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Assessment of landslide susceptibility along the Araniko Highway in Poiqu/ Bhote Koshi/Sun Koshi Watershed, Nepal Himalaya

Nirdesh Nepal [a,c], Jiangang Chen [a,b,*], Huayong Chen [a,b], Xi'an Wang [a,c], Til Prasad Pangali Sharma [c,d]

[a] Key Laboratory of Mountain Hazards and Land Surface Processes, Institute of Mountain Hazards and Environment, Chinese Academy Sciences (CAS), Chengdu 610041, China
[b] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China
[d] Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, CAS, Beijing, 100094, China

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ABSTRACT

Landslide susceptibility assessment along the Araniko highway was done using the relationship between the landslide causative factor and presence/absence of landslide using linear discriminant analysis, and divided into Low, Medium, High, and Very High susceptibility zone. The spatial analysis of landslide distribution with its conditioning factors depicts 40°-60° of the slope, South-east and South direction of aspect, 0–5 km North from MCT, 10–20 km of distance from the epicentre, where barren land and forest area are found most susceptible to a landslide. This research can help undertake the proper mitigation and adaptation measures for the landslide risk along the Araniko highway.

1. Introduction

Landslides denote downward or outward movement of slope materials [1], a major hazard in high mountainous areas which accounts for 83% of the total land topography of Nepal [2–4]. The country has a fragile environment which is prone to different hazards [5], due to its physiographic and topographic condition [6], high seismicity [7], and highly concentrated rainfall during monsoon season (June–September) [8–10]. In addition to that, anthropogenic factors like road construction [11], unplanned urbanization or expansion of the built-up area in the hill slope [12], deforestation [13,14] and improper land use [15,16] have further deteriorated the fragile environment resulting in more erosion and landslides. The country is highly susceptible to landslides and stands in the seventh position for human causalities from floods, landslides, and avalanches [17]. Landslides cause devastating economic as well as human losses every year [18,19]. According to the data published by MoHA [20], during last 45 years (1971 to 2016), total 22,216 disaster events have been recorded, where landslide (3246) is a third most frequent hazard in Nepal after the fire (8721), flood (3950) and epidemic (3452). Over 40 thousand people lost their lives, about 80 thousand were injured and approximately 1.32 million became homeless during this time period (1971 to 2016). In total, more than 5.94 million people were affected by disasters [20] where landslide alone caused an economic loss of about USD 8.11 million in 2015–2016 [20].

Highway construction along mountain region in particular increases the likelihood of landslide occurrence [11,21,22]. Generally, roads and other linear structures are laid along the rugged topography with deep river valleys and high mountain ridges which makes them more vulnerable to landslide [23,24]. Roads and other such infrastructures, therefore, increase landslide activity where they are constructed, and when the infrastructure development leads to an increased human settlement in its vicinity the landslides causes additional damage to human life [25] and economy [26]. While a variety of causal mechanism can contribute to an increase in landslide incidents near highways, it has been pointed out that areas near highways in developing countries are particularly vulnerable due to an often poor engineering design [27,28].

Landslide susceptibility assessment has been carried out in Nepalese Himalayas using direct geomorphological mapping [29,30], heuristic [31,32], and statistical [33,34] approaches. Some researchers [8,35] have used physically based methods to quantify the hazard in terms of factor of safety. Researches has been carried out to determine the influence of construction of a new and extensive network of low technology rural roads

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[*] Corresponding author at: Key Laboratory of Mountain Hazards and Land Surface Processes, Institute of Mountain Hazards and Environment, Chinese Academy Sciences (CAS), Chengdu 610041, China.
E-mail address: chenjg@imde.ac.cn. (J. Chen).

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that are being connected to the national highways and are found to be at even greater risk of landslide [36,37]. Despite several studies conducted to assess the overall risk from landslide hazard in a regional context, little focus has been provided to assess the landslide susceptibility of the strategically important mountain highways which connect Nepal with China. In this context, this paper focuses on the assessment of the landslide susceptibility along Dolalghat to Kodari/Liping section of the Araniko highway. The previous studies done by Acharya and Lee [38], Tae, Acharya [39] have determined landslide susceptibility in this area using multiple statistical methods. This research follows a similar route, but only takes the factors that can be easily grasped in the field using a different statistical method. This research also focuses on understanding the gap in the research to develop mitigation measures to minimize the landslide disaster in the area. These researches can each provide some insights into the consideration of development scheme in the area and land use planning. Linear discriminant analysis is used to determine the importance of each landslide conditioning factor. The spatial analysis of landslide with categories of landslide conditioning factors is also done to identify its importance. This would help the policy-maker with preliminary assessment for formulating development activities along the highway, and also encourage them to design highway in a way without causing landslides in the future. This would reduce the loss of life and properties, improve the safety of transportation, and reduce the maintenance cost of the highways.

2. Study area

This study focus along the Araniko Highway in Poiqu/Bhote Koshi/Sun Koshi watershed from Dolalghat to MiteriSangu in Nepal. Poiqu is a transboundary river that originates in Tibet Autonomous Region (TAR) China and also known as Bhote Koshi/Sun Koshi in Nepal side, which flows through the high mountain region of Nepal and India [40]. The elevation ranges from 584 m above sea level (msl) at Dolalghat to more than 4061 msl in the study area. High precipitation trend has been observed in the study area of 2000 mm/year [41] where 80% of the precipitation occurs during the monsoon season. The total length of Araniko highway from Kathmandu to Kodari/Liping (China- Nepal Friendship Bridge) is about 144 km and the length of the road from Barhabise to Kodari/Liping section covers a total of 58.6 km. Araniko highway along the Poiqu/Bhote Koshi/Sun Koshi watershed, one of the two highways that connect China to Nepal, have helped to increase international trade and tourism. It links Kathmandu, the capital of Nepal, with Khasa (Zhang-Mu) in TAR, China. Based on the presence of landslide event in the area, this study covers more than the two-kilometre area of either side of the highway in the Nepalese side (Fig. 1).

