5. LANDSLIDE HAZARD ASSESSMENT, MAPPING AND EVALUATION OF HAZARD MAPS

5-1 METHODS OF ANALYSIS

The landslide distribution data extracted from remote sensing means and brought into GIS (Geographic Information Systems) and thematic information stored in a GIS were used for the landslide hazard assessment. The conventional aerial photographs, which was still the most important remote sensing means for landslide studies, was used to produce landslide distribution map. To determine the factors and classes influencing landsliding, layers of topographic factors derived from a digital elevation model, geology, and land use/cover were analyzed by quantification scaling type II (discriminant) analysis and univariate statistical analysis (Failure rate: FR) analysis, and the results used for hazard mapping. In addition, in Q-S II analysis, the effects of different samples of landslide and non-landslide groups on the critical factors and classes, and subsequently on hazard maps were evaluated. Simple random sampling was used to obtain samples of the landslide group and either an unaligned stratified random sampling or an aligned systematic sampling method generated the non-landslide group. For the analysis, one set of the landslide group was combined with each of five different sets of the non-landslide groups. Two FR analyses based on area or frequency (number) of landslide were employed.

The scores of the classes of the factors quantified by the five analyses in Q-S II and two analyses in FR were used for the hazard mapping with the GIS, with four levels of relative hazard classes: high, moderate, less, and least. In order to determine which sample combination best represents the population (in Q-S II analysis), the accuracy of hazard maps (i.e. evaluation of Q-S II results) was assessed. An evaluation method of the spatial agreement between the hazard maps was introduced, and the spatial agreements between the hazard maps were measured to comprehensively examine the effect of sampling on the final outcome of the analysis. The accuracy of hazard maps produced from the FR analyses were compared to the hazard map produced from the Q-S II analysis. Similarly, the agreements in the hazard maps produced from the FR analyses to that of the Q-S II analysis were also evaluated to determine the effect of method used on the final outcome. Figure 5-1 depicts the flow of the study.

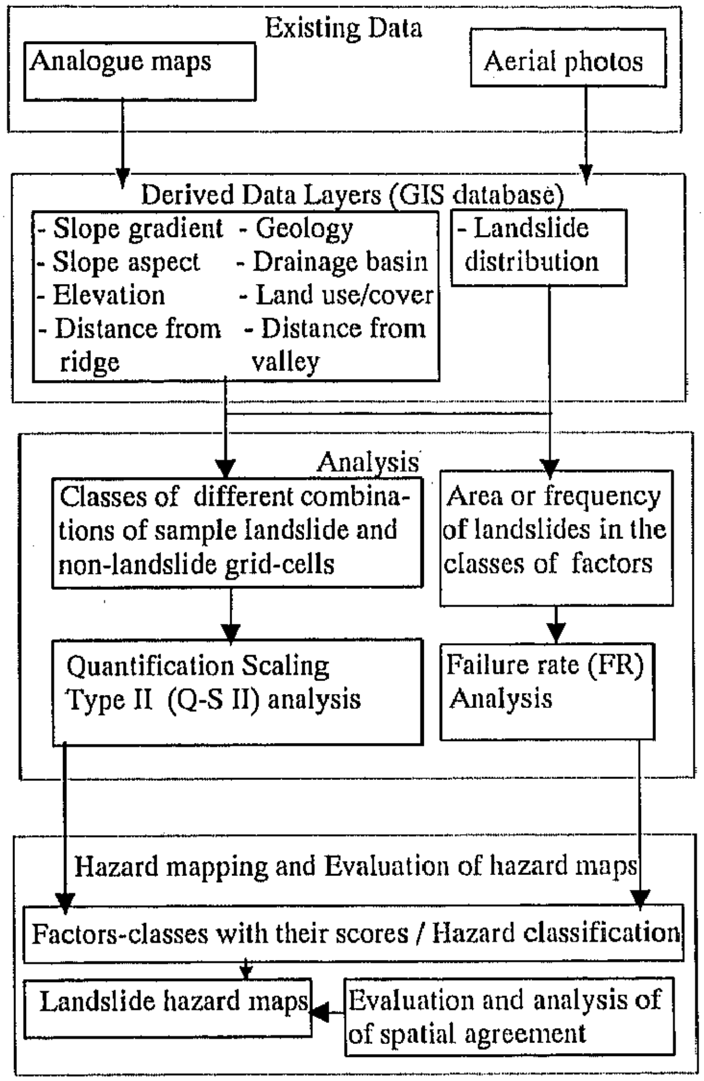

Figure 5-1 Flow diagram of landslide hazard assessment, mapping and evaluation.

5-1-1 Data Acquisition and GIS Data Layers

The stereopairs of black and white vertical aerial photographs (1: 20,000) taken in March 1994 were interpreted for landslide identification, and using a stereo zoom-transferscope landslides identified on the aerial photographs were plotted on a topographic map at a scale of 1:12,500 (photographically enlarged from 1:25,000). As the aerial photographs were taken during dry season, the landslides were not concealed by vegetation, and therefore were distinct. The landslide distribution map was finalized after field checking. It was then digitized and was formatted to the Universal Transverse Mercator (UTM) map projection (Figure 5-2).

A Digital Elevation Model (DEM) was generated from a Triangulated Irregular Network (TIN) model using digitized contours of topographic maps (contour interval 20 m). Slope gradient, slope aspect and elevation layers were derived from the DEM. The slope gradient was divided by a 10 degree-interval into five classes (Table 5-1, Figure 5-3). Elevation and slope aspects were divided into four classes each. Ridges and valleys were also defined from the DEM. Employing the Strahler (1957) method for numbering the stream orders, the drainage basin order layer was derived from the topographic map, and divided into three classes. After minor modifications based on fieldwork and aerial photographic verifications, land use/cover layer was created with five classes from land use/cover map (1:25,000) produced in 1991 (Department of Forest, Nepal, 1991). The geological map at a scale of 1:50,000 (Nepal Electricity Authority, 1994) was digitized to produce the geology layer. The scale of the geological map is relatively smaller than the other maps used. However, the spatial variation in geology (rock types) relating to landslides is not as fine as other factors such as slope gradient or land use/cover. The selection and classifications of these factors were primarily guided by the sample landslides surveyed in the field, and previous knowledge of the causal relationships between slope failure and instability factors (e.g. Coates, 1977; Varnes, 1978; Aniya 1985; Crozier, 1986; Zinmermann *et al.*, 1986; Dhakal *et al.*, 1997). All the eight layers (Figure 5-3) were formatted to the Universal Transverse Mercator (UTM) map projection.

