

Landslide inventory, susceptibility mapping and recommendation of the mitigation measures in Nuwakot District

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ABSTRACT

Nepal earthquake of 25th April 2015 and subsequent big aftershocks impacted people, land, and water resources significantly. Following the devastating earthquake, land and water management has become one of the primary focus of the Government of Nepal as these resources are foundations of people's livelihood and prosperity. The weakened, cracked, and destabilized slopes and surfaces due to the earthquake become even more susceptible to landslides that can be aggravated due to rainfall and inappropriate anthropogenic activities. Due to the devastating earthquake, 31 districts of Nepal out of 75 were affected with 14 being severely affected resulted huge loss of human life, property, and ecosystem services. These 14 districts were categorized as severely hit and crisis hit districts by the post disaster need assessment (PDNA) carried out by Government of Nepal. Nuwakot district is one of the severely hit district. In order to reduce vulnerability and/or threat of potential landslide disasters and protect local people, infrastructures, land and water resources from potential landslide disaster, identification of the most susceptible slopes as well as treatment and mitigation of the most critical landslides deemed essential. This study has identified the landslides and its impact within different VDCs of Nuwakot district. The mitigation measures for the urgent and treatable landslides are purposed with the tentative estimation of the cost and prioritized them based on the social, environmental and economic criteria. Out of 542 landslides identified, 105 landslides were studied in detail based on social and physical risk. The study showed that the northern part of the district is more susceptible to landslides and consequent disaster. VDCs like Bhalche, Ghyangphedi, Salme, Urleni, Kimlang, Lachyang, Ralukadevi are more susceptible to the landslides in Nuwakot district.

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INTRODUCTION

Landslide is most prominent hazard in mountainous region in all around the world (Gerrard 1994; Larsen 2001). A global data set of fatalities from non-seismically triggered landslides that resulted in loss of life between 2004 and 2010 reported that a total of 2620 fatal landslides were recorded worldwide during the 7 years period of the study, causing a total of 32,322 recorded fatalities (roughly 4600 people each year), the majority of human losses occur in Asia, especially along the Himalayan Arc (Petley 2012). Landslides are one of the main natural disasters responsible for huge social and economic losses in Nepal. The number of deaths due to landslide and flood has remained significantly high (Dhital 2005). Floods and landslides are common during the monsoon season and invariably kill a large number of people and destroy or damage properties. The flood and landslide disasters of 1993, 2008 and 2014 are the most devastating which have caused enormous loss to human lives and physical properties. According to the data of Ministry of Home Affairs, the floods and landslide disasters of the year 2013 claimed the lives of 219 people and 241 people lost their lives in the year 2014 (MoHA and DPNET 2015). Identification of landslide susceptible slopes/areas and

effective prevention works help preparedness and mitigate the impact of landslide disaster which begins with landslide susceptibility mapping. Landslide susceptibility is defined as likelihood of landslide occurring in an area controlled by their local terrain conditions (Brabb 1984). Thus produced susceptible maps would be supportive tools to identify potentially future landslide occurrence area.

In Nepal, urgency of landslide susceptible areas zonation was realized after catastrophic earthquake of 25th April 2015. Due to earthquake 31 districts were affected, out of which 14 districts were categorized as severely hit and crisis hit districts by the Post Disaster Need Assessment (PDNA) carried out by Government of Nepal. PDNA has identified seven districts namely Gorkha, Dhading, Nuwakot, Rasuwa, Sindhupalchowk, Dolakha, and Ramechhap as severely hit districts. Besides human casualties and huge economic-loss, the earthquake triggered numerous landslides which affected the lives and livelihood of local people. The weakened, cracked, and destabilized slopes and surfaces, after shaken by the main 25th April Earthquakes and its after shocked have become even more susceptible to landslides that can be aggravated due to rainfall and by further working on those land systems.

These landslides and accelerated soil erosion in upstream of watersheds due to rainfall/runoff or by other means may cause flooding and huge amount of sediment deposition in the downstream areas.

In post-earthquake scenario, Government of Nepal has highly prioritized the recovery works, mitigation measures and supporting people to overcome from the disaster. As land and water resources and eco systems are majorly impacted by the earthquake, many development partners are supporting on land protection and water management. Department of Soil Conservation and Watershed Management (DSCWM) has major mandates to work on the landslide treatment and mitigation measures to protect people, settlements, development infrastructures, water and land resources. Immediately after earthquake, District Soil Conservation Offices (DSCOs) started preparatory and relief works with the resources that they had and by the additional financial resources provided by Government of Nepal at the time. Then DSCWM has prioritized its works and allocated resources for the earthquake induced landslides mitigation and prevention activities.

Although different agencies has been engaged in working on the landslide inventory and hazard assessment, it has been realized that there are still gaps in terms of the reliable primary database related to the scale and types of landslides, current and possible future impacts due to landslides, urgency for the treatment, treatability of the landslides and major on recommendation for the structural and non-structural measures to treat the landslides. So before the time of implementation, government and other supporting agencies are in need to work on the landslide assessment more on identifying critical landslides, segregating landslide to be treated immediately with high priority, planning and recommendation for different conservation /mitigation measures (activities to be undertaken on critical landslides identified) in different watersheds/sub-watersheds of landslide affected districts. In this context, landslide inventory with identification of their types, vulnerability status, and appropriate measures for mitigation are most crucial.

STUDY AREA

Nuwakot is one of the seven severely affected districts by earthquake of 25th April 2015. It lies to the north of Kathmandu (Fig. 1). Trishuli River, one of the major river in the Gandaki Basin, flows through the district that drains out many small watersheds. There are numbers of landslides that were induced before and after earthquake needs to be studied for treatment or mitigation measures. mitigation measures.

METHODOLOGY

Landslide inventory and classification

Landslide inventory of pre-earthquake period (i.e., prior to Gorkha earthquake) was accomplished with digitization on Google Earth image prior to April 2015. Similarly, post-

earthquake landslides were digitized from the Google Earth image, published after earthquake events. Landslides are broadly categorized into i) Landslide and erosion (Le), ii) Debris flow and erosion (De), iii) Rock fall and erosion (Fl), and iv) Complex slope failure (EDL), taking consideration of nature of mass wasting, their shape, tune, texture and area.