The study area was selected considering the ridges of the hills along the highway and past landslides. Based on field experience, informal talk, and review of past literature and historical Google Earth imageries, this study

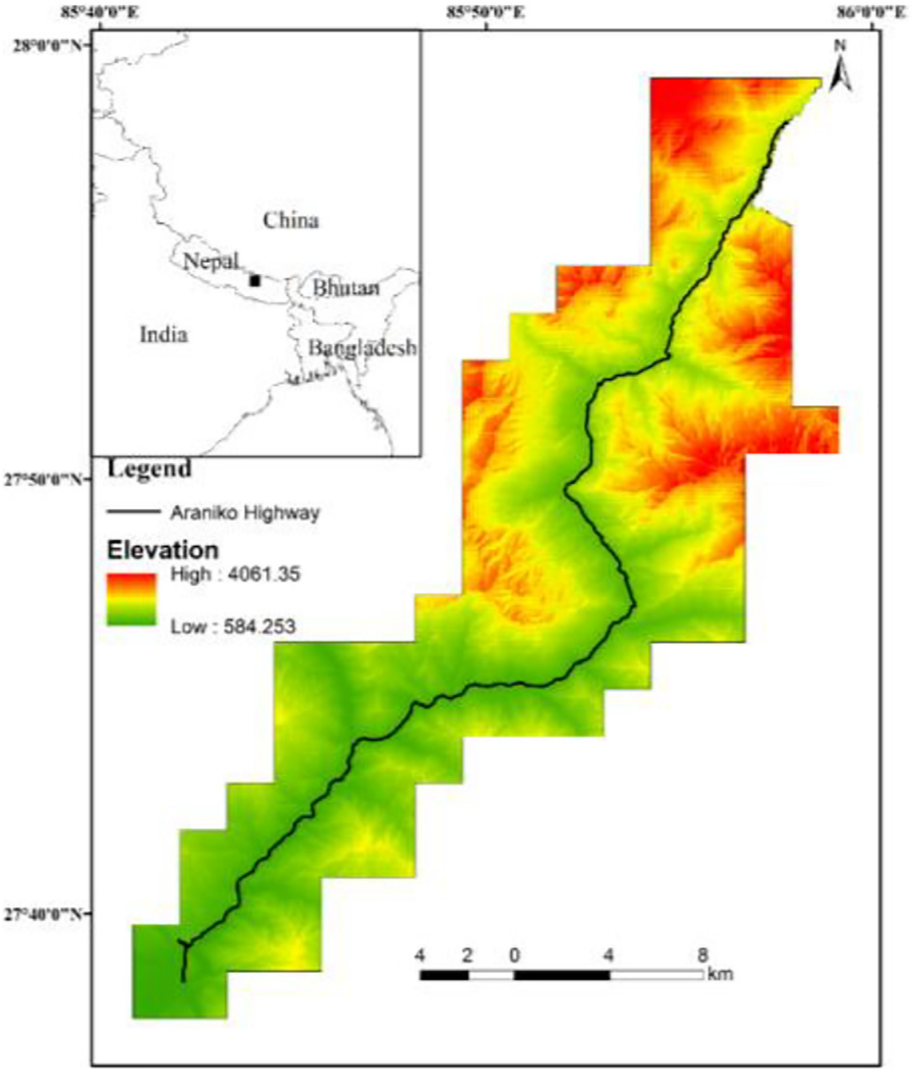

Fig. 1. Location Map of the study area.

area is delineated. A similar approach was used to delineate study area by Bhandary, Yatabe [2], they used the rectangular strip to cover the landslide area along the highway; since landslide along the highway is a major concern of this study, rectangular strip is found more suitable for this study too. In addition, demarcating the study area in the form of rectangular strips reduce lots of errors during calculation along the curve boundary surfaces and provided an easier approach to analyze the data.

3. Materials and methods

The landslide inventory was prepared using the base map of ArcGIS (v10.3.1) (ESRI Inc., Redlands, California, USA) for landslide susceptibility assessment along the Araniko highway (Fig. 2). The basic landslide triggering factors were taken from the landslides around the study area, and selection criteria were determined based on the review of various literature [2,42]. The spatial database was then constructed considering the factors for the study area. The relationship between each factor and presence/absence of landslide on the study area was analyzed using linear discriminant analysis method. Accuracy of the result was determined by the AUC value from the ROC curve using RStudio [43].

3.1. Spatial datasets used in the study

Geo-spatial datasets are limited in the context of Nepal, which is a challenge for the susceptibility assessment. The current study accounts the spatial datasets represented in Table 1 for the analysis of landslide susceptibility.

3.2. Preparation of landslide inventory

This study focuses on the landslides along the Araniko highway starting from Dolalghat to Kodari. This highway runs along the river surrounded by mountainous topography which is vulnerable to different forms of landsides. Fresh/active landslides along the highway were mapped using the base map in ArcGIS, especially considering the road infrastructure [46,47]. These landslides were then exported to Google Earth for 3D visualization and visual confirmation of landslide to minimize errors due to the similar texture of an image. In addition to that, the landslide inventory was updated during the field visit along the highway (Fig. 3). Xu [48] has explained the importance of preparation of complete inventories using the visual interpretation rather than the automation. Considering this, landslide polygon were prepared manually, as well as previous landslide inventories prepared by ICIMOD [49] and Roback, Clark [50] were considered and included as according to the state of activity of landslide in the current scenario. Rockfall, rockslide and debris flow were the most prevalent type of landslide in the area. In total, 304 landslides were mapped as a polygon in the study area with size ranging from 2.1×10^{-5} km^2 to 0.769 km^2. Landslide information was then transferred into fishnet of 25 m*25 m with value 0 and 1 using spatial analysis in ArcGIS, where 1 represents the mesh containing landslide and 0 represents the mesh without a landslide. This mesh was then rasterized for statistical analysis to determine the relationship of landslide with different factors.

