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A Quantitative Approach for Improving the BIS (Indian) Method of Medium-scale Landslide Susceptibility

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Abstract: In India, the Bureau of Indian Standards (BIS) recommends a heuristic method for medium-scale (1:25,000/ 1:50,000) landslide susceptibility mapping. This is based on fixed ratings of geofactors, without the inclusion of landslide inventory information. In BIS method, the pre-defined ratings of geofactors are applied over diverse areas, irrespective of the terrain-specific spatial inter-dependence of geofactors and landslide types, which leads to rather moderate prediction. In this paper, we evaluate the effectiveness of the existing BIS method in Darjeeling Himalaya through a quantitative method adapting weights of evidence (WofE) modeling. The quantified spatial associations between specific geofactors for different landslide types and failure mechanisms that were generated, using this method showed improved prediction rates as compared to the BIS method of fixed ratings of geofactors. We therefore recommend adjusting the existing BIS guidelines by inclusions of weights, derived locally through quantitative spatial analysis of landslide inventories and geofactor maps.

Keywords: Landslide susceptibility, BIS method, Weights of evidence, Darjeeling Himalaya.

INTRODUCTION

A wide range of techniques are available for landslide susceptibility mapping and their quantitative validation, which can be classified into inventory, heuristic, statistical, deterministic and probabilistic (Hansen, 1984; Soeters and Van Westen, 1996; Varnes, 2000). In India, the Bureau of Indian Standards (BIS) has formulated guidelines (BIS, 1998) for landslide susceptibility zonation at medium scales (1:25,000-1:50,000). The BIS guidelines recommended an indirect approach to landslide susceptibility mapping according to the method originally proposed by Anbalagan (1992). It provides a generalized heuristic system of fixed weighting or ranking of a set of pre-defined geofactors called Landslide Hazard Evaluation Factor (LHEF) rating (Table 1). According to Anbalagan (1992), the LHEF rating scheme is based on expert knowledge in the study of geofactors and their effect on causing landslides and therefore the numerical values of ratings are fixed mostly on the basis of qualitative assessment. These LHEF ratings are applied irrespective of variations in the terrain conditions and are determined without directly considering the existing landslide inventory data. Since the spatial extents of landslide geofactors and their respective causal association with different types of landslides and failure mechanisms are mostly variable, the application of a fixed LHEF rating of geofactors can be inappropriate and can lead to moderate landslide prediction rates when applied to different areas.

The above aspect also refers to the recent research carried out by some of the present authors in the same study area (Ghoshal et al. 2008), where validation was done by landslide (LS) abundance values. The LS abundance is obtained by normalizing the absolute landslide density (No. of slides per unit area) to 100 for each susceptible zone, which can only indicate the changes in landslide density values in different susceptible zones. But, the LS abundance value can not fully estimate the actual predictive power of any model since the distribution of cummulative landslide area% against the cumulative map area% is not revealed. Moreover, like any other heuristic method, BIS method

Table 1. LHEF ratings of different causative geofactors (please refer BIS, 1998 and Anbalagan, 1992)

Geofactor	Description	Category		LHEF
			Quartzite and Limestone	0.2
	Rock type	Type 1	Granite and Gabbro	0.3
	Type – 1**		Gneiss	0.4
	Highly weathered (4);		Sandstone and minor beds of claystone	1.0
	moderately weathered (3);	Type 2	Poorly cemented sandstone with minor clay/shale	1.3
	Slightly weathered (2)			
Lithology	Type – 2 **		Slate and phyllite	1.2
	Highly weathered (1.5);	Type 3	Schist	1.3
	Moderately weathered (1.25);		Shale with interbedded clayey and non-clayey	1.8
	Slightly weathered (1.0)		Highly weathered shale, phyllite and schist	2.0
		Older well compacted alluvial fill material		0.8
		Clayey soil with naturally formed surface		1.0
		Sandy soil with naturally formed surface (alluvial)		1.4
	Soil type	Debris comprising mostly rock pieces mixed with clayey/ sandy soil (colluvial) – older well compacted		1.2
		Debris comprising mostly rock pieces mixed with clayey/ sandy soil (colluvial) – younger loose material		2.0
		> 30^{o}		0.20
	Relationship of parallelism	21^{o} – 30^{o}		0.25
	between the slope and	11^{o} – 20^{o}		0.30
	vulnerable discontinuity	6^{o} – 10^{o}		0.40
		< 5^{o}		0.50
	Relationship of dip of	> 10^{o}		0.3
	vulnerable discontinuity	0^{o} – 10^{o}		0.5
	and inclination of slope	0^{o}		0.7
Structure		0^{o} – (-10^{o})		0.8
		< -10^{o}		1.0
	Dip of vulnerable	< 15		0.20
	discontinuity	16^{o} – 25^{o}		0.25
		26^{o} – 35^{o}		0.30
		36^{o} – 45^{o}		0.40
		> 45^{o}		0.50
	Depth of soil cover	< 5 m		0.65
		6 – 10 m		0.85
		11 – 15 m		1.30
		16 – 20 m		2.0
	Escarpment / cliff	> 45^{o}		2.0
	Steep slope	36^{o} – 45^{o}		1.7
Slope	Moderately steep slope	26^{o} – 35^{o}		1.2
	Gentle slope	16^{o} – 25^{o}		0.8
	Very gentle slope	≤ 15^{o}		0.5
	< 100 m			0.3
Relative relief	101 – 300 m			0.6
	> 300 m			1.0
	Agricultural land / populated flat land			0.60
Landuse and land cover	Thickly vegetated forest area			0.80
	Moderately vegetated area			1.20
	Sparsely vegetated area with less ground cover			1.50
	Barren land			2.0
	Flowing			1.0
Hydrogeological conditions	Dripping			0.8
	Wet			0.5
	Damp			0.2
	Dry			0.0

** Numerical values within parenthesis are correction factor for weathering

(Anbalagan, 1992) also does not recommend any specific quantitative validation method, but the predictive power of any model can only be compared and judged through such quantitative cross-validation. Therefore, in the present research, a more robust and internationally-accepted method of cross-validation was employed, through construction of success/ prediction rate curves (Chung and Fabbri, 1999, 2003). Application of this validation technique in the current research revealed that in similar BIS-susceptible areas, higher cumulative map area% is actually required to classify a substantially higher cumulative area% of landslides, which indicates actually a rather moderate rate of prediction in BIS susceptible maps.