5-1-2 Quantification Scaling Type II (Q-S II) analysis

The Q-S II is a multidimensional quantification analysis (Hayashi, 1950,

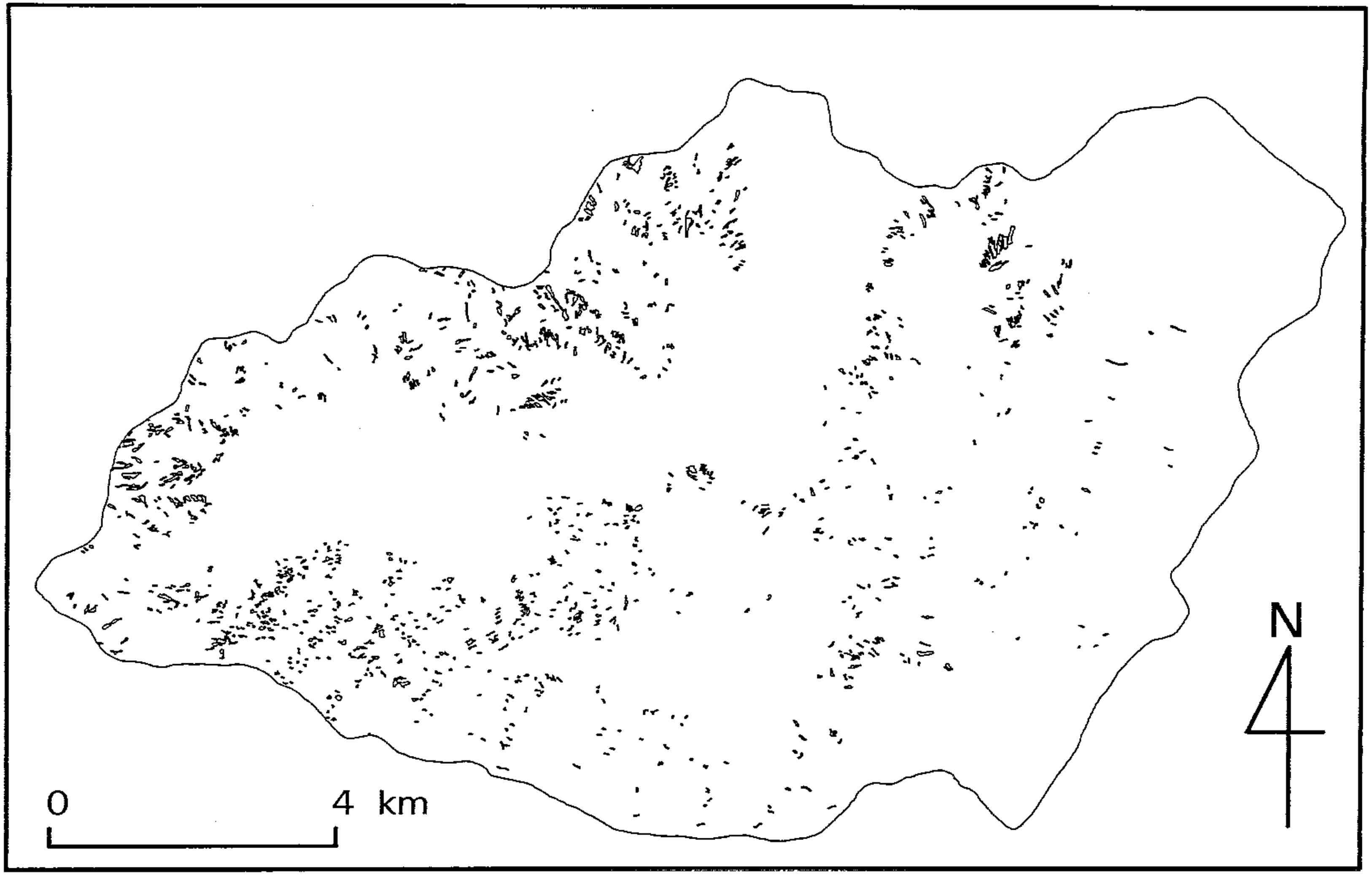

Figure 5-2 Landslide (black spots) distribution map of Kulekhani watershed (interpreted from aerial photo of (March 1994). A total of 1,246 landslides were identified. The size of the landslides was greater than 600 m^2, which was the size which could be surely identified.

Table 5-1 Factors and their classes in GIS for a Q-S II analysis.

Factors	Class code						
	1	2	3	4	5	6	7
Slope gradient	<15°	15° - 25°	25° - 35°	35° - 45°	> 45°	-	-
Slope aspect	North (315°-45°)	East (45°-135°)	South (135°-225°)	West (225°-315°)			
Elevation	< 1800 m	1800 m - 2000 m	2000 m - 2200 m	> 2200 m	-	-	-
Drainage basin order	First	Second	Third	-	-	-	-
Distance from ridge	< 50 m	50 m - 100 m	> 100 m	-	-	-	-
Distance from valley	< 50 m	50 m - 100 m	> 100 m	-	-	-	-
Geology	Slates with quartzites or limestones	Limestones	Slates with meta-sandstones and phylites	Schists with quartzites and marbles	Biotite schists and micaceous quartzites	Granite	Alluvium
Land use/cover	Crops	Coniferous forest	Broad leaf forest	Mixed forest	Shrub land	-	-

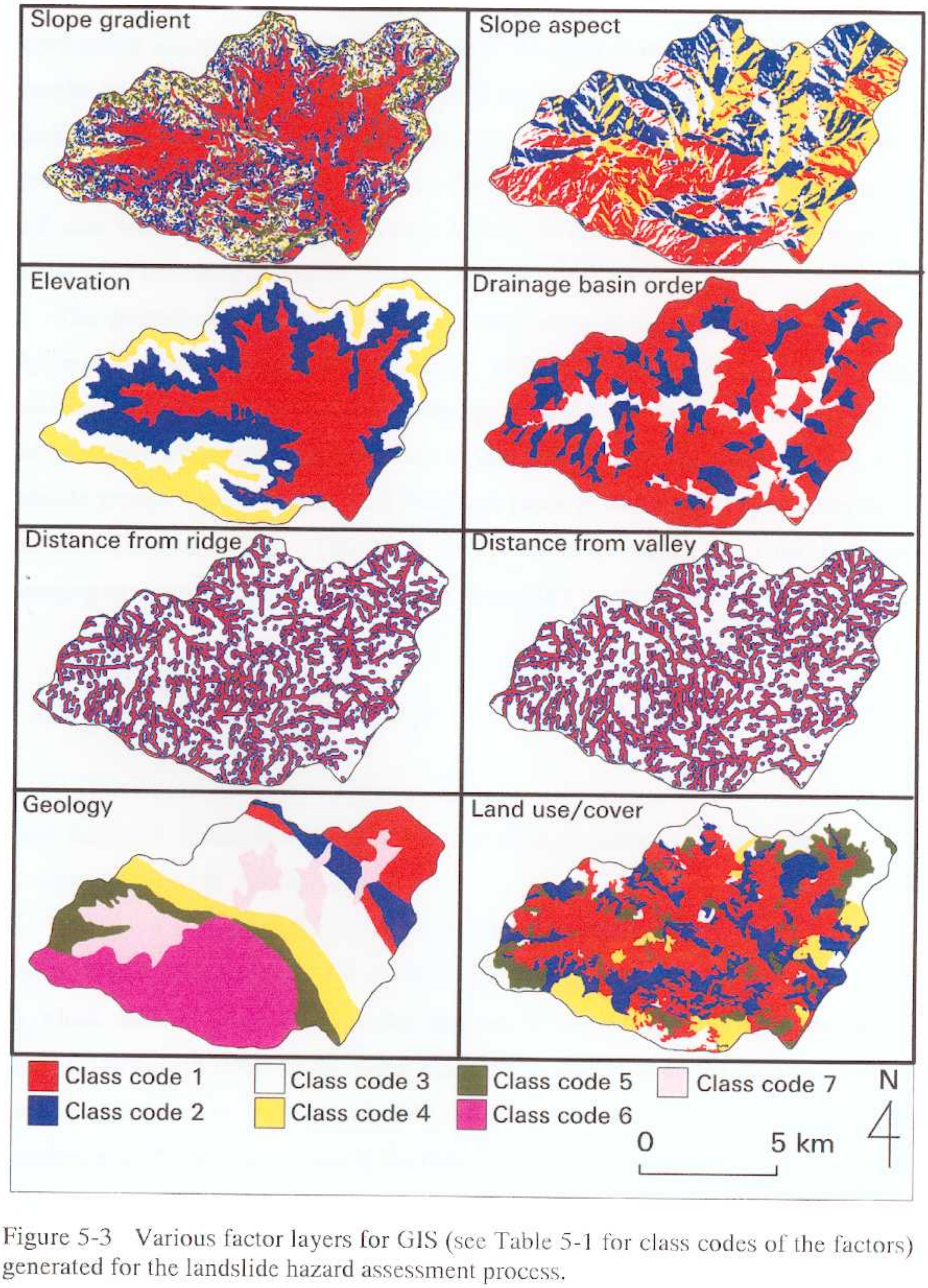
Slope gradient
Slope aspect
Elevation
Drainage basin order
Distance from ridge
Distance from valley
Geology
Land use/cover

Figure 5-3 Various factor layers for GIS (see Table 5-1 for class codes of the factors) generated for the landslide hazard assessment process.

1954a) which incorporates nominal data, and is the same as discriminant analysis. For example, in Figure 5-4, group A and group B may be regarded as landslide, and non-landslide group, respectively. These groups can not readily be distinguished with respect to parameters (factors) X_1 and X_2. However, if the two groups are projected on the Z axis, they can be clearly separated. This is the concept of discriminant analysis, which can be expanded into many factors.

The quantification is attained by using frequencies as input data to maximize the efficiency of discrimination (Hayashi, 1952, 1954a). The method is suitable to the landslide hazard assessment, because nominal variables (factors) such as geology or land use/cover are often most important to discriminate between landslide and non-landslide groups. Other discriminant functions (such as canonical) require interval or ratio data (Klecka, 1983). The linear Q-S II function (score; αa_q) for a sample belonging to a group q with n factors and m classes in a factor can be written as;

$$\alpha a_q = \sum_{j=1}^{n} \sum_{i=1}^{m} \delta a(ji)\ Xji \text{ - - - - - - - - - - - - } (6)$$

where, $\delta a(ji) = 1$, if sample a belongs to the i-*th* class of factor j, otherwise 0;
Xji = score of the i-*th* class of factor j.

