Landslide Hazard Mapping in Panchase Mountain of Central Nepal

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ABSTRACT

Numerous slope failures have been noticed in the Panchase region of central Nepal posing threats to people and biodiversity. Considering the need to reduce landslide risks, this research determined the spatial extent of landslide hazard degrees in the Panchase area. The research site, with an area of 278.324 km^2, consists of parts of the Kaski, Parbat, and Syangja Districts. A Statistical Index Method was used for hazard analysis that produced weights. Positive weight values for each factor class represented a higher hazard and vice versa. An inventory of the study area identified 556 landslides measuring 1.511 km^2 indicating a landslide density of 2 per km^2 area. Thirteen percent (36.18 km^2) of the total experimental area was rated as a very high hazard zone. Similarly, the area occupied by high hazard and moderate hazard zones were 77.66 km^2 (28%), and 81.83 km^2 (29%) respectively. The validation showed that the method can produce results with of accuracy of 82.8%. This indicated the hazard assessment process is acceptable and replicable. The factor classes having greater influence for higher landslide hazard are: near the streams, near the roads, barren or grassland, land with phyllite bedrocks, land receiving rainfalls greater than 4,000 mm, lands with an elevation range from 1,000 m to 1,500 m, slopes steeper than 30°, and south-facing slope. During risk management work by local authorities, considerations should be given to these factors and areas with higher hazards.

1. INTRODUCTION

Varnes (1984) defined landslides as ‘almost all varieties of mass movements on slope including rock falls, topples and debris flow that involves little or no true sliding’. There is the influence of gravity beside natural and human-induced factors that initiate slope forming materials to move outward and downward along a definite plane of failure. This process has been described as a landslide. Landslides are the product of a complex interplay of various triggering and conditioning factors. Landslides, when combined with human interferences, become complex and hazardous. The landslides and erosion induced geomorphic events bring disaster and land degradation, which in turn aggravates poverty and seriously impairs development efforts. This necessitates the identification of the locations where landslide incidents can occur in the future, quantification of probable loss, and proposal of measures to mitigate the impacts. Landslide risk mapping can be a useful tool (Maes et al., 2017) which includes landslide inventory, hazard zonation, and vulnerability estimation. A hazard can be defined as “a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage” (UNISDR, 2009). The determining factors for landslide hazards are altitude, slope angle, aspect, vertical curvature (Alkhasawneh et al., 2013), landforms, lithological characteristics, tectonic units, illumination coefficient (Ghimire, 2010), intense rainfall, and the hill slope alteration (Bhusan and Goswami, 2013). When triggering factors like extreme rainfall or zones of tectonic movements are used then results are explained as hazard maps.

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Landslide hazard is one of the most lethal geological hazards in Nepal in terms of the frequency of its occurrence and cumulative loss and damage. In Nepal, most landslides hazards can be observed occurring in the hilly and mountainous regions. Such mountains are active and fragile (Upreti, 2001), and have high relief which makes them landslide-prone during high-intensity monsoon rainfall, and earth tremors (Kayastha et al., 2013). During monsoon, the orographic effect is activated as clouds can't cross the Himalayas forcing greater rainfall in Central and Eastern Nepal, and this, in turn, triggers many landslide related disasters (Dahal, 2012). In the hazard-prone country like Nepal, landslide risk mapping is an essential tool that helps planners to decide the suitable sites for the construction of roads, bridges, hydropower plants, and so on. Landslide hazard and risk studies imply the assessment of various scenarios according to the type and intensity of the triggering mechanism, in which local and regional developments of landslide mechanisms must be considered, as well as their direct and indirect consequences (Cascini et al., 2004). Landslide losses can be avoided if problems are recognized before the happening of a landslide event. Some studies have been previously carried out (Budha et al., 2016; Ghimire, 2010; Kayastha et al., 2013) on landslide hazard assessment in Nepal Himalaya.

This research was carried out in an ecologically important Panchase Mountain Ecological Region (PMER) of central Nepal, which is an essential element of the corridor linking the middle mountain species to that of higher mountains as a part of the Chitwan-Annapurna Landscape. Threatened and endangered species like *Cyathea spinulosa*, *Michealia champaca*, and *Taxus wallichiana* have been noticed in this area during field visits. Thirty seven ecosystem services were identified in PMER ranging from provisional services, regulating services, cultural services, to supporting services (Adhikari et al., 2018) and the services are beneficial to local and national economies along with global impacts (Bhandari et al., 2018). Such services are at higher risk of being diminished by the occurrence of landslides. The current approach of constructing rural roads in PMER had caused many shallow landslides and debris flows (Leibundgut et al., 2016). In addition, there are natural triggering factors of landslide occurrences like rainfall and earthquakes. Such landslides carry debris and deposit heavily in forest areas, cultivated lands, and settlements (Dhakal, 2016). This process reduces the benefits of ecosystem services. Phewa Lake is shrinking due to landslides and soil erosion as there is heavy sedimentation in the lake area (Watson et al., 2019). Ramsar Sites Information Service (RSIS) mentioned that the wetlands in Kaski district were incorporated in Ramsar sites (RSIS, 2016) as Lake Cluster of Pokhara Valley which also included Phewa Lake (Figure 1) and its watershed. Streams flowing from PMER carries a huge amount of debris that causes sedimentation in Phewa Lake which in turn destroys the biodiversity of the area. It seems that there occurs a chain of impacts starting from landslides and erosion, to sedimentation in river and lake to loss of biodiversity of the lake. The losses incurred by nature in this area are intangible.

It can be seen that PMER is an ecologically important area that forms the corridor for north-south connection, inhabited by endangered species, and providing water storage for Phewa Lake. In the meantime, many landslides observed in PMER are deteriorating the natural habitat of wild flora and fauna which necessitate the mapping of landslides and preparation of hazard maps. Thus, the objective of this research was to conduct a landslide inventory of the PMER and prepare hazard zonation for landslides with the application of remote sensing and Geographical Information System (GIS) for effective landslide hazard mapping.