The objectives of this paper thus, are (a) to test the hypothesis of such moderate performance of the existing BIS method with fixed LHEF rating and (b) to demonstrate that the performance of the BIS method can be improved by modifying the recommended LHEF ratings based on empirically-derived weights for geofactors for each particular study area. This was achieved by comparing the results of applications of the BIS method with those derived from adapting the applications of the weights of evidence (WofE) method (Bonham-Carter, 1994) in the same study area.

STUDY AREAS AND LANDSLIDE OCCURRENCES

For this purpose, two adjoining areas in Darjeeling Himalaya, India were selected (Fig. 1), which represent parts of Survey of India (SOI) topographic sheets (TS) 78A/8 (Area 1) and 78A/12 (Area 2). They have differences in terrain attributes (Table 2) that could influence the location, types, and intensities of landslides occurrences. Although the BIS method does not require a landslide inventory database, a landslide distribution map was prepared for both areas for the validation of results of the BIS method and for the application of the WofE method. The known landslide occurrences in the case study areas were represented as discrete polygons of various sizes and shapes. To prepare the landslide distribution maps of TS78A/8 and TS78A/12 (Figs.2a, b), landslide occurrences from SOI topographic sheets (surveyed during 1961-62), old landslide inventory maps (Chatterjee, 1983; Sengupta, 1995; Bhattacharya et al. 1998) and the data from recent ground surveys were used. The landslide distribution maps contain various types of landslides recorded within the last five decades. Some of the old landslides are stable but many of them are also reactivated. It can be concluded that, in TS78A/8 the predominant landslides are rock slides followed by few debris slides, whereas in TS78A/12 there is an almost equal amount of rock and debris slides, though, dimensions of debris slides are comparatively larger. For WofE analysis, these landslide occurrences in each of the two areas were randomly partitioned into two sets of almost equal number of training and testing landslide polygons. Since BIS method does not consider landslide data, to have a comparative analysis, in WofE, the landslide inventory data are not partitioned into different types/ failure mechanisms.

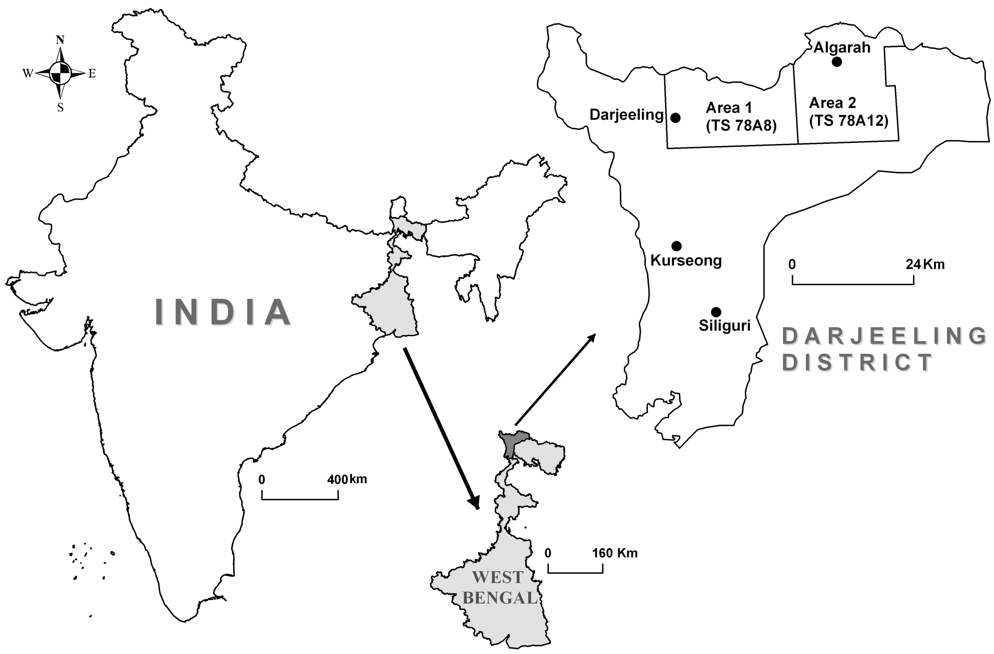

Fig.1. Location map of the study areas.