Location information of such extracted landslides was transferred to GPS for field verification and update. Similarly, color print of higher resolution Google image with landslide polygon were provided to field teams. During field visit all available information such as their types, geo-engineering properties of place, landslide initiated year, associated risk and possible mitigation measures were collected. Locations of all visited landslides were marked by GPS and sketches were drawn. Elements at risk, such as house unit, cultivation, school, road, bridge and others were attributed to each digitized landslide. Thus produced database were then used to update and validate the Google earth interpretation.

Generation of landslide contributing parameters

Altogether 13 landslide contributing parameters were prepared in Arc-GIS environment. These parameters are broadly categorized into four domains: i) Topographic domain (Aspect, Elevation, Relative relief, Slope gradient, Slope shape, and Topographic position index), ii) Hydrological domain (Annual rainfall, Drainage density, Topographic wetness index, and Stream power index), iii) Anthropogenic domain (Land-use/ Land-cover and NDVI), and iv) Geology (rock/soil).

Bivariate statistical analysis

Landslide susceptibility map was prepared by using the GIS based bivariate statistical technique, which is widely accepted scientific methodology. It is common to assume that landslide occurrence is determined by landslide inducing factors, and that future landslides will occur under the same conditions as past landslides did. For this analysis, all the landslides except rock falls and slides are incorporated. The quantitative analysis used here is called the landslide index method. A weight-value for a parameter class, such as a certain lithological unit or a certain slope class is defined as the natural logarithm of the landslide density in the class divided by the landslide density in the entire map (van Westen 1997).

$$W_i = \ln \frac{\frac{L_i}{A_i}}{\frac{\sum L_i}{\sum A_i}}$$

i.e. W_i = (Density class/Density map)

where,

W_i = Weight assigned to certain parameters class.

Density Class = the landslide density within the parameter class.

Density Map = the landslide density within the entire map.

L_i = Area, which contain landslide, in a certain parameter class.

A_i = Total area, in a certain parameter class.

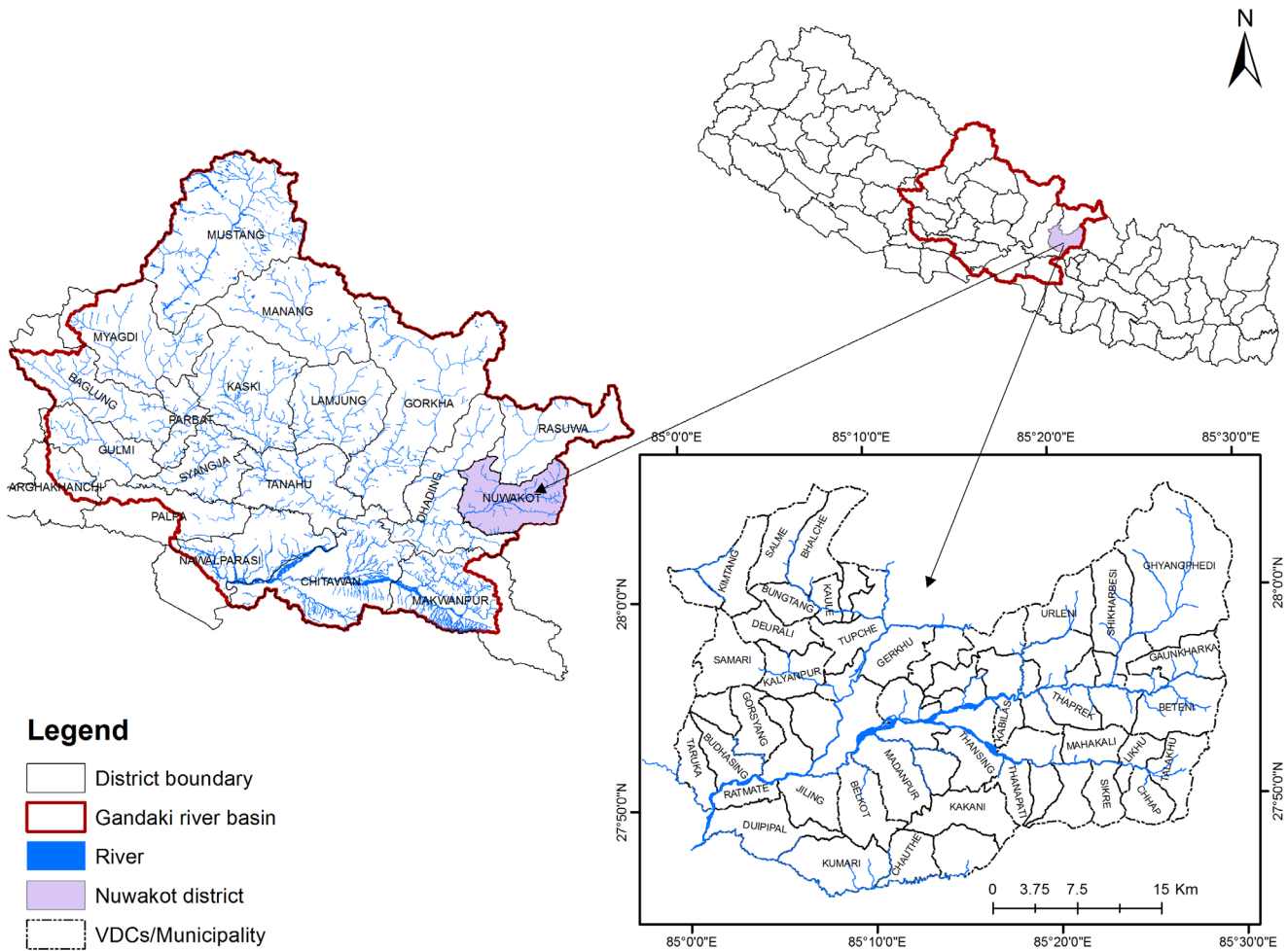


Fig. 1: Location map of the study area.

The method is based on map crossing of landslide map with a certain parameter map. Map crossing results in a cross table can be used to calculate the density of landslide per parameter class. Landslide susceptibility index (LSI) is determined by summation of each factor’s ratings using equation (Lee and Pradhan 2006).

$$LSI = \sum_{i=1}^N W_i$$

Where,

W_i = Weight assigned to each i parameters

N = Total number of parameters

Then, the reclassification procedure was utilized for reclassifying the LSI map into five different landslide susceptibility zones: very low, low, moderate, high and very high.

