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Landslide hazard assessment using analytic hierarchy process (AHP): A case study of National Highway 5 in India

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ABSTRACT

Slope failure along highways is a crucial problem in hilly regions. Landslide hazard maps are very efficient and effective tools for planning and management of landslide disasters. Aim of this study is to prepare a landslide hazard map along national highway 5 (197.600–283.200 Km) using analytic hierarchy process (AHP) model. The different causative factors of landslides considered in this study are slope, aspect, curvature, relative relief, fault density, drainage density, geology, topographic wetness index (TWI), distance from road and lithology. The causative factors are divided into sub-factors and weightage are assigned according to analytic hierarchy process (AHP). The causative factor layers are overlaid using weighted linear combination (WLC) technique and a landslide hazard map is prepared. A landslide inventory of 215 landslides is used for validation of the landslide hazard map. The map shows a prediction rate of 0.825 on area under curve (AUC) technique. The study can be used by the construction planners and decision makers.

1. Introduction

Road network plays an important role in socio-economic development of a nation. The roads in hilly regions are generally subjected to heavy landslides and slope failure events. Landslides are the most destructive phenomenon that occur in hilly regions frequently. The failure of slopes along highways results into heavy traffic jamming and causes inconvenience to the passengers. Landslides are responsible for economic losses and sometimes cause the loss of lives too.

The construction of roads in the hilly region accelerates the failure of slopes due to cutting works [47,1]. The anthropogenic activities during highway construction disturbs the natural slopes and make them more vulnerable to the failures. So, the landslide hazard assessment along highways is essential for proper planning and management of road infrastructure [47].

Landslide hazard maps are important tools in planning and mitigation of landslide disaster. A landslide hazard map shows the possibility of occurrence of landslide in a particular region. Landslide hazard assessment studies require good understanding of the causative factors of landslides [5,47]. The researchers have considered slope, aspect, curvature, lithology, geology and drainage characteristics of the region as causative factors of landslides [8,7]. The triggering factors like earthquake, rainfall, erosion etc. accelerates the frequency and speed of the landslide disaster [4,51]. Geographic information system (GIS) helps in managing the spatial and temporal data effectively. The main advantage of GIS is that it gives utility of changing the input so that output can be varied. Landslide hazard zonation and landslide susceptibility mapping in GIS environment are performed by the various researchers [15,9,12,47].

1.1. Literature review

There are three approaches used in landslide hazard mapping in GIS environment i.e. qualitative approach, quantitative approach and semi-quantitative approach [48]. Qualitative approach gives a descriptive solution to landslide susceptibility mapping while quantitative approaches consider the mathematical estimates

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[31,42]. The expert based methods for landslide hazard assessment falls in qualitative approach category [3]. The opinion of expert is considered to assign the relative weightage to the different causative factors of landslides. The factors which are responsible for occurrence of landslides are selected and their impact on landslide occurrence is evaluated based on the expertise of expert. The result in the expert based method depends upon the subjective judgment of the expert which may not be right always.

The quantitative approach involves in establishing a mathematical relationship between occurrence of landslide and causative factors [2]. The impact of causative factors and sub-factors is simulated using mathematical models like frequency ratio [36,33,41], logistic regression [36,33,34], bivariate [45,20,37] and multivariate statistical models [36,43,2,47]. While the accuracy of the quantitative methods is higher as compared to the qualitative techniques but it depends upon the availability of an accurate landslide inventory. The semi-quantitative or semi-qualitative approaches are the hybrid of both the approaches. The methods like analytic hierarchy process (AHP), analytic network process (ANP), fuzzy-AHP etc. are the semi-qualitative or semi-quantitative approaches [17,6].

Analytic hierarchy process (AHP) helps in breaking a complex problem in the different simple criteria and the criteria are given weightage according to their relative importance [49,50,38,40]. A complex problem is the one which depends upon multiple causative factors. In our study, landslide is the complex natural problem which depends upon the multiple causative factors like slope, aspect, curvature, drainage characteristics, geological and lithological characteristics of the study area.

AHP has been used for landslide hazard mapping by many researchers [18,14,27,21,16]. AHP helps in finding a consistent solution for the problems [49,50]. Table 1 shows the findings of the literature review and Table 2 shows the source of input data used in this study.

In this study, landslide hazard assessment is performed using analytic hierarchy process (AHP) due to the following reasons:

a. The historical landslide data/landslide inventory is available in point form for the study area.
b. Due to the pandemic, the movement is restricted throughout the study area. So, it is not possible to arrange frequent field visits for preparation of landslide inventory.
c. Analytic hierarchy process (AHP) helps in checking the consistency of weightage given by experts. So, this technique helps in avoiding the inconsistent solutions.
d. The output can be improved by varying the input weightage in analytic hierarchy process (AHP) which helps in improving the accuracy of the output.

The study area selected for this study is National Highway 5 (NH-5) from Kalka, Haryana to Shimla, Himachal Pradesh (H.P.), India. NH-5 is an important highway corridor from the point of view of transfer of goods and passengers. The highway faces frequent landslide events which are triggered in rainy season. The route is damaged due to heavy landslides at different locations.

2. Study area

National Highway 5 is 660.2 KM long and passes through plain and hilly terrains. The highway is very important from strategic and social point of view. It connects the remote areas of the hilly regions. It establishes the connection between India and Tibet which makes it important for international trade too. The stretch selected for the study lies from 197 Km to 283 Km along National Highway 5. The selected stretch of highway connects Haryana province to the capital of Himachal Pradesh (H.P.) province and facilitates the transportation of goods and crops from the plain area to the hilly terrain of high elevation. The highway has been functioning since the British period. The up-gradation to four lanes of Kalka to Shimla stretch is under progress. The highway stretch consists of few tunnels which reduces the distance through hilly terrain.

A buffer of 1 KM at both sides of the road is taken. The study area lies between 30°50′17.88″N, 76°56′8.52″E to 31°06′17.28″N, 77°10′24.24″E. The altitude of the study area varies from 591 m to 2459 m above mean sea level. The temperature of the study area varies from 6.2 °C to 36.7 °C (District survey document, Shimla). Annual rainfall of the Solan district is 1413 mm and average annual rainfall of Shimla district is 1575 mm. Fig. 1 shows the details of the study area.

2.1. Geological setting

The study area lies in the districts of Solan and Shimla in Himachal Pradesh (H.P.). Solan. Dolomitic granite stones covers the region with its rugged topography. The Tethys Tectogen are found in Shimla region which are characterized by the diversity in the stratigraphy. The study area is covered with Miocene, Eocene and Neoproterozoic aged deposits. The region has sandstones, shale,

Table 1
Summary of the previous literature.

Method	Summary	Findings from the literature review
Qualitative techniques	The weightage to the causative factors and sub-factors are given by experts based on their judgment [29,48,44]. The evaluator selects the causative factors and their relative importance [48]. These techniques are the simplest to implement as no historical landslide data is required.	The accuracy of the susceptibility and hazard map depends upon the subjective judgment of the expert [26,48]. The hazard maps can vary from expert to expert [48]. Generally, accuracy of the expert based methods is lesser as compared to quantitative techniques [30].
Quantitative techniques	The quantitative techniques establish a mathematical relationship between occurrence of landslides and the causative factors [2]. Frequency ratio, info value, weight of evidence and logistic regression are the examples of quantitative methods [42]. These methods depend on the spatial distribution of landslides and their relationship with causative factors [48,29].	These methods can be applied to the large areas [48]. These techniques give more accurate results as compared to the qualitative techniques [29]. The weightage can be derived statistically from the distribution of landslides. A well distributed landslide inventory is required for calculation of weightage of causative factors [42,48]. The preparation of landslide inventory requires large efforts. The methods are not suitable for inaccessible regions.
Semi-quantitative techniques	The semi-quantitative techniques are a hybrid of qualitative and quantitative techniques. The human perception is considered in these studies and validated mathematically [30]. Analytic hierarchy process, fuzzy logic etc. are the examples of this technique.	The human perception is included in these methods. The consistency of the causative factors can be checked and validated using mathematical relationship [48]. While there is no need of landslide inventory but the use of landslide inventory can improve the consistency and accuracy of the results [30].