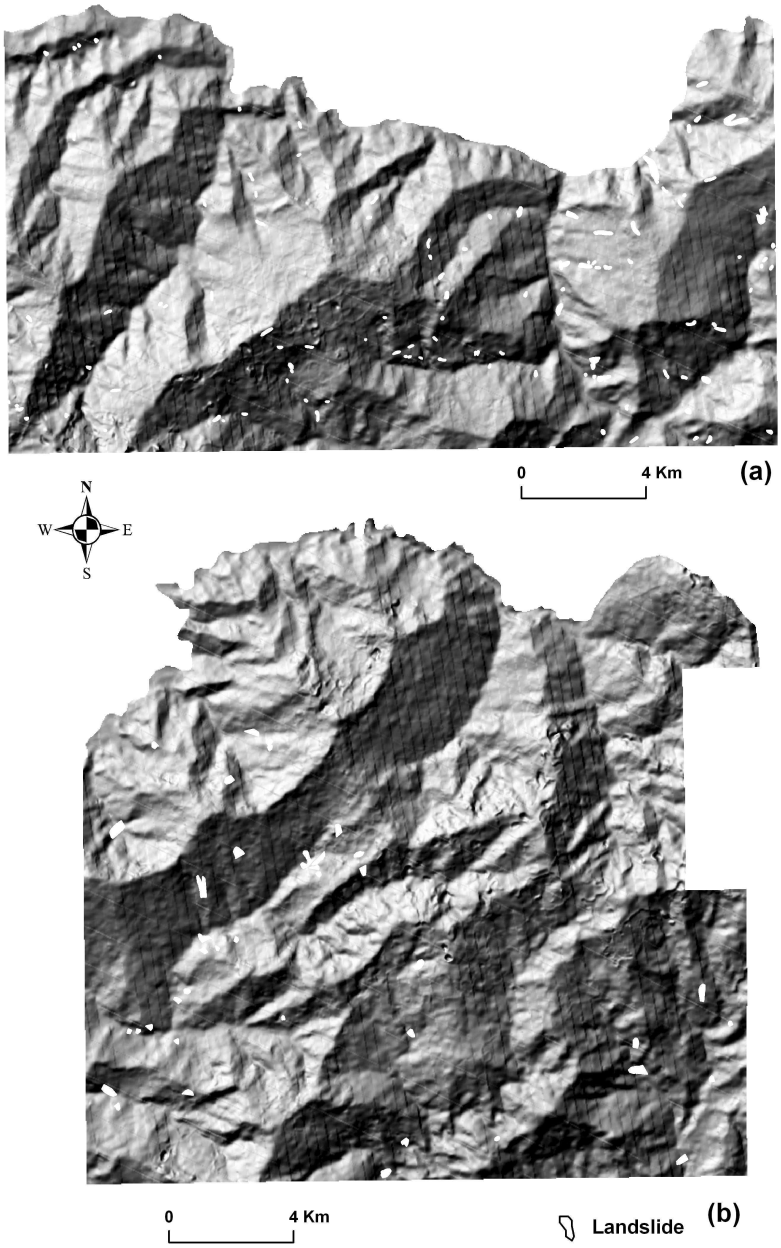

Fig.2. Landslide distribution map of **(a)** Area 1 (TS 78A8) and **(b)** Area 2 (TS 78A12).

APPLICATION OF THE BIS METHOD IN THE STUDY AREAS

Following the BIS guidelines (BIS, 1998; Table 1), thematic maps of geofactors (lithology; slope; relative relief; geological structure; landuse and land cover; and hydrogeology) were generated in a GIS, after extensive image interpretation and fieldwork. The two areas have different spatial extents of landslide geofactors (Table 3). Mapping units were generated as slope facets from a Digital Elevation Model by combining slope classes and aspect classes via a map intersection operation in GIS (Surendranath et al. 2008). The data processing and BIS-modeling were carried out in ArcGIS 9.2 platform.

The rating scheme for structure categories (Table 1) is somewhat complicated, thus needs some elaboration. Areas with rock cover are rated according to three different structural geometric parameters (Table 1). In Darjeeling Himalaya, most of the rock slides are caused by the presence of unfavourable dispositions of joints (for planar failures) or intersection of two joints (for wedge failures) vis-à-vis the slope aspect (or direction) and inclination. Thus, in areas of rocky slopes, the ratings according to the three structural

Table 2. Attributes of the two case study areas

Attributes	Area 1 (TS78A/8)	Area 2 (TS78A/12)
Map area	289 km^2	395 km^2
Number of landslide polygons	122	44
Landslide area	1.68 km^2	1.45 km^2
Landslide types	Predominantly rock slides, followed by few debris slides	Mixed types – near equal proportion of both rock and debris slides; debris slides are comparatively larger in dimension.
Causal mechanisms	Higher level of rock weathering, fragile lithology, predominance of moderate to steep slope, higher relief, higher anthropogenic activity etc	Toe cutting by stream, fragile lithology, presence of sheared gneiss, predominance of thick loose and unconsolidated colluviums etc
Morphometry	Predominant slope is above 25^o (50% of the area); slopes steeper than 35^o is 12% of the area	Predominant slope is below 25^o (64% of the area); slopes steeper than 35^o is only 8% of the area.
Geology	Near-equal area% of competent gneisses (33%) and fractured/ sheared schists/ phyllites (27%)	Predominance of competent gneissic rocks (33%) over fragile schists/ phyllites (17%) and sheared gneiss (1%)
Landuse	Higher proportion of tea garden and agricultural areas (64%); forest (both thick & moderate) areas are comparatively lesser (27%).	Comparatively lower proportion of flat agricultural land (47%); forest areas (both thick and moderate) are comparatively higher (40%)

geometric parameters as proposed in BIS guidelines are highly relevant.

Calculations of angular relationships between the dip direction/dip of joints (for planar failures) or the plunge direction/plunge of intersection of two joints (for wedge failures) and the direction/inclination of slope facets with rock exposures were carried out to assign different structural sub-ratings (Table 1). The structural data (dip and strike of joints) were collected from available geological maps and recent field data and zones of possible planar and wedge failures within the rocky areas were assessed. The degree of parallelism of inclination direction of slope with either the dip direction of joint (for planar failures) or the plunge direction of intersection of two joints (for wedge failures) is obtained as the absolute difference between these two values and subsequently fixed sub-ratings are assigned (Table 1). The inclination of slope of any facet is subtracted from either the dip of joints (for planar failures) or the plunge amount of intersection of two joints (for wedge failures) and subsequently fixed sub-ratings are assigned as per the ranges of angular differences given in Table 1. The third structural fixed sub-rating is assigned directly depending on the respective dip amount of joints (for planar failures) or plunge amount of intersection of two joints (for wedge failures). The LHEF rating for structural theme is obtained by summing up all the above three sub-ratings per individual facet (Anbalagan, 1992; BIS, 1998).

All the six thematic layers with their respective LHEF ratings were then represented per individual mapping unit or facet to calculate the total estimated hazard (TEHD) values (BIS, 1998; Anbalagan, 1992). The resulting landslide susceptibility maps were classified into five classes according to the BIS-recommended ranges of TEHD values (Figs. 3a and 4a; Table 4).

For validation of the BIS method, the resulting landslide susceptibility maps were combined with the landslide inventory maps for both areas. For overall validation of BIS susceptibility, prediction rate curves (Figs. 5a and b) were prepared by plotting the cumulative percentage of all known landslide area (along y-axis) versus the cumulative percentage of the area of the susceptibility map, ordered from high to low TEHD values following method proposed by Chung and Fabbri (2003). If the prediction rate curve is steep at lower cumulative map area percentage of highest TEHD values, then the corresponding landslide susceptibility map has strong ability to predict areas that are most susceptible to landsliding.

