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Qualitative rock-fall hazard mapping around the Siddhababa area along the Siddhartha Highway in western Nepal

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ABSTRACT

The Butwal-Dobhan road section of the Siddhartha Highway is highly hazardous and problematic section due to rock-fall. In this road section, the Siwalik rocks are exposed that contains inter-bedding of hard and soft rocks. The differential weathering pattern of hard rock sandstone and soft rock mudstone exhibit different properties in the presence of water. Mudstone can easily be softened by water and flow down as slurries when saturated, whereas sandstone cannot easily be softened in water resulting overhanging of sandstone and finally dislodges rock blocks as a rock-fall. The main aims of this study are to investigate and understand the causes of rock-fall, to prepare rock-fall hazard map and ultimately to protect people, properties, man-made structures and to spread public awareness against rock-fall problem. For these set objectives, the study area is divided into twenty-three zones based on segment length along the highway, topography and orientation of discontinuities. Two bases are used to collect field data; one is the rock classification basis viz. rock quality designation, rock mass rating, geological strength index, and slope mass rating, and another basis is kinematic analysis viz. planar sliding, planar sliding no limit, wedge sliding, flexural toppling and direct toppling. The collected data are rated and prepared individual susceptible values. Finally, combining the entire individual's susceptible values along with topographic mosaic, final hazard map was prepared where five different hazard zones have been identified and are categorized into very low, low, medium, high and very high hazard zones. Results from the study could be used as the preliminary study for hazard assessment and land use planning, and to disseminate public awareness.

Keywords: Siwalik, rock-fall, susceptible, hazard, failure, kinematic analysis

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INTRODUCTION

The debris flow, rock-fall and slope removal are common problems in Siwalik hill of Nepal during the monsoon season. The inter-bedding of mudstone and sandstone along with steep slope and road alignment, presence of groundwater, toe cutting of hill slope, orientation of discontinuities and so on are major causative factors for debris flow and rock-fall in the Siwalik.

Rock-fall has been defined (Varnes, 1978) as the movement of fragments of blocks of rock along a vertical or sub vertical cliff which occurs mainly as a consequence of the pre-sequence of intersecting discontinuities in rocks. The economic impact of rock-fall is potentially important because they often lead to traffic disruptions or delays, and require remedial measures (Turner and Schuster, 1996). The identification of areas from which a rock-fall might originate, and the assessment of the hazard of unstable areas, allows for the implementation of stabilization or protective measures before the occurrence of a catastrophic event, thereby reducing cost significantly (Carere et al., 2001; Crosta et al., 2001). Landslide presents a threat to life and livelihood throughout the world, ranging from minor social disruption to huge economic catastrophe. Most works on landslide hazard assessment has been site-based and driven by development projects and engineering concerns (Crozier and Glade, 2005). The study of landslide has drawn worldwide attention mainly due to increasing awareness of the socio-economic impact of landslides, as well as the increasing pressure of the urbanization on the mountain environment (Aleotti and Chowdhury, 1999). Landslide hazard zonation is defined as the mapping of areas with an equal probability of occurrence of landslides within a specified period of time (Varnes, 1984).

In Nepal, Brunsden et al. (1975) is one of the first to develop a geomorphological map of a road corridor. Kojan (1978) studied the landslide problems along the Godavari–Dandeldhura Road and identified the main hazardous areas along the road section and recommended various methods of slope stabilization. Wagner (1981) is the first to prepare a landslide and gully erosion hazard map based on field observation in Nepal. Rainfall threshold for landslides in certain part of Nepal has been calculated by Dahal and Hasegawa (2008). Petley et al. (2006) analyzed a database of landslide fatalities in Nepal from

1978 to 2005 and found that there is a high level of variability in the occurrence of landslides from year to year, but its overall trend is increasing.

The present study area is located at the latitudes 27°43'17" N to 27°44'21" N and longitudes 83°20'34" E to 83°28'32" E in Palpa and Rupandehi districts. In this area, the Sub-Himalayan rocks are present and lying between the Lesser Himalayan and Indo-Gangetic Plain separated by the Main Boundary Thrust (MBT) to the north and Main Frontal Thrust (MFT) to the south, respectively. The elevation of the study area is increasing from south to north having lowest at 190 m and highest at 850 m. In Nepal Himalaya, Siwalik Group is divided into three litho-units based on change in lithology and increasing grain sizes (Medlicott, 1875) such as the Lower, Middle and Upper Siwalik. The Siwalik is made up of geologically very young sedimentary rocks such as mudstone, shale, siltstone, sandstone and conglomerate. These rocks are very soft and can be easily disintegrated and eroded into another form in short period of time. The Lower and Middle Siwalik's rocks are loose and showing differential weathering pattern due to presence of alternating beds of mudstone and sandstone as well as presence of less calcareous cementing materials in sandstone. The hard rock sandstone and soft mudstone have different properties in the presence of water. Mudstone can easily dissolve in water and when saturated flow down as slurries whereas sandstone cannot easily dissolve in water which results overhanging of sandstone takes place and finally dislodge as a rock-fall. The Upper Siwalik contains thick beds of conglomerates which are loose in nature. The Siwalik rocks are young and highly susceptible for rock-falls during monsoon season. They are deposited in varieties of fluvial environments, including piedmonts, outwash plain, flood plains, and oxbow lakes. They comprise a fining-upwards sequence on the scale of individual cycles, but a coarsening-upwards succession as a whole.

In the study area, only the Lower Siwalik and Middle Siwalik rocks are exposed such as sandstone and mudstone. These rocks are situated alternatively look like jam between the cakes and oriented with large angle to the Siddhartha Highway which results rock-fall. The other causes of rock-fall are topography and elevation above the highway. Historical data shows that more than three main accidents and several minor number of accidents have been recorded every year. During 2018 monsoon, traffic had obstructed for one month due to rock-fall and colluvium debris flow which results thousands of passengers affected, eight people, injured and four people were died. The location map of the research area is as shown in Figure 1.

