure of the degree of risk associated with a particular element of the slope. High scores indicate those elements where remedial measures may be needed to reduce the risk:

Criticality Score = (Element Score) x (Confidence) (2.6)

This gives a measure of the hazard that a particular indicator-cause pathway creates for the slope. High criticality scores can reflect uncertainty in consequence and likelihood scores, highlighting the need for further investigation.

A measure of the relative risk associated with failure of particular elements of the slope can be established from the product of the criticality score and an impact score:

Relative Risk = (Criticality Score) x (Impact Score) (2.7)

An impact score can be determined through the use of the types of scoring or ranking systems. Table 2.3b (Hughes et al., 2000) shows an expanded scoring framework for assessing the impact. The scores for each type of economic impact are combined to provide a single measure of impact for the site or area. This is achieved by adjusting each impact score by a weighting factor, and adding the adjusted scores; these factors are finalised by experts depending on the local circumstances. Loss of life is estimated from the total number of people at risk. The exposure factor may vary with the length of forewarning time and the ability of people to escape or be evacuated. The vulnerability factor may range from 0.5 if there is little or no forewarning to only 0.0002 for a warning time of 90 minutes.

The economic impact scores are combined with the estimated loss of life to give an overall impact score (Table 2.3c).

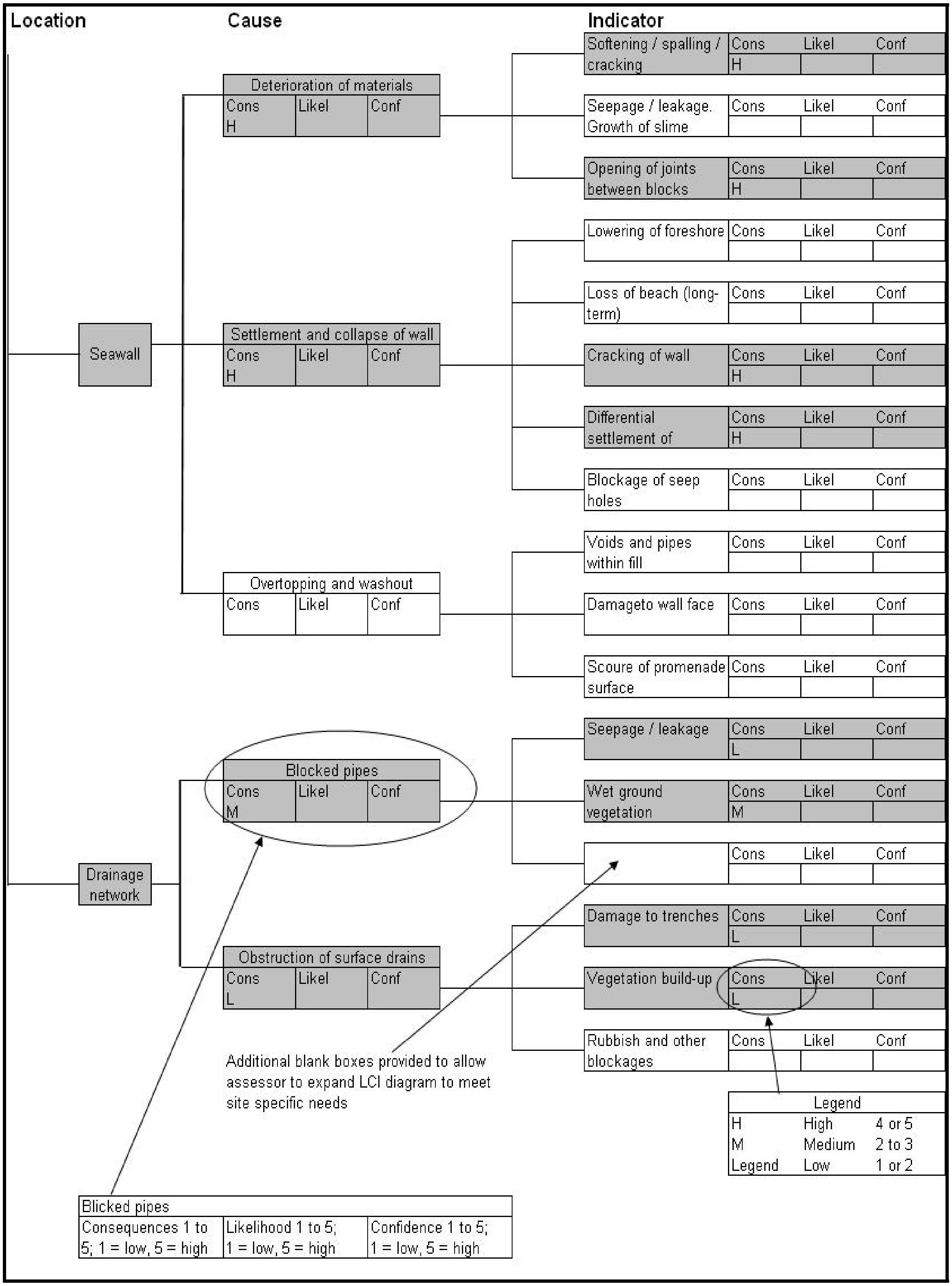

Fig. 2.12. A Typical LCI Diagram (Lee, 2003)

Table 2.3a. The FMECA Approach: Key Considerations for Defining a Confidence Score in an LCI Diagram (Hughes et al., 2000)

Issue	**Comment**
Detectability	The ease with which potential failure mechanisms can be detected prior to failure occurring, through the use of instrumentation, that is a function of the cost/resources required to monitor signs of pre-failure movement within different components.
Construction Quality	The quality of construction materials and the workmanship will vary between engineered slopes and between individual components of a slope. This can sometimes be readily identified and incorporated into the likelihood score. Sometimes, evidence of poor quality or bad workmanship may not be readily apparent. The confidence score should take account of any uncertainty regarding construction quality.