2. METHODOLOGY

2.1 Experimental site

The study area for this research is part of the PMER, a protected forest area presented in Figure 1, and will be referred to as Panchase hereafter. Panchase occupies portions of the Kaski, Parbat and Syangja Districts covering an area of 278.324 km^2. With the changed administrative structure of Nepal as Rural Municipality (RMP) and Municipalities (MP), there are now six administrative units, as illustrated by Figure 1, as local units. These are Pokhara and Annapurna of Kaski District, Modi and Kushma of Parbat District, and Aandhikhola and Phedikhola of Syngja District. Altogether, there are 20 wards in this area.

The altitude of Panchase ranges from 715 m to 2,504 m above mean sea level and the highest point is the Panchase peak. Topographically, the area ranges from moderate to steep terrain. As one ascends towards higher altitudes from Phewa Lake the slopes become steeper. The Panchase Mountain comprises the headwater of three river systems, one end to the Phewa Lake, and forms the most important source of water for the lake. The area surrounding the peak is a dense forest with *Alnus-Schima*, *Castanopsis-Pinus*, *Daphniphyllum*, and *Rhododendron-Quercus* the major tree types (Phuyal et al., 2015). These trees are representative of lower subtropical, upper subtropical, and lower temperate bioclimatic zones, respectively. Temperatures in the Pancahse region range from a mean minimum of 5.3ºC to a mean maximum of 29ºC and it is located in a region of Nepal that receives the highest amount of annual average rainfall of 3,882 mm. This climatic information was obtained from the Department of Hydrology and Meteorology, Government of Nepal.

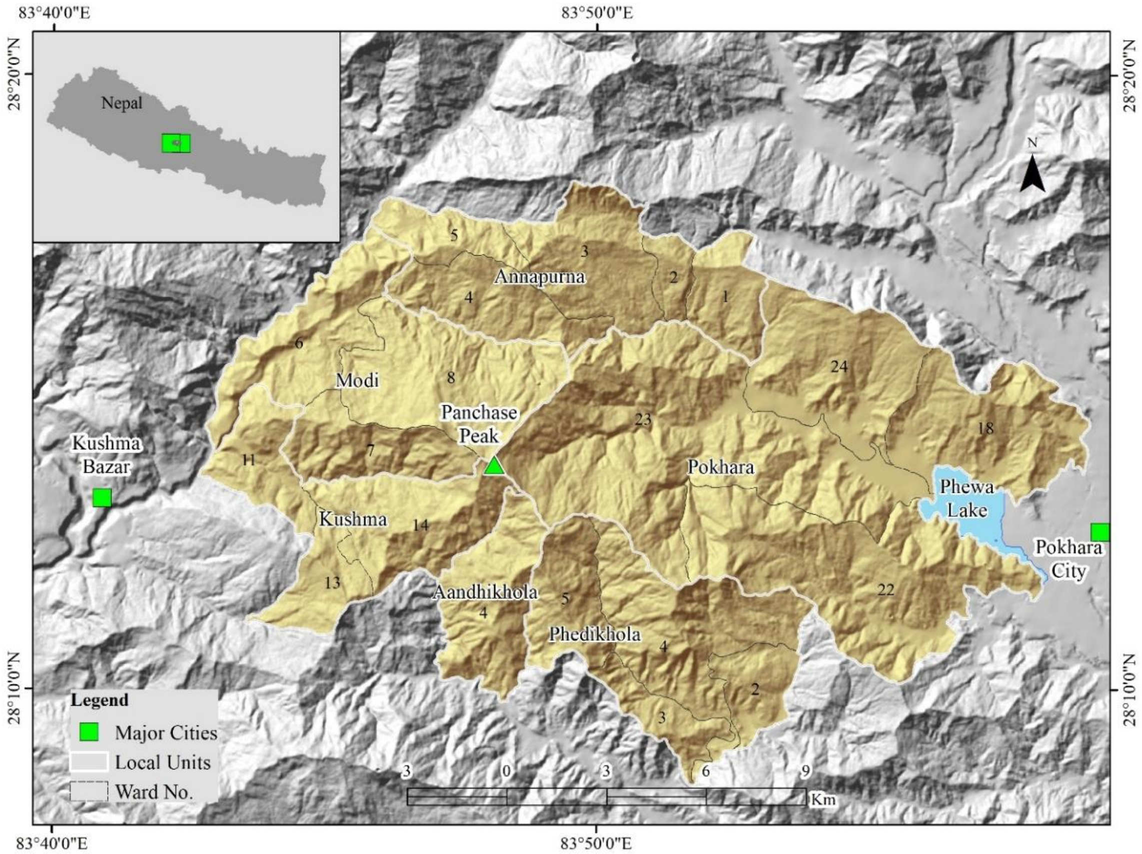

Figure 1. Panchase showing local units and ward numbers (inset; location in central Nepal)

2.2 Data and sources

The data used in this study are composed of both primary and secondary sources. Table 1 lists all the data used in this research and their sources. The inventory of landslides was done from Google Earth and updated after the fieldwork. Some of the secondary data used in this research were digital data of topographic maps, rainfall readings, and geological maps. Open Street maps were also explored to obtain the data of roads. Digitization was done over Google Earth for drawing major rivers.

2.3 Hazard assessment process

The technique of hazard mapping includes analysis of landslides inventoried and development of some relations with factors associated with the process of land-sliding so that hazard status of specific area can be estimated. Figure 2 represents the elaborated form of the landslide hazard mapping process. Landslides were located on Google Earth and digitized as polygons to estimate their coverage. The inventory was divided into two groups consisting of 70 and 30 percentages (Nachappa et al., 2020) of landslides to be used in hazard mapping and validation processes respectively.