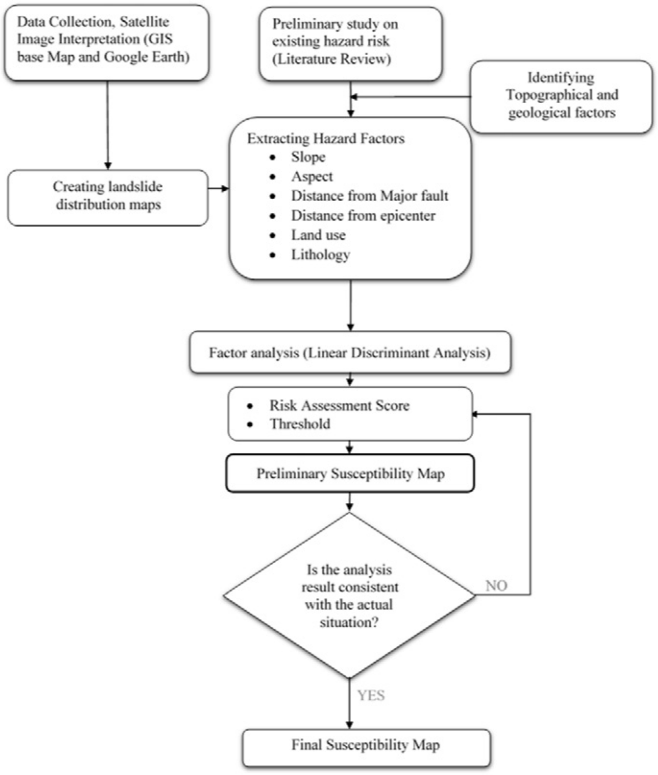

Fig. 2. The methodology of landslide susceptibility assessment

3.3. Field study

Transect survey along the highway from Bahrabise to Kodari was conducted using the XLS Contour Laser, GPS, and Tablet to determine the physical condition of the landslide and to determine the runout of the landslide to verify whether it could reach to the highway. In addition, we determined the state of activity of the landslide and identify the major slope failures in the vicinity which are constantly interrupting the traffic flow in the highway as well as damaging physical infrastructures causing higher fatalities and socio-economic losses.Description 1Jure Landslide [51–54].

Selection of the boundary of the area was done considering the runout, ridges, and state of activity of landslides. Some portion of the area to be considered lied on China which was neglected during this study due to the variation of geospatial data between two countries specifically, geological datasets. Some of the major landslides that have caused huge damage or regular intervention of traffic are Jure Rock avalanche (Description 1), Larcha debris flow (Description 2), and re-activated Balephi landslide.

Retaining walls are under construction along the toe of the landslide in case of Jure landslide, but there is no protection for the debris near the head scarp. Fractures in the rock and seepage along the rock are seen, with the debris gully in the area. Bhandary, Tiwari [54] noted that the slope is unstable at certain peak ground acceleration and groundwater conditions mentioned in **Description 1**. Larcha debris flow still contains a huge amount of loose materials and is at high risk to cause huge damage in the future.Description 2Larcha Debris flow [6,55,56].

3.4. Factors/parameters used in the study

The basic causative factors identified for this study were slope, aspect, distance/direction from major fault (Main Central Thrust (MCT)), distance from the epicentre, basic geology, and land use. Digital elevation model of 25 m*25 m was prepared from the spot heights, contour maps, and drainage patterns. Digitization of the base map in GIS was done to determine the route and location of the highway as well as to determine the land use pattern of the study area. These data combined with epicentre, fault data, and lithological data in different layers were analyzed in GIS using ArcGIS 10.3. Each of these factors was divided into different categories for analysis. The topographic factors like slope and aspect were derived from the DEM prepared using ArcGIS 10.3. Slope inclination was one of the major factor influencing the occurrence of a landslide [57] since a larger inclination increases the shear stress on soil [58–60] which adds to

Table 1
Spatial datasets used in the study.

S.N.	Data	Source	Scale/Spatial Resolution
1	Google Earth Imageries	ESRI Inc., Redlands, California, USA and Google Earth	0.5 m – 2 m
2	Contour and Spot Height	Topographic map (Survey Department of Nepal)	1:25,000
3	Drainage	Topographic map (Survey Department of Nepal)	1:25,000
4	Landcover and landuse	ICIMOD [44]	30 m
5	MCT	Geological Map of Nepal (Department of Mines and Geology)	1:1,000,000
6	Epicentre	Baillard, Lyon-Caen [45]	Co-ordinates
7	Geology (Lithology)	Geological Map of Nepal (Department of Mines and Geology)	1:1,000,000

the occurrence probability of landslide [61]. The slope has been divided into eight categories at every 10-degree interval for the analysis. For an earthquake-triggered landslide, aspect plays an important role in the direction of propagation of the waves or the direction of movement of blocks, hence varying the pattern of co-seismic landslides [62]. Slope/aspect is an important factor for landslide occurrence because in a dry environment it affects the evapotranspiration which in turn have an effect on the weathering process as well as the development of vegetation and roots [63,64]. The aspect was categorized into eight directions for analysis.