Operational Maintenance	Maintenance is essential for ensuring the continued integrity of the structures. The confidence score should take account of any uncertainty regarding the future maintenance programme actually being undertaken. For example, poorly funded or ad hoc programmes may be subject to significant change and are likely to be unreliable.
Quality of Records	A full record of the 'as-built' construction and operational maintenance is essential for a reliable assessment of structural performance. Good records do not reduce the likelihood of failure, but they increase the confidence in the allocated likelihood score.
Incompleteness of Knowledge	The confidence score should take account of any significant gaps in knowledge about the condition, behavior and performance of the structures.

Table 2.3b. FMECA Approach: Impact Scoring System (Hughes et el., 2000)

	Score	Population at Risk
Residential Properties Affected		
0	0	0
0-15	1	30
15-50	2	100
50-250	3	500
Estimate (>250)	4	2 x estimate
Non-Residential: Number of People Affected		
0	0	0
0-150	1	150
150-500	2	500
500-1000	3	1000
Estimate (> 1000)	4	Estimate
Infrastructure Affected		
None	0	0
Minor roads	1	25
Major regional infrastructure	2	50
Major national infrastructure	3	1000
Major international infrastructure	4	Estimate
Recreational Sites: Number of People Affected		
0	0	0
0-10	1	10
10—50	2	50
50-100	3	100
Estimate (> 100)	4	Estimate
Industrial Sites		
None	0	N/A
Light industrial	1	N/A

continued

Table 2.3b FMECA Approach: Impact Scoring System (*continued)*

Public health industries	2	N/A
Heavy industrial	3	N/A
Nuclear, petrochemical	4	N/A
Utilities		
None	0	N/A
Local loss of distribution	1	N/A
Local loss of distribution/supply	2	N/A
Regional loss of distribution/supply	3	N/A
Significant impact on national services	4	N/A
Agriculture / habitat site		
Uncultivated/grassland	0	N/A
Pasture	1	N/A
Widespread farming	2	N/A
Intensive farming / vulnerable habitat / monument	3	N/A
Loss of international habitat/monument	4	N/A.

Note. N/A = not applicable.

Table 2.3c. FMECA Approach: Standard Tables for Calculating Impact Scores (Hughes et al., 2000)

Impact	**Population at Risk (PAR)**	**Exposure Factor***	**Total (PAR X Exposure)**
Residential property		0.5	
Non-residential property		0.5	
Infrastructure		0.5	
Recreation		0.5	
Total loss of life			
Impact	**Score**	**Weight**	**Total (Score X Weight)**
Residential property		0.15	
Non-residential property		0.15	
Infrastructure		0.10	
Recreation		0.05	
Industrial		0.25	
Utilities		0.25	
Agriculture/habitats		0.05	
Total Score			
Impact	**Score**	**Factor**	**Total (Score x Weight)**
Economic impact		100	
Potential loss of life		1	
Total impact score			

Note: *Exposure varies with forewarning