The quantification of classes of the factors (Xji) is done in such a way that the proportion of variance between the groups to the total variance (i.e. the correlation ratio, η^2), which takes the value between zero and one, is maximized. *Eta* (η) measures the degree of difference between the group means. The efficiency of the discrimination is therefore given by η or η^2 (Hayashi, 1952, 1954a). Since a large class score in a factor contributes more than a small one in the Q-S II functions, a class score and the range of scores of a factor (difference between the maximum and minimum scores of the classes) can be interpreted to determine their importance. For the data, which are not sampled, the factor-classes are measured, and the group to which they belong is predicted from the score of the classes.

5-1-2.1 Sampling of landslide and non-landslide groups

Considering the minimum size of the landslides, the study area was tiled into grid-

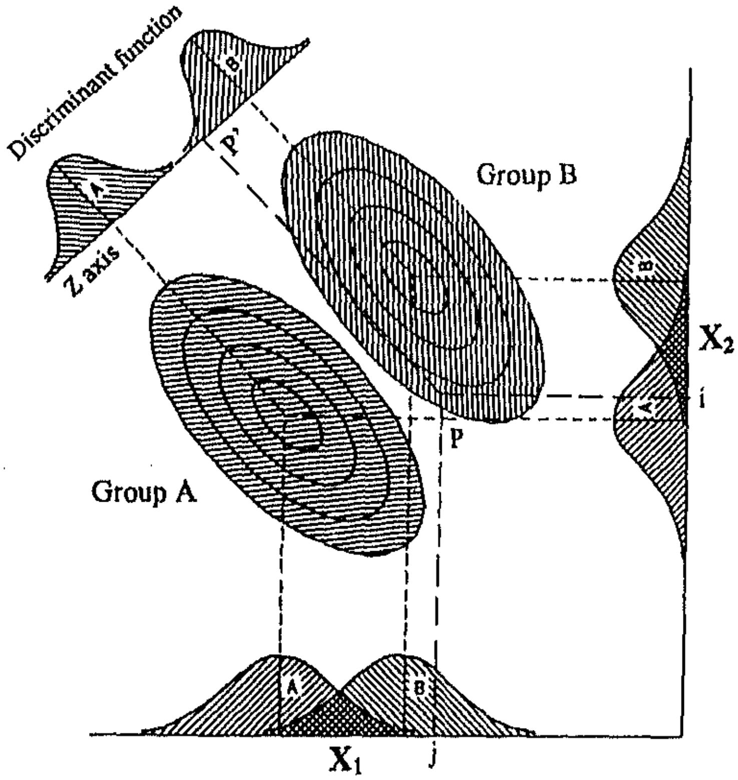

Figure 5-4 Concept of discriminant function (quantification scaling type II), modified after Davis (1986).

cells of 25 m x 25 m, and one set of grid-cells (566) representing the landslides was randomly chosen. These grid-cells represent about 45 percent of the total number of 1,246 landslides. The remaining 680 landslides (referred to as "test landslide") were later used for the evaluation of the hazard maps produced (for the results of Q-S II analysis). Subsequently, the area was stratified into a rectangular block of 2.4 km x 1.5 km, and three sets of non-landslide groups were derived with the same number of grid-cells from each block using the unaligned stratified random sampling method. In addition, using the aligned systematic sampling method, two sets of non-landslide groups, with a prior estimation of a sample size, were derived from the same starting value but with a different sampling interval. Altogether, five sets of samples were obtained for the non-landslide group (Table 5-2). For each grid-cell of a set of landslides and five sets of non-landslides, class codes of eight terrain factors (see Table 5-1) were assigned for the Q-S II analysis.

5-1-2.2 Association between the factors

A high correlation of factors may simply reflect redundancy without contributing much improvement in the analysis. To address this issue correlation coefficients between these factors were calculated. Table 5-3 shows that the results for combination 1 lack a strong correlation. The degree of the correlation between factors may be different depending on different samples (Liebetrau, 1983). In reality, we can not expect the causative factors of landslides to be entirely independent. The correlations of factors in five different sample combinations (see Table 5-2) were examined, and some factors were excluded in order to see their effect on the results of the Q-S II analysis. Based upon field information, the results using all the eight factors in the analysis appeared more reasonable in all combinations. Moreover, the maximum separation, as indicated by η or η^2, and the Q-S II accuracy (discussed later) were notably higher when all the eight factors were used.

5-1-3 Failure rate analysis (FR analysis)

The FR analysis is a univariate statistical approach in which the importance of each factor or combined-factor is individually analyzed from the spatial distribution of existing landslides. To evaluate the influence of each class of a factor to landsliding, a

Table 5-2 Combinations of landslide and non-landslide sample groups for the Q-S II analysis.

Combination	Number of non-landslide grid-cells	Number of landslide grid-cells	Total number of grid-cells	Sampling method for non-landslide group	Sampling method for landslide group
1	572	566	1138	unaligned stratified random	Simple random
2	571	566	1137	"	"
3	1143	566	1709	"	"
4	1285	566	1851	Aligned systematic	"
5	643	566	1209	"	"

Table 5-3 Correlations between factors (Sample of combination 1).

	Slope gradient	Slope aspect	Elevation	Drainage basin order	Distance from ridge	Distance from valley	Geology	Land use/cover
Slope gradient	1.000							
Slope aspect	-0.003	1.000						
Elevation	0.153	0.014	1.000					
Drainage basin order	0.165	0.068	0.224	1.000				
Distance from ridge	-0.005	-0.001	-0.053	-0.056	1.000			
Distance from valley	-0.020	0.011	0.020	0.030	-0.086	1.000		
Geology	0.032	-0.094	0.108	0.100	-0.029	0.037	1.000	
Land use/cover	0.085	-0.036	0.128	0.113	-0.033	0.012	0.131	1.000

numerical score is computed using either number of the landslides or area of the landslides falling in the class. In this study, the calculation of a score (susceptibility score) involves the computation of the ratio of relative areal distribution of landslides in each class to the relative areal distribution of that particular class. It was calculated as,

FR Score = R (L) / R (A) ---(7)

where, R (L) = a ratio of the landslide grid-cells in a particular class of a factor to the total landslide grid-cells, or a ratio of number of landslides to the total landslide area

R (A) = a ratio of the grid-cells belonging to that particular class to the total study area

In FR (A) analysis, the score for the classes were computed from area of landslides falling in a class, whereas in FR (B) analysis, number (frequency) of landslides were used. For example, if a class of a factor occupies 20 km^2 of the total area (100 km^2) and 0.5 km^2 of landslide occurs in that class, with the total landslide area of 2 km^2, a FR (A) score for that class would be 1.25 {(0.5 / 2) / (20 / 100)}. The score greater than 1 suggests that the class contributes to landsliding, whereas that smaller than 1 inhibits landsliding.

The difference between the Q-S II analysis and the FR analysis is that the former is based on multivariate statistical technique and takes into account the interrelationships between the factors, whereas the latter, a univariate statistical technique, considers factors independently. Because of the nature of the analysis, the Q-S II analysis depends to some extent on the sampled data, whereas this is not the case with the FR analysis in which the total area of landslides and the total area of classes of a factor are utilized. The scores computed in the Q-S II analysis tend to depend on the frequency of landslides (the number of landslides in a class), whereas in FR analysis if it is calculated based on area, higher FR score is assigned to the classes with bigger landslides. However, in FR analysis if it is calculated based on the number of landslides on a class of a factor, a higher FR score is assigned to the classes with a large number of landslides.

5-2 RESULTS

5-2-1 Q-S II Analysis

The values of η, η^2 and the separation between the group centroid (Table 5-4, bottom) are generally higher for combinations in which the non-landslide group was obtained using the unaligned stratified random sampling method. For the sample size employed in the analysis, the values of η are reasonable (Hayashi, 1954b) in all combinations for the discrimination between the landslide and non-landslide groups. The class scores and the range of scores are shown in Table 5-4. Based upon the range of scores, geology is found to be the most important factor contributing to landsliding in all combinations. The ranking order of the other factors shows some minor variations. Elevation, land use/cover and slope aspect fall within the second group of importance, while slope gradient is in the third group. This is true in all combinations except for combination 2, which shows the importance of drainage basin order. Distance from ridge, and distance from valley have the least importance.