Geological factors like lithology and distance from major fault i.e. MCT was analyzed from the geological map of Nepal. MCT is the major thrust present in the study area as it is tectonically active in nature, its presence has made the tectonically sensitive and geologically fragile region in Himalayan/Mountain System more susceptible to the landslides [65–67]. The

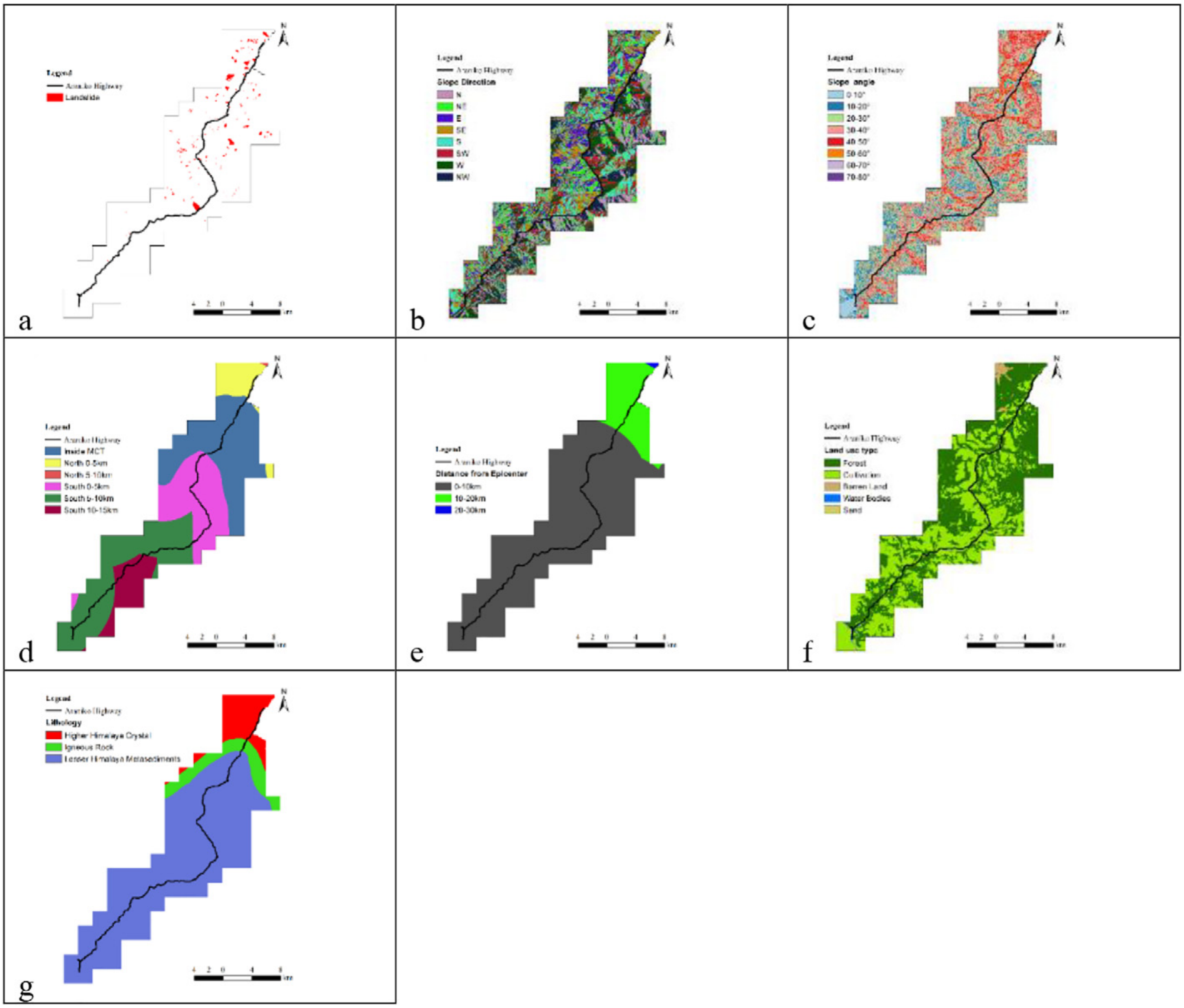

Fig. 3. Landslide inventory and causative factors. **a)** Landslide Inventory along the Araniko Highway with the boundary of Study Area; **b)** Slope Direction in the boundary area; **c)** Slope Inclination in the boundary area; **d)** Main Central Thrust (MCT) and distance from MCT in the boundary area; **e)** Epicentre and distance from epicentre in the boundary area; **f)** Land use in the boundary area; **g)** Geology type in the boundary area.

intersection of the highway by the MCT results in a weak geological condition which conduces landslides [2]. MCT is classified into six categories for further landslide susceptibility assessment based on the direction (North or south) and distance from the thrust. Similarly, lithology of the area affects the nature and rate of geomorphological process and also plays an important role for type, distribution, and movement of groundwater, which triggers a landslide event [68,69]. Lithology plays an important role in landslide susceptibility assessment, but because of the absence of detail geological map of the study area, only a basic lithology is considered and given less importance during the final evaluation scoring. Three lithological categories are present in the study area.

Distance from the epicentre, seismological factor, are considered for the current study. Nepal is in a seismically active zone and highly vulnerable to earthquakes [7]. Lots of landslides were recorded after the Gorkha earthquake in 2015. Therefore, earthquake epicentre magnitude greater than or equal to 5.0 is taken as an important factor for landslide susceptibility assessment; Dai et al. 2008 have also used earthquake's epicentre as an important factor for landslide susceptibility assessment [67]. This study divides epicentres into three categories based on the magnitude of susceptibility assessment. In addition, land use is also an important factor for landslide in the beginning. Urbanization and associated land-use pattern change, cultivation practice, and so on affects the stability of soil and make it more susceptible to landslide [68,70]. Accordingly, land use of the study area is categorized into five types for statistical analysis.