The main objective of this research is to prepare qualitative rock-fall hazard map. The specific objectives are to classify the rocks on the basis of classification system, to study lithology and geological structures of the area, to identify critical zones of rock-fall and to compare the hazard map with historical data

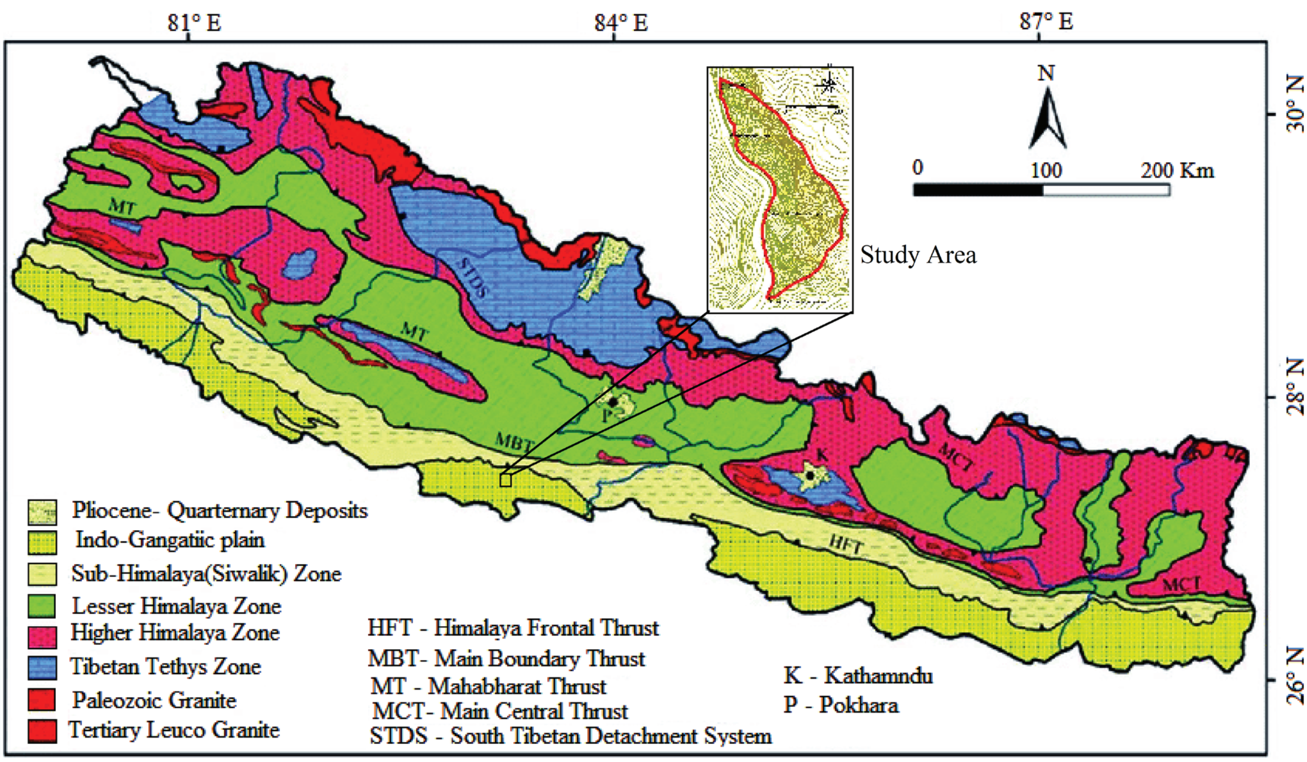


Fig. 1: Geological map of Nepal showing the study area (after Amatya and Jnawali, 1994).

METHODOLOGY

There are many methods for the assessment of landslide hazard. Three types of approaches can be distinguished (Guzzetti et al., 1999; Crosta et al., 2001): (a) methods comparing the distribution of observed landslides (by means of an inventory) with the distribution of physical factors thought to cause landslides either directly or indirectly. These methods use statistical techniques (Carrara, 1983; Carrara et al., 1995; Chung et al., 1995), (b) Heuristic or multi-criterion methods (Leroi, 1996) associating weights to various instability factors, based on expert experience (Wagner et al., 1990; Gupta et al., 1999; Meissina et al., 2001), (c) physically based approaches that evaluate stability using physical laws (Terlien et al., 1995).

The method employed in this study belongs to the Heuristic or multi-criterion methods. It is based on the analysis of topographic, geomorphological and geological parameters derived from the location of the observed rock fall. The topographic map of 1:25,000 scale published by the Department of Survey, Nepal has been used for the field mapping. To achieve the objectives of study, the whole area is divided into twenty-three zones based on length along highway, topographic features of the area and orientation of discontinuities. The study area is started from chainage 0+000 to 2+300 (considering the chainage starting from boundary of Palpa district to the Dobhan village and unit of chainage is meter). The attitude of beds each twenty three zones are measured with the help of Brunton Compass and the thickness of the beds are measured by Trimmer scale. The rock types, grain size, sedimentary structure, cementing materials, mineral composition etc. are observed and studied in field.

Based on the Hoek and Bray (1981) criteria for three basic modes of failure which are dependent upon the geometrical configuration of discontinuities within the rock mass. There are mainly three types of failures; planar sliding, wedge sliding and toppling sliding. The discontinuity information such as orientation of beds or joints: spacing, persistence, aperture, roughness, joint infilling, joint wall strength and seepage are taken in the field in twenty three zones. On the other hand, different parameters have been measured for rock classification such as rock quality designation, slope mass rating, rock mass rating and geological strength index.