Table 1. List of data and the sources used in this research

Data	Sources
Landslides	Google Earth
Topographic data	Department of Survey
Geological maps	Department Mines and Geology
Rainfall data	Department of Hydrology and Meteorology
Roads	Open street maps, Google Earth
Streams	Department of Survey, Google Earth

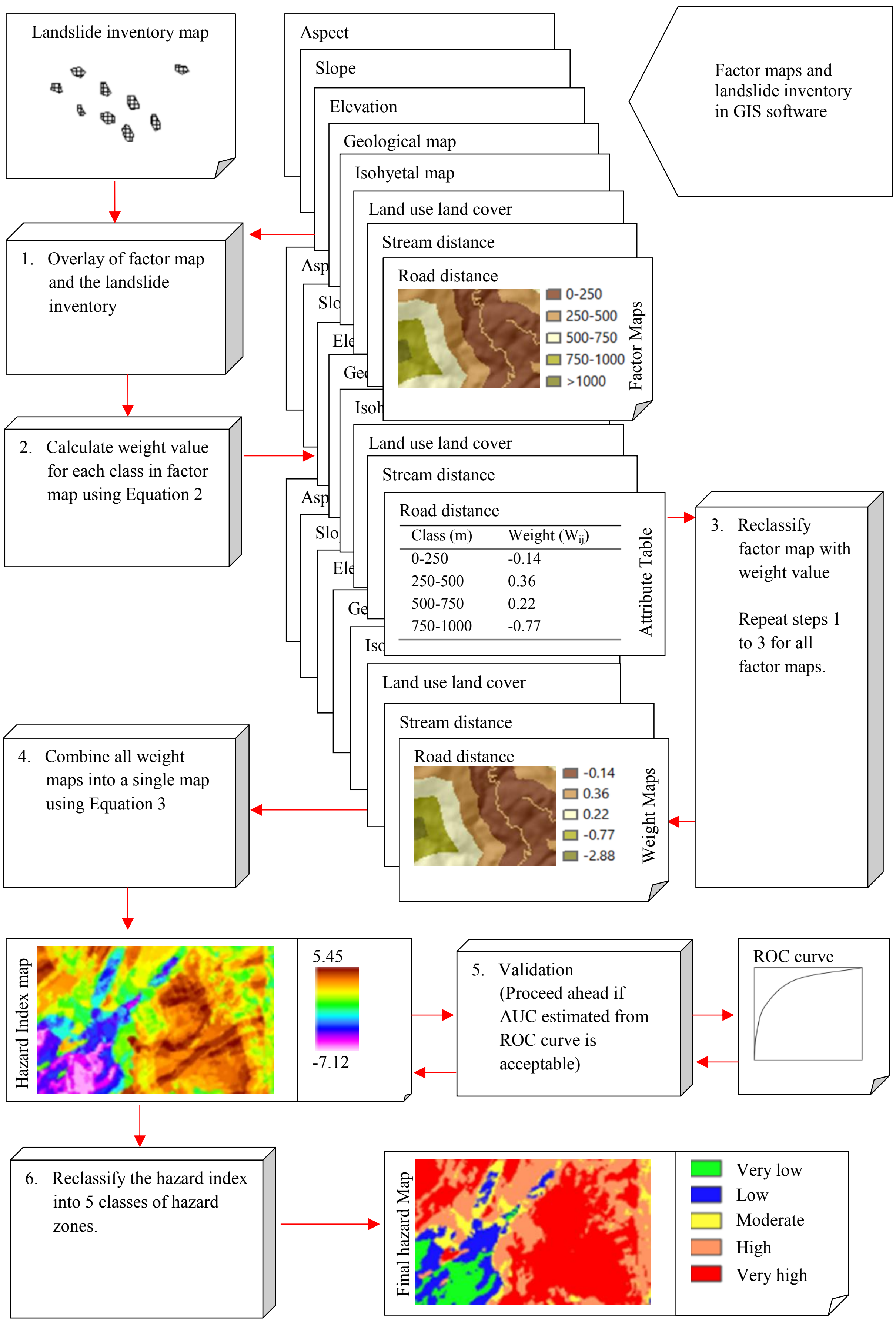

Figure 2. Flowchart of the method used in the hazard mapping process (modified after van Western et al., 1997)

2.3.1 Landslide inflicting factors

There were eight factors considered for landslide hazard mapping in this research with assumptions that they influenced the formation of landslides. These factors are listed in Table 2 and shown in Figure 3. Three topography based factors (elevation, aspect, and slope gradient) were derived from Digital Elevation Model (DEM) produced from contours of 20 m interval. Two distance-based maps were created: the distance from streams and the distance from roads. Other factors used were land use map from topographic sheet modified with recent satellite imagery in GIS, geological maps digitized from a scanned copy of geological maps, and isohyetal map produced from the interpolation of rainfall data of 14 rainfall stations.

Table 2. The factors and their derivation techniques

Factor	Derivation of factors
Aspect	DEM processing
Slope	DEM processing
Elevation	DEM processing
Stream distance	Stream buffering
Road distance	Road buffering
Land use and land cover	Topographic sheet digitization and update
Geology	Digitization of geological map
Isohyetal map	Interpolation of rainfall data