For the classes of geological factor, the score is high for “granite”, followed by “biotite schists with micaceous quartzites”. Granite in the study area has been characterized as highly weathered and permeable. With respect to elevation, a zone of “2,000 m - 2,200 m” is most susceptible, followed by “ 1800 m - 2000 m”. In land-use/cover, “coniferous forest” shows the highest importance followed by “shrub land” in combinations 1 and 3, whereas “shrub land” is followed by “coniferous forest” in combinations 2, 4, and 5. Most of the areas covered by coniferous species are characterized as immature and poorly stocked. As for slope aspect, “East” followed by “South” facing slopes in combinations 1 and 3, and “South” followed by “East” in combinations 2, 4, and 5 are shown to be the most important. This pattern reflects the monsoon rainfall distribution, which contributes 80 percent of the total annual rainfall, giving southern and eastern faces more rainfall. For slope gradient, the score is highest at class “35^o - 45^o”. The first order drainage basin is found most susceptible in combinations 1, 2 and 3 while combinations 4 and 5 show higher importance of the second order drainage basin. The greater the distance from the ridge (>100 m) and the shorter the distance from the valley (<50 m) the susceptibility to landslides increases.

In summary, the most critical association of classes for landsliding are “granite”, “2000 m - 2200 m”, "coniferous forest" (“shrub land” in combinations 2, 4

Table 5-4 The results of the Q-S II analysis. A large range of scores indicates more discriminating potential of the factor and a negative class score implies the contribution to landsliding.

Factors	Class	Class-code	Combination 1		Combination 2		Combination 3		Combination 4		Combination 5	
			CS	RS	CS	RS	CS	RS	CS	RS	CS	RS
Slope gradient	< 15°	1	0.138	0.573	0.074	0.268	0.109	0.438	-0.059	0.399	-0.040	0.476
	15° - 25°	2	-0.098		-0.040		-0.088		-0.025		-0.028	
	25° - 35°	3	0.025		0.060		0.038		0.141		-0.009	
	35° - 45°	4	-0.350		-0.194		-0.288		-0.160		-0.079	
	> 45°	5	0.223		-0.024		0.150		0.240		0.397	
Slope aspect	North	1	0.396	0.775	0.473	0.831	0.484	0.834	0.343	0.832	0.173	0.862
	East	2	-0.379		-0.214		-0.350		-0.289		-0.251	
	South	3	-0.215		-0.358		-0.286		-0.412		-0.333	
	West	4	0.247		0.128		0.149		0.420		0.529	
Elevation	< 1800 m	1	0.283	0.707	0.335	0.835	0.318	0.856	0.507	1.055	0.316	0.705
	1800 m - 2000 m	2	-0.103		-0.177		-0.134		-0.063		-0.006	
	2000 m - 2200 m	3	-0.365		-0.412		-0.485		-0.548		-0.389	
	> 2200 m	4	0.342		0.423		0.371		0.045		0.173	
Drainage basin	First	1	-0.023	0.143	-0.078	0.502	-0.054	0.332	0.028	0.204	0.010	0.267
	Second	2	-0.003		-0.043		-0.033		-0.137		-0.126	
	Third	3	0.120		0.424		0.278		0.067		0.141	
Distance from	< 50 m	1	0.067	0.135	0.002	0.081	0.043	0.106	0.090	0.247	-0.007	0.249
	50 m - 100 m	2	0.028		0.048		0.045		0.103		0.147	
	> 100 m	3	-0.068		-0.033		-0.061		-0.144		-0.102	
Distance from Valley	< 50 m	1	-0.090	0.156	-0.097	0.145	-0.096	0.137	-0.069	0.173	-0.135	0.199
	50 m - 100 m	2	-0.010		0.033		0.036		0.104		0.064	
	> 100 m	3	0.066		0.048		0.041		-0.029		0.051	
Geology	Slates with quartzites or limestones	1	1.883	2.472	1.849	2.557	1.607	2.333	1.657	2.364	1.848	2.415
	Limestones	2	0.630		0.894		0.818		0.771		0.717	
	Slates with meta-sandstones and phylites	3	0.075		0.169		0.112		0.109		0.121	
	Schists with quartzites and marble	4	0.195		0.069		0.110		0.162		0.101	
	Biotite schists and micaceous quartzites	5	-0.266		-0.099		-0.210		-0.311		-0.321	
	Granite	6	-0.589		-0.708		-0.726		-0.707		-0.567	
	Alluvium	7	1.359		1.370		0.888		1.097		1.454	
Land use/cover	Crops	1	0.368	0.804	0.326	0.769	0.348	0.789	0.309	0.824	0.420	0.881
	Coniferous forest	2	-0.436		-0.327		-0.441		-0.315		-0.393	
	Broad leaf forest	3	0.137		0.219		0.179		0.140		0.009	
	Mixed Forest	4	-0.175		-0.136		-0.193		-0.037		-0.111	
	Shrub land	5	-0.262		-0.443		-0.395		-0.515		-0.461	
η			0.450		0.460		0.412		0.379		0.423	
η^2			0.203		0.211		0.170		0.143		0.179	
Group centroid:												
Landside group			-0.452		-0.462		-0.585		-0.571		-0.356	
Non-landslide group			0.448		0.457		0.289		0.251		0.314	

CS = Class score, RS = Range of scores

and 5), "East" ("South" in combinations 2, 4 and 5) "35° - 45°", "first order" ("second order" in combinations 4 and 5), <50 m (distance from valley) and >100 m (distance from ridge).

5-2-2 FR Analysis

Table 5-5 lists the scores obtained for the FR (A) and FR (B) analyses. For comparison the results of the Q-S II analysis for combination 1 is also listed. Since the FR analysis considers the importance of classes of a factor independently, the interpretation of ranges of scores is difficult. In other word the ranges of score can not be interpreted easily to determine the important factors. The results of the FR (B) analysis are very much close to the results of the Q-S II analysis. It might be because the Q-S II analysis also tends to depend on the number of landslides in a class, because each sample of landslide grid-cell represents a single landslide. Though the scores obtained for the FR (A) also resemble with the Q-S II analysis, the class "shrub" replaces "coniferous forest" in land use/cover, and "limestones", replaces "granite" in geology, though the score for granite and coniferous are also higher. These differences are encountered because the class "limestones" (geology) where a few large landslides are located received the highest score in the FR (A) analysis, whereas "granite", where the large numbers of small landslides are located, received the highest score in the Q-S II analysis.

In summary, when the results of FR (A), FR (B) and combination 1 (Q-S II) are compared, the association of classes "granite" (Limestones in FR (A)), "2000 m-2200 m", "coniferous forest" ("shrub land" in FR (A)), "East" "35° - 45°", "first order" <50 m (distance from valley) and >100 m (distance from ridge) are found most critical to landsliding.

5-3 CLASSIFICATION OF HAZARD CLASSES AND MAPPING

The factor layers with scores for their classes were superimposed to obtain a cumulative score at each grid-cell. The following discussion illustrates the classification of grid-cells into different hazard classes. Figure 5-5 shows the plots of cumulative frequencies for the sample data of combination 1 (Q-S II analysis), with the landslide group starting from the smallest score and the non-landslide group from the

Table 5-5 The results of FR (A) and FR (B) analyses. A large class score implies the contribution to landsliding. For comparision the results of the Q-S II analysis (Combination 1) is also added (first five important factors are listed).

Factor	Class	Q-S II analysis		FR (A)		FR (B)	
		CS	RS	CS	RS	CS	RS
Geology	Slate with quartzite or limestone	1.607	2.333	0.17	1.70	0.135	1.45
	Limestone	0.818		1.69		0.885	
	Slate with meta-sandstones and	0.112		1.17		1.095	
	Schist with quartzite and marble	0.110		0.97		0.795	
	Biotite schist and micaceous quartzite	-0.210		1.32		1.275	
	Granite	-0.726		1.16		1.453	
	Alluvium	0.888		0		0	
Land Use/cover	Crops	0.348	0.789	0.62	1.05	0.717	0.766
	Coniferous forest	-0.441		1.51		1.483	
	Broad leaf forest	0.179		0.93		0.721	
	Mixed forest	-0.193		0.89		1.236	
	Shrub land	-0.395		1.66		1.327	
Elevation	< 1800 m	0.318	0.856	0.40	1.4	0.495	1.172
	1800 m - 2000 m	-0.134		1.0		1.123	
	2000 m - 2200 m	-0.485		1.80		1.667	
	> 2200 m	0.371		1.06		0.946	
Slope aspect	North	0.484	0.834	0.80	0.77	1.043	0.780
	East	-0.350		1.32		1.271	
	South	-0.286		1.32		1.187	
	West	0.149		0.55		0.497	
Slope gradient	< 15°	0.109	0.438	0.51	0.94	0.654	1.31
	15° - 25°	-0.088		1.20		1.396	
	25° - 35°	0.038		1.44		1.508	
	35° - 45°	-0.288		1.45		0.831	
	> 45°	0.150		1.13		0.193	

CS = Class score, RS = Range of scores, PCC = Partial correlation coefficient

Table 5-6 Percentage area of different hazard classes in five hazard maps (Q-S II analysis).