The rock quality designation of each zone is measured on the bases of Palmstorm (1974), (Eq. 1).

$$RQD=115-3.3J_v \quad (1)$$

where, J_v= Joint volume

Also, the rock mass rating of each zones are calculated based on Bieniawski (1989).The six parameters such as uniaxial compressive strength of rock, rock quality designation, spacing of discontinuities, condition of discontinuities, groundwater conditions and orientation of discontinuities are used to classify the rock mass using the RMR system. Also, for Slope Mass Rating (Romana, 1995), following formula has been used, equations 2 to 4.

$$SMR = RMR + (F1.\ F2.\ F3) + F4 \quad (2)$$

where, the RMR is computed according to Bieniawski 1989 proposal,

$$F1= (1-sinA)^2 \quad (3)$$

where, A is the angle between strike of the slope face and the joint, and

$$F2= (tanB)^2 \quad (4)$$

where, B denotes joint dip angle. For toppling mode of failure, F2 remains 1 and F3 reflects the relationship between the slope face and the joint dip and F4 is a factor for the method of excavation and its adjustment factor has been fixed empirically (Romana, 1995). The geological strength index of each zones have been measured based on the Hoek, Kaiser and Bawden (1995). The data sheets are filled on the basis of weathering condition such as very fresh, rough, un-weathered surface to slickenside, highly weathered, soft clay coating and the structures such as intact or massive, blocky, very blocky, blocky or disturbed, disintegrated and laminated.

DATA ANALYSIS

The collected data during fieldwork have been analyzed by using different computer tools such as Dips, Excel, and Microsoft word. Ilwis3.3 software was the main tool used to prepare hazard map and the individual susceptible values are used to prepare the combined hazard map (Table 1, 2). Further, reclassifying the combined hazard map along with topographic mosaic, final qualitative hazard map was prepared. For this, two broad methods such as kinematic basis and rock classification basis were used to collect data. On the Kinematic analysis (Table 2), discontinuities of rock mass were collected and analyzed by projecting them in Dips 6 Software. Dips software facilitate the tools for kinematic analysis of joint data. The nature of failure of rocks due to the orientation of discontinuities surface in rocks is given by kinematic tools of this software. The percentage of the failure of the rocks such as planar sliding (PS), planar sliding no limit (PSN), wedge sliding (WS), flexural toppling (FT) and direct toppling (DT) are calculated. Similarly, on rock classification basis (Table 1) such as rock quality designation (RQD), rock mass rating (RMR), slope mass rating (SMR) and geological strength index (GSI) are analyzed in each twenty-three zones of the study area. For both kinematic and rock classification bases, the collected data are classified into five classes on the basis of 20% distribution value.

Combined hazard map

The collected data were classified into five categories; 1 to 5 based on 20% distribution values and combining of these values to obtain combined hazard map. The five categories are very low, low, moderate, high and very high hazard.

Qualitative hazard map

Finally, reclassifying the combined hazard map with topographic mosaic, the qualitative hazard map was prepared. In the qualitative hazard map, the five categories are very low, low, moderate, and high and very high hazard.

Table 1: Rock mass classification values and their respective rating.

Zones	RQD %	RQD rating	RMR %	RMR rating	GSI %	GSI rating	SMR %	SMR rating
1	68	1	66	3	56	1	72	2
2	62	2	65	3	57	1	73	2
3	75	1	77	1	60	1	84	1
4	72	1	73	1	53	2	80	1
5	66	1	66	3	55	2	77	2
6	49	3	61	3	48	3	54	5
7	55	2	74	1	46	3	59	3
8	52	3	67	2	51	3	79	1
9	49	3	66	3	50	3	80	1
10	45	3	66	3	47	4	73	2
11	55	2	51	5	42	5	60	3
12	58	2	54	5	43	5	63	3
13	55	2	55	5	44	4	64	3
14	62	2	69	2	39	5	51	4
15	49	3	58	4	40	5	38	5
16	39	4	61	4	45	4	51	4
17	52	3	65	3	48	3	73	2
18	58	2	61	4	53	2	69	2
19	68	1	62	3	56	1	71	2
20	39	4	64	3	52	2	72	2
21	31	5	70	1	59	1	60	3
22	22	5	65	3	57	1	55	4
23	62	2	66	3	56	1	78	1

Table 2: Types of sliding and their respective rating.

Zones	PS (%)	PS rating	PSN (%)	PSN rating	WS (%)	WS Rating	FT (%)	FT Rating	DT (%)	DT rating
1	8.20	5	18.40	4	25.00	3	4.10	4	21.10	4
2	14.00	5	27.90	3	36.90	2	2.30	5	25.10	3
3	22.70	4	31.80	2	44.70	1	6.80	3	34.70	2
4	32.60	4	41.90	1	50.20	1	2.30	5	39.90	1
5	9.30	5	14.00	5	27.00	3	0.00	0	18.20	4
6	22.70	4	25.00	3	33.60	2	2.30	5	36.90	2
7	6.80	5	11.40	5	15.60	4	6.80	3	29.00	3
8	4.70	5	11.60	5	19.50	4	0.00	0	9.60	5
9	7.00	5	23.30	3	35.00	2	0.00	0	19.50	4
10	6.80	5	22.70	3	27.70	3	0.00	0	15.00	5
11	83.90	1	42.20	1	38.00	2	0.00	0	20.70	4
12	12.70	5	21.70	4	36.80	2	0.00	0	29.50	3
13	24.40	4	33.30	2	4.60	5	0.00	0	46.20	1
14	4.40	5	8.70	5	26.80	3	2.20	5	14.60	5
15	13.00	5	37.00	1	31.40	2	10.90	2	18.40	4
16	10.60	5	31.90	2	34.50	2	2.20	5	16.40	5
17	9.30	5	11.60	5	34.60	2	0.00	0	33.00	2
18	14.00	5	18.60	4	28.60	3	0.00	0	25.70	3
19	6.70	5	15.60	5	26.30	3	0.00	0	17.30	4
20	11.60	5	34.60	2	34.00	2	0.00	0	26.10	3
21	6.70	5	32.60	2	25.50	3	15.60	2	27.30	3
22	18.20	5	38.60	1	39.10	2	0.00	0	32.30	2
23	8.00	5	31.10	2	30.10	3	0.00	0	22.50	4