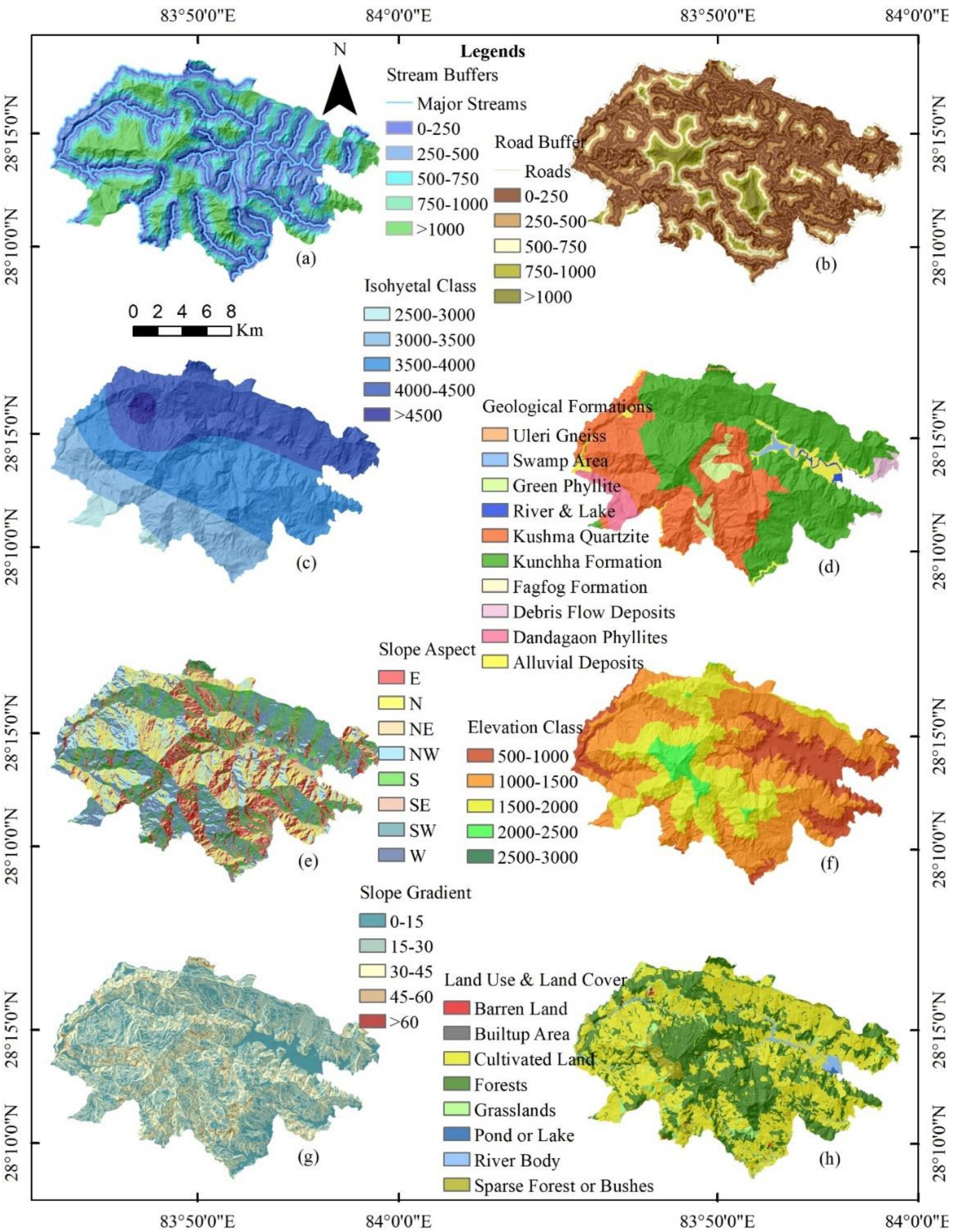

Figure 3. Map of Panchase showing (a) stream buffers in meters; (b) road buffers in meters; (c) isohyetal classes in millimeter; (d) geological formations; (e) aspect showing eight directions; (f) elevation in meters; (g) slope in degrees; and (h) land use land cover

2.3.2 Landslide inventory

Landslide inventory includes an enumeration of location, date of occurrence, and type of movement (Guzzetti, 2005) of landslide incidents which can be extracted satellite imageries, topographic sheets, or field surveys. The inventory of landslides was done from the digitization of landslides scars observed on Google Earth imageries of different times. The inventory was verified in the subsequent field visits and updated thereafter. In the field study data regarding the surrounding conditions, impacted areas, and elements were also recorded.

2.3.3 Hazard zonation and validation

Statistical index method or bivariate analysis was used in this research for the process of hazard mapping. This method was first introduced by van Westen et al. (1997) for landslide hazard analysis. In this method, a weight value for a factor class, such as a certain land-use type or a certain slope class is defined. A weight value is the natural logarithm of the ratio of landslide densities. Ratio being landslide density (f_{ij}) in a certain class (i) of factor (j) divided by the landslide density (f) in the entire map as depicted by the following equations (van Westen et al., 1997):

$$W_{ij} = \text{Ln}\left[\frac{f_{ij}}{f}\right] = \text{Ln}\left[\frac{\left(\frac{A_{ij}^*}{A_{ij}}\right)}{\left(\frac{A^*}{A}\right)}\right] \quad (1)$$

$$W_{ij} = \text{Ln}\left[\left(\frac{A_{ij}^*}{A_{ij}}\right) \times \left(\frac{A}{A^*}\right)\right] \quad (2)$$

Where; W_{ij}=weight given to class i of factor j, A_{ij}^*=area of the landslide in class i of factor j, A_{ij}=area of class i of factor j, A^*=total area of landslides in the entire map, A=area of the entire map.

Each factor maps are classified according to their weight values. Overlaying factor maps using their weight values in the GIS environment produce the hazard map. The process used for overlaying was the weighted sum method and equal importance was given to all parameters. Thus, this summing method can be represented by the following equation:

$$HI = \sum_{j=n}^{n} W_{ij} \quad (3)$$

Where; HI=Hazard Index of landslides, W_{ij}=weight of class i of parameter j, n=number of parameters.

The validation process includes the preparation of the Receiver Operational Characteristics (ROC) curve and estimating the area under the curve (AUC). The AUC varies between 0 (worse-than-random model), 0.5 (random model), and 1 (best discriminating model) (Hirzel et al., 2006). The AUC greater than 0.6 are generally accepted models but higher accuracies are preferred.

3. RESULTS AND DISCUSSION

3.1 Landslide inventory

In Panchase, there were altogether 556 landslides inventoried covering 1.51 km^2 in total area. Five hundred landslides were marked from the Google Earth that had a measured area of 1.176 km^2. Fifty six landslides were updated via field visits adding an area of 0.335 km^2. The landslide density thus became 1.99 per km^2 in this research area. Figure 4 represents the landslide inventory map of Panchase.

Size of the smallest landslide recorded was 40.253 m^2 and the largest one measured 105,722.156 m^2. The largest landslide was located in Annapurna RMP, ward number 3. Table 3 lists the landslides according to the wards of six local administrative units. The highest numbers of landslides were seen in ward 3 of Annapurna RMP. There were 108 landslides in this ward that also measured the highest coverage in the area. There were 281 landslides in Annapurna RMP alone, which is almost half of the entire landslide's inventories. This probably plays a crucial role in hazard mapping. On the other hand, a portion of Kushma MP had the least number of landslides which was 14.