In Area 1, 30% of the map with highest TEHD values contains 47% of the landslides (Fig.5a) and in Area 2, 30% of the map with highest TEHD values contains 52% of the landslides (Fig.5b). Table 5 indicates the landslide density and the percentage of total landslides in different BIS susceptibility classes for the two areas. Although the landslide density increases with increasing landslide susceptibility, similar to the increasing trend of "LS abundance" values (Ghoshal et al. 2008), the differences in landslide densities between the landslide susceptibility classes are generally small. In addition, there are more landslides in the "low" and "moderate" classes (78% in Area 1 and 58% in Area 2) than in the "high" to "very high" classes

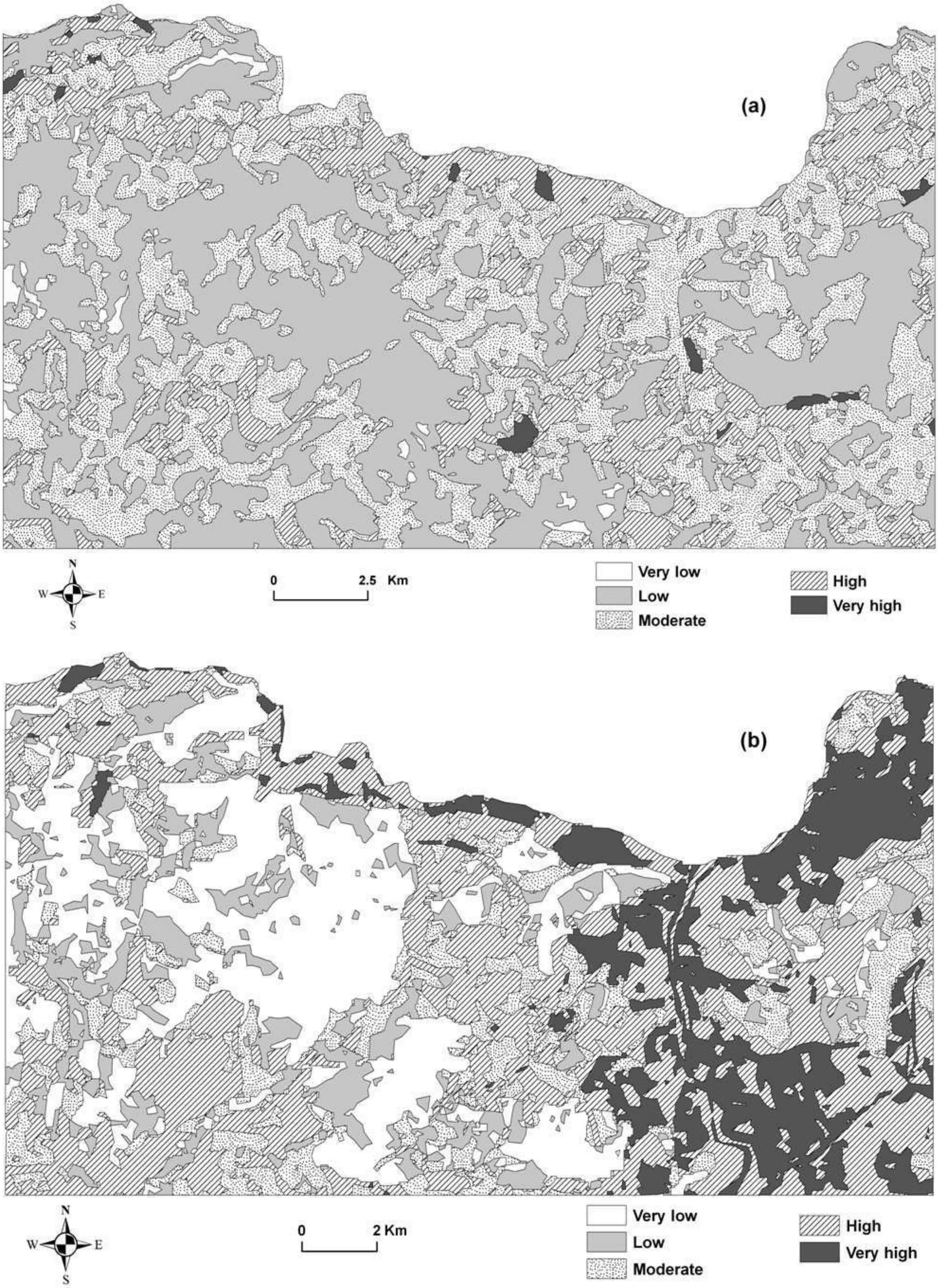

Fig.3. Landslide susceptibility map of Area 1 according to **(a)** the BIS method and **(b)** the WofE method.

Table 3. Area percentage distribution of the geofactors in the study areas

Geofactors (BIS)	% area in Area 1 (TS78A/8)	% area in Area 2 (TS78A/12)
Lithology		
Rock cover		
Phyllite/Quartzite/Schist	27	17
Gneiss & Quartzite	33	33
Sheared Gneiss	1	1
Soil cover		
Older Well Compacted Alluvial Fill Material	4	2
Older Well Compacted Debris	32	36
Sandy Soil With Naturally Formed Surface	0	4
Younger Loose Debris Material	3	3
Clayey Soil	0	4
Slope		
Very gentle slope(<15º)	13	40
Gentle slope (15º-25 º)	37	24
Mod. Steep slope (25º-35 º)	38	28
Steep slope (35º-45 º)	11	7
Escarpment (>45º)	1	1
Relative relief		
Low (<=100 m)	23	14
Medium (101 -300 m)	45	44
High (>300 m)	32	42
Landuse and land cover		
Agriculture, Populated Land	34	47
Tea Garden	30	1
Cinchona Plantation	0	2
Thickly Vegetated area	23	26
Moderately Vegetated area	4	14
Sparsely Vegetated area	5	3
Barren Land	4	7
Hydrogeology		
Damp	19	26
Wet	78	57
Dripping	2	15
Flowing	1	2

in both areas (Table 5). This indicates that the recommended classification according to the fixed ranges of TEHD values of the BIS-method tends to be ineffective to delineate or predict zones with actually high to very high landslide susceptibility. The results corroborate further that the fixed nature of LHEF weights in the BIS guidelines for diverse terrain conditions as well as the fixed ranges of TEHD values can be ineffective.