Usually, many topographical factors can be used for the landslide susceptibility mapping, but many factors are difficult to grasp in the actual site. So, only two topographical factors including slope and aspect are used in this study which could represent the significant amounts of other factors in itself, and these can actually be grasped in the field. For the geological factors in a small area, the bedrock has similar hardness, while the surface geological condition is difficult to grasp for the whole area and requires a detailed study, and the influence of geology in the occurrence of the landslide is much higher. So, this study has included multiple geological related factors to actually evaluate its influence on the occurrence of the landslide. This research tries to focus more on the factors that could be interpreted in the field rather than software-generated DEM related factors which may or may not have any influence on the actual physical phenomenon of the landslide.

Table 2
Factors and evaluation points from quantitative analysis.

Factors	Classification	Final evaluation index (linear discriminant analysis method)
Slope Inclination (degree)	0–10°	0
	10–20°	0
	20–30°	6
	30–40°	7
	40–50°	8
	50–60°	14
	60–70°	0
	70–80°	0
Slope Direction (8 directions)	N	3
	NE	2
	E	3
	SE	7
	S	5
	SW	3
	W	3
	NW	3
Relationship with MCT	Inside MCT	3
	North 0-5 km	4
	North 5-10 km	1
	South 0-5 km	3
	South 5-10 km	2
	South 10 or above	1
Distance from Epicentre	0–10 km	8
	10–20 km	10
	20–30 km	2
Land-use type	Forest	8
	Cultivation	6
	Barren Land	14
	Water	0
	Sand	6
Geology	Higher Himalaya Crystalline	4
	Igneous Rock	8
	Lesser Himalaya Meta-sediments	7

Rainfall is an important factor for landslide, mostly high-intensity rainfall in short duration increase pore water pressure and decrease stability that ultimately triggers landslides. There are high rainfall variation and lack of adequate meteorological stations in the study area (whereas it has one regional meteorological station but less relevance in the study area due to distance). In addition, TRMM satellite data could be the best option for the rainfall factor for this study but has a considerably poor spatial resolution for small-scale studies. Therefore, since there is no option for reliable precipitation data for this study area, this factor is omitted in this study to reduce the error in landslide susceptibility mapping. The landslide triggering factors and their categories were analyzed using linear discriminant analysis to get the evaluation point (coefficient) for the preparation of landslide susceptibility map which is shown in Table 2.

3.5. Analysis method

The study area is divided into a mesh of 25 m*25 m along the route of Araniko highway starting from Dolalghat to Kodari. The analysis was performed on a mesh based on the relationship between each factor and presence/absence of landslide using linear discriminant analysis method (LDA) [71,72].

LDA classifies objects from a set of independent variables that are divided into different categories, producing a linear function grouping data into 'n' categories, known as discriminant function [73]. The discriminant function for the n input variables is:

$$D_i = c_1X_{1i} + c_2X_{2i} + c_3X_{3i} + \ldots\ldots\ldots\ldots\ldots + c_nX_{ni} \qquad (1)$$

where X_{ji} is the i^{th} value of the independent variable j; c_j is discriminant coefficient for the variable j; D_i is value or discriminant score i.

The discriminant coefficient maximizes the distance between the vector of mean values in each of the categories i.e. landslide and non-landslide pixels.

Using the linear discriminant analysis, evaluation points for each mesh in the analysis area was calculated. The acquired evaluation point was converted to scale of 0–20 for the easier depiction of its importance, and every evaluation point is converted to a whole number. Then, the total evaluation points for each mesh is calculated by summing up all the factors affecting each analyzed mesh (25 m*25 m) individually. Based on the final score, the study area is divided into four susceptibility zones namely very high, high, medium, and low susceptibility zone using ArcGIS 10.3.

4. Results and analysis

4.1. Final evaluation score of each factor

The result of the quantitative analysis provides a final value based on the factors inducing or controlling the landslides with respect to the presence or absence of landslide, to prepare landslide susceptibility index which is shown in Table 2. The final evaluation index represents the quantitative importance of each factor and its categories for inducing landslide, which is used in a GIS environment to depict the landslide susceptibility of the area.

4.2. Spatial analysis of landslide

The spatial analysis of landslides on the basis of various factors and subcategories within those factors causing the landslide was performed.

Graphical representation of the percentage of landslide area to the percentage of the total area was plotted to depict the spatial distribution of landslide in the area using the following equations:

$$Percentage\ of\ landslide\ area\ (PLA) = \frac{Area\ \ of\ landslide\ in\ each\ category}{Total\ area\ of\ landslide} \times 100 \tag{2}$$

$$Percentage\ of\ total\ area\ (PTA) = \frac{Total\ area\ in\ each\ category}{Total\ study\ area} \times 100 \tag{3}$$

Fig. 4 represents the relationship between landslide distribution and various landslide conditioning factors. Slope angle between 40°-60° is the inclination range which has found most susceptible to landslides. Similarly, SE and S direction of slope aspect have the maximum percentage of landslide area to percentage of total area. Furthermore, 0–5 km north from MCT, a distance of 10–20 km from the epicentre; barren land and forest of land use type and lithology with igneous rock has a high susceptibility to a landslide. Since detailed geology of the area was not available, and the geology map considered for this study was of low resolution. This study suggests that detailed geological investigation of the area is required to get a better picture of the effect of geology on the occurrence of landslide hazard.

4.3. Landslide susceptibility mapping

Using the final evaluation score shown in Table 2, the study area represented by a unique value for each grid along the Araniko highway from Dolalghat to Kodari. The final results were divided into four susceptibility zones i.e. low, medium, high, and very high represented in Fig. 5.