Combination	Percentage area of different hazard classes (%)			
	High	Moderate	Less	Least
Combination 1	7.7	30.9	44.1	17.3
Combination 2	7.8	30.5	44.1	17.6
Combination 3	7.3	30.6	44.8	17.3
Combination 4	8.3	29.0	43.7	19.0
Combination 5	8.0	29.0	44.5	18.5

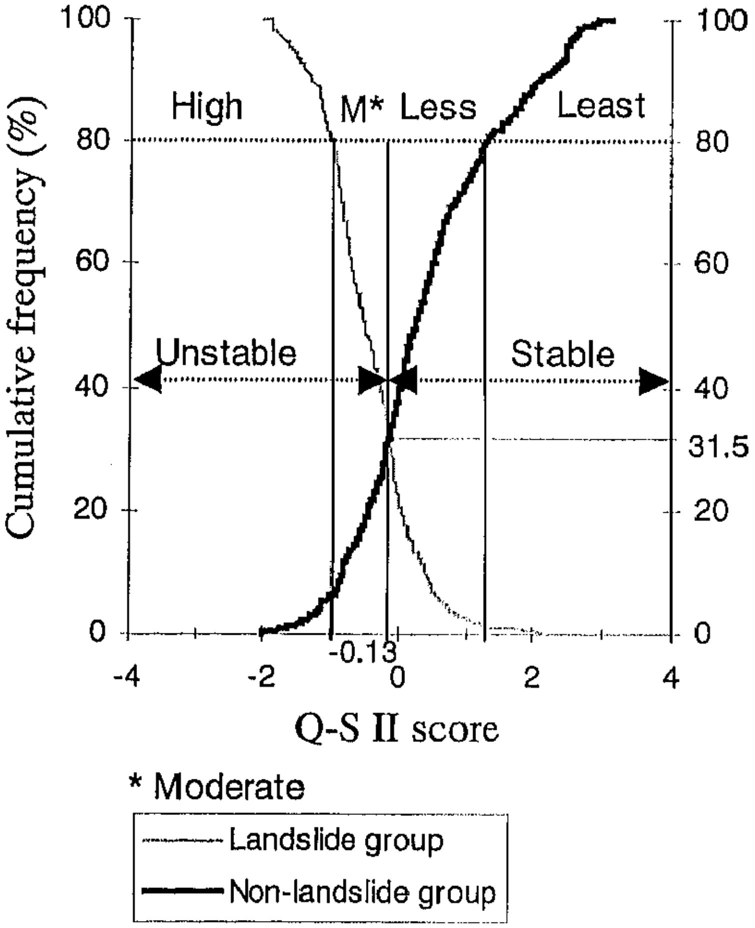

Figure 5-5 Cumulative frequencies and Q-S II scores for landslide and non-landslide groups (combination 1; see Table 5-2 for explanation of combination 1).

largest score. If the curves of these two groups do not intersect then separation is perfect. However in this case, the curves do intersect and misclassifications will occur. For a boundary score that would separate the two groups, it appears logical to choose the score at which the two curves intersect, i.e. -0.13 (discrimination score) in this case, because it is as important to locate correctly stable slopes as unstable ones. Consequently, grid-cells whose total score of the classes was equal to or less than -0.13 were classified into the landslide group (unstable), whereas those with the score greater than -0.13 were placed in the non landslide group (stable). Then the overall accuracy (Q-S II accuracy) for the sample data of combination 1 is 68.5 percent (100-31.5; Figure 3). The Q-S II accuracy for combinations 2, 3, 4, and 5 are 70.1 percent, 69.2 percent, 67.5 percent and 67.3 percent, respectively. In order to differentiate the categories very unstable and marginally unstable, and very stable and marginally stable, scores at which the accuracy of decision would be about 80 percent were selected. This resulted in the division of each category into two classes, resulting in four classes of relative hazard: high, moderate, low and least. Figure 5-6 depicts five hazard maps produced from the results of the five sample combinations (see Table 5-2) in Q-S II analysis. Table 5-6 compares the percentage area of hazard classes in five hazard maps in which hazard classes do not show substantial differences.

For two FR analyses, the factor layers with FR scores for their classes were superimposed to obtain a cumulative score at each grid-cell. In order to classify grid-cells into different hazard classes, the cumulated scores that separate the different hazard classes into the same number of grid-cells as that of the hazard map produced using combination 1 (Q-S II analysis) were obtained and hazard maps were produced with four different hazard classes. Figure 5-7 shows hazard maps produced from the results of FR (A), and FR (B) analyses. For comparison, the hazard map produced from combination 1 (Q-S II analysis) is also shown.

5-4 EVALUATION OF HAZARD MAPS

In order to determine which sample combination for the Q-S II analysis, best represents the population the accuracy of hazard maps (i.e. evaluation of the Q-S II results) was assessed. In addition, the spatial agreements between the hazard maps were measured to comprehensively examine the effect of sampling on the final outcome in

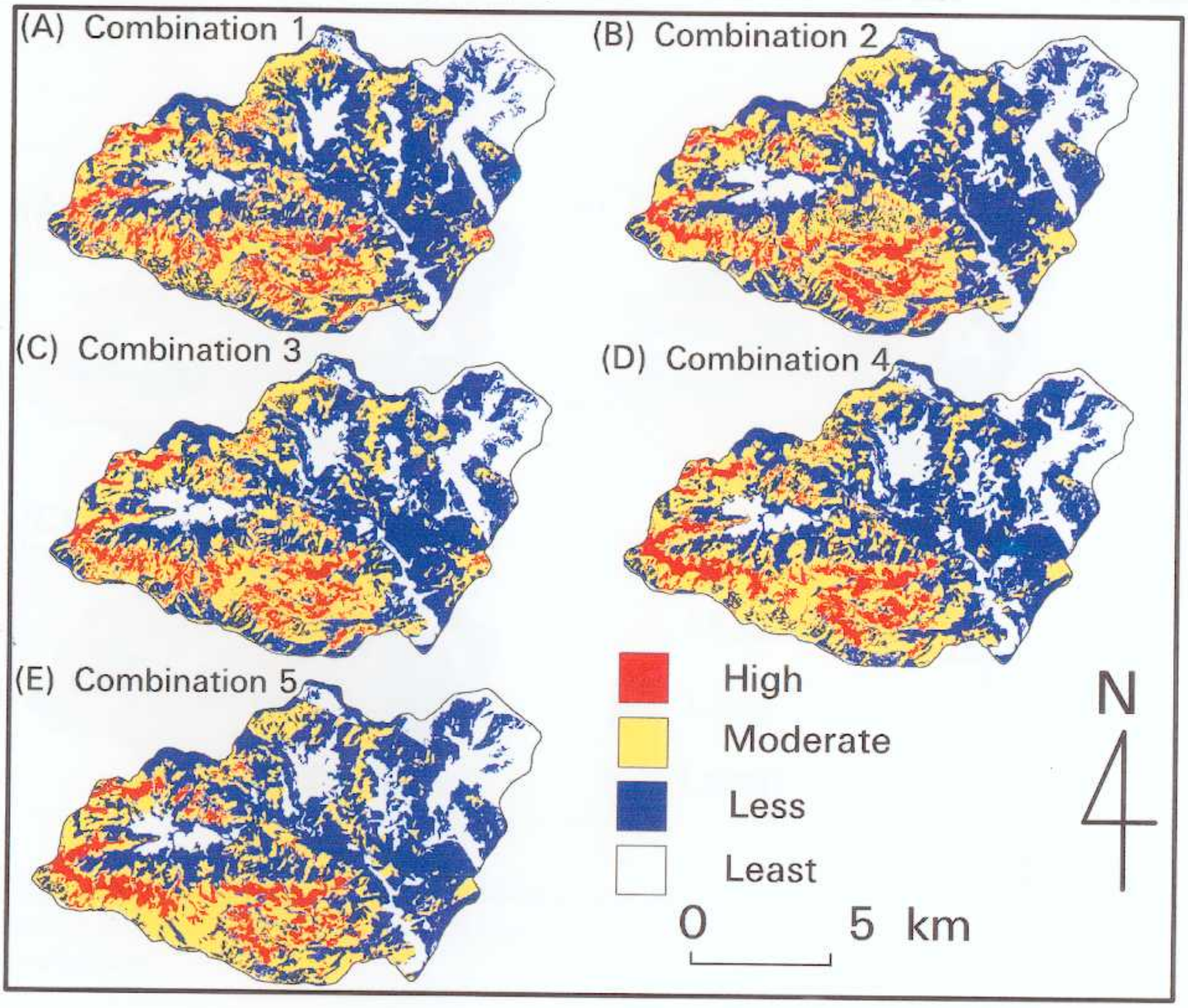

Figure 5-6 Landslide hazard maps produced from the results of the five different combinations in the Q-S II analysis.