Prioritization of landslides for mitigation measures

All the landslides are enlisted and ranked on the basis of vulnerability and treatability. This list of prioritization of landslides helps to choose the most critical one at first

for the mitigation. For the purpose of landslide ranking and prioritization, a rating table was developed on the basis of seven different attributes and their respective classes (Table 1). For each attribute class, a minimum rating value of 1 and the maximum of 4 were assigned. For some complex landslides, where more than one failure type occurred, the rating value was calculated by averaging the rating of each involved class. A total rating for each landslide type was obtained by multiplying the ratings of the seven attributes listed in Table 1. For the purpose of prioritizing landslide control and mitigation works, the total rating was then arranged in an ascending order and the landslides were prioritized accordingly.

RESULTS AND DISCUSSION

Landslide distribution

A total number of 542 landslides are mapped in the study area (Fig. 2). These landslides range from very small with an area of 0.1 sq. m. to very large with an area more than 140,000 sq. m. The study shows that there was a dominance of complex landslides in the study area before earthquake, while the shallow rock falls have been mapped in large numbers after the Gorkha earthquake 2015 (Fig. 3).

Table 1: Rating scheme for ranking landslides based on their attribute classes

Attribute	Class			
Landslide type	Gully erosion and Landslide (Le)	Debris flow, Debris slide, and erosion (De)	Rock fall/rock slide, wedge, toppling (Fl)	Complex slide (EDL)
Landslide depth	Up to 3 m	3–5 m	5–7 m	More than 7 m
Hydrology	Dry	Wet, spring, seeps, saturated ground		
Land use or land cover	Cultivated land, paddy field	Forest, bushes, grassland	Barren land	
Proximity to village, infrastructure, or property	Village, settlement, town	Cultivated land (dry or wet)	Road or trail	Others (hydropower project site, tunnel portal, etc.)
Treatability	Easily Treatable	Moderately Treatable	Difficultly Treatable	
Rating for each class	1	2	3	4

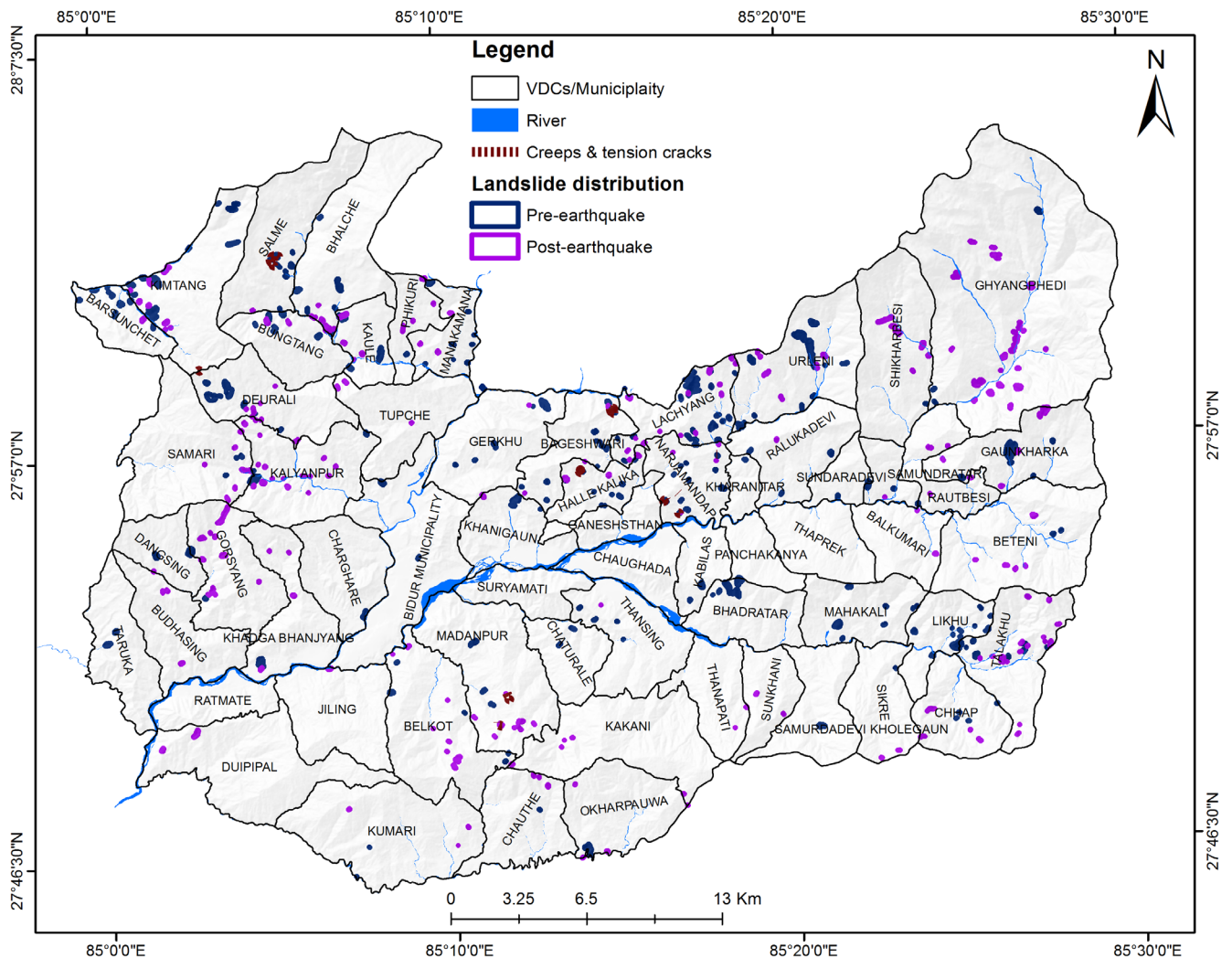


Fig. 2: Spatial distribution of landslides in study area.