Table 3. Number and area of landslides according to ward numbers of municipality and rural municipality in Panchase

Municipality/rural municipality	Ward number	No. of landslides	Area of landslides (m^2)
Aandhikhola	4	24	98,549.04
Annapurna	1	28	35,900.91
Annapurna	2	32	46,045.57
Annapurna	3	108	327,401.65
Annapurna	4	99	200,778.07
Annapurna	5	14	53,418.38
Kushma	11	5	16,894.98

Table 3. Number and area of landslides according to ward numbers of municipality and rural municipality in Panchase (cont.)

Municipality/rural municipality	Ward number	No. of landslides	Area of landslides (m^2)
Kushma	14	9	17,323.08
Modi	6	24	55,775.86
Modi	7	6	24,149.09
Modi	8	28	29,093.46
Phedikhola	2	8	41,722.18
Phedikhola	4	21	146,026.86
Pokhara	18	17	32,793.83
Pokhara	22	15	33,440.51
Pokhara	23	105	283,565.88
Pokhara	24	13	67,185.67
		556	1,510,260.06

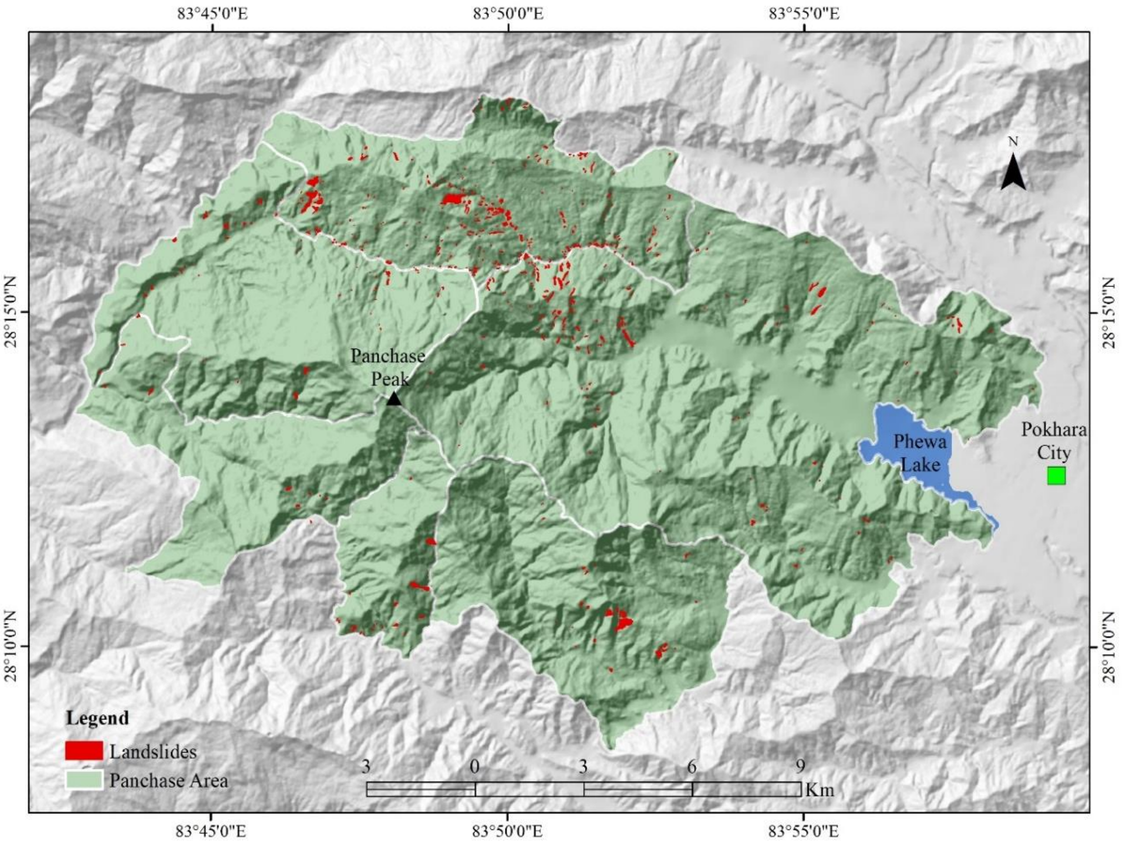

Figure 4. Landslides inventory of Panchase area

3.2 Hazard zonation and validation

A set of 388 landslides were separated by random selection to be used for hazard mapping. The remaining landslides were kept for the validation of the results. In Table 4, we can see the area of landslides occurred in different factor classes and weight values. The total area of landslides (A) is 1.51 km^2. Nearest buffers for stream and road buffers categories, forests for land use land cover classes, and Kunchha Formation for geological formations, respectively, bear higher landslide areas. Parts with 4,000-4,500 mm rainfall, 1,000-1,500 m elevation and south-southwest slope faces with gradients of 15°-45° covered more area of landslides than other classes in respective factors.

From Table 4, it can be said which factor class played a key role in hazard output by looking at their weight values. As the weight values of each pixel in a factor class are added to produce a hazard map, pixels with positive weight values produce higher hazard zones. Thus, factor classes such as near the streams, near the roads, in barren lands or grasslands, with phyllite rocks, having rainfall greater than 4,000 mm, 1,000 m to 1,500 m of elevation, south-facing and steeper than 30º slope, are liable for developing higher hazard. On the contrary, negative values of pixels are summed in the process of hazard map production and result in lower hazard categories.