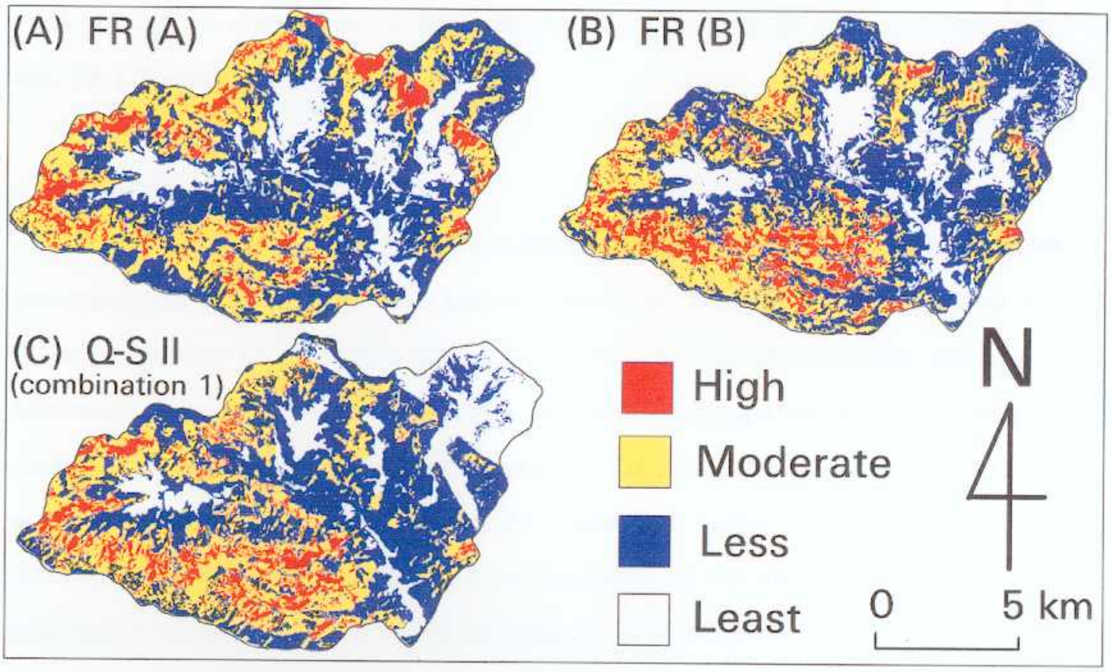

Figure 5-7 Landslide hazard maps produced from the results of the FR analyses. The hazard map produced from the Q-S II analysis (combination 1) is also shown for the comparison.

the Q-S II analysis. The accuracy of the hazard maps produced from the two FR analyses, FR (A) and FR (B), were also carried out. The spatial agreements in the three hazard maps produced from the results of FR (A), FR (B) and combination 1 (Q-S II analysis) were measured in order to examine the effect of method of analysis on the final outcome. In the following two sections, the discussion is made for hazard maps produced from five different sample combinations in the Q-S II analysis. At the end of each section the discussion on the evaluation of hazard maps produced from the FR (A) and FR (B) analyses are done.

5-4-1 Accuracy of Hazard Maps

A common method for the evaluation of landslide hazard map is to compute the percentage of landslides in each hazard class (Van Westen, 1993; Dhakal *et al.*, 1999). A large number of landslide grid-cells in the unstable area should indicate a higher accuracy of the hazard map. Grid-cells that lack landslides but are classified as unstable may indicate that they are potentially unstable (Neuland 1976; Carrara, 1983). The percentage of "test landslide" grid-cells (other than sampled landslides for analysis) in the unstable category is a measure of accuracy of the hazard maps. Then, for the evaluation of hazard maps, the percentage of "test landslide" grid-cells in the unstable category can be compared to the Q-S II accuracy of the sampled landslide data (see Figure 5-5).

Combinations 4 and 5 are those in which non-landslide groups were obtained by using an aligned systematic sampling method. The accuracy for these two combinations is lower than the other combinations (Table 5-7). In the aligned systematic sampling method, the selection of the starting grid-cells predetermined the position of all subsequent grid-cells. In this study, 196 non-landslide group grid-cells in combination 4 were found partially or fully existing within the 50-m range of landslides. This number is only 3 for combination 1. These suggest the periodicity of the landslide distribution. In the aligned systematic sampling method, a large number of non-landslide grid-cells adjacent to or near the landslides might have given those grid-cells similar site characteristics as landslides, due to the effect of autocorrelation, thereby lowering the accuracy. Combination 2 has the highest accuracy of landslide identification in the Q-S II analysis (sample data). However, this combination resulted

Table 5-7 Test landslide grid-cells falling on unstable category for five different combinations used for Q-S II analysis. For comparison Q-S II accuracy is also listed.

Combination	Test landslide in unstable category (%)	Q-S II accuracy (%)
Combination 1	67.7	68.5
Combination 2	65.9	70.1
Combination 3	67.7	69.2
Combination 4	65.7	67.5
Combination 5	62.8	67.3

Table 5-8 *Landslide grid-cells (all) falling in unstable* category for FR (A) and FR (B) analyses. For comparison of methods used all landslide grid-cells falling on unstable category of hazard map produced from Q-S II (combination 1) analysis is also listed.

Combination	Landslide grid-cells (considering all landslides) in unstable category (%)
FR (A)	64.0
FR (B)	63.0
Q-S II analysis (Combination 1)	68.0

in a comparatively low accuracy of hazard map compared to combinations 1 and 3 (see Table 6), although not significant.

The analyses FR (A) and FR (B) use all the landslide area and landslide number in calculating the score. Hence, instead of evaluating them only from "test landslide" all landslide grid-cells (using all landslides) falling on unstable class was used as a measure of the accuracy of the hazard maps. In order to compare the two hazard maps produced from FR analyses with that of the Q-S II, all the landslide grid-cell (using all landslide) falling on unstable class for the hazard map produced from combination 1 (Q-S II analysis) was also calculated. Table 5-8 compares the results of the evaluation of three hazard maps. The accuracy is low for the results of the FR analyses compared to the result of the Q-S II analysis. Since area of hazard classes in these three hazard maps are same, it can be concluded that the result of the Q-S II analysis is better than the results of the FR analyses.

5-4-2 Evaluation of Spatial Agreement

To evaluate the spatial agreement of the hazard classes between the hazard maps, two of the five hazard maps (produced from Q-S II analysis) were overlaid in turn and all the grid-cells classified into the same hazard class (agreed grid-cells) were counted. The "overall spatial agreement" was then calculated by taking the proportion of agreed grid-cells to the total number of grid-cells, in the similar manner to the evaluation of overall accuracy from the error matrix (e.g., Congalton *et al.*, 1983; Congalton, 1991). Table 5-9 is an error matrix of the evaluation of the spatial agreement in which the hazard maps of combination 2 was compared against that of combination 1. The overall accuracy of the error matrix shown in table 5-9, which represents the accuracy of the entire spatial agreement, is the ratio of the sum of the major diagonal (agreed grid-cells) to the total number of grid-cells. Table 5-10 compares the overall spatial agreement between the five hazard maps produced from the results of the Q-S II analysis. Figure 5-8 is a visual example, which depicts the agreed and disagreed hazard classifications when the hazard map of combination 1 was crossed with the remaining four. The disagreement in the five hazard maps produced from the Q-S II results varies between 10 to 20 percent. The agreement between the hazard maps is higher for the hazard maps resulted from sample combinations that used the same method for selecting a non-landslide group (see Table 5-2 and Table 5-10). It is also important to point out that disagreement between the hazard maps was introduced only from the immediate class, i.e. no "high" hazard class identified in a hazard map was classified as "less" or "least" in the other and vice versa (see Table 5-9).

In the similar manner, to evaluate the spatial agreement of the hazard classes between the hazard maps produced from the results of FR (A), FR (B) and combination 1 (Q-S II), two of the them were overlaid in turn and the overall spatial agreement between the hazard maps were calculated. The overall spatial agreement was calculated for hazard maps classified into four hazard classes, and also for hazard maps classified into only two hazard categories (i.e. stable and unstable). Table 5-11 shows the agreements in the three hazard maps when they are classified into four hazard classes or two hazard categories.