Causative factors and landslide susceptibility map

There is a relationship between landslide occurrence and internal classes of each causative parameters. The result shows that most of the landslides (45.3% of total landslides)

occurred in intermediate slope class or between 25–35 degree slopes (Fig. 4). Similarly, most of the landslides (i.e., 51.7%) occurred in the concave slope terrain, which might be favorable for landslides because of holding moisture effectively. There is high occurrence of landslides in cultivated land (31.1%),

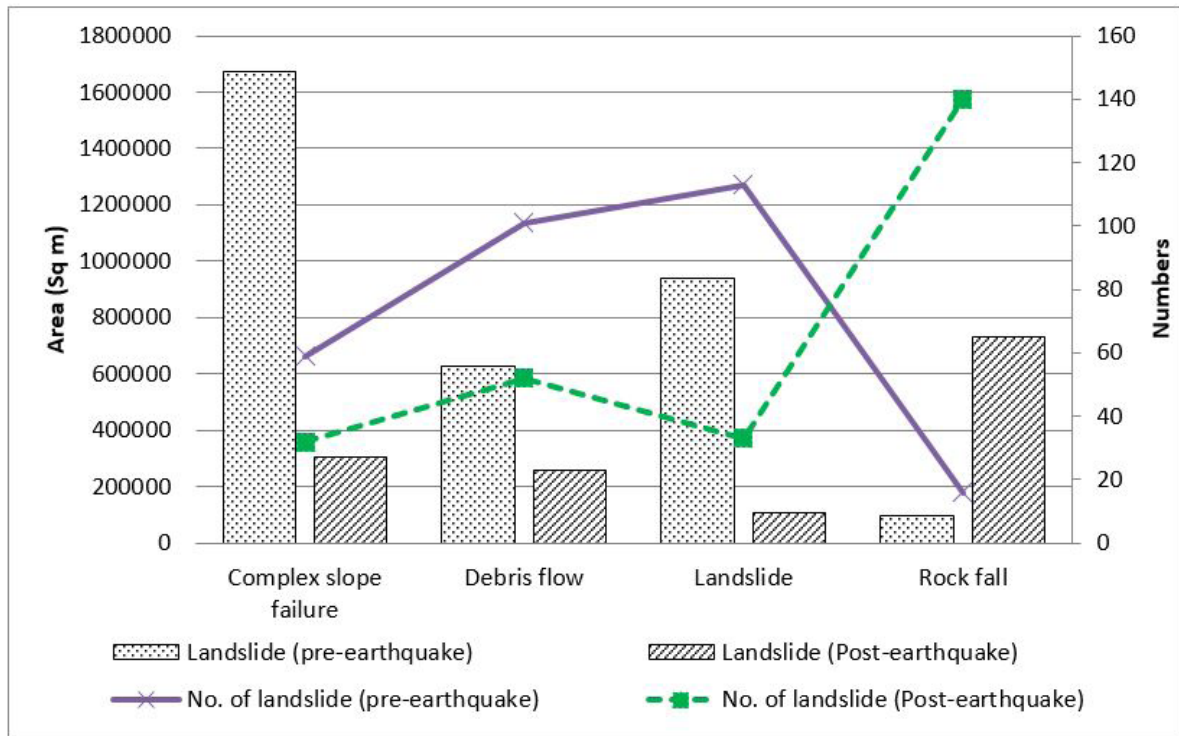


Fig. 3: Distribution of landslides in Nuwakot district based on their types and time of occurrence.

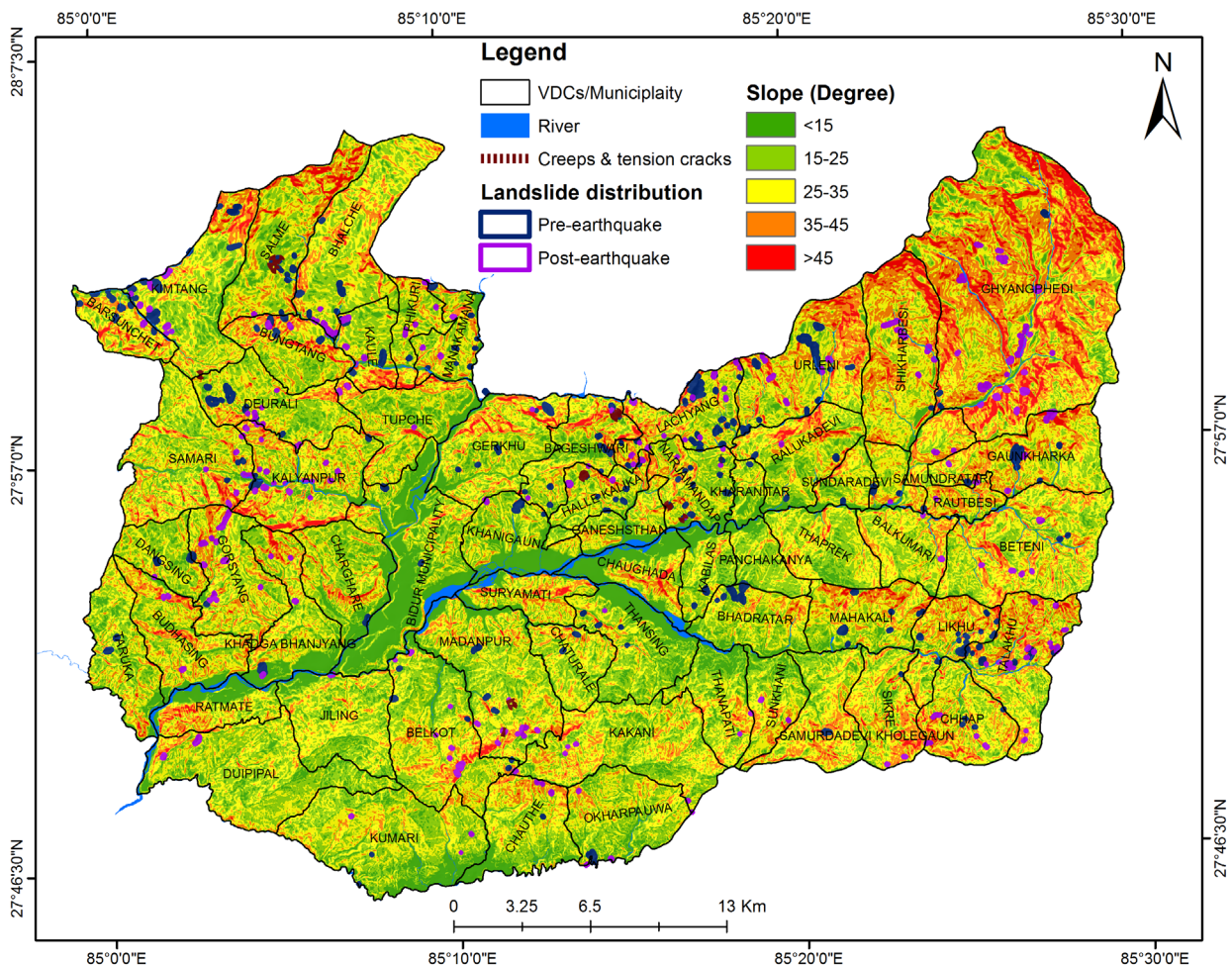


Fig. 4: Spatial distribution of slope gradient and relation with landslides.