Table 4. Calculation of weight value for each factor class for hazard analysis

Factor	Factor class	Factor area (A_{ij})	Landslide area (A_l)	Landslide area modeled (A_{ij}*)	A_{ij}*/A_{ij}	Weight (W_{ij})
Stream buffer (m)	0-250	79.5780	0.612	0.374	0.005	0.22
	250-500	69.5536	0.317	0.237	0.003	-0.10
	500-750	53.0668	0.247	0.177	0.003	-0.12
	750-1,000	35.2868	0.140	0.116	0.003	-0.14
	>1,000	41.2488	0.185	0.147	0.004	-0.06
Road buffer (m)	0-250	165.554	0.752	0.540	0.003	-0.14
	250-500	65.3872	0.558	0.355	0.005	0.36
	500-750	28.6172	0.170	0.134	0.005	0.22
	750-1,000	11.6452	0.020	0.020	0.002	-0.77
	>1,000	7.5304	0.001	0.002	0.000	-2.88
Land use land cover classes	Cultivated land	143.1240	0.358	0.277	0.002	-0.67
	Bushes	10.4216	0.042	0.032	0.003	-0.21
	River body	6.1456	0.016	0.005	0.001	-1.57
	Forests	109.7008	0.762	0.474	0.004	0.14
	Grasslands	8.4980	0.177	0.132	0.015	1.41
	Barren land	0.4272	0.145	0.132	0.309	4.41
	Pond or lake	0.4136	0.000	0.000	0.000	0
	Builtup area	0.0032	0.000	0.000	0.000	0
Geological formations	Fagfog formation	0.0264	0.000	0.000	0.000	0
	Alluvial deposits	11.3288	0.011	0.008	0.001	-1.68
	Dandagaon phyllites	8.8050	0.000	0.000	0.000	0
	Sidhane green phyllite	8.9136	0.011	0.004	0.000	-2.13
	Kunchha formation	147.2744	1.071	0.772	0.005	0.33
	Kushma quartzite	95.4952	0.400	0.264	0.003	-0.31
	Debris flow deposits	3.5012	0.001	0.001	0.000	-2.40
	Swamp area	1.7812	0.000	0.000	0.000	0
	Uleri gneiss	0.3390	0.006	0.001	0.004	-0.06
Isoheytal map (mm)	2,500-3,000	7.8312	0.019	0.013	0.002	-0.84
	3,000-3,500	58.2320	0.296	0.211	0.004	-0.04
	3,500-4,000	106.4440	0.207	0.152	0.001	-0.97
	4,000-4,500	101.4888	0.930	0.644	0.006	0.52
	>4,500	4.7380	0.048	0.031	0.007	0.54
Elevation range (m)	500-1,000	47.6520	0.109	0.077	0.002	-0.84
	1,000-1,500	138.8040	0.984	0.735	0.005	0.34
	1,500-2,000	81.5628	0.406	0.237	0.003	-0.26
	2,000-2,500	10.7092	0.001	0.002	0.000	-2.82
	>2,500	0.0060	0.000	0.000	0.000	0
Aspect (Slope directions)	N	37.6744	0.132	0.085	0.002	-0.51
	NE	33.6220	0.180	0.106	0.003	-0.18
	E	29.8532	0.175	0.116	0.004	0.03
	SE	30.8232	0.260	0.148	0.005	0.24
	S	41.1036	0.318	0.264	0.006	0.53
	SW	43.0896	0.319	0.244	0.006	0.40
	W	30.0888	0.070	0.049	0.002	-0.84
	NW	32.4792	0.046	0.038	0.001	-1.16
Slope (degree)	0-15	59.4276	0.059	0.041	0.001	-1.69
	15-30	145.6352	0.718	0.500	0.003	-0.09
	30-45	66.6100	0.656	0.457	0.007	0.60
	45-60	7.0156	0.067	0.052	0.007	0.67
	>60	0.0456	0.001	0.001	0.018	1.54

Figure 5 shows the hazard map overlaid by the boundary of the RMP/MP. The research observed that the flood plain area of Harpan Khola which is upstream of Phewa Lake and areas surrounding the Panchase peak have low hazard categories. A higher hazard can be observed in most areas of the Annapurna and northern part of Pokhara. Also, the lower or southern portion of Aandhikhola and Phedikhola RMP have an area of high hazard.

Looking at the overall map, the moderate hazard was found occupying a large area of about 81.83 km^2 which makes 29% of the experimental site. High and very high hazard zones occupy the area up to 77.66 km^2 and 36.18 km^2, respectively. The percentage of area covered by these categories is shown in the legend of Figure 5. Similarly, low and very low hazard zones measure 58.8 km^2 and 24.27 km^2 respectively together forming 30% of the total area.