RESULT

Geology of the area

The study area lies (Tokuoka et al., 1990) in the middle member of the Arung Khola Formation, upper member of the Arung Khola Formation and middle member of the Binai Khola Formation (Fig. 2). The rippled and sheet-like sandstone beds interbedded with mudstone represent crevasse splay deposits (Ulak and Nakayama, 2001). The upper member of the Arung Khola Formation consists of grey, calcareous, "salt and pepper" appearance of sandstone interbedded with variegated mudstone where proportion of sandstone is greater than mudstone.

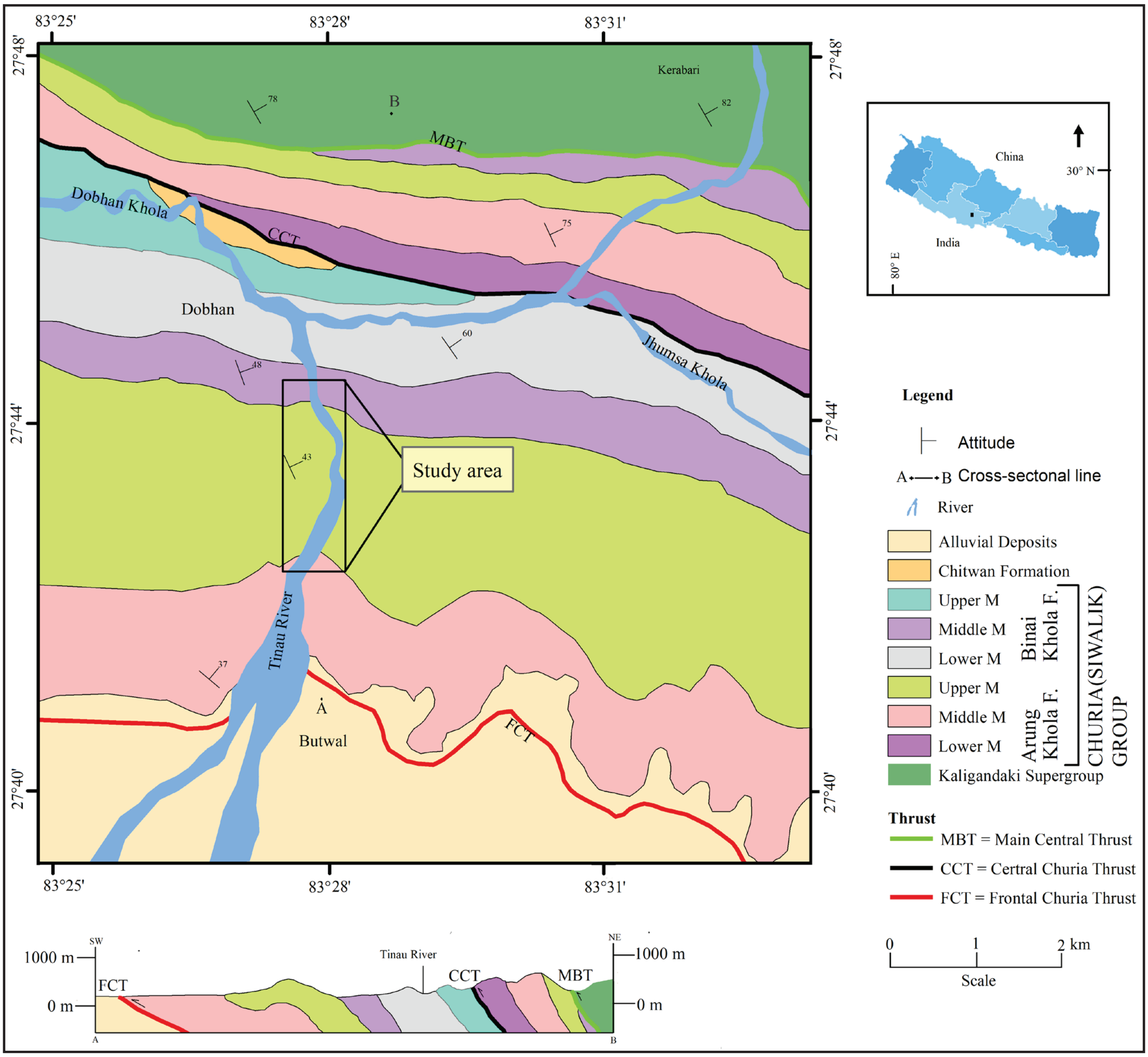


Fig. 2: Geological map of the Tinau Khola, west central Nepal (modified after Tokuoka et. al., 1990).

Thickness of sandstone is 1 to 10 m and mudstone is1 to 3 m. Cross-stratification and lateral and down accretion architectures were observed in sandstone. The middle member of the Binai Khola Formation consists of coarse-grained, "salt and pepper" appearance sandstone having thickness 1 to 12 m interbedded with dark grey mudstone. In the upper part of this member, pebbly sandstone is also observed.

The zonation map shows twenty-three zones, based on 100 m length along the Siddhartha Highway (Fig. 3). The combined hazard map is prepared by combining of planar sliding, planar sliding no limit, wedge sliding, flexural toppling, direct toppling, RQD, RMR, GSI and SMR values. The combined hazard map (Fig. 4) shows that zone 5, 8 and 19 belongs to very low hazard zone and zones 1, 2, 3, 7, 9, 10, 14, 18 and 23 belongs to low hazard zone. The zones 4, 17 and 20 represent moderate hazard zone. Zones such as 6, 12, 13, 16 and 21 are belongs to high hazard zone. Remaining zones 11 and 15 belongs to very high hazard zone.