Table 2: Calculated weights of each parameter for landslide susceptibility.

Parameters	Parameter class	Area (sq Km)	Landslide occurrence (sq. Km)	Weight
Aspect	N	133.7	0.21	-0.5
	NE	122.11	0.13	-0.93
	E	128.57	0.24	-0.33
	SE	169.85	0.58	0.26
	S	180.68	0.76	0.47
	SW	170.05	0.65	0.37
	W	147.31	0.33	-0.17
	NW	144.88	0.25	-0.44
Elevation (m)	<800	206.74	0.19	-1.05
	800-1500	507.04	1.74	0.27
	1500-2200	305.18	0.92	0.13
	2200-2900	102.19	0.28	0.03
	>2900	76	0.03	-1.98
Relief	1.0-140.6	121.24	0.1	-1.14
	140.7-226.5	408.07	0.8	-0.3
	226.52-305.97	393.06	1.31	0.24
	305.98-414.04	212.21	0.8	0.36
	414.05-814.54	62.58	0.15	-0.12
Slope gradient (Degree)	<15	167.09	0.11	-1.41
	15-25	344.84	0.51	-0.57
	25-35	432.51	1.43	0.23
	35-45	208.16	0.89	0.49
	>45	44.57	0.21	0.58
Plan Curvature	Concave	459.71	1.63	0.29
	Flat	238.69	0.5	-0.23
	Convex	498.75	1.03	-0.24
Topographic Position Index	0.067-0.341	66.56	0.07	-0.94
	0.342-0.442	230.97	0.56	-0.08
	0.443-0.513	435.35	1.28	0.11
	0.514-0.591	368.4	1.1	0.12
	0.592-0.925	95.79	0.15	-0.52
Annual rainfall	2110-2310	173.97	0.13	-1.27
	2310.1-2475	423.56	0.71	-0.46
	2475.1-2675	342.33	1.28	0.35
	2675.1-2925	170.87	0.55	0.2
	2925.1-3175	81.66	0.48	0.8
Drainage Density (Km/Sq km)	1.15-2.72	199.79	0.48	-0.09
	2.73-3.57	410.07	1.67	0.43
	3.58-4.7	340.56	0.88	-0.02
	4.71-6.29	114.76	0.1	-1.09
	6.3-8.16	131.97	0.02	-2.67
Topographic Wetness Index	-3.56	157.84	0.25	-0.5
	-3.35	432.11	1.22	0.07
	-2.082	447.49	1.26	0.06
	0.253-4.02	136.91	0.37	0.04
	4.03-18	22.81	0.05	-0.22

Table 2: (Contd.)

Parameters	Parameter class	Area (sq Km)	Landslide occurrence (sq. Km)	Weight	
Stream Power Index	-6.33	22.22	0.02	-1.18	
	-3.36	141.44	0.24	-0.46	
	1.1-4.66	408.24	0.76	-0.35	
	4.67-7.21	532.94	1.77	0.23	
	7.22-17.4	92.32	0.37	0.41	
Land cover	Barren Land	36.15	0.12	1.71	
	Pond or Lake	0.19	0	-1.76	
	Sand	14.94	0.01	-1.76	
	Grassland	75.38	0.78	1.36	
	Forest	279.45	0.38	-0.67	
	Cutting/Cliff	1.51	0.21	2.36	
	Cultivated Land	647.42	0.98	-0.55	
	Shrub/Bushes	135.55	0.68	0.64	
	River	5.76	0	-1.76	
	Orchard	0.43	0	-1.76	
Plantation Area	Plantation Area	0.39	0	-1.76	
	NDVI	-0.0987	436.01	0.88	-0.27
		-0.0172	324.68	0.69	-0.21
		-0.019	232.62	0.69	0.12
		-0.0221	155.29	0.58	0.34
0.016-0.128		48.56	0.32	0.91	
Geology	Formation I	439.47	1.22	0.06	
	Kuncha Formation	390.23	1.45	0.35	
	Ulleri Augen Gneiss	5.21	0	-0.19	
	Dhading Dolomite	3.93	0	-0.19	
	Ghandruk Quartzite	20.39	0.12	0.78	
	BB	78.79	0.25	0.18	
	Limestone	16.68	0.01	-1.52	
	Higher Himalayan Gneiss	233.45	0.1	-1.83	
	Formation II	3.49	0	-1.53	
	Upper Quartzite	1.36	0	-0.19	
Unknown	Unknown	2.22	0	-0.19	
	Tistung Formation	1.93	0	-0.19	

followed by grassland (24.7%), and shrub /bush lands, where 21.6% of landslides have been occurred. Intermediate slope class seems more favorable for the landslides because it is very close to the internal frictional angle of most of the rock and soil materials in the hilly region of Nepal. The weight assured by the classes of each parameter directly indicates its importance in causing landslide. If the weight is positive and higher, the factor is favorable for landslide, whereas if it is negative, it is unfavorable. For instance, cutting feature in land cover acquired the highest positive weight among all which indicates that previous slope failure areas have maximum chances of potential failure (Table 2). As landslide susceptible zonation is a product of multiple factors summed up to their weightage values, the landslide susceptibility map shows the combined effect of all the landslide causative factors. The landslide susceptibility map of the study area was prepared

using landslide susceptibility index (LSI) method, in which the weightage for each parameter was calculated by crossing them with different types of landslides except rock falls and slides. The landslide susceptibility map (Fig. 5) is categorized into five classes to show the different levels of landslide hazard in the study area. About 16% of the total area lies under very high landslide susceptibility zone in the study area (Table 3).

Table 3: Distribution of landslide susceptibility class

Susceptibility Class	Area (sq km)	Percentage (%)
Very low	183.34	15.36
Low	234.35	19.63
Moderate	324.97	27.22
High	261.81	21.93
Very high	189.21	15.85

Table 4: Rating of each landslides and their prioritization ranking. CSF=Complete Slope Failure, DF=Debris Flow, RFDf = Rock Fall Debris Flow.