Figure 5-9 is a visual example, which depicts the agreed and disagreed hazard classifications when each of the three hazard maps is crossed with another. It is found that two third of the area is classified into the same hazard classes when hazard maps are classified into four classes. However, if study area is classified into only two hazard categories, unstable and stable, the overall spatial agreement is about 80 percent.

5-5 DISCUSSIONS

Two methods of hazard assessment models called the Q-S II analysis and the FR analysis were applied. I have shown in this study that the use of GIS is invaluable for determining the best sampling techniques for the grid-cell based hazard assessment in the Q-S II analysis. The methods of evaluation of spatial agreement of hazard maps was developed to compare the hazard maps produced from FR analysis to that of the Q-S II analysis. The subsequent discussions are based primarily on the results of the analysis and secondarily on the overall aspect of the hazard assessment and mapping.

5-5-1 Factors and Classes Contributing to Landsliding

In this study geology is found to be the most important factor contributing to landsliding in all combinations. Though the different sample combinations employed in the Q-S II analysis showed some minor variations, elevation, land use/cover and slope aspect fall within the second group of importance, while slope gradient is in the third

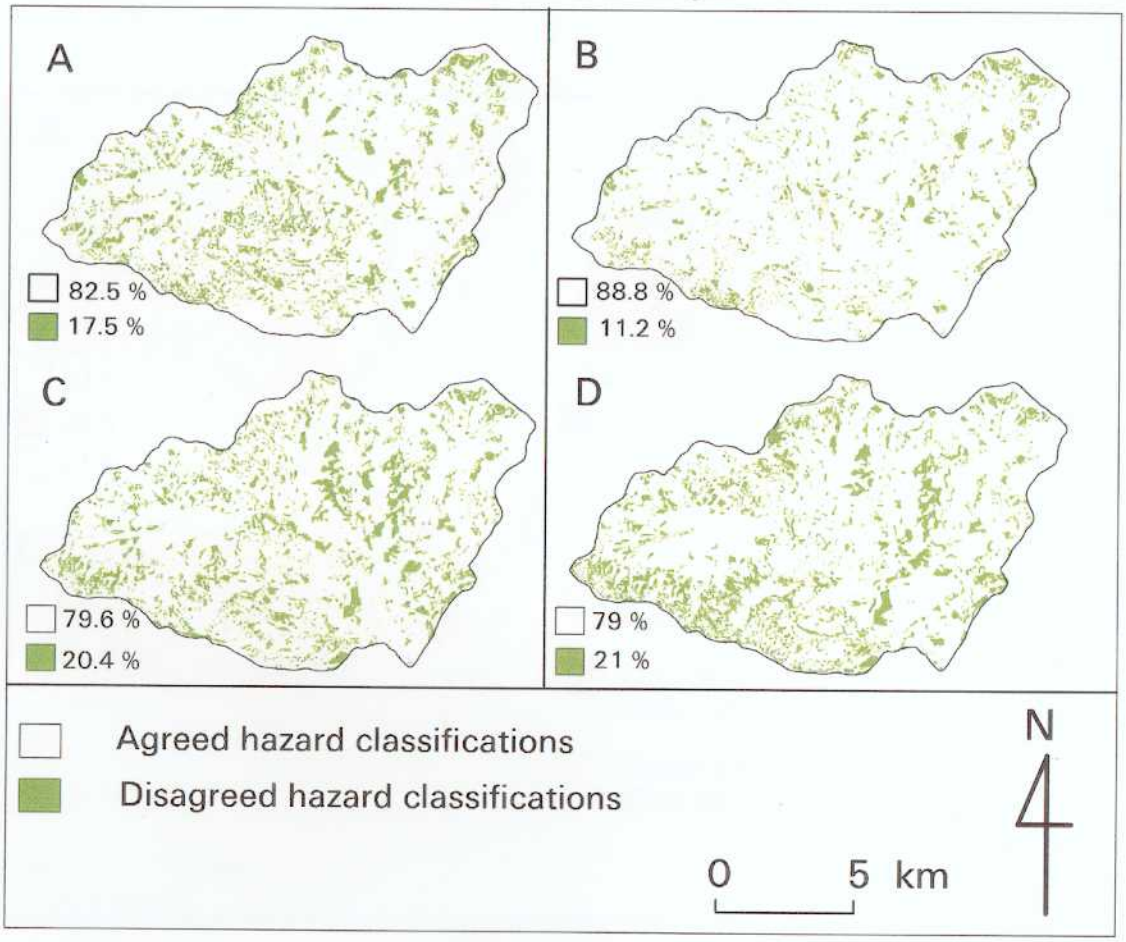

Figure 5-8 Spatial agreements between the hazard maps produced from results of Q-S II analysis; (A) combination 1 and combination 2, (B) combination 1 and combination 3, (C) combination 1 and combination 4, and (D) combination 1 and combination 5.

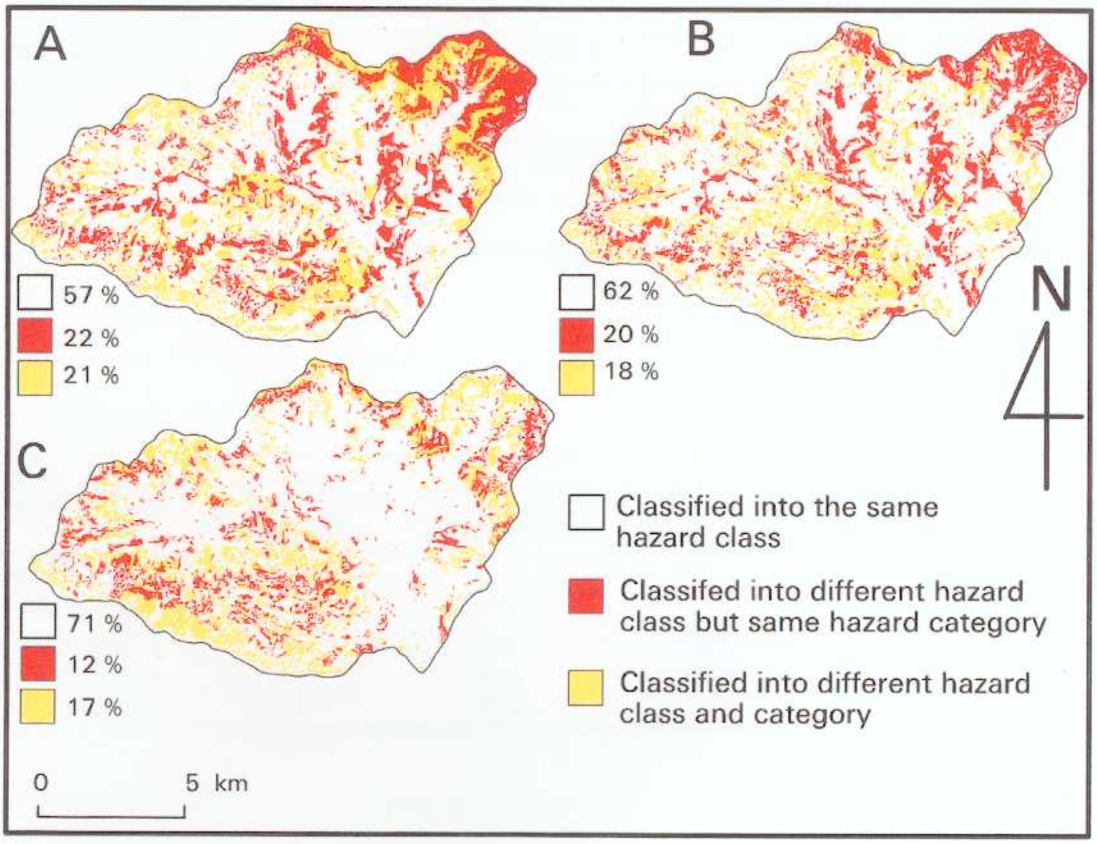

Figure 5-9 Spatial agreements between the hazard maps produced from different methods. (A) Q-S II (combination 1) and FR(A), (B) Q-S II (combination 1) and FR(B), and (C) FR (A) and FR(B).

Table 5-9 Error matrix of spatial agreement assessment for the landslide hazard map of Combination 2 against that of combination 1 in the Q-S II analysis.