4.4. Validation of the result

Relative operative characteristics (ROC) curve of the analysis result was plotted using RStudio and presented in Fig. 6, and the validation was done using the area under the curve (AUC). The AUC of the curve is 0.713 which represents the strength percentage of model. Fig. 7 represents the distribution of susceptibility in the area with respect to the occurrence of the landslides in the area. It shows that very high susceptibility zone occupies 13.43% of the total area with the presence of 37.78% of the total landslide, high susceptibility zone occupies 44.45% of the total area with the presence of 40.90% of the total landslide, medium susceptibility zone occupies 35.78% of the total area with the presence of 20.67% of the total landslide, and low susceptibility zone occupies 6.34% of the total area with the presence of 0.65% of the total landslide. The increment in landslide with each susceptibility classes also depicts accuracy of result [42,74].

Furthermore, on evaluating the landslide area density calculated from the equation below and presented in Table 3 of each susceptibility classes, it was seen that landslide area density values gradually decline from very high to low susceptible zones; revealing the accurate field instability conditions.

$$Landslide\ Area\ Density\ (LAD) = \frac{Area\ \ of\ landslide\ in\ each\ category}{Total\ area\ of\ that\ category} \tag{4}$$

5. Discussion

Some part of Araniko highway is selected for this study, that passes through the rugged topography with deep valleys and high mountains intercepting the main central thrust making it susceptible to frequent landslides. The situation exacerbated after the 2015 Gorkha earthquake, triggering a large number of landslides and interrupting the highway frequently [62]. The landslide has also increased due to the conducting effect of high precipitation within the short monsoon period further decreasing the stability of the disturbed slope due to the earthquake and subsequent aftershocks. The factors selected for this study have tried to correlate these complex conditions and their impact on the numbers of landslides. Interpreting the distribution pattern of landslides in the area, 10% of the largest landslides cover 77% of the total landslide area (Fig. 8). This represents that only a few large active landslides cover a major proportion of landslide area, so prioritizing these areas for further study for a risk management plan can be an asset for a disaster-resilient infrastructure. This portion of the highway is a very important part of available highways connecting China to Nepal is vital for trade and tourism for a landlocked country like Nepal. Proper management of the hazards along infrastructures can reduce the damage significantly, and minimize the socio-economic losses.

The result shows that the slope between 50°-60° is most susceptible to a landslide. This research has identified that slope plays an important role in

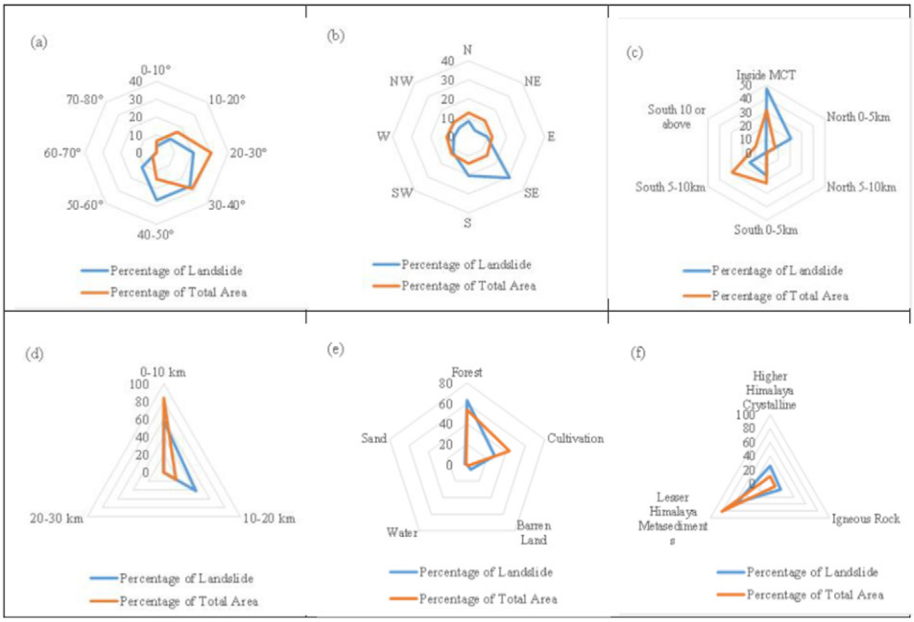

Fig. 4. Relative distribution of different factors and Landslide occurrence with (a) slope; (b) aspect; (c) relationship with MCT; (d) distance from epicentre; (e) land use; (f) geology