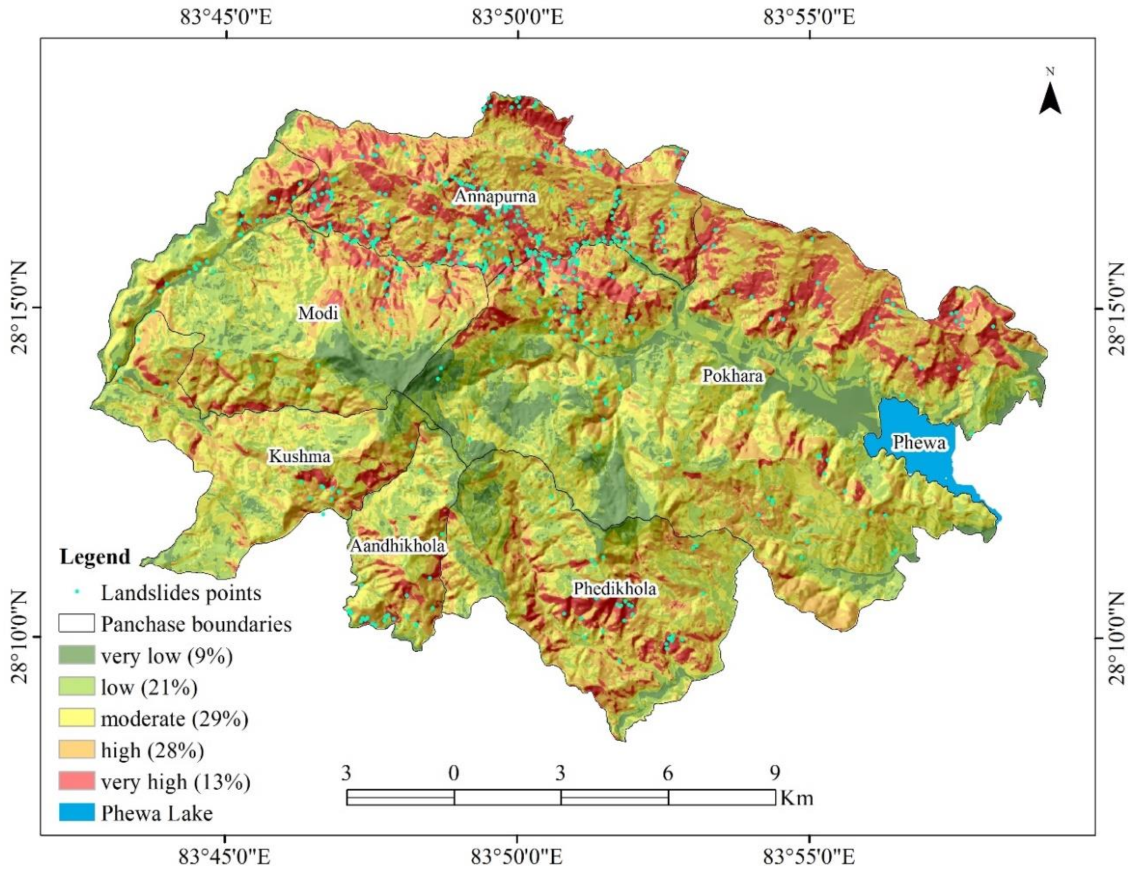

Figure 5. Hazard zonation map of PMER with municipalities and rural-municipalities

The validation for the hazard map showed 0.828 part of AUC as indicated by Figure 6. This means the model's predictability is 82.8% in this experimental site. Also, this implies the results of hazard assessment are acceptable and can be used in similar research in other areas of similar topography. The AUC showed 0.762 for higher Himalayas (Budha et al., 2016) and was 0.758 near Mahabharata Range (Kayastha et al., 2013), as both used the same statistical index method as used in this research. This specifies higher accuracy in the middle mountains of Nepal.

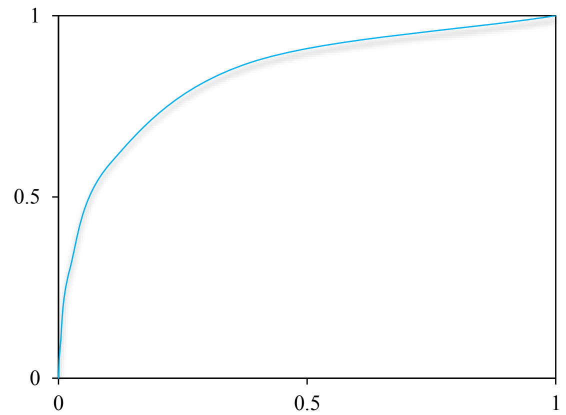

Figure 6. ROC curve for validation of results (AUC=0.828)

When we standardize the raster values of hazard from zero to one most of the local units seem to have a mean value around 0.5 as shown in Figure 7. We can see that the average hazard value of Annapurna RMP is higher than the others. This indicates the area of Panchase that belonged to Annapurna RMP is more prone to landslide hazards. Similarly, the average hazard value of Aandhikhola and Phedikhola RMP is greater than 0.5. Modi RMP and Kushma MP have relatively lower hazard from landslides than other areas. This average score can be linked to the occurrence of landslides from Table 3, which revealed that Annapurna RMP has a greater hazard score as well as a higher number of landslides.

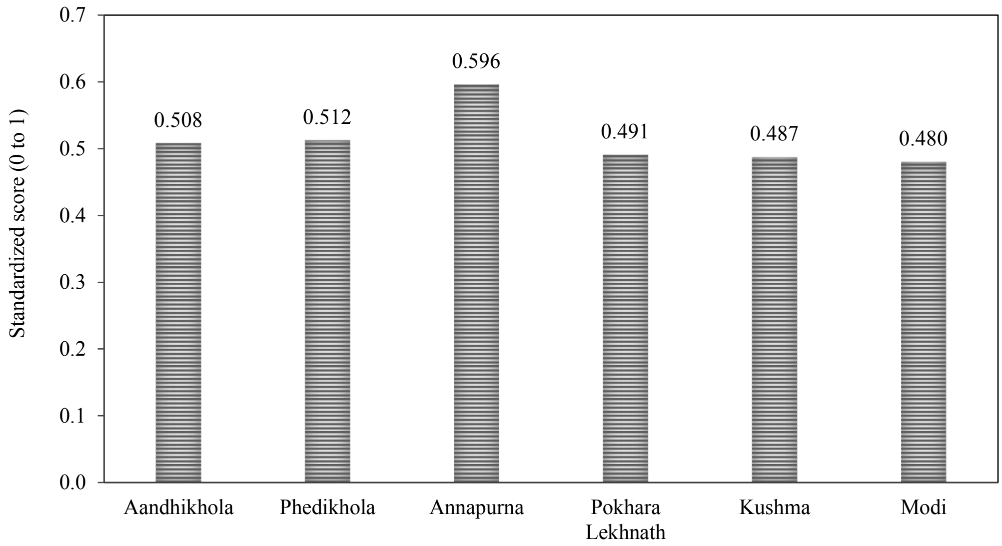

Figure 7. The average hazard value of each municipality/rural municipality

4. DISCUSSIONS

4.1 Landslide inventory

With 556 landslides, the landslide density in the Panchase area was found to be 1.99 per km^2. In research conducted at a location nearby this experimental site, landslide densities of 0.44 per km^2 (Basnet et al., 2006) and 0.571 per km^2 (Bhatt et al., 2013) were found in Phewa and Rupa watersheds, respectively. Phewa watershed is a part of the present study area. The landslide densities had increased by four folds since 2006 when the first research was carried out in Phewa watershed. Only 16 landslides recorded by Basnet et al. (2006), in Sarangkot and Kaskikot which are now ward number 18 and 24 of Pokhara respectively, had now increased to 30. The landslide susceptibility mapping done in 2016 used 80 landslides (Pradhan and Kim, 2016) which had increased to 260 during the time of this research. Thus in Phewa watershed of 123 km^2 landslide density had increased from 0.65 per km^2 to 2.1 per km^2. Above figures indicates that numbers of landslides are increasing annually in Phewa watershed and in larger difference. These results can be the outcome of haphazard road construction without considering fragile geology of the area besides natural triggers of highly saturated slopes and excess rainfall.