		Combination 1				
		High	Moderate	Less	Least	Total
Combination 2	High	11710	3794	0	0	15504
	Moderate	3540	47041	9557	0	60138
	Less	0	10205	73575	3501	87281
	Least	0	0	4055	30752	34807
	Total	15250	61040	87187	34253	197730

Overall accuracy = (11710 + 47041 + 73575 + 30752) / 197730 = 0.825

Table 5-10 Comparision of spatial agreement (%) between five hazard maps produced from the results of five different combinations in the Q-S II analysis.

	Combination 1	Combination 2	Combination 3	Combination 4	Combination 5
Combination 1	100				
Combination 2	82.5	100			
Combination 3	88.8	90.1	100		
Combination 4	79.6	81.1	82.7	100	
Combination 5	79	77.9	79.2	87.7	100

Table 5-11 Overall spatial agreements between three hazard maps produced from the FR (A), FR (B) and Q-S II (combination1) analyses. Overall spatial agreement is calculated for hazard maps produced with four hazard classes as well as for two hazard categories.

		Q-S II (Combination1)		FR (A)		FR (B)	
		Four classes	Two categories	Four classes	Two categories	Four classes	Two categories
Q -II (Combination 1)	Four classes	100					
	Two categories		100				
FR (A)	Four classes	57		100			
	Two categories		79		100		
FR (B)	Four classes	62		71		100	
	Two categories		82		83		100

group. The results of the FR analysis are also similar. The most critical association of classes for landsliding in the Q-S II analysis are "granite", "2000 m - 2200 m", "coniferous forest" ("shrub land" in combinations 2, 4 and 5), "East" ("South" in combinations 2, 4 and 5) "35° - 45°", "first order" ("second order" in combinations 4 and 5), <50 m (distance from valley) and >100 m (distance from ridge). In the FR (A) and FR (B) analyses, the association of classes "granite" (Limestones in FR (A)), "2000 m-2200 m", "coniferous forest" ("shrub land" in FR (A)), "East" "35° - 45°", "first order" <50 m (distance from valley) and >100 m (distance from ridge) are found most critical to landsliding.

A similar study conducted for the Amahata river basin in Japan by Aniya (1985) found that vegetation, slope gradient, and slope aspect were the factors critical to landsliding. A study in Omichi-Dani, Japan, by Amada *et al.* (1995) found geology and slope aspect as the important factors causing landslides. Dikau (1990) found slope angle and concave form elements (plan and profile) as the significant descriptors of the landslides in the Mainz Basin, southwest Germany. It is to be expected that different regions have different critical factors, because the environmental factors, such as geology, land use, and topography also are likely to be different as well as the climatic and hydrological conditions.

The factors considered may also be dependent upon the data available since creating new data is time consuming and costly, if not impossible. Also local site

characteristics are often difficult to incorporate into hazard assessment for large areas. The selection of factors and their classification are most important tasks in this kind of analysis. These should be primarily decided by the sample landslides surveyed in the field, and previous knowledge of the causal relationships between slope failure and instability factors. It is, hence, necessary to survey few landslides in the field before carrying out the analysis. A good planning is necessary to sample the landslides for investigation. This was the approach employed in this study. Some authors prefer to use large set of variables in the beginning and to eliminate those, which prove to be unrelated to the occurrence of landslides (Van Westen, 1993). The idea is good when the fieldwork is not enough and less is known about the characteristics of landslides but is not ideal.

5-5-2 Methods of Analysis for Landslide Hazard Assessment

The methods used in this study are practical methods at the medium scale (1:25,000-1:50,000) for large areas such as several tens of square kilometers. The Q-S II analysis is based on multivariate statistical analysis and is theoretically a superior method than the FR analysis. In this study the Q-S II analysis yielded better results than the FR analysis. In the Q-S II analysis, sampling schemes had been shown to be crucial in the small grid-cell based models; however, no study existed which had attempted to clarify the problem. The results suggest that the unaligned stratified random sampling method is better than the aligned systematic sampling method for selecting a non-landslide group, because the former yielded the highest QS-II indices, and resulted in the most accurate hazard map. The disagreement in the five hazard maps, which use the results of different sample combinations from the Q-S II results, varies from 10 to 20 percent. A small variation in the overall spatial agreements can be recognized in the three hazard maps, which used the results from the unaligned stratified random samples of non-landslide group. These results are likely to indicate that although the outcome depends to some extent on the sampled data, the difference may be small enough for the practical use of a hazard map.

The FR analysis did not consider the correlation or weight between the factors because a variable was considered independently when calculating the score; however it's operation is simple and easy. Irrespective of the method employed or condition introduced (in FR analysis), two third of the areas were classified into the same hazard class, when hazard map was produced with four hazard classes. If the purpose of the hazard map would be to delineate only two categories (unstable and stable), 4/5 of the area will be classified into the same category. This suggests that depending on method, the sites classified into marginal hazard classes (such as moderate and low) may differ in different maps. Hence, areas that fall into marginal hazard classes may need attention during the use of the hazard map.

Whether to use the area of landslides or frequency of landslides in the calculation of score in the FR analysis should be decided by the intended application of the hazard map. For example, when the hazard maps are produced for sediment yield modeling, smaller landslides may not be as important as bigger ones (in terms of sediment yield). Hence, it might be better to use the area of landslides in the analysis.

However when the hazard map is intended for risk mapping the analysis based on the number of landslides might be wiser.

5-5-3 Delineation of Landslides Using Arial Photographs

The hazard mapping carried out in this study can be categorized as the medium scale as most of the maps used are in the scale of 1:25,000. In the medium scale hazard mapping based on smaller grid-cells, the spatial resolution of imagery or aerial photographs must allow for the identification of the smallest individual landsliding phenomena in the study area, for example, 10 m-12 m in dimension. Hence, among the presently available remotely sensed data, only the aerial photographs serve as the accurate remote sensing data for interpretation, because delineation of landslides was the most important aspect of the hazard assessment approach employed in the study.

The identification of landslides, however, can contain a high degree of uncertainty. The scale of the aerial photographs used for this study was 1 : 20,000. At this scale it is often possible to identify landslide with the dimension of 10 m - 15 m. However, aerial photographs has the disadvantages that a large number of photographs are needed to analyze and mapping is greatly influenced by the experience of the analyst. In addition, many times photographs may not be available for the required date. About estimated 7,500 photographs (scale 1:30,000) were interpreted by Brabb *et al.* (1989) to produce landslide distribution map for the entire state of New Mexico (area 121,122 km^2). Carrara *et al.* (1995) estimated the total error ranging from 50 percent to 80 percent in the interpretation of landslides carried out for five test areas in Italy, when each test area was mapped independently by surveyors with equal or different experience, and equal or different mapping techniques. A similar test carried out in a Colombian sample area by Van Westen (1993), shows a very large discrepancy leading an overall error greater than 90 percent. Great differences in landslide mapping are also reported by Fookes *et al.* (1991) when surveyor with different experience attempted to interpret the same set of aerial photographs.

In this study the quality of photographs used was good. Vegetation was sparse hence landslides were easy to locate and recognize due to the high bright tone. However, small landslides were often confused with the exposed rocks. Especially in the granite areas a lot of exposed rocks had been misidentified as landslides. For this reason, I limit the minimum size of the landslide that could surely be identified on the aerial photographs to 600 square meter (roughly 25 x 25), because it was most important to locate the landslide correctly for the hazard model employed in the study.

5-5-4 Geographic Information Systems and Landslide Hazard Mapping

In landslide hazard mapping there is a need to acquire a large spectrum of morphological features and their interrelations with respect to landslides. Traditionally, the acquisition of this type of data is a long, tedious and error-prone operation. The development of GIS has greatly facilitated the handling, processing and manipulation of elevation data through DEM. Morphological parameters can be automatically derived from DEM, which, in turn, can be obtained from existing detailed topographic maps.

In this research three main factors, slope gradient, slope aspect, and elevation were derived from the DEM. GIS also served as an important tool in reducing the subjectivity during the analysis. For example, in this kind of analysis, the classification of factors is often very important. It should generally be guided by the measurement of sample landslides in the field. The previous knowledge of casual relationship is also important. With the use of GIS it was possible to quickly change the required classification.

The conclusion on the sampling schemes for the Q-S II analysis that was derived in this study is an important achievement in the field of landslide hazard assessment. Such analysis would have been nearly impossible without the aid of GIS.

One of the disadvantages often pointed out for GIS is that data input procedure is lengthy and time consuming. However, when data input is completed, the improvement on the model is possible by performing various alternatives. Hence, it has become necessary to convert any kind of analogue data into digital form so that data can be directly used for modeling any environmental problems with GIS.