Relative Rank	S.N.	Landslide Code	VDC-Ward-Village	Northing	Easting	Type	Pre/Post EQ	Rating					Total rating	
								Landslide type	Landslide depth	Hydrology	Land use	Proximity to village/infra		Treatability
1	41	NKK-4	Kakani-4, Devithan	3079358	620618	Landslide	Post	1	1	1	1	1	1	2
2	28	NBG-6	Bageswori-2, Gogane	3091348	622344	Landslide	Post	1	1	2	1	1.5	1	3
3	14	NKL-1, NBL-1	Kahule-2 and Balche-2	3102026	609904	Landslide	Pre	1	1	2	1	1	2	4
4	9	NGA-1	Gaukharka-7	3092141	643869	DF	Post	2	1	1	1.5	1	1	6
5	23	NMK-3	Manakamana-7 Bhadre	3100139	614517	Rock Fall	Post	3	1	1	1	1	1	6
6	5	NBG-4	Bageshwari-8	3094927	621205	Landslide	Pre	1	1	2	1	1	2	8
7	30	NNM-9	Narjmandap-6, Samantole	3090519	625733	Landslide	Pre	1	1	2	1	1	2	8
8	31	NNM-10	Narjmandap-7, Puwakhok	3090031	625010	Landslide	Pre	1	1	2	1	1	2	8
9	26	NBT-2	Bungtang-1 Barchet	3098413	608760	Landslide	Pre	1	1	1	2	2.5	1	10
10	2	NBHD-2	Bhadratar-1, Ghattekhola	3084112	630797	Landslide	Post	1	2	2	1	1	1	12
11	29	NNM-8	Narjmandap-7 Dotel	3089433	625709	DF	Pre	2	1	2	1	1	1	12
12	33	NKBS-2	Kabilas-8, Sikre	3085211	626118	Landslide	Pre	1	1	1	1	1.5	2	12
13	34	NMP-4	Madanpur-9, Simkuna	3079729	617545	Landslide	Pre	1	1	1	1.5	1.5	2	13.5
14	7	NGH-1	Gyanphedi-5	3096405	641847	Landslide	Post	1	1	1	2	2	2	16
15	38	NLC-8	Lachyang-7 Shyamran/Kaule	3095021	627875	Landslide	Post	1	1	2	2	1	1	16
16	43	NGA-3	Gaunkharkha-7, Tallotakpasang	3092438	643651	DF	Post	2	1	1	1	2	2	16
17	39	NUR-1	Urtleni-4	3094836	630697	Rock Fall	Post	3	1	1	2	1	1	18
18	3	NBH-2	Nuwakot, Balche-2	3098912	609419	DF	Post	2.5	1	1	2	1	2	20
19	40	NLC-9	Lachyang-8	3092992	626037	Landslide	Pre	1	1	2	2	1	3	24
20	22	NST-4	Samundratra-5	3090506	635584	Landslide	Pre	1	2	1	2	2.5	1	30
21	25	NGS-6	Gorsyang-6, Pakhari	3086606	603128	Landslide	Post	1	1	2	2	2.5	1	30
22	35	NJI-1	Jiling-2, Jiling	3082355	608826	Landslide	Post	1	1	1	2	2.5	2	30
23	8	NGH-2	Gyanphedi-3	3095069	640539	Landslide	Post	1	2	1	1.5	1	3	36
24	17	NLC-6	Lachyan 9, Phautpur	3092597	622951	Rock Fall	Pre	3	1	1	1.5	1	3	40.5
25	11	NHK-6	Hallekalika 5, Birtathok (Mayu)	3091557	621381	DF	Pre	1	3	2	2	1	2	48
26	15	NKBS-1	Kalibas 3,9, Keurini, Vasvase	3086331	626868	DF	post	2	4	1	1	2	1	48
27	36	NGS-7	Gorsyang-2, Kapre	3089532	603751	DF	Post	2	2	2	1	1	2	48
28	13	NKP-4	Kalyanpur 7, Kagune	3091605	607696	CSF	Post	4	1	1	2	2.5	1	60
29	24	NNM-7	Narjmandap-2 Sahare	3089403	625669	Landslide	Pre	1	4	2	1	1	3	72
30	27	NKL-2	Kaule-1 Khursanibari	3097145	610382	DF	Post	2	1	1	2.5	2.5	2	75
31	6	NGH-3	Gyanphedi-5	3096634	641530	Rock Fall	Post	3	2	1.5	1.5	1	3	81
32	10	NGK-1	Gerkuh 8, Guhikhola (Barugau)	3092802	617213	Rock Fall	Pre	3	2	1	1.5	1	3	81
33	37	NLC-7	Lachyang-5	3093359	626487	Rock Fall	Pre	3	1	1	3	2.5	1	90

Table 4: Rating of each landslides and their prioritization ranking. CSF=Complete Slope Failure, DF=Debris Flow, RFDf = Rock Fall Debris Flow.

Relative Rank	S.N.	Landslide Code	VDC-Ward-Village	Northing	Easting	Type	Pre/Post EQ	Rating					Total rating
								Landslide type	Landslide depth	Hydrology	Land use	Proximity to village/infra	
34	18	NSL-1	Lachyang 5, Salyandada	3093557	627679	Landslide	Pre	1	3	4	4	96	
35	46	NCH-1	Chauthe-3, Patleagan	3076530	619134	CSF	Post	1	2.5	2.5	2	100	
36	32	NNM-11	Narjmandap-4, Sathyya	3091866	637565	DF	Post	2	1	2.5	2	120	
37	42	NLI-1	Likhu-8, Hille	3082759	638789	CSF	Pre	1	2.5	2	3	120	
38	1	NGA-2	Gaukharka4, (Thamdada)	3090951	640790	CSF	Pre	4	1	1	3	144	
39	45	NRK-1	Ralukadevi-2, Chilauneagan	3092123	633039	CSF	Pre	1	2	3	1	144	
40	19	NMH-2	Mahakali 4, Serabagar	3083142	633305	DF	Post	4	1	2.5	1	150	
41	4	NBS-1	Barsunchet-8,9 Gerchu	3098090	599370	CSF	Pre	1	2	2.5	1	180	
42	21	NS-1	Saltme 4,5, Tarsingkhola	3101961	607173	DF	Pre	4	1	1	3	192	
43	44	NTA-1	Talakh, Talloedandakharka	3082757	643320	CSF	Post	1	2	2.5	2	300	
44	20	NMH-1	Mahakali 4, Mulabari	3083959	633289	RFDf	Pre	1	2	4	4	320	
45	12	NBG-5	Bageshowri 6, Katunje	3094311	622864	RFDf	Pre	4	1.5	1	3	360	
46	16	NKG-3	Khangau-6, 7 and 9	3090725	618019	CSF	Pre	4	2	2.5	2	640	

Landslide ranking, prioritization, and recommendation of mitigation measures

A total of 46 landslides are mapped to be more critical based on their exposure to physical and social risks. To make more practical and ease to treat or mitigate these landslides, they are ranked in an order of urgency. The prioritized landslides with their relative rank are presented in Table 4. Though it is necessary to carry out detailed site survey before the implementation of mitigation measures, the present study gives an overview of treatment or mitigation measures. The details of landslide control measures can also be referred from Deoja et al. (1991) and Howell (1999). Landslide treatment or mitigation measures are designed and costs are estimated by following guidelines that was approved by Department of Soil Conservation and Watershed Management (DSCWM 2016). Site specific control or mitigation measures are recommended (Table 5; Fig. 6). Since these recommendations are made based on preliminary field survey alone, a detailed site investigation will be required before implementation of mitigation measures.