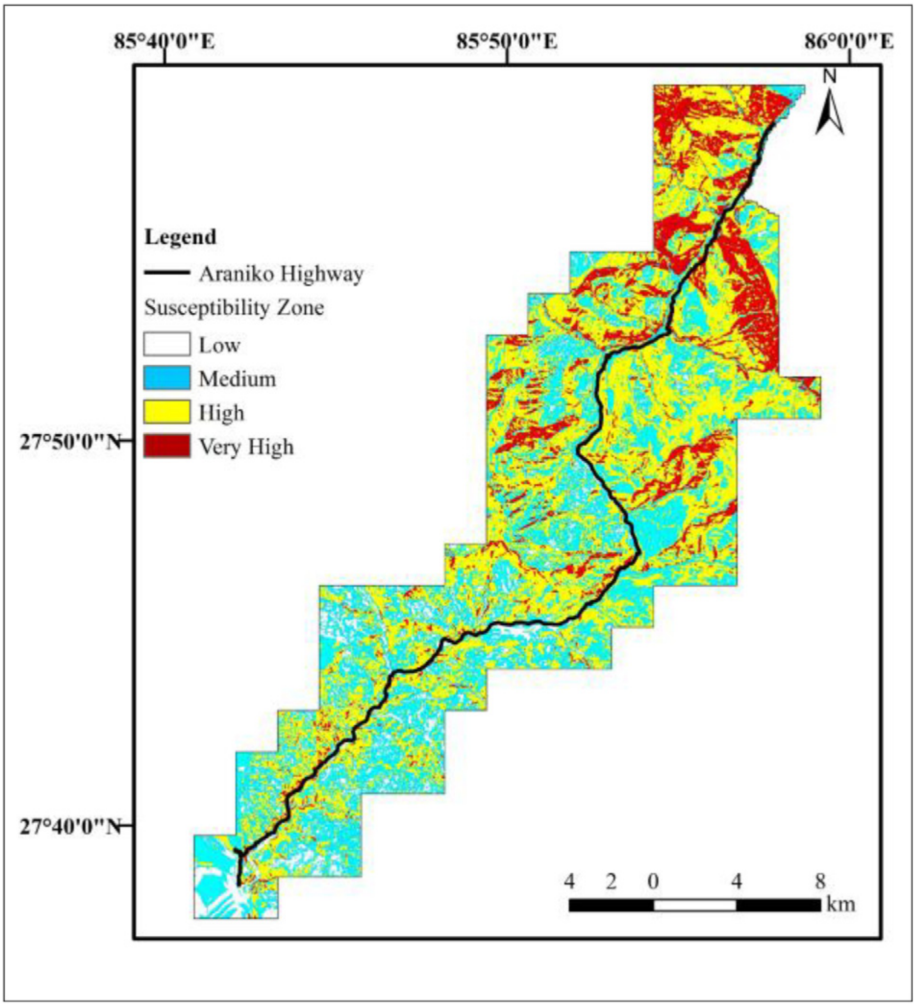

Fig. 5. Final Landslide Susceptibility Map

triggering landslide in the area. In addition, Dai, Lee [69] and Intarawichian and Dasananda [75] observed that the frequency of landslides increases with elevation to a certain extent. In most cases, the slope becomes steeper with increased elevation and possesses high chances of landslide occurrences. Similarly, South-east and South direction of the hill slope, 0–5 km North from MCT, 10–20 km from the epicentre are found to be highly susceptible to a landslide. A similar study conducted by Bhandary, Yatabe [2] also found that the chance of a landslide event is always high near to the thrust zone and the highways passing through it are always facing trouble. The epicentre was used in the current study to determine the seismic influence on the landslide, and the analysis shows that landslides are concentrated along the vicinity of the epicentre which is similar to the result by Shrestha, Kang [76]. Landslides are assumed to be in a limited number in forest areas, but the result shows a rather counterintuitively large number which may be because the plant roots which stabilizes the soil against landslides aren't deep enough to influence the stability significantly [77].

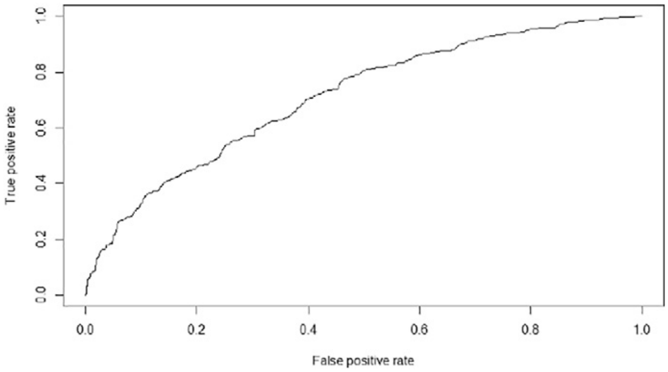

Fig. 6. ROC curve of analysis.

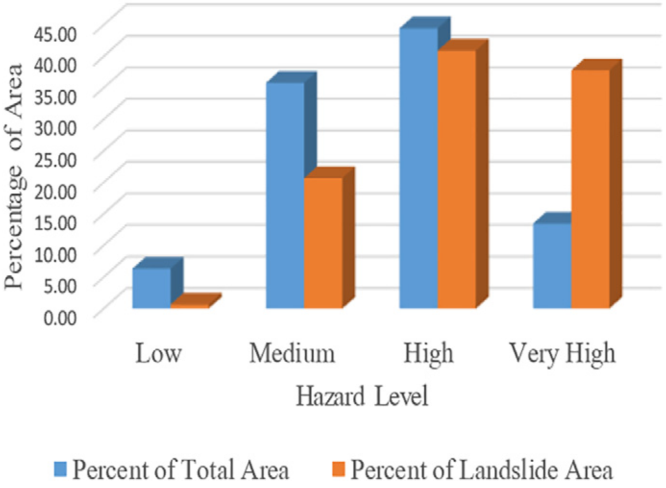

Fig. 7. Relative distribution of susceptibility levels and landslide occurrence.

Table 3
Distribution of susceptibility zones with landslide area and landslide area density.

Hazard Level	Area of the landslide (m^2)	Total Area (m^2)	Percent of Landslide Area	Percent of Total Area	LAD
Low	40,625	25,160,000	0.648	6.335	0.002
Medium	1,295,625	142,093,125	20.666	35.779	0.009
High	2,564,375	176,550,625	40.903	44.455	0.015
Very High	2,368,750	53,341,875	37.783	13.431	0.044
Total	6,269,375	397,145,625	100	100	0.0158

Furthermore, the division of susceptibility to different levels provides key insights to minimize the implications of landslide hazard in the area using different engineering measures and proper planning and prioritization of the protection work along the area. This can also serve as a pre-feasibility assessment tool for any development scheme in the area.