4.2 Factors influencing landslide hazard

In Table 4, there can be noticed the spatial coverage of different factor classes along with the area of landslides occurred in the respective class. The total area of landslides (A) is 1.51 km^2. While we consider stream as a factor 0.612 km^2 of landslide area had occurred in 0m to 250 m factor class. It was observed that there were higher occurrences of landslides in the buffers nearer to the streams. Saturation of the slopes near the streams is altered by the excess amount of water available which promotes the instability in the slopes. The higher the instability, the higher the chances of landslide occurrences. Similar situations prevail in road buffers as well, as we can observe in Table 4 there is a higher frequency of landslides occupied. Fifty percent of the total landslide area was found within 250 m distance from the road. The occurrence of landslides within 100m from the roadside was more than twice as likely as that triggered by an earthquake (McAdoo et al., 2018). In mountain regions, roads are closely connected with landslide risk as they destabilize slopes and often lead to the expansion of settlements into hazard zones (Lennartz, 2013). This phenomenon of landslide occurrence due to fresh road cuttings had happened in some parts of Panchase as well. The current style of road construction is inducing soil erosion and shallow landslides which is in turn affecting the road structures as well as downslope land-use types (Leibundgut et al., 2016). Field observation reflected that some households are under threat due to the openings of new tracks. Those households were mainly located at the down-slope of road cuts.

In the case of land use, we can observe a higher amount of landslide area in forests and cultivated lands which are 0.762 km^2 and 0.358 km^2 respectively which together accounted for 75% of the total landslide area. A study in Phewa watershed had also found higher landslides among forests (Basnet et al., 2006) whereas cultivation lands had higher landslides in a study at Mugu District (Budha et al., 2016). Bhatt et al. (2013) also found higher landslides in cultivated lands than in forests. Landslides in cultivated lands may be attributed to the regular disturbance of the soil and the surface but in the case of forested areas, landslides can be related to steep topography, less surface cover, and weak geology.

Among geological types, the highest landslide occurrence was observed in Kunchha formation as it is formed of phyllite rocks that get weathered easily. This formation had landslides of 1.071 km^2 which is almost 70% of the total landslide area. In a study by Budha et al. (2016), landslides were observed more often in geology with rock combinations of phyllite with gneiss and schists. Rocks along with road cuts in the field were observed as highly weathered which may be responsible for landslides. In some weathered rocks, the occurrence of clay mineralization further influences landslides. Clay mineralization in phyllite and quartzite rocks were responsible for Dumre landslides due to rainfall which was a major triggering agent (Regmi et al., 2013). Such processes are slow and prolonged which enhances the weathering of rocks.

In the case of the isohyetal factor, landslides were observed highly occurring in the class having 4,000 mm to 4,500 mm of annual average rainfall as shown in Table 4. In this category 0.93 km^2 of landslides were observed that accounted for 60%. The occurrence of landslides decreased in other classes of the isohyetal factor. Here, landslide occurrence was seen higher in areas with greater rainfall. The orographic effect of the Himalayan range is responsible for extreme rainfall in central and eastern Nepal causing higher landslide incidents in these regions (Dahal, 2012). The rainfall in Panchase area is generally greater as the orographic effect is onset by the Annapurna and Machhapuchhre Mountains. This may be responsible for triggering the landslides in the hilly region. In the Himalayas, up to 53 mm of continuous rainfall for 24 h can trigger landslides (Dikshit et al., 2019). On average, a rainfall of 10 h or less requires a rainfall intensity above 12 mm/h to trigger failure, but a rainfall duration of 100 h or longer with an average intensity of 2 mm/h can also trigger landslides in the Himalaya (Dahal and Hasegawa, 2008).

We can see most landslides occurring in mid-elevations of 1,000-2,000 m. Factor class 1,000-15,000 m of elevation occupied 0.984 km^2 of the landslide area. The elevation is taken as a factor in landslide hazard assessment. The elevation of the place can reflect certain type of climatic conditions because temperature decreases as height is increased. A climatic character such as temperature change and rainfall distribution is dependent upon the elevation (Dawadi, 2017). Also, in areas with weak rocks, relative relief is an important factor to determine the landslide hazard (Ghimire, 2010). Again, when we consider the aspect of the slopes, most landslides were observed in south-facing slopes whether they may be southeast, southwest, or just south. This is similar to the results of Bhatt et al. (2013) in a study of Phewa watershed, where the south and east face of slopes had higher landslide occurrences. There is differential solar input in different aspects and the rainfall amount also varies for various aspects. This, in turn, affects slope stability. South and east slopes generally receive higher solar radiation and a higher amount of rainfall. Similarly, in the case of the slope, gradients with 15° to 45° have a higher area of landslides. Together they occupy 1.374 km^2.

5. CONCLUSION

In the Panchase area, 556 landslides were inventoried that showed landslide density had increased by four-fold since 2006. This should be a key concern for organizations working in disaster risk management of districts in Panchase. Likewise, hazard zonation showed 41% of the total study area under high and very high hazard of landslides. Major contributing factors to the landslide hazard were southern and eastern slopes, with gradients greater than 30º, barren lands and forests, having geology of Kunchha Formation with phyllites as major rock type, areas with annual average rainfall greater than 4,000 mm, and streams and roads proximities. Thus, the hazard analysis of Panchase revealed the whole area of Annapurna and the northern part of Pokhara in the Panchase area being located in higher hazard category along with half the area of the ecologically important Phewa Lake watershed. Still, very fewer tasks are being done to reduce landslide happenings: rather, more anthropogenic disturbances are increasing its frequency. The research findings can be key insights for local administrative units of Kaski, Syangja, and Parbat district to manage the landslide hazard and inclusion in the annual plans of disaster risk management.

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