Table 4. Landslide susceptibility classes according to TEHD values (BIS, 1998)

TEHD Values	Landslide hazard zone (LHZ)	
	Class	Category
< 3.5	1	Very Low Susceptibility
3.5 – 5.0	2	Low Susceptibility
5.0 – 6.0	3	Moderate Susceptibility
6.0 – 7.5	4	High Susceptibility
> 7.5	5	Very High Susceptibility

Table 5. Area, density, and percentage of landslides in different landslide susceptibility classes mapped in the study areas according to the BIS method

Study area	Landslide susceptibility		Cross-validation		
	Class	Area covered (km^2)	Area (km^2) of known landslides	Land-slide density	Percent of total landslide area
Area 1 (TS78A/8)	Very low	4	0.00	0.00	0
	Low	119	0.27	0.23	16
	Moderate	113	1.04	0.92	62
	High	52	0.34	0.66	20
	Very high	2	0.03	1.27	2
Area 2 (TS78A/12)	Very low	5	0.00	0.00	0
	Low	188	0.43	0.23	29
	Moderate	133	0.42	0.31	29
	High	66	0.59	0.90	41
	Very high	3	0.02	0.67	1

APPLICATION OF THE WofE METHOD IN THE STUDY AREAS

The calculation of empirical weights of geofactors can be done by various statistical and mathematical methods in a GIS using the quantified spatial relation of geofactors and landslides. Either bivariate or multivariate methods can be selected. Bivariate methods, such as the information value method (Yin and Yan, 1988), weights-of-evidence (Bonham-Carter, 1994), and evidential belief functions (Carranza and Castro, 2006) are flexible to use and allow exploring the importance of individual geofactors in an interactive manner. Multivariate quantitative methods such as multiple discriminant analysis (Carrara et al. 1991), logistic regression (Mark and Ellen, 1995) and artificial neural network (Lu and Rosenbaum, 2003) have proven to lead to better prediction results than the bivariate methods, although the interpretation of the contribution of each geofactor is less straightforward. Given the objective of this paper to verify the fixed LHEF rating per geofactor class, which represents an implicit bivariate relation with landslide occurrence, the well-established WofE method was preferred over the other bivariate and multivariate methods.

The WofE Method

The WofE method, which is based on Bayesian probability framework, was originally developed for mineral potential mapping (Bonham-Carter, 1994). The method has

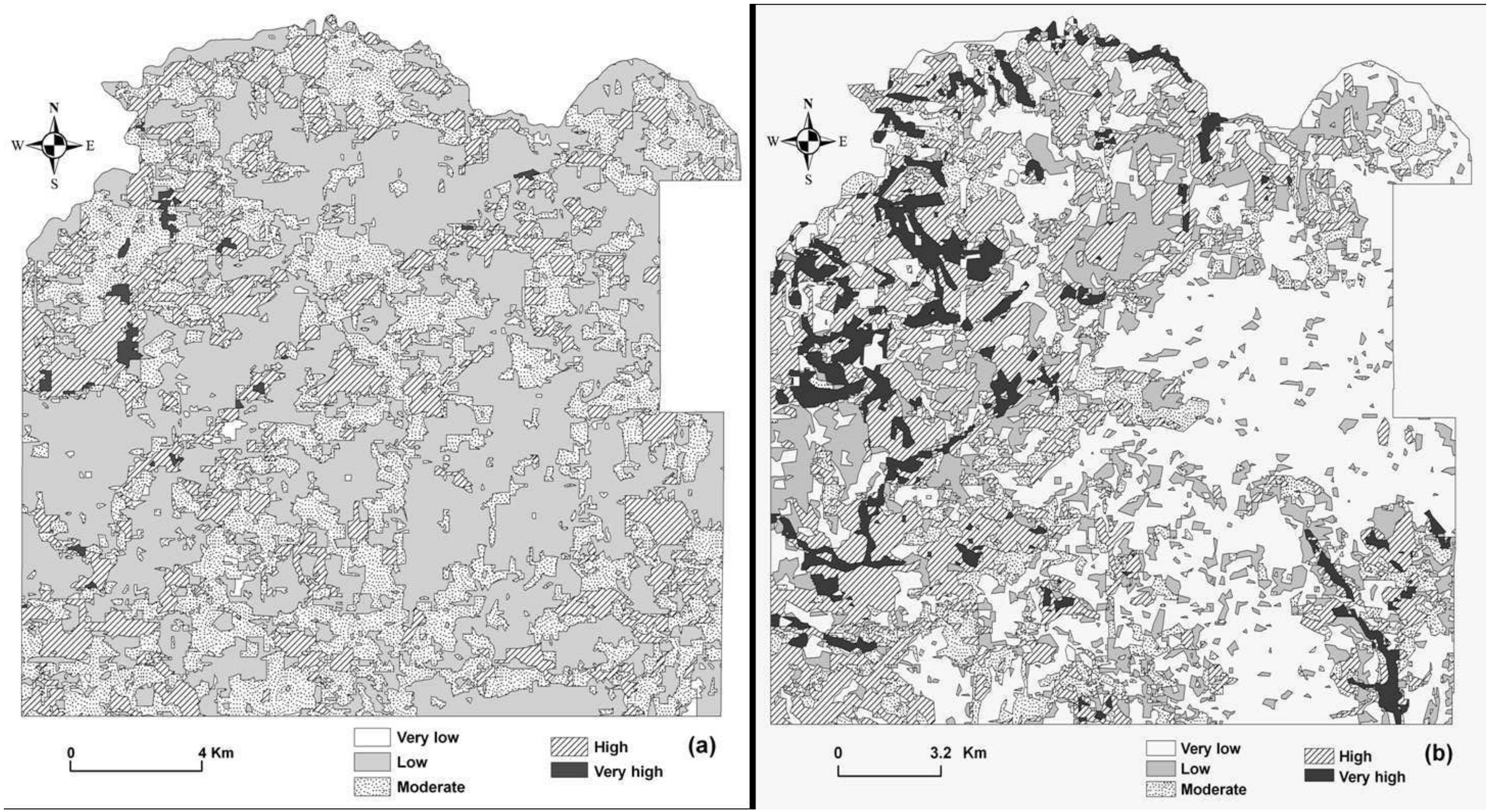

Fig.4. Landslide susceptibility map of Area 2 according to **(a)** the BIS method and **(b)** the WofE method.

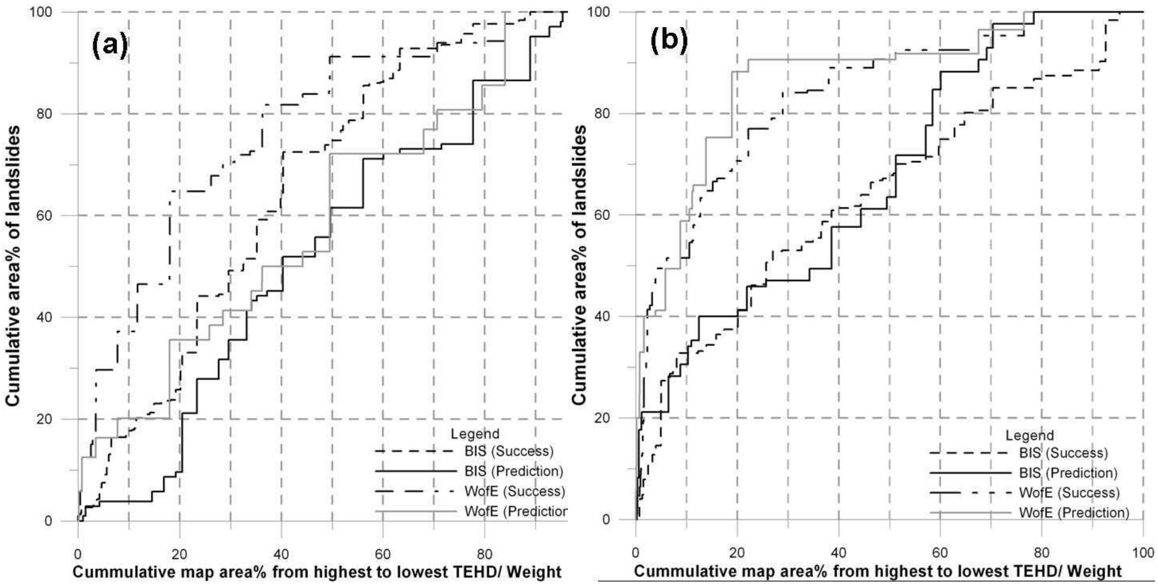

Fig.5. Comparison of success and prediction rate curves of BIS and WofE methods in **(a)** Area 1 and **(b)** Area 2.

later been adapted by several workers in landslide susceptibility mapping (e.g. van Westen, 2000; Mathew et al. 2007).

To briefly explain the WofE method, we consider a study area *T* which has *N (T)* number of unit cells. Suppose also that a geofactor *G* is present and occupies *N(G)* number of unit cells, and that a landslide *L* is present and occupies *N(L)* number of units cells. Suppose further that *G* and *L* overlaps in $N(G \cap L)$ number of unit cells. The *Wp* (Eqn. 1) represents spatial association of landslides with areas where a geofactor is present, whereas *Wn* (Eqn. 2) represents spatial association of landslides with areas where a geofactor is absent. On the one hand, if there is positive spatial association between *L* and *G*, then the value of *Wp* is positive and the value of *Wn* is negative. A positive spatial association between *L* and *G* could mean that a geofactor is a causal factor of *L*. On the other hand, if there is negative spatial association between *L* and *G*, then the value of *Wp* is negative and the value of *Wn* is positive. A negative spatial association between *L* and *G* could mean that a geofactor is not a causal factor of *L*.

$$Wp = \log_e \frac{N(G \cap L) \times N(\bar{L})}{N(G \cap \bar{L}) \times N(L)} = \log_e \frac{N(G \cap L) \times [N(T) - N(G)]}{[N(G) - N(G \cap L)] \times N(G)} \quad (1)$$

$$Wn = \log_e \frac{N(\bar{G} \cap L) \times N(\bar{L})}{N(\bar{G} \cap \bar{L}) \times N(L)} = \log_e \frac{[N(L) - N(G \cap L)] \times [N(T) - N(L)]}{[N(T) - N(L) - N(G) + N(G \cap L)] \times N(L)} \quad (2)$$

The statistical significance of the weights can be verified based on their variances, which are estimated as follows:

$$s^2(Wp) = \frac{1}{N(G \cap L)} + \frac{1}{N(G \cap \bar{L})} = \frac{1}{N(G \cap L)} + \frac{1}{[N(G) - N(G \cap L)]} \quad (3)$$

$$s^2(Wn) = \frac{1}{N(\bar{G} \cap L)} + \frac{1}{N(\bar{G} \cap \bar{L})} = \frac{1}{[N(L) - N(G \cap L)]} + \frac{1}{[N(T) - N(L) - N(G) + N(G \cap L)]} \quad (4)$$

The overall spatial association between *L* and *G* is estimated by the contrast (*C*), viz:

$$C = Wp - Wn \quad (5)$$

The value C is positive if there is positive spatial association between L and G; otherwise, it is negative. The statistical significance of the contrast can be verified by calculating a studentized contrast, which is the ratio of the contrast to its standard deviation. The standard deviation of contrast [s(C)] is calculated from the variances of the weights, viz. (Bonham-Carter, 1994):

$$s(C)=\sqrt{s^2(Wp)+s^2(Wn)} \quad (6)$$

If studentised contrast > 1.96, then positive overall spatial association between L and G is statistically significant; If studentized contrast < -1.96, then negative overall spatial association between L and G is statistically significant. The statistical significance of overall positive spatial association between L and G could mean that their physical relationship is due to real or natural processes but not to artificial or random processes (Bonham-Carter, 1994).

Calculation of Weights following WofE

The classes and categories of the same geofactor maps, except the different components of structure geofactor maps, used in BIS method were each used to represent the variable G in the preceding equations. Following BIS method, the structure geofactor classes in rock are based on two variables (slope morphometry and orientation of structural fabric), which indicate that the structure geofactor class maps are dependent on more than one independent variables, which violates the conditional independence of evidences in the WofE method. Therefore, a new structure geofactor map was created for WofE by classifying the original combined structure ratings of BIS into five categories of increasing values (Table 6). The combined structure LHEF ratings of the original BIS theme were used to create the new structure geofactor map in order to maintain the importance of structure as a causal geofactor of landslides in WofE. For calculation of WofE weights and parameters, through establishing spatial correlation between landslides (training data) and geofactors, apart from ArcGIS, ILWIS 3.3 (an open-source GIS package: http://www.itc.nl/ilwis/downloads/ilwis33.asp, developed by ITC, The Netherlands) was also used. The results of the WofE calculations are given in Table 6 and are discussed below.

Discussion on WofE Weights

According to the results of the WofE modeling, landslides occur more frequently in phyllites/schist/quartzites in both areas. “Younger loose debris” has statistically significant positive spatial associations with landslide occurrences in TS78A/8. “Older well compacted debris” and “Gneisses” in either of the two case study areas have statistically significant negative spatial associations with landslide occurrences. If we follow the above quantified spatial association, higher LHEF rating should be given to “phyllites/schists/quartzites” than “weathered gneisses” in both the case study areas. Maximum LHEF rating for “younger loose debris” is appropriate in Area 1 but not in Area 2. Similarly, older and compacted debris material on slope should be given lowest LHEF rating in both the areas. During ground surveys, it has also been observed that landslide occurrences are comparatively lesser in “gneiss” and “older well compacted debris” than in “phyllites/ schists/ quartzites” and “younger loose material”, which corroborates the above WofE calculations.

In Area 1, increasing slopes generally have increasing contrast factors, starting from negative values in gentle slopes to highly positive ones in the escarpments and cliffs. This is in line with the fact that most landslides are rockslides in Area 1 which occur on steep slopes in general. In Area 2, the pattern is different: there gentle to moderate slopes have positive factors, whereas steeper slopes have negative ones, which indicates presence of large debris slides in lower slope classes. Therefore, the increasing trend of LHEF ratings with steeper slope classes is not always appropriate or highly depends on types of failure mechanism and use of the part of the landslide polygon (depletion or accumulation zone) for analysis.

Relative relief, the other topographic factor in the BIS method, does not show a consistent relation with landslides in both study areas, as it is difficult to explain why the medium class has a negative spatial correlation while the other classes have a positive one. The increasing weights for higher internal relief as indicated in the LHEF rating in BIS is therefore not correct in both study areas. Question should be raised whether this geofactor is useful to include in such an analysis, as it has also a large overlap and obvious conditional dependence with slope angle and size/area of the slope facet.

The weights and contrasts derived for the landuse classes (Table 6) also show large variations, among the two study areas, and also among the two methods used. Apart from the tea gardens, which show negative spatial correlations with landslides, and the barren lands, the contrast factors are reverse for all landuse types in both areas. According to the WofE calculations, in Area 1, maximum LHEF rating should be given to thick forest, followed by successively lower LHEF ratings to barren land, agriculture/settlement and moderate forest and lowest LHEF rating for tea garden. In Area 2, the highest LHEF is appropriate for barren land, but sparse forest must be given the lowest LHEF rating.

Table 6. Weights and statistical parameters of geofactors classes according to the WofE method

Geofactors	Area 1 (TS 78A8)			Area 2 (TS 78A12)		
	Contrast (C)	Studentised C	Re-assigned weight	Contrast (C)	Studentised C	Re-assigned weight
Lithology						
Phyllite/Schist/Quartzite	0.79	9.2	0.78	0.98	10	1.02
Gneiss **	-0.97	-8.3	-0.98	-0.03	-0.3	0.01
Sheared gneiss	-1.11	-1.9	-1.12	0.62	2	0.66
Alluvial fill	0.69	4.3	0.68	?	?	-0.86
Older compacted debris	-1.19	-9.3	-1.20	-0.90	-8.2	-0.86
Younger loose debris	2.13	19.6	2.12	-0.29	-1	-0.25
Sandy soil	N.A	N.A	N.A	0.29	1.4	0.33
Clayey soil	N.A	N.A	N.A	0.59	3.5	0.63
Structure						
Type 1 (LHEF <0.8)	-0.05	-0.5	-0.06	-0.57	-6.1	-0.05
Type 2 (0.8 ≤ LHEF < 1)	-0.63	-3.7	-0.64	0.38	3.6	0.26
Type 3 (1 ≤ LHEF < 1.3)	0.24	2.7	0.22	0.47	5	0.20
Type 4 (1.3 ≤ LHEF < 1.6)	0.04	0.3	0.02	-0.56	-2.1	-0.47
Type 5 (LHEF ≥ 1.6)	0.35	1	0.33	?	?	-0.47
Slope						
Very gentle	-0.57	-3.5	-0.58	0.10	1	0.06
Gentle	-0.06	-0.7	-0.07	0.07	0.6	0.03
Moderate	0.12	1.4	0.11	0.17	1.7	0.13
Steep	0.16	1.2	0.15	-3.60	-3.6	-3.63
Escarpment/cliff	1.10	4.5	1.09	?	?	-3.63
Relative relief						
Low	0.09	0.9	0.11	0.51	4.6	0.54
Medium	-0.30	-3.4	-0.29	-0.35	-3.7	-0.32
High	0.25	2.8	0.26	0.05	0.5	0.08
Landuse						
Agri/settlement	0.23	2.6	0.21	-0.48	-5	-0.52
Tea garden	-1.65	-10.6	-1.67	?	?	-1.78
Cinchona	N.A.	N.A.	N.A.	-0.69	-1.4	-0.74
Moderate forest	0.25	1.4	0.23	-0.71	-4.4	-0.75
Thick forest	0.60	6.8	0.58	-0.57	-1.7	-0.61
Sparse forest	0.00	0	-0.02	-1.74	-9.4	-1.78
Barren land	0.85	5.5	0.82	2.99	32.8	2.94
Hydrogeology						
Damp	-1.21	-7	-1.19	-0.79	-6.1	-0.74
Wet	-0.03	-0.2	0.00	-0.57	-6.2	-0.51
Dripping	1.94	15.8	1.96	1.48	16.2	1.53
Flowing	0.74	2.3	0.77	?	?	-0.74

N.A. = not applicable because geofactor class is not mapped in that study area
? = Undefined quantified relationship

The above analysis points towards a complex causal relationship between landslides and land use. The relationship of landuse with rock slide is not direct and thus use of "landuse" as a direct causal geofactor to rock slide has some obvious limitations. Tea gardens in general ensure a better stability due to the good land management practices, whereas other agricultural or densely habitated land on moderate to steep slope can contain higher concentration of shallow debris slides depending on poor landuse practices.

The hydrogeological factors of the BIS method are difficult to include in the analysis. The classification as shown in Table 4 is highly depending on the season in which the field data were collected, and the classes are not defined in a very scientific manner. Moreover, the recommended classes can barely be correctly mapped on medium scale in field. According to WofE results, the class indicated as "dripping" has the most statistically significant positive spatial association with landslide occurrences in both areas, whereas the class indicated as "flowing" has only a positive but lower relation in Area 1 but a negative relation in Area 2. In Area 1 there is a relationship with the proximity to streams, which is lacking in Area 2, where landslides are occurring more on gentle slopes and agricultural terraced lands. Thus, the weights derived from the WofE do not correspond with those from the BIS method for the hydrogeological factors.

WofE Landslide Susceptibility Maps

To prepare the final landslide susceptibility maps, the weight of each class of a theme was re-assigned by applying a formula that is "[(Wp of a particular class in a geofactor theme) + (Sum of Wn of all classes in that geofactor theme) – (Wn of that respective geofactor class)]". The above formula was applied to rationalise the positive/ negative weight of each geofactor class to its maximum by simultaneously considering the sum of the negative influence of the rest of the geofactor classes of that theme (Van Westen, 1993). Through this re-assignment of new weights, contrasting multi-class evidential themes with rationalised weights for all geofactors were prepared. By applying the above conversion formula, highest positive weights were assigned only to the causal geofactor class whereas, other, insignificant geofactor classes or the geofactor classes having undefined quantified relations (the geofactor class which contains no training landslide data) were assigned the lowest maximum negative weight values. Multi-class weight maps of all evidences, thus produced were finally combined to derive the accumulated WofE weight for further susceptibility classification.

The final WofE weight maps of Area 1 and 2 were then spatially combined with the training landslide data and the success rate curves (also known as "goodness of fit") were prepared (Figs. 5a and b) following the similar method of constructing prediction rate curves (Chung and Fabbri, 1999, 2003). The results indicate that 30% of the area with the highest weight contain 71% (Area 1) to 83% (Area 2) of the cummulative landslide areas. The different success rates in both study areas indicate the presence of different slope failure mechanisms, which require different combinations of geofactors and segregation of landslide data into different types/ failure mechanisms. The available geofactors gave a better 'goodness of fit' in Area 2.

The WofE-based landslide susceptibility maps of the case study areas were classified into five susceptibility classes (Figs. 3b, 4b) like that of BIS method. The class boundaries of WofE weights were determined according to the steepness of the respective success rate curves of the two areas (Figs. 5a and b) and considering the fixed specified ranges of cummulative landslide area percent values (Table 7). In case of WofE susceptibility maps, landslide density and percentage of total landslide area in each susceptibility class were also calculated considering the entire population of known landslide occurrences of both areas. The "high" and "very high" susceptibility classes contain around 80% of the total landslide areas in Area 1 and around 83% of total landslide areas in Area 2 (Table 8). The landslide densities also sharply increase with increasing landslide susceptibility from "high susceptiblity" onwards. These results further indicate better goodness of the spatial associations between geofactors and landslides as quantified by the WofE method than those by BIS method (Table 5).

Table 7. Landslide susceptibility classes according to the steepness of success rate curves

Landslide susceptibility	%-le break (Cummulative landslide area in success rate)	Range of re-assigned weight values	
		Area 1 (TS78A/8)	Area 2 (TS78A/12)
Very low	100	≤ -2.50	≤ -1.81
Low	95	-1.71 to -2.50	-1.35 to -1.81
Moderate	90	-0.94 to -1.71	-0.87 to -1.35
High	85	1.31 to -0.94	1.43 to - 0.87
Very high	55	> 1.31	> 1.43

Table 8. Area, density, and percentage of landslides in different landslide susceptibility classes mapped in the study areas according to the WofE method

Study area	Landslide susceptibility		Cross-validation		
	Class	Area covered (km^2)	Area (km^2) of known landslides	Land-slide density	Percent of total landslide area
Area 1 (TS 78A8)	Very low	74	0.11	0.15	7
	Low	35	0.10	0.29	6
	Moderate	42	0.12	0.29	7
	High	95	0.52	0.55	31
	Very high	43	0.83	1.93	49
Area 2 (TS78A12)	Very low	169	0.07	0.04	5
	Low	61	0.09	0.15	6
	Moderate	43	0.08	0.18	6
	High	94	0.45	0.48	31
	Very high	27	0.75	2.78	52

Comparison of Prediction Capabilities of BIS and WofE Methods

To properly compare the results of the BIS and WofE methods, the prediction rate curves of the landslide susceptibility maps of either of the case study areas created via the BIS and WofE methods were prepared (Figs. 5a, b) by using the same landslide testing dataset. The prediction rate curves indicate that the landslide susceptibility maps created via the WofE method are comparatively better than the landslide susceptibility maps created via the BIS method. For Area 1, 30% of the map areas with highest weights according to the WofE method could predict 42% of the landslide areas, whereas the same 30% of map areas with highest TEHD values according to the BIS method could predict only 30% of landslide areas. Similarly, for Area 2, 30% of the map areas with highest weights according to the WofE method could predict 90% of the landslide areas, whereas the same 30% of map areas with highest TEHD values according to the BIS method could predict only 48% of landslide areas. This quantitatively demonstrates that the WofE method performs better than the BIS method both in "goodness-of-fit (success rate) and "prediction rate" analysis, though in both cases the prediction rates are not always equally high. This further indicates that (a) the geofactors which are selected in the BIS method (and the same which were also used to calculate the weights in the WofE method) are still not the optimal ones for prediction of the landslide types in the two study areas, (b) less-accurate and insufficient spatial representation of some of the existing geofactors such as structure, geohydrology, rock weathering and soil depth due to the higher level of bias, uncertainty and scale constraints, (c) existing BIS guidelines do not warrant selection of geofactor specific to landslide types and failure mechanisms, and (d) non-selection of landslide data as per their type and morphometry in the modeling. Moreover, several of the geofactors, such as structure, hydrogeology owing to their limitations in applicability on medium scale for a larger area are clearly not contributing in improving the present prediction.

SUMMARY AND CONCLUSION

In this paper, the performance of a fixed-rating based landslide-independent heuristic method (BIS) for landslide susceptibility has been tested with a quantitative method (adapted from WofE) in two adjacent terrains, where the importance of the same geofactor classes is analyzed objectively through their spatial associations with landslide occurrences. The landslide susceptibility maps of WofE shows better success/ prediction rates than those of the BIS susceptibility maps in both study areas. Due to different landslide types and related geofactor combinations in two study areas, the success/ prediction rates differered substantially. However, by selecting only the relevant geofactor classes per se landslide types and failure mechanisms, the success/prediction rates could be further improved. The results show that landslide susceptibility in complex environment such as Darjeeling Himalaya, should not be done using a fixed set of geofactors and a fixed set of weights, as indicated in the BIS guidelines. In each area, experts should select those combinations of geofactors only that best predict the occurrence of the specific landslide types that happen in these areas. Depending on the scale of susceptibility mapping, care should also be taken so that lesser amount of bias or uncertainty is introduced in the spatial geofactors, since, in any statistical modelling, such inaccurate spatial data can generate meaningless outputs. Guidelines for landslide susceptibility mapping at medium scales should therefore not concentrate on fixed factors and rating schemes but on the method to be carried out interactively analyzing the importance of geofactors using simple tools such as bivariate statistical analysis, combined with area specific knowledge on landslide types and causal mechanisms and a fixed and effective standards for quantitative validation and output susceptibility maps.

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