5.1. Implication

The landslide has been the major concern for the highways in Nepal, as a highway in Nepal is usually planned alongside the river in a steep mountainous slope which makes it more susceptible to slope failure due to slope instability caused by slope cutting for road construction and river cutting. The proposed solution by many types of research is to develop a tunnel in these kinds of terrain which is economically unfeasible for the developing nation like Nepal. In the case of Araniko highway, it has been of greater concern for rehabilitation due to the importance of trade between Nepal and China.

During the informal interview with local people, trade was a major income source along the highway as agriculture isn't much profitable income source due to difficult terrain, gravelly soil and unfertile land. They also mentioned that the migration to city area from these areas is increasing day by day due to lack of income opportunities, and interruption of the highway for the longer period of time due to the collapse of Friendship Bridge at Kodari.

China Aid Araniko Highway Long Term Opening Maintenance Project in Nepal (Phase II) which is constructed by 14th CHINA BUREAU GROUP CO. LTD. is working on the reconstruction of the highway and is about to complete very soon. This project has constructed retaining walls, and check dams for the prevention of regular slope collapse, but due to the lack of geotechnical and geological investigation of the area, the effectiveness of this measure is questionable. Previously established mitigation measures in the highway seem to be in critical condition and most of the check dams were completely filled.

Economical bio-technical measures to mitigate landslide disaster and promotion of the site-specific research to understand the physical phenomenon of the landslide is to be encouraged. Lessons can be learned from the damage and rehabilitation done on the Wenchuan earthquake area which was done along the Longmenshan fault. Nepal can use those ideas to implement the monitoring mechanism, early warning system and mitigation measures in the study area. Chen, Cui [78], Liu, Zhang [79], Liu, You [80] have studied the impact of the Wenchuan earthquake on the area and proposed some of the mitigation measures which could be relevant in the context of Nepal. Recent successful implementation of research in the real field can be considered as the relocation of the dry port to 2.5Km downstream from Kodari which was at risk of the landslide as suggested by Wu, Cunningham [81].

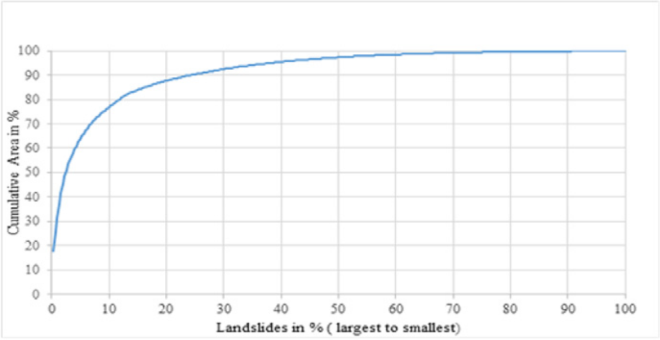

Fig. 8. Active landslides distribution and area.

Land use planning and control in the landslide-prone area is a new concept in Nepal and moreover difficult to implement due to the socio-economic and cultural values involved in the place, so the establishment of a proper automated monitoring station, regular evaluation and technology-based early warning system with community involvement is needed wherever the mitigation measures are too expensive or difficult to implement. This research deals with the regional susceptibility of the area and proposes a change of the land use pattern or development of infrastructures in the area with relatively lower risk.

The major problem identified by this study is the lack of the physical information of the soil characteristics, water table, pore-water pressure, etc. which can be much relevant to the planning of the early warning system in the area. Nevertheless, during the field study, it has been noticed that there are some limited landslides that are causing major problems in terms of damage, traffic interruptions and major economic losses. Regular monitoring and evaluation of these landslides may provide some major information for the study of landslides in this area. If the mitigation measures are expensive, an early warning system with proper automated monitoring instruments is the must. This research proposes mainly improvement of the early warning system in the area for major landslide as well as the provision of excavators at a certain section of the highway so as to regulate the traffic flow in the area. Pecoraro, Calvello [82] can be referred for the importance and type of the monitoring instruments and the relevance of parameters and its importance for the implementation of the early warning system. Understanding the patterns of geologic hazards and duration of the effect of the earthquake in a region is really important to deal with the disasters and these could help in effecting mitigation planning to minimize the risk in the area [83].

6. Conclusion

Road construction along the deep river valleys and mountainous areas come with high chances of landslides causing enormous loss and damage to human life and properties. Recognition of potential landslide area can have a positive impact on landslide management. Therefore, this study assesses the landslides distribution along Araniko Highway from Dolalghat (confluence of Indrawati and Sun Koshi) to Kodari (China-Nepal Friendship Bridge). The susceptibility map was prepared using Linear Discriminant Analysis method and divided into four susceptibility zones i.e. low, medium, high, and very high covering with 6.34%, 35.78%, 44.45%, and 13.43% respectively. The basic causative factors identified for this study were slope, aspect, distance from MCT, distance from the epicentre, lithology, and land use. However, due to the absence of detail geological map of the study area, only a basic lithology was considered, and hence, given less weight during the final evaluation. The factors involved in analysis depicted a complex relationship with landslide distribution. The analysis result showed that the slope between 40°-60° was more susceptible to a landslide. Similarly, South-east and South direction of the hill slope, distance of 0–5 km North from MCT and 10–20 km from the epicentre were found to be highly susceptible. Barren land and forest area of the study area had the maximum percentage of landslides in terms of percentage area covered. A large number of the landslides (63.24%) were identified in the forest area. Thus, this study identifies the potential areas of landslides in the study area and can make important contributions to landslide hazard management through engineering measures and proper planning. The findings of this study can be useful particularly for preliminary assessment of the study region during the feasibility study of development schemes, but detailed site investigation is a must during the implementation of the scheme. This study also proposes to install monitoring systems in the area and get detailed information on the geo-hazards in the area to tackle the future risks.

Conflict of interest

The authors declare that no conflict of interest exists.

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