The qualitative rock-fall hazard map (Fig. 5) represents very low hazard zone lies in some portions of the zone 3 (Ch. 0 + 200 to 0+300), 4 (Ch.0+300 to 0+400), 5 (Ch. 0 + 400 to 0+500) and 19 (Ch.1+800 to 1+900) and the low hazard belongs to major parts of the zones 9 (Ch.0+800 to 0+900) and 10 (Ch. 0+900 to 1+000) and some parts of zones 12(Ch.1+100 to 1+200), 14 (Ch.1+300 to 1+400), 17 (Ch. 1+600 to 1+700) and 18 (Ch.1+700 to 1+800). The moderate level of hazard belongs to 1(Ch.0+000 to 0+100), 2 (Ch.0+100 to 0+200) and some parts of zones 3 (Ch.0+200 to 0+300), 4 (Ch.0+300 to 0+400), 7 (Ch.0+600 to 0+700), 8 (Ch.0+700 to 0+800), 15 (Ch.1+400 to 1+500), 16 (Ch.1+500 to 1+600), 17 (1+600 to 1+700) and 19 (Ch.1+800 to 1+900). High level of hazard belongs to some parts of zone 6 (Ch. 0 + 500 to 0+600), major parts of 11 to 13 (Ch.1+000 to 1+300) and all parts of zones 14 to 16 (Ch.1+300 to 1+600). The very high level of hazard zones belongs to some parts of zones 5 (Ch.0+400 to 0+500), 6 (Ch.0+500 to 0+600), 11 (Ch. 1+000 to 1+100), 15 (Ch. 1+400 to 1+500) and 16 (Ch. 1+500 to Ch.1+600).

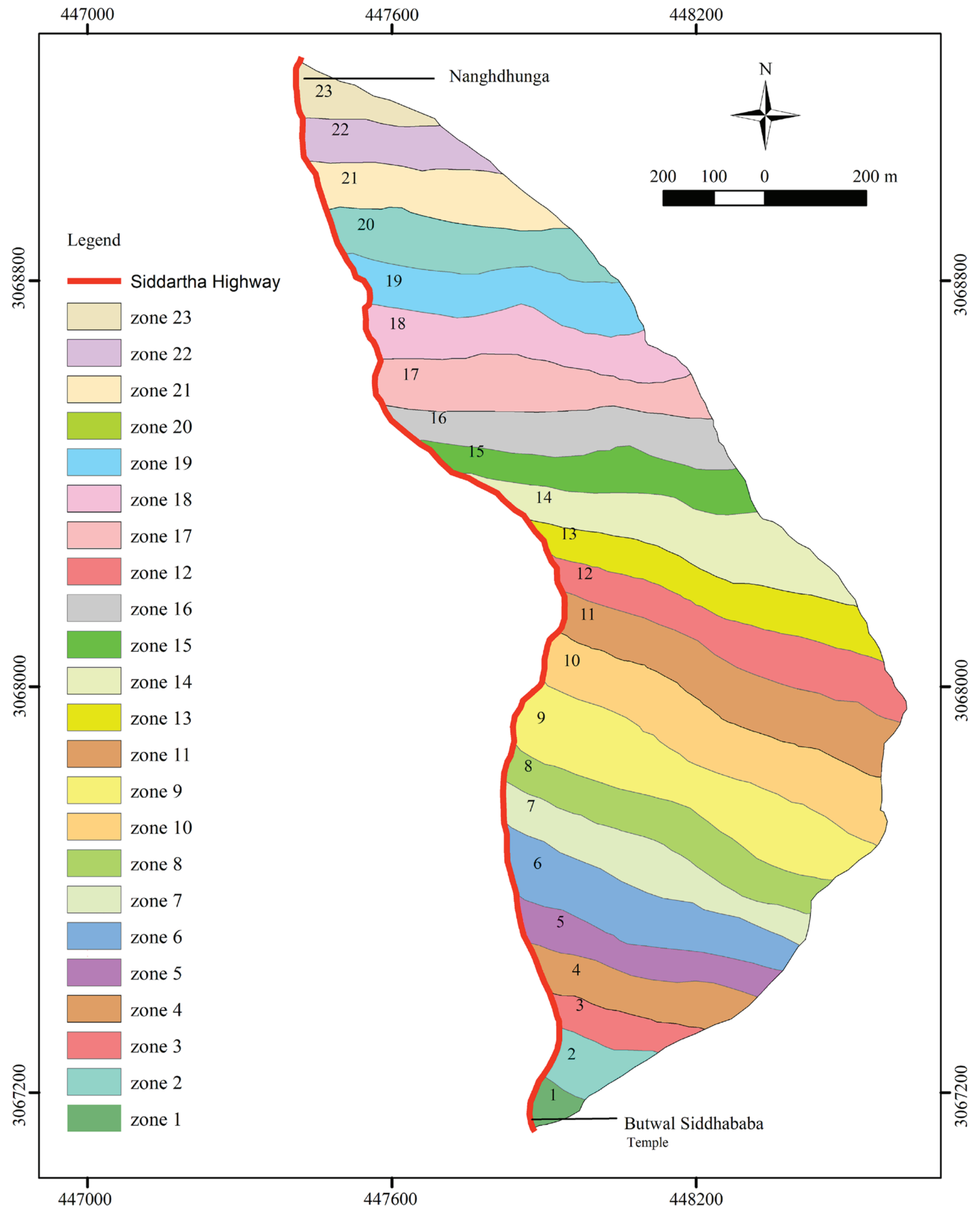


Fig. 3: Zonation map of the study area along the Siddartha Highway.

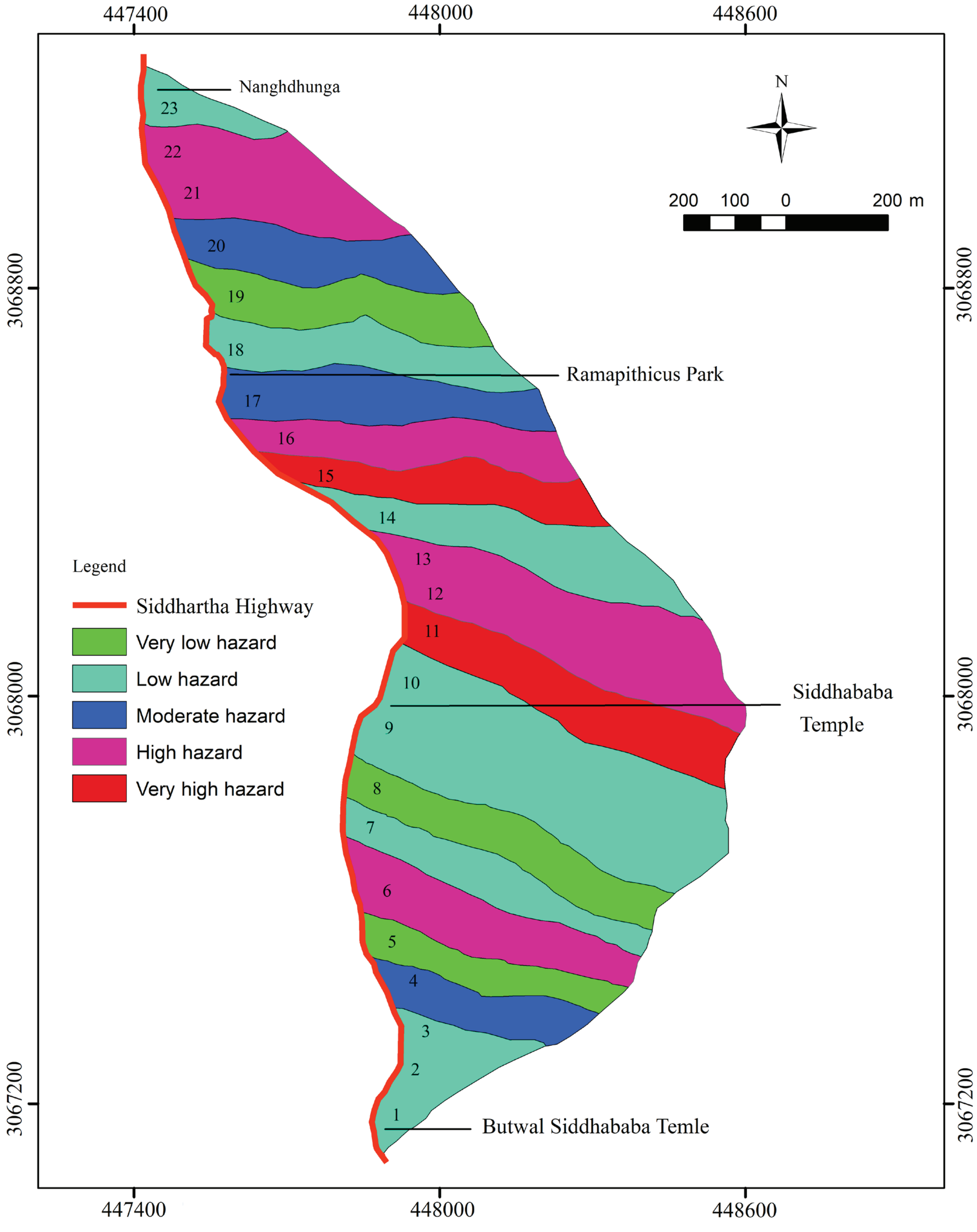


Fig. 4: Combined hazard map of study area.

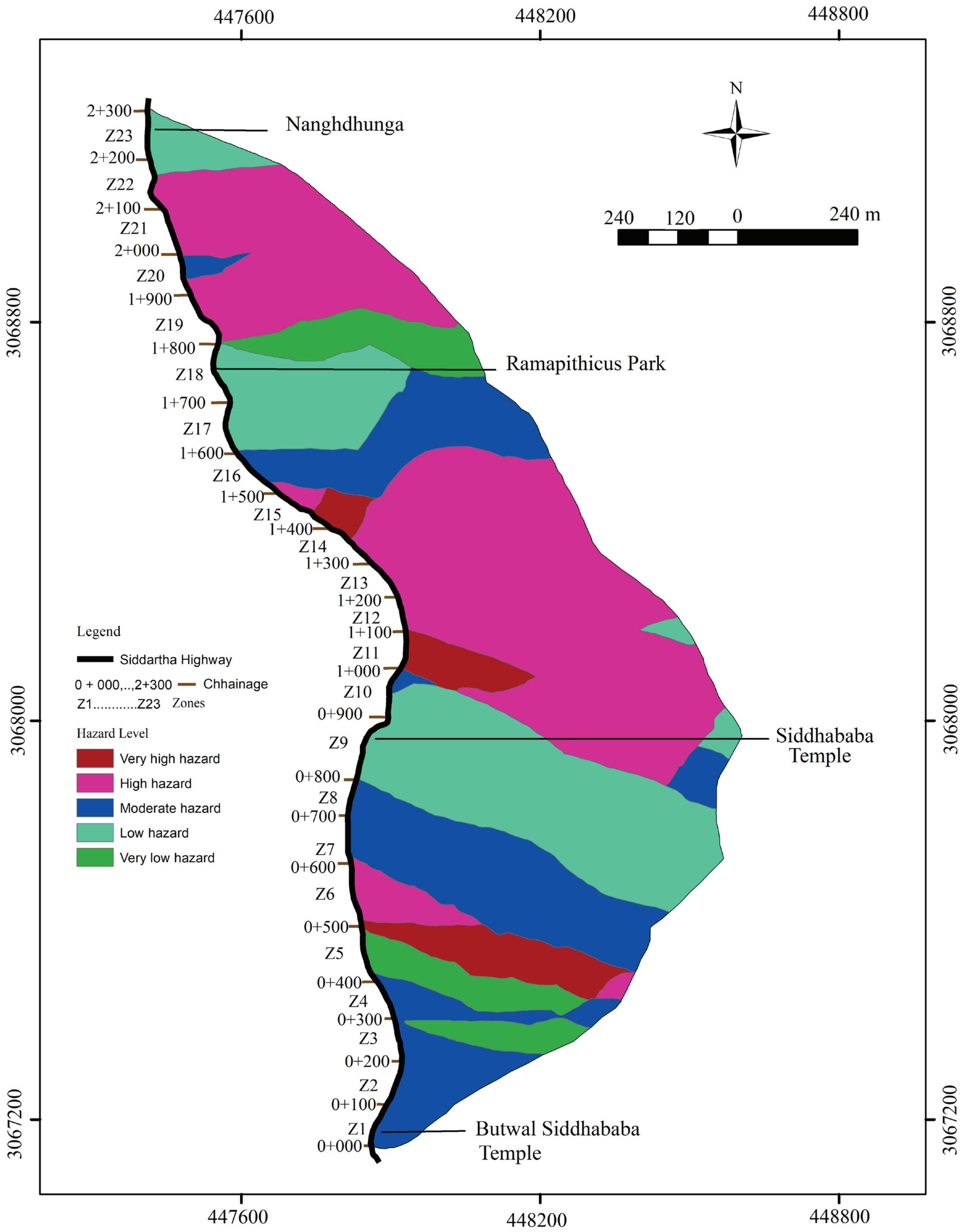


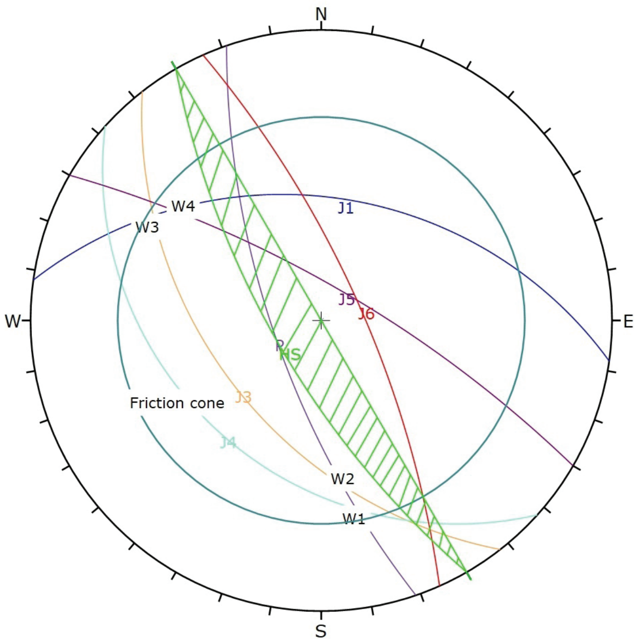
Fig. 5: Qualitative rock-fall hazard map of study area.

There are major three persistence joint sets and three minor joint sets (Fig. 6). The orientation of persistence joint sets J3, J4 and J2 with road cut alignment NS, and presence of groundwater is responsible for rock-fall.

On slope, mainly seepage and groundwater are moving from NE to SW direction as the alternate band of mudstone and sandstone are aligned on that direction (Table 3).

Validation

The validation of result is based on relationship between hazard level and historical events on study area. The data and information is given in Table 4.



	Color	Dip	Dip direction	Lebel
User Planes				
1		71	251	P
2		44	08	J1
3		49	232	J2
4		35	222	J4
5		76	30	J5
6		74	66	J6
7		71	240	HS

Pole mode	Pole vectors
Vector count	0
Hemisphere	Lower
Projection	Equal angle

Fig. 6: Kinematic analysis of regional joint sets.

Table 3: Relation between joint sets orientation and seepage of water.

Types of rock-slope failure		Potential discontinuities and their orientation	Discussion	Seepage	Potential for failure
Plane failure		J3: 49/232 and J4: 35/222	Dip direction of J3 and J4 are nearly parallel to dip direction of natural slope, their dip amount is less than dip amount of natural slope and their dip is greater than friction angle of rock	J3 and J4 are seepage plane	High
Toppling failure		J6: 76/66	J6 dips opposite to natural slope and its dip amount is nearly 75	Low	Moderate
	Central	W3: 301/35 W4: 306/33	Wedges are formed within 0°-32° of the hill slope direction, wedge plunge is greater than friction angle of rock, and less than natural slope	J1, J3 and J4 are seepage planes	High
Wedge Failure	Lateral	W1:179/36 W2: 185/40	Wedges are formed within 32°-65° of the hill slope direction, wedge plunge is greater than friction angle of rock, and less than natural slope	J1: persistent joint sets and J3 and J4 are highly seepage plane	Moderate
	Very lateral	No	No wedges are formed within 65°-90° of the hill slope direction	Low to moderate seepage plane	None

Table 4: Relationship between hazard level and historical events on study area.

Level of hazards	Date	No. of accidents	Dead	Injured	Zones	Effects
Very low hazard	2015	1	1	1	Zone 5	Bike accident
Low hazard	2012	1	0	12	Zone 23	Bus accident
Moderate hazard	2015	1	0	1	Between 2 and 3	Bike accident
	2017	1	0	3	Zone 20	A bike and truck impacted by rock-fall.
	2015	1	1	3	Zone 12	Truck struck by rock-fall.
	2017- Sept 23	1	3	8	Zones between 15 and 16	Totally damage a car and a truck
High hazard	2012	1	0	12	Between 22 and 23	Bus accident due to rock-fall and debris.
Very high hazard	2016 June 17	1	2	2	Zone 11	A car struck by rock-fall and death of Doctors

DISCUSSION

According to Tokuoka et al. (1990), the Siwalik Group has been divided into four lithological units such as the Arung Khola Formation and Binai Khola Formation, Chitwan Formation and Deorali Formation in ascending order. The study area lies in the Arung Khola Formation and Binai Khola Formation. These formations are subdivided into lower, middle and upper members. The present study area is represented by the middle member of the Arung Khola Formation, upper member of the Arung Khola Formation and middle member of the Binai Khola Formation.

The various factors contribute to trigger rock-fall are orientation of rocks, heterogeneity of rocks, slope aspect, road alignment, toe cut, elevation, drainage, seepage of ground water and rainfall etc. The stability of the rock slope along the Siddhartha Highway in the Chidiya Khola to Dobhan section is assessed using rock classification system and kinematic analysis. Twenty-three zones have been considered where in situ rocks are exposed along the Siddhartha Highway. Some of the field photos are as shown in Figure 7.

Fig. 7: Field photographs (a) A truck hit by rock-fall at zone 15, (b) Bending of beam due to rock-fall at zone 17, (c) Data collection during the field d) Measurement of length of different zones.

The combined hazard map and qualitative hazard map show zones 4, 8 and 19 belongs to high level of hazard, where zone 4 is the area around lower Ramapithecus Botanical Park, zone 8 is the area around upper Siddhababa Temple and zone 19 is the area above the dam site of Tinau Hydropower project. The zones such as 11 and 15 belong to very high hazard. The historical data (Table 4) also shows that around zone 11, a car had hit by rock-fall and two doctors were died on the spot and others two injured in 2016.

Among 82.36 square kilometer area, 39.53% land belongs to high level of hazard and 5.76% to very high level of hazard (Fig. 8, Table 5). This shows that the Siddhababa-Kuhirebhir is highly dangerous area in the geological and geotechnical point of view.

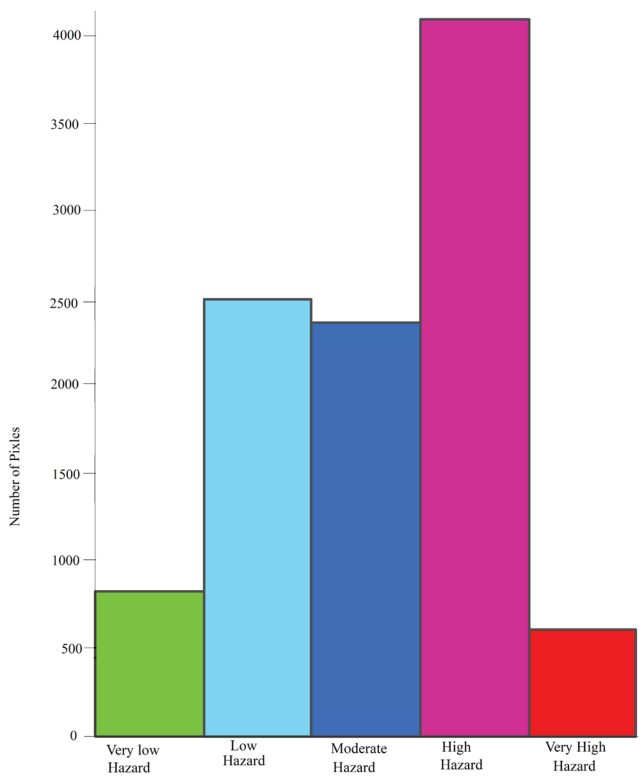


Fig. 8: Histogram showing number of pixel and level of hazard in hazard map.

Table 5: Showing hazard level, area covered in study.

Hazard level	Npix	Covered (%)	Area covered (m^2)
Very low hazard	814	7.86	81400
Low hazard	2498	24.12	249800
Moderate hazard	2354	22.73	235400
High hazard	4093	39.53	409300
Very high hazard	596	5.76	59600

CONCLUSIONS

Since rock-fall and debris flow in Siwalik pose a serious threat to the life and property, the susceptibility mapping can be one of the preliminary steps toward minimizing the damages induced by them. In this research, the kinematic analysis and rock mass classification basis were used for identifying the areas susceptible to rock-fall around Siddhababa along Siddhartha Highway.

To achieve the objectives of research, nine conditioning factors such as RQD, RMR, SMR, GSI, PS, PSN, WS, FT and DT for twenty-three zones were measured. Their individual sub-conditions were studied in field and combining all values individually and classified into five categories based on 20% distribution values. Based on hazard map, the area between Chidiya Khola and Dobhan is found to be critical site for rock-fall along the road section. In chainage 0+500 to chainage 0+600, 2 deaths (2015) were recorded due to rock-fall which belongs to high hazard level in hazard map. From hazard map, the second critical hazard area lies between chainage 1+100 to 1+300, where nearly three or more than three accidents have been recorded in every year. Similarly, the third critical area lies between chainage 1+400 to 1+600, where four people were died and four injured in 2018. Fourth critical area lies in chainage 1+900 to 2+200, where debris flow occurred in 2020. The least critical zones are 1, 2, 7, and upper part of zone 16. The low to medium susceptible zones are relatively safe for the development of engineering structures and the high and very high susceptible zones require further engineering geological and geotechnical investigation for each domains. Thus, prepared qualitative rock-fall hazard map can be suitable for rock-fall mitigation plan.

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