CONCLUSIONS

Different types of landslides (rock falls, debris flows, rock slides, and debris falls) caused by 2015 Gorkha earthquake as well as torrential rainfalls during the monsoon had damaging effects and caused serious threats to life and property in the Nuwakot district. The damage was confined mainly to steep cut slopes (by river scouring and road cut), rock cliffs, and erosive gullies with fractured rock or colluvium. Most of the triggered slides comprise shallow (less than 5 m deep) and short sliding part but the run out materials reach quite far.

Landslide susceptibility map is a result of combination of various landslide causative parameters, such as existing landslides, hydrological and wetness index, land use and vegetative index, geological setting, topographical and morphological setting that depict the landslide susceptible areas in the study area. It excludes the existing rock falls and rock slides. Rock fall susceptibility map shows the potential rock fall and/or slide sides in the study area. Owing to the lack of good DEM and the temporal landslide occurrence data and rainfall intensities, it is not possible to prepare event based landslide hazard map. On the other hand, the entire region suffered from almost complete building collapse due to earthquake shaking. So, physical vulnerability and risk assessment of the district was not appropriate. Instead, a proper methodology for social vulnerability analysis is presented.

A proper landslide ranking and prioritization is proposed. There are some essential mitigation measures suggested for prioritized landslides based on field survey with satellite image analysis that may require further modification and detailed survey before the implementation of treatment or mitigation activities.

Table 5: Landslides in the study area and proposed mitigation measures

S.N.	Location of landslides		Proposed structures					
	VDC and Village name	Landslide ID	Safe drainage channel at crown (m)	Check dam (nos.)	Gabion wall for toe protection (m)	Bio-engineering (sq. m.)		
						Jute netting works	Grass seeds broadcasting	Medium-sized shrub and tree seedlings plantation
1	Gaukharka 4, Beptho (Thamdada)	NGA-2	160	2	50	2000	1000	50
2	Balche-2	NBH-2	150	0	0	0	4000	200
3	Barsunchet	NBS-1	25	0	25	0	300	0
4	Bageshwari-8	NBG-4	50	0	15	0	2000	100
5	Bhadratar-1, Ghattekhola	NBHD-2	100	0	20	0	1500	0
6	Gyanphedi-5	NGH-3	180	0	0	0	2000	50
7	Gyanphedi-5	NGH-1	80	0	0	1000	0	100
8	Gyanphedi-3	NGH-2	50	0	40	2000	3000	50
9	Gaukharka-7	NGA-1	20	8	0	0	4000	0
10	Gerkhu 8, Guhikhola (Barugau)	NGK-1	40	8	15	0	100	50
11	Hallekalika 5, Birtathok (Mayu).	NHK-6	300	2	250	0	0	0
12	Bageshowri 6	NBG-5	200		100		300	
13	Kalyanpur 7, Kagune	NKP-4	50	0	35	0	400	0
14	Kahule-2 and Balche-2	NKL-1, NBH-1	100	0	0	0	2000	200
15	Kalibas 3,9, Keurini, Vasvase	NKBS-1	70	8	0	0	3000	50
16	Khanigau-6, 7 and 9	NKG-3	60	0	15	6000	3000	500
17	Lachyan 9, Phautpur	NLC-6	220	0	0	0	5000	400
18	Lachyang 5, Salyandada	NSL-1	70	0	0	1000	400	200
19	Mahakali 4, Serabagar	NMH-2	40	5	20	0	800	0
20	Mahakali 4, Mulabari	NMH-1	60	4	0	4000	0	0
21	Salme 4,5, Tarsing Khola	NS-1	60	6	30	0	3000	0
22	Samundratra-5	NST-4	50	3	20	0	2000	50
23	Narjamandap-2 Sahare	NNM-7	40	5	30	0	2000	60
24	Gorsyang-6, Pakhari	NGS-6	110	6	0	0	5000	40
25	Bungtang-1, Barchet	NBT-2	150	0	0	0	10000	50
26	Kaule-1, Khursanibari	NKL-2	65	0	30	0	0	200
27	Bageswori-2, Gogane	NBG-6	75	0	0	0	4000	100
28	Narjamandap-7, Dotel	NNM-8	115	0	10	0	6000	200
29	Narjamandap-6, Samantole	NNM-9	110	0	0	0	20000	150
30	Narjamandap-7, Puwakhok	NNM-10	100	0	0	0	4000	100
31	Narjamandap-4, Sathyaa	NNM-11	200	0	20	0	5000	200
32	Kabilas8-Sikre	NKBS-2	100	0	50	0	1000	50
33	Madanpur-9, Simkuna	NMP-4	40	3	20	0	2000	30
34	Jiling-2, Jiling	NJI-1	100	0	20	0	5000	200
35	Gorsyang-2 Kapre	NGS-7	65	10	0	0	2000	50
36	Lachyang -5	NLC-7	50	5	30	0	3000	50
37	Lachyang-7, Shyamran/Kaule	NLC-8	30	4	50	0	5000	100
38	Urleni-4	NUR-1	65	1	0	3000	3000	100
39	Lachyang-8	NLC-9	55	0	0	0	10000	300
40	Kakani-4, Devithan	NKK-4	40	0	20	0	0	0
41	Likhu-8, Hille	NLI-1	25	3	10	0	2000	50
42	Gaunkharka-7, Tallo Takpasang	NGA-3	55	3	0	0	4000	25
43	Talaku, Tallo Dandakharka	NTA-1	105	0	25	0	5000	100
44	Ralukadevi-2, Chilaunegaun	NRK-1	75	3	23	0	1000	100
45	Chauth-3, Patlegaun	NCH-1	25	2	15	0	1000	100

