Landslide susceptibility assessment of the Chure Khola Catchment area of the Siwalik region, Central Nepal

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ABSTRACT

Landslide susceptibility analysis is carried out in the Chure Khola Catchment, between Amlekhganj and the Churia Mai Range of the Bara District, covering area of 20 sq. km. The catchment lies in the Siwalik Hills composing the Siwalik Group of rocks of Middle Miocene to Early Pleistocene age. Owing to the week and fragile geology, the Siwalik Hills are prone to the gully erosion, shallow landslide and debris flow, during the heavy rain storms in monsoon seasons. In the present study, landslide susceptibility assessment was carried out using two methods, rapid field-based assessment and statistical index methods. For the susceptibility mapping of the river bank slopes, field- based method was used. The seven parameters such as slope angle, slope material, reduction to groundwater, effect of drainage, effect of past failure, effect of vegetation cover and effect of land use were used to calculate the factor of safety in the field. The slope areas were classified as highly susceptible (FS<0.7), susceptible (0.7<FS<1), marginally stable (1<FS<1.2) and stable (FS>1.2) categories, and finally, a susceptibility map was prepared. For the total 4.179 sq. km area where rapid field-based assessment was carried out, the areas covered by highly susceptible, susceptible, marginally stable and stable zones are respectively, 21.56%, 22.11%, 17.37% and 38.95%. Among the highly susceptible and susceptible zones identified, 71% sites have experienced recent slope failures. Landslide susceptibility mapping of the whole catchment area was prepared using statistical index method, and considering seven causative parameters such as elevation, slope, slope aspect, curvature, river proximity, stream density and lithology, which were determined and prepared from DEM using Arc GIS. Eighty percent landslides were used as the training sample for the spatial analysis, whereas 20% landslides were used for the validation of the study. The landslide susceptibility map exhibits the areas covered by very high, high, moderate, low and very low susceptibility zones are 47.18%, 25.28%, 19.77%, 3.60% and 4.16%, respectively. Validity of the study was determined using Riemann Sums method. Success Rate Curve shows that 78.04 % of the areas lie under the curve. Evaluating susceptibility in small watershed is important to mitigate shallow landslide related problems and in rehabilitating forest areas in the Churiya Hills of Nepal.

INTRODUCTION

Landslide is generally used to denote the downward and outward movement of slope forming materials along surfaces of separation (Varnes, 1978). Landslide in which the sliding surface is located within the mantle or (upto 3-10 m) is called a shallow landslide. Landslides are natural phenomena which occur under the favorable terrain conditions and are usually triggered by heavy rainfall, human activities and earthquake. Landslides occur due to combination of trigger mechanisms and susceptibility factors such as fragile and complex geology, steep slopes, rugged topography, variable climatic and microclimatic conditions, rainfall, earthquake and vegetation degradation (Gerrard and Gardner, 2002; Hasegawa et al., 2009). The Siwaliks Hills are vulnerable to landslides because of fragile geology, weak lithology and tectonics (Tamrakar et al., 2002; Tamrakar and Yokota, 2008). Landslides cause loss of lives and property each year during the monsoon season in hilly regions of Nepal where geology is very fragile.

Landslide susceptibility is defined as a function of the degree of the inherent stability of the slope together with the presence and activity of causative factors capable of reducing the excess strength and ultimately triggering movement (Crozier and Glade, 2005). The identification of causative factors is the basis of many methods of susceptibility/stability assessment. The factors may be dynamic, or passive and may also be considered in terms of the roles they perform in destabilizing a slope (Crozier, 1986). Mostly, heuristic approach, statistical approach and deterministic approach are used for landslide susceptibility mapping. Among these techniques, Sikrikar et al. (1998), Dhakal et al. (1999), Dangol and Ulak (2002), Dhital et al. (2005) and Dahal et al. (2008) used the statistical analysis methods for the landslide susceptibility mapping in Nepal. Lee and Evangelista (2006) used artificial neural network to prepare landslide susceptibility map.

In the bivariate models each individual thematic map in terms of landslide distribution is considered and implemented

in GIS (Van Westen, 1997). The statistical index method is a bivariate statistical analysis as introduced by Van Westen (1997) for landslide susceptibility analysis. In the beginning, the statistical index method was called landslide index method. However, researcher further used this statistical bivariate method in the name of statistical index method. Statistical approach is an indirect susceptibility mapping technique which involves statistical determination of the combinations of variables that have led to landslide occurrence in the past. All possible intrinsic variables are entered into a GIS and crossed for their analysis with a landslide inventory map. In most of the cases, the statistical approach to landslide hazard mapping is either bivariate or multivariate.

Landslides and gully erosion are the sources of materials for the debris flow. Debris flows also scour the banks of the river channels. Landslides and debris flows cause the extensive damage of landmass property and occasionally the lives. These problems are quite frequent in the Siwalik region. Therefore, it is necessary to assess and manage the areas, which are susceptible to landslide, to mitigate any associated damage. A large volume of sediments from the Siwalik Hills is carried away as a form of debris flow and flashflood. Studying slope sediments properties, and landslide types, mechanism, causes and distribution help to evaluate susceptibility of landslide in a small watershed. Such study is important to mitigating shallow landslide related problems and in rehabilitating forest areas in the Churiya Hill regions of Nepal.

STUDY AREA

The study area constitutes a hilly terrain of the Sub Himalaya (Siwalik) along the Chure Khola from Amlekhganj to the Churiya Range (Fig. 1). The altitude ranges from 345 m at the Amlekhganj to 807 m at the Churiya Range and covers the 20 sq. km area. The maximum and minimum temperatures of the area are 38ºC and 6°C, respectively. The area experiences an average yearly rainfall of 2160 mm, and a sub-tropical climate. The drainage pattern of the study area is dendritic. The north to south flowing Chure Khola is the trunk river and is contributed by the Bhedi Khola from the eastern portion. These streams are originated from the southern face of the Churiya Range and are seasonal.

GEOLOGICAL SETTING

The study area belongs to the Siwalik Group (the Middle Siwalik and the Upper Siwalik) of Central Nepal. The Chure Khola watershed area consists of three lithological units namely the Amlekhganj Formation, the Chure Khola Formation and the Churia Mai Formation (Sah et al., 1994). The Amlekhganj Formation is characterized by multistoreyed, coarse-grained, 'salt and pepper' sandstone to pebbly sandstone interlayered with greenish grey mudstone. The Chure Khola Formation consists of loosely consolidated and matrix- to clast-supported pebble to cobble conglomerate. The upper part of this formation is characterized by calcareous cemented conglomerate beds.
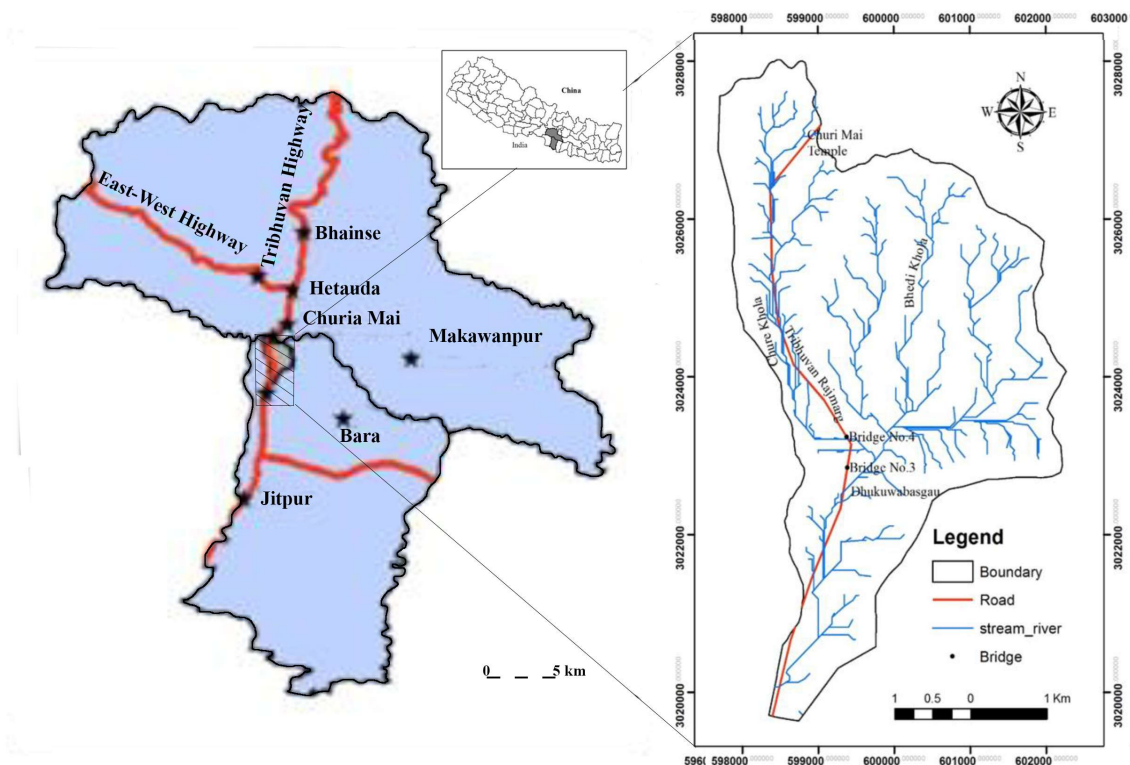

Fig. 1: Study Area

The Churia Mai Formation consists of loosely consolidated and matrix-supported pebble to boulder conglomerate having poorly sorted and randomly oriented clasts.

METHODOLOGY

In this study, landslide susceptibility mapping of the river bank slope of the Chure Khola in central Nepal Churia region was prepared using the field-based method after Peckley and Bagtang (2010) and bivariate (statistical-index) method after Van Westen (1997).

In the field-based susceptibility analysis, factor of safety was calculated using various parameters. The susceptible areas were identified and delineated in the field. The parameters used to calculate the factor of safety were slope angle, slope materials, reduction to ground water, effect of reduction drainage, effect of past failure, effect for vegetation and land use (Fig. 2). The factor of safety (Fs) was determined by using the following equation after Peckley and Bagtang (2010):

$$F_s = \frac{[v\,Factor * f\,Factor\,(S\,Rating - s\,Red - d\,Red)]}{[\alpha\,Rating * I\,Factor]} \qquad (1)$$

where,

Alpha Rating = slope angle, S Rating = slope material, s Red = reduction due to ground water, d Red = effect of drainage

RATING SYSTEM						
Alpha Rating	100	32	17	10	5	2
Slope Angle	>75	60-75	45-60	30-45	15-30	<15
s-red	2		1		0	
	Year long		Only during rainy season		No flow/ spring	

ID		S-Rating
HR1	Massive and intact hard rocks	100
HR2	Blocky interlocked hard rock with cubical block	45
HR3	Very blocky fragment rock with 4 or more discontinuities	25
HR4	Disinter rock and boulders producing rock fragments	13
SR1	Massive and intact soft rocks	30
SR2	Very blocky fragment rock	15
HS1	Stiff gravelly, sandy, silty muddy soil	25
SS1	Gravely soil	10
SS2	Sandy soil	8
SS3	Mud soil	5

d-Red		F-red	
No drainage System	2	Once a year or more than a year	0.5
Totally clogged with debris	2	Past failure but not occur yearly	0.7
Partially clogged with debris	1	Tension cracks in ground	0.7
or over flow during heavy rain		With retaining wall deform	0.7
Water leaks in to slope	1	None	1.2
Good working condition	0		

V-factor		I-Factor	
No vegetation	1	Dense residence area with closely spaced	1.4
Grass or vegetation with shallow roots	1.1	Commercial building >2 stories	1.4
Coconuts bamboo moderate to deep root	1.2	residential area spacing >5m	1.25
Dense forest with tree <20 years	1.5	Road/highway with traffic>1/ 1minute	1.4
Dense mixed forest with tree<20 years	2	Road with low traffic	1.25
Dense mixed forest with tree>20 years	2.5	Agriculture area, grass land	1
		Forest	1
		Uninhabited or no vegetation	1

FS = [V-Factor x f-Factor(S Rating - s Red - d Red)/ (a-Rating x 1 Factor)]

Fig. 2: Rating system for field-based susceptibility mapping (after Peckley and Bagtang, 2010)

Table 1: Factor of safety for landslide susceptibility zonation

Landslide susceptibility	Factor of Safety (Fs)
Stable	**Fs** > 1.2
Marginally Stable	1.0 < **Fs** <1.2
Susceptible	0.7 < **Fs** < 1.0
Highly Susceptible	**Fs** < 0.7

or surface runoff, f Factor = effect of past and ongoing slope movement, v Factor = effect of vegetation covering, and I Factor = effect of land use. The landslide susceptibility zonation was based on the factor of safety (Table 1).

Various methods have been developed and used for landslide susceptibility mapping in watershed-scale. In this study, statistical index-based method was used. This method is based upon the following equation (Van Westen, 1997b),

$$W_{ij} = ln[f_{ij}/f] = ln[A*_{ij}/A_{ij} * A/A*]$$
$$= ln[A_{ij}/A* A/A_{ij}] \quad (2)$$

where, W_{ij} - the weight given to a certain class i of parameter j,

f_{ij} = landslide density within the class i of parameter j,

f = landslide density within the entire map,

$A*_{ij}$ = area of landslides in a certain class i of parameter j,

A_{ij} = area of a certain class i of parameter j,

A = total area of the entire map, and

A* = total area of landslides in the entire map.

For the preparation of the susceptibility map, a landslide inventory map, geological map, aspect map, slope angle map, and distance from drainage were prepared. Using these thematic maps like slope, aspect, curvature, elevation, stream density, river proximity and geology, the susceptibility analysis was carried out applying bivariate (statistical-index) methods (Van Westen, 1997). These data were integrated in Arc GIS and weighted for each class determined from the statistical index method (Van Westen, 1997). The final susceptible zonation map was categorized into very low, low, moderate, high and very high susceptibility classes based on landslide susceptibility index value (LSI).

Percentage of landslide occurrence in any susceptible zone is termed success rate. This is also a way to validate a susceptibility map. The cumulative percentage of landslide occurrences in the susceptibility zones ordered from high to low were plotted against the cumulative percentage of area of the susceptibility zone. The resulting curve is called success rate curve. Success rate curves were prepared by calculating an

AUC value by using Riemann Sums methods as below:

$$AUC = [(b1 + b2)/2] . (A2–A1) \quad (3)$$

where, b1 and b2 are cumulative percentage of area of landslide within given LSI value, whereas A1 and A2 are the cumulative percentage of the study area within given LSI value.

RESULT AND DISCUSSION

Field based susceptibility mapping

According to factor of safety, river bank slopes were summarized into four zones, i.e., highly susceptible, susceptible, marginally stable and stable. The results of landslide susceptibility analysis, factor of safety and susceptibility zones are tabulated for 74 locations assessed (Fig. 3; Table 2).

Thirty-three sites lie in highly susceptible zone, 12 sites in susceptible zone, 3 sites in marginally stable zone and 26 sites in stable zones. The slope area covers 4.179 sq. km area
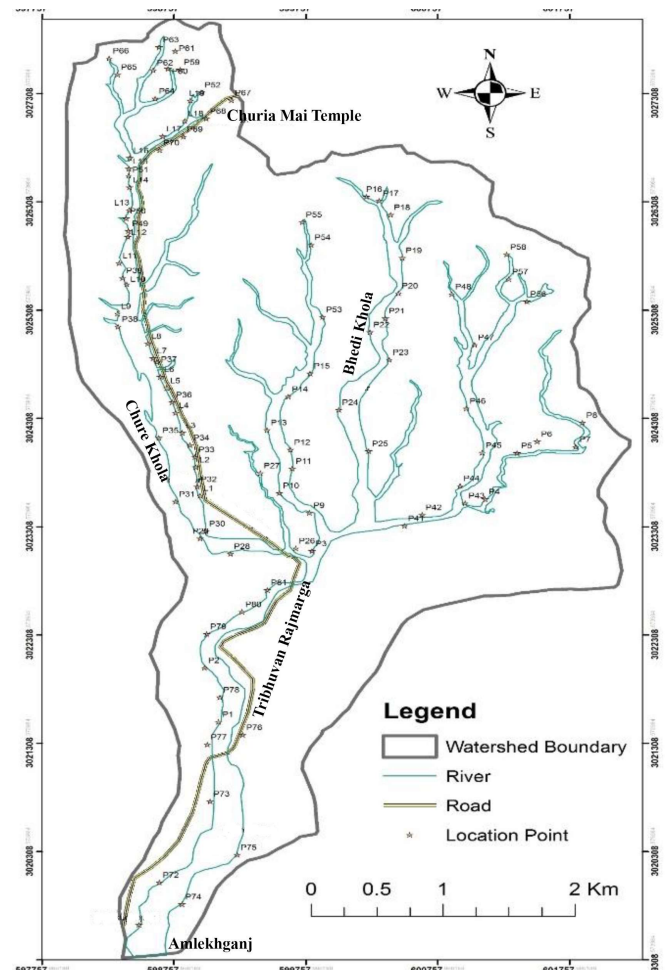

Fig. 3: Location sites of the observation for susceptibility mapping

Table 2: Summarized table of factor of safety for field based susceptibility mapping

S. N	Location	a-Rating	s Red	S Rating	d-Red	V Factor	f- Factor	I Factor	F_s	Susceptibility
1	L1	100	1	25	2	1.1	0.7	1.4	0.1489	Highly Susceptible
2	L2	100	1	25	2	1.1	0.5	1.4	0.106	Highly Susceptible
3	L3	32	1	25	2	1.1	0.5	1	0.6328	Highly Susceptible
4	L4(a)	17	1	25	2	1.1	0.7	1.4	0.87	Susceptible
5	L4(b)	17	1	25	2	1.1	0.7	1	1.22	Stable
6	L5	32	1	25	2	1.1	0.5	1.4	0.3	Highly Susceptible
7	L6	10	1	25	2	1.5	0.7	1	1.223	Stable
8	L7	10	1	25	2	1.1	0.7	1	1.735	Stable
9	L8	32	1	25	2	1.1	0.5	1	0.46	Highly Susceptible
10	L9	100	1	25	2	1.1	0.5	1	0.1485	Highly Susceptible
11	L10	100	1	25	2	1.1	0.5	1.4	0.106	Highly Susceptible
12	L11	17	1	25	2	1.1	0.5	1	0.873	Susceptible
13	L12	32	1	25	2	1.5	0.7	1.1	0.464	Highly Susceptible
14	L13	17	1	25	2	1.1	0.7	1.4	1.191	Stable
15	L14	17	1	25	2	1.1	0.7	1	0.873	Susceptible
16	L15	100	1	25	2	1.1	0.5	1	0.1485	Highly Susceptible
17	L16	32	1	25	2	1.1	0.7	1	0.7146	Susceptible
18	L17	32	1	25	1	1.1	0.7	1	0.708	Susceptible
19	L18	17	1	25	2	1.1	0.5	1	0.874	Susceptible
20	L19	17	1	25	2	1.1	0.5	1	0.874	Susceptible
21	P1	5	0	15	2	1.1	1.2	1	3.4	Stable
22	P2	5	0	15	2	1.1	1.2	1	3.4	Stable
23	P3	32	1	30	2	1.1	0.7	1	0.7	Susceptible
24	P10	5	1	25	2	1.5	1.2	1	1.58	Stable
25	P11	17	1	25	2	1	0.5	1	0.53	Highly Susceptible
26	P12	32	1	25	2	1.1	0.7	1	0.76	Susceptible
27	P13	32	1	25	2	1.1	0.5	1	0.38	Highly Susceptible
28	P16	32	0	25	2	1.5	0.7	1.1	0.38	Highly Susceptible
29	P17	17	0	25	2	1	0.5	1	0.34	Highly Susceptible
30	P18	17	1	25	2	1.1	0.7	1	0.87	Susceptible
31	P19	32	1	25	2	1	0.5	1	0.38	Highly Susceptible
32	P20	17	0	25	2	1	o.5	1.1	0.38	Highly Susceptible
33	P24	32	0	25	2	1	0.5	1	0.34	Highly Susceptible
34	P27	17	1	25	2	2	1.2	1	5.4	Stable
35	P29	17	0	25	2	1.1	0.7	1	1.32	Stable
36	P30	32	0	25	2	1.1	0.5	1	0.52	Highly Susceptible
37	P31	17	0	25	2	1	0.5	1	0.68	Highly Susceptible

Table 2: continued

S. N	Location	a-Rating	s Red	S Rating	d-Red	V Factor	f- Factor	I Factor	F_s	Susceptibility
38	P32	32	1	25	2	2	0.7	1	1.06	Marginally stable
39	P33	10	0	25	2	2	0.7	1	2.3	Stable
40	P35	17	0	25	2	1.1	0.7	1	0.51	Highly Susceptible
41	P36	17	0	25	2	1.1	1.2	1.4	2.07	Stable
42	P38	100	0	25	2	1	0.5	1	0.2	Highly Susceptible
43	P39	32	0	25	2	1.1	0.5	1	0.26	Highly Susceptible
44	P40	32	0	25	2	1	0.5	1	0.72	Susceptible
45	P41	10	0	25	2	2	1.2	1	6.44	Stable
46	P42	10	1	25	2	2	0.7	1	2.31	Stable
47	P43(a)	32	0	25	2	1.1	0.7	1	0.83	Susceptible
48	P43(b)	17	0	25	2	2	0.7	1	0.18	Highly Susceptible
49	P44	17	0	25	2	1.1	0.5	1	3.22	Stable
50	P45	32	1	25	2	1	0.5	1	1.89	Stable
51	P46	32	0	25	2	1.1	0.7	1	0.55	Highly Susceptible
52	P47	100	0	25	2	1	1.2	1	0.18	Highly Susceptible
53	P48	10	0	25	2	2	0.7	1	3.22	Stable
54	P49	17	0	25	2	2	0.7	1	1.89	Stable
55	P50	32	0	25	2	1.1	0.7	1	0.55	Highly Susceptible
56	P51	5	0	25	2	2	1.2	1.1	6.7	Stable
57	P52	17	0	25	2	1.1	0.7	1	1.04	Stable
58	P53	32	0	25	2	1.1	0.5	1	0.54	Highly Susceptible
59	P54	17	0	25	2	1.1	0.7	1	0.67	Highly Susceptible
60	P67	32	0	25	2	1.1	0.5	1	0.4	Highly Susceptible
61	P68	32	0	25	2	1.1	0.5	1	1.35	Stable
62	P69	10	0	25	2	1.1	1.2	1.25	0.99	Susceptible
63	P70	17	0	25	2	1.1	0.7	1	5.28	Stable
64	P71	2	0	10	2	1.1	1.2	1	5.28	Stable
65	P72	2	1	10	2	1.1	1.2	1	5.28	Stable
66	P73	2	0	10	2	1.1	1.2	1	5.28	Stable
67	P74	2	0	10	2	1.1	1.2	1	0.4	Highly Susceptible
68	P75	17	1	15	1	1.1	0.5	1	3.19	Stable
69	P76	5	1	15	1	1.1	1.2	1	3.19	Stable
70	P 77	5	0	15	2	1.1	1.2	1	5	Stable
71	P78	2	1	15	2	1.1	0.7	1	0.23	Highly susceptible
72	P 79	32	0	15	1	1	0.5	1	0.23	Highly Susceptible
73	P 80	32	0	15	2	1	0.5	1	0.23	Highly Susceptible
74	P81	32	0	15	2	1	0.5	1	0.23	Highly Susceptible

of river bank slope of the Chure Khola and the Bhedi Khola (Fig. 4). Landslide susceptibility map shows that 0.901 sq. km (21.56%) area fall in highly susceptible zone, 0.924 sq. km (22.11%) in susceptible zone, 0.726 sq. km (17.37%) in marginally stable zone and 1.28 sq. km (38.95%) in stable zone (Fig. 4; Table 3). Most of the stable area (more than 60% of it) lies in the plain area near Amlekhganj. Most of the slope area of the Chure Khola Formation and the Churia Mai Formation lies in the susceptible and highly susceptible zones.

For the validity of the study, it was cross checked to know whether the observation sites that lie in the susceptible and highly susceptible zone have undergone recent failure or not. None of the sites with factor of safety above 1 failed and almost 71% of the sites with the factor of safety below 1 have failed (Table 3). For those with the factor of safety below 0.7, the percentage of failure is 84% as only recent failure have been included for this analysis. If we take some old failures, then all sites with Fs below 1 lie in failure and very few surveyed sites
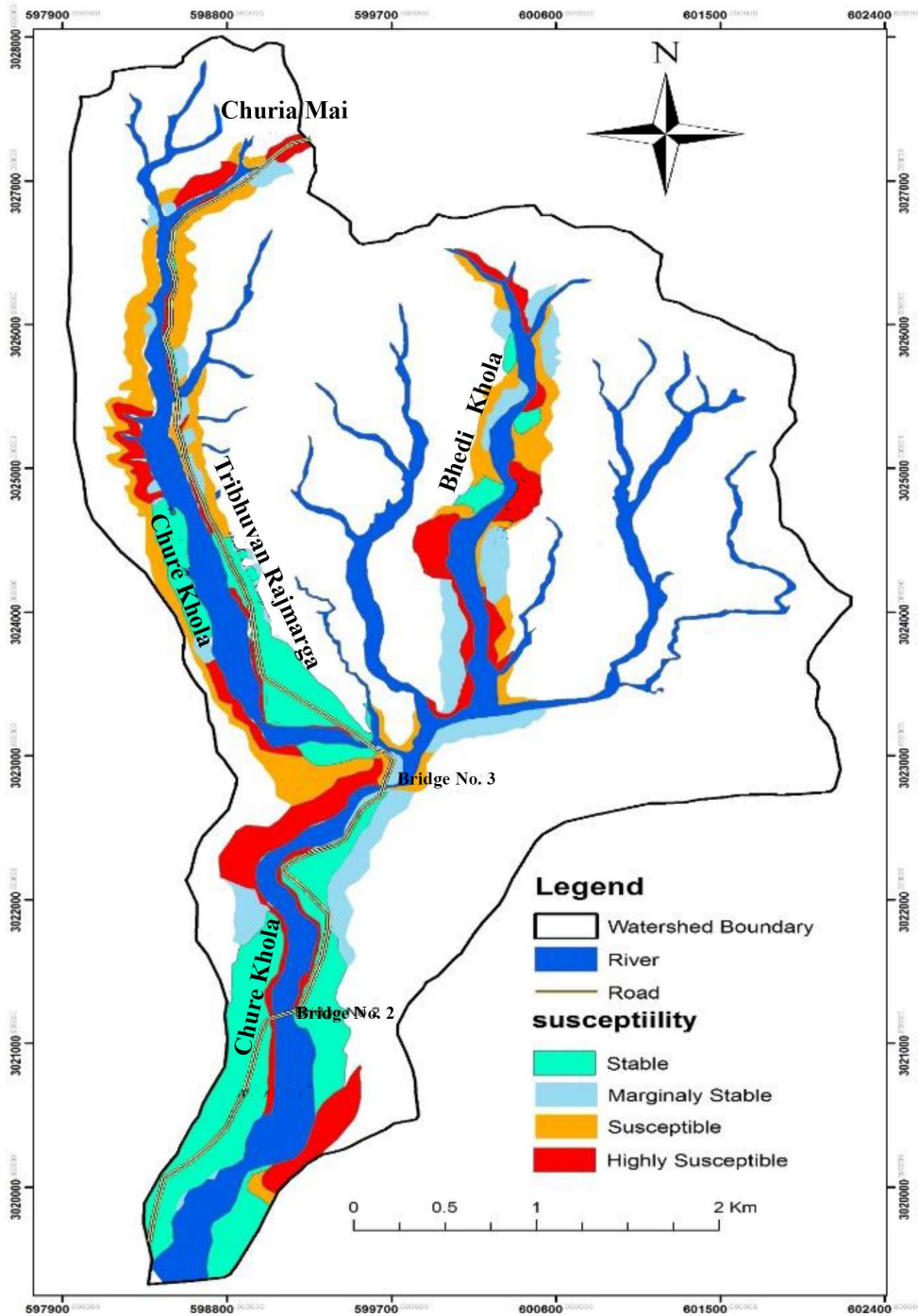

Fig. 4: Susceptibility map of the river bank slope

Table 3: validation chart representing relation of observed site and failure condition

Factor of safety (Fs)	No of sites Surveyed	No of site that Fails	Percentage failure	Past failure	% including Past failure
Fs < 0.7: Highly susceptible	33	28	84	5	100
0.7 < Fs < 1.0: Susceptible	12	4	33.33	8	100
1< Fs<1.2: Marginally stable	3	0	0	3	
Fs >1.2: Stable	26	0	0	8	
Total	74	32	71	24	

with Fs above 1 lie in the past failure.

Landslide Susceptibility Analysis Using Bivariate Statistical Methods

From the field observation, 152 landslides were identified. Only the 80% of total landslide were used for the spatial analysis as a training sample where as 20% landslides were used to determine the succession rate. The landslide inventory map was prepared with 80% training landslides and 20% landslide (Fig. 5).

Causative factors are those parameters, which have the role for the stability of the slope. Some of them are favorable for the landslides triggering and some of them are unfavorable. Seven thematic maps for factors considered in the analysis: slope angle, slope aspect, elevation, drainage density, lithology (Fig. 6), curvature and river proximity, were extracted from the constructed spatial database. Bivariate analysis method uses the landslide densities within each parameter map and its classes to derived weight value for those classes (Table 4). It is based on the assumption that causative factors of landslides can be quantified by calculating landslides densities to each class.
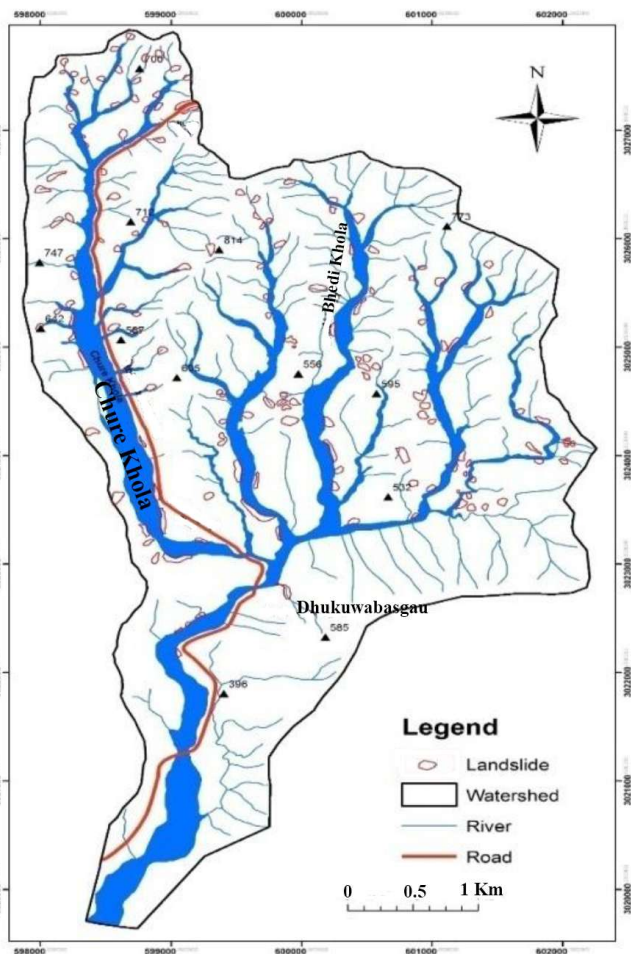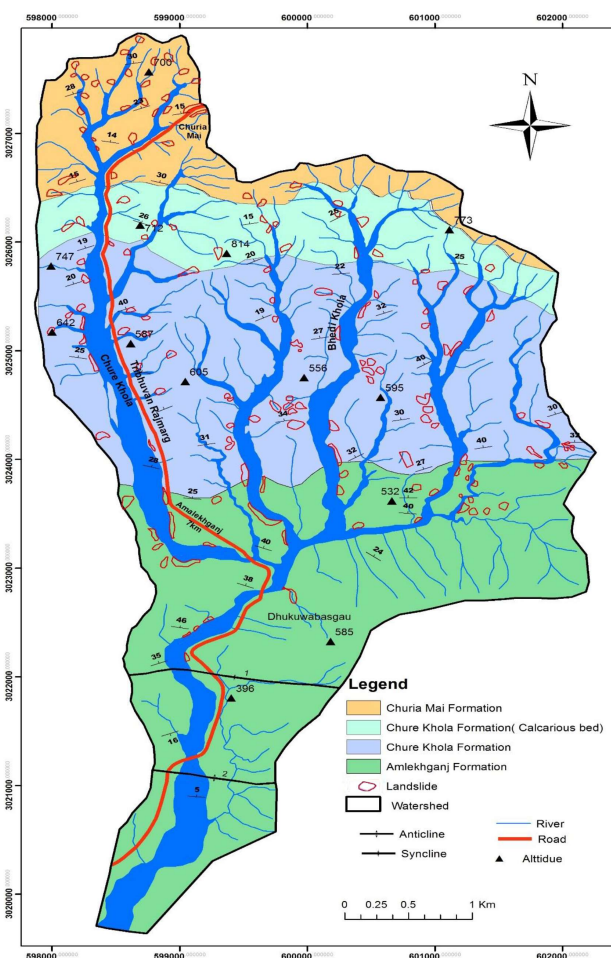

Fig. 5: Landslide Inventory Map

Fig. 6: Lithological Map

Table 4: Summary of weight for various parameters

S. N.	Parameters/Class	Dense map (Aij/A) %	Dense class (Aij*/A*)	Weight [ln{(Aij*/A*)/(Aij/A)
	Geology			**0.0793**
1	Churiya Mai Formation	14.20	18.12	0.24419
2	Chure Khola Formation (Calcarious Beds)	10.08	11.00	0.08728
3	Chure Khola Formation (Siliciclastic Beds)	34.64	47.68	0.31943
4	Amlekhganj Formation	41.08	23.19	-0.57159
	Elevation (m)			**-2.34264**
1	300-400	9.79	0.86	-2.42849
2	400-500	22.96	27.94	0.19628
3	500-600	33.62	37.97	0.12160
4	600-700	22.99	25.67	0.11024
5	700-800	10.63	7.55	-0.34227
	Slope			**2.9697**
1	0-7°	26.48	22.25	-0.17418
2	7-15°	22.32	19.48	-0.13606
3	15-25°	31.70	30.89	-0.02606
4	25-35°	15.11	21.68	0.36090
5	35-45°	3.59	4.56	0.24090
6	45-60°	0.78	0.98	0.22103
7	60-90°	0.01	0.16	2.48322
	Aspect			**-2.03145**
1	Flat	8.71	3.99	-0.78029
2	North	2.82	1.40	-0.70033
3	North-East	5.89	10.36	0.56435
4	East	9.64	22.22	0.83518
5	South-East	14.84	18.77	0.23500
6	South	13.79	11.11	-0.21598
7	South-West	16.22	13.16	-0.20892
8	West	13.97	13.05	-0.06791
9	North-West	10.06	4.10	-0.89743
10	North	4.06	1.83	-0.79511
	Curvature			**-0.25013**
1	Concave	10.50	17.48	0.50906
2	Straight	77.78	72.17	-0.35523
3	Convex	11.72	10.36	-0.40396
	Drainage Density			**-0.17816**
1	Low	57.70	71.41	0.21323
3	High	42.30	28.60	-0.39138
	River Proximity			**1.79303**
1	0-10	14.39	10.57	-0.30821
2	10-20	3.32	15.43	1.53740
3	20-50	9.62	30.74	1.16161
4	50-100	14.54	19.96	0.31642
5	>100	58.13	23.30	-0.91419

These weighted parameter maps were then combined to produce landslide susceptibility map. The resultant landslide susceptible index Map (Fig. 7) has landslide susceptibility index (LSI) value varying from 7 to 30. The LSI map should be classified into susceptibility zones to facilitate assessment of hazards.

The LSI was classified according to natural break method. The landslide susceptibility zonation map (Fig. 8) shows that 4.16 % areas lie in very low, 3.6% areas in low, 11.77% in moderate, 25.28% in high and 47.18% lie in very high susceptibility zones. The areal relationship of susceptibility
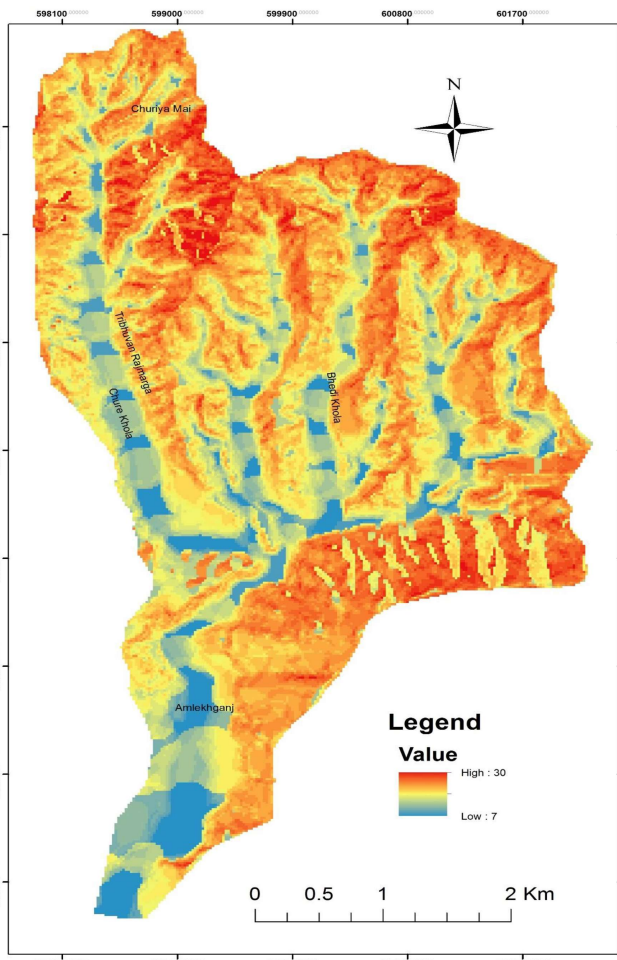
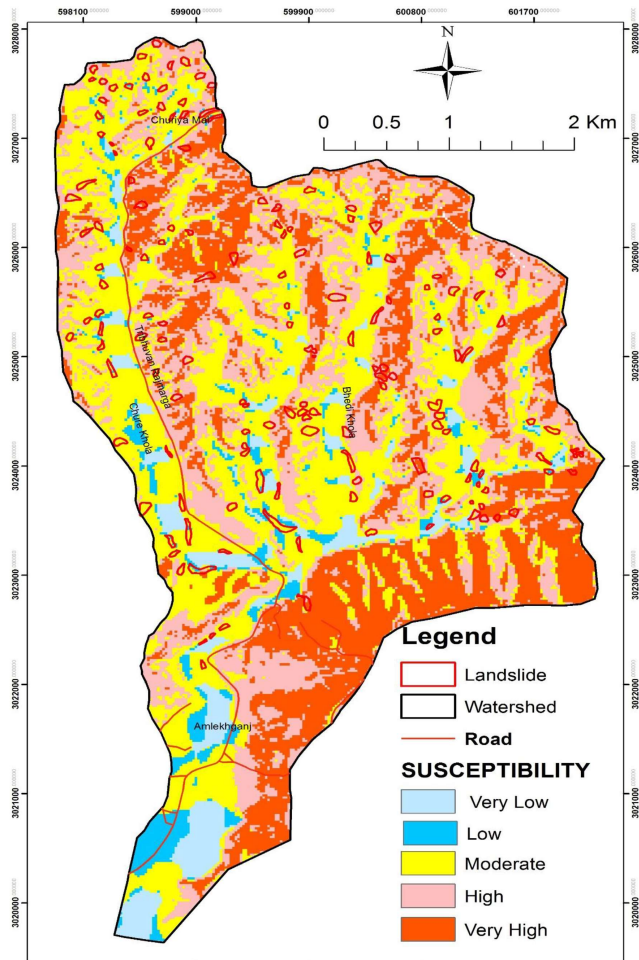**Fig. 7: Landslide Susceptibility Index Map**

Fig. 8: Landslide Susceptibility Zonation Map

zones with their landslide occurrence has been tabulated (Table 5). Among the 20% separated for validation, 4.32% lie in low susceptible, 6.35 % in moderate susceptible, 38.49% in high susceptible and 56.49% in very high susceptible class.

For the validation of susceptibility map, a success rate curve that indicates the suitability of map was prepared by

plotting the cumulative percentage of landslide to the cumulative percentage of susceptibility index value (Fig. 9). The area under curve was calculated by using the Riemann Sums method. The success rate curve shows 78.0434 % of the areas lie under the curve.

Table 5: the areal relationship of the susceptibility zone with study area and training sample

S.N.	Susceptibility	% landslide in each class with total validating landslides	% Area of susceptible class with total area
1	Very Low (7-9)	0	4.16
2	Low (9-12)	4.32	3.60
3	Moderate (12-16)	6.35	19.77
4	High (16-20)	38.49	30.28
5	Very High (20-30)	56.49	42.18

Fig. 9: Validation landslide susceptibility mapping using Success Rate Curve

CONCLUSIONS

The field-based susceptibility mapping yields (i) stable, (ii) marginally stable, (iii) susceptible and (iv) highly susceptible zones. Among the 4.179 sq. km area, 38.95% lie in stable zone, 17.37% in marginally stable, 22.11% in susceptible and 21.56% in highly susceptible zone. Seventy one percent of the survey sites lie in the highly susceptible zone and have recent failure. The slope material deformation condition plays important role for slope instability.

Altogether 152 landslides were observed in the study area. Factor effects reveal that all factors have relatively positive influence on the resulting landslide susceptibility map but the most effective factors on analysis are: river proximity (1.793), slope (2.970), and lithology. Landslide susceptibility zonation mapping using the Bivariate Statistical Index method yields five susceptible zones. Among the 23.52 square km area, 4.16 % area lie in the very low, 3.6 % lie in the low, 19.77 % lie in the moderate, 30.28 % lie in the high and 42.18 % lie in the very highly susceptibility zone. Twenty percent landslides were separated for validation. Among the 25% landslides, which were separated for validation, 87% landslides lie in moderate to very high susceptibility zones. The Success Rate Curve shows that the 78.04 % area lies under the curve. The majority of the areas that lie in moderate to very high susceptibility zones due to their proximity to the river and weak lithology, should be protected and preserved applying not only the light vegetation which intercepts direct rainfall impact quite effectively but also managing the watershed drainage applying bio-engineering techniques.

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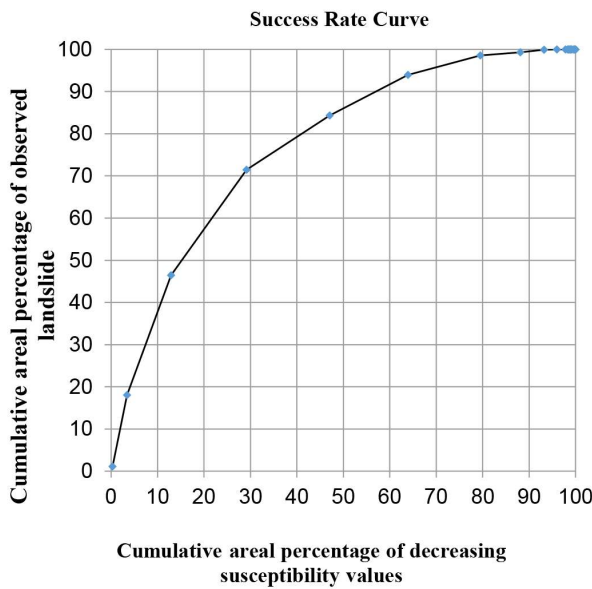
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