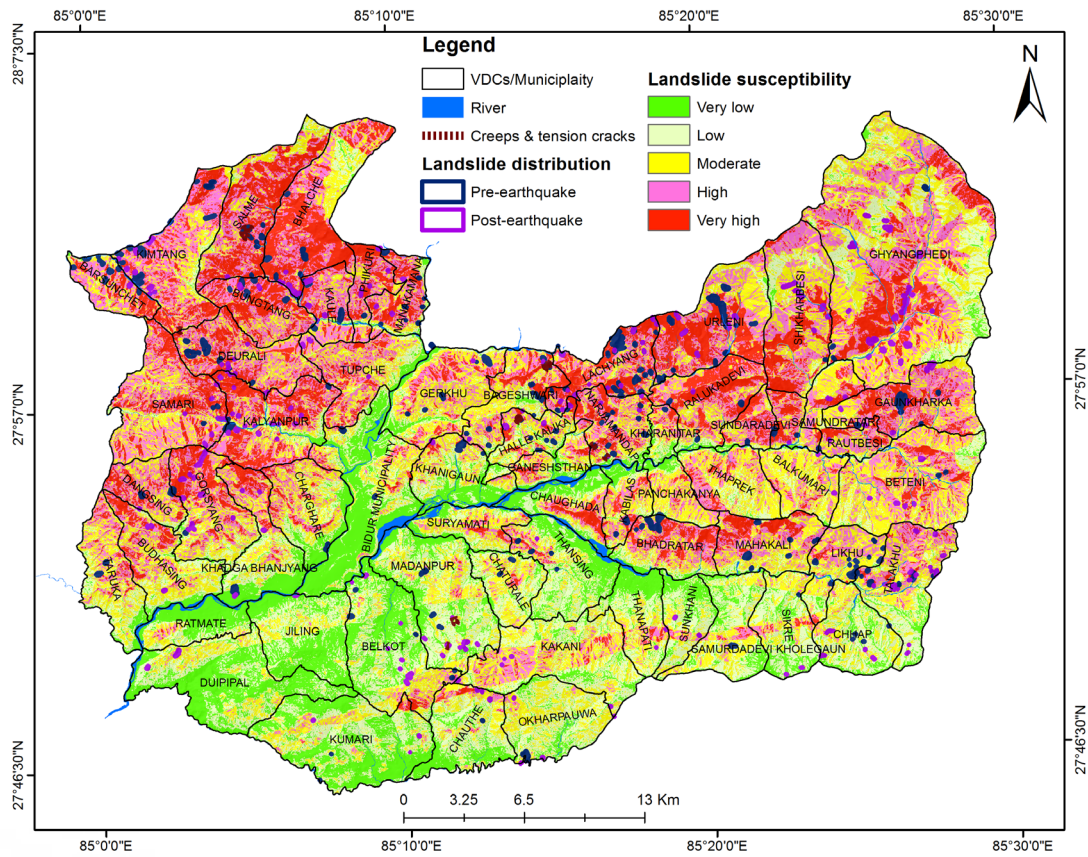


Fig. 5: Spatial distribution of landslide susceptibility zones.

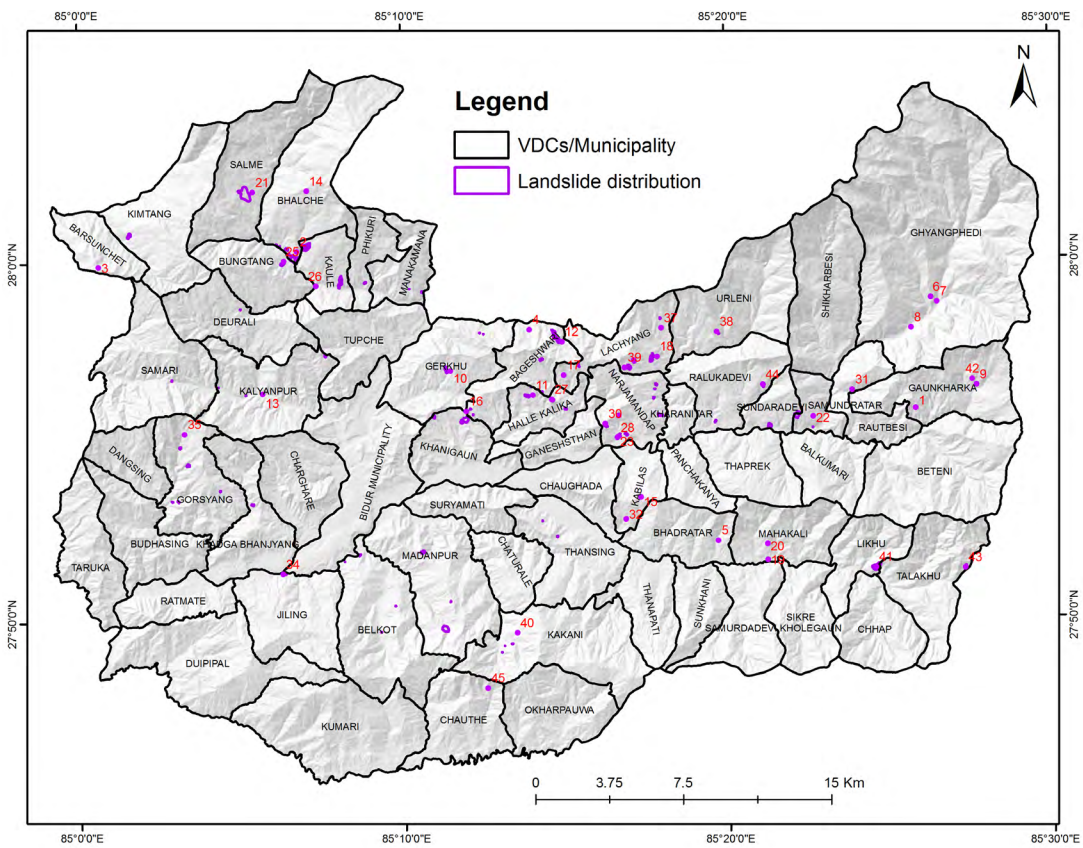


Fig. 6: Spatial distribution of prioritized landslides (Numbers indicate S. N. enlisted in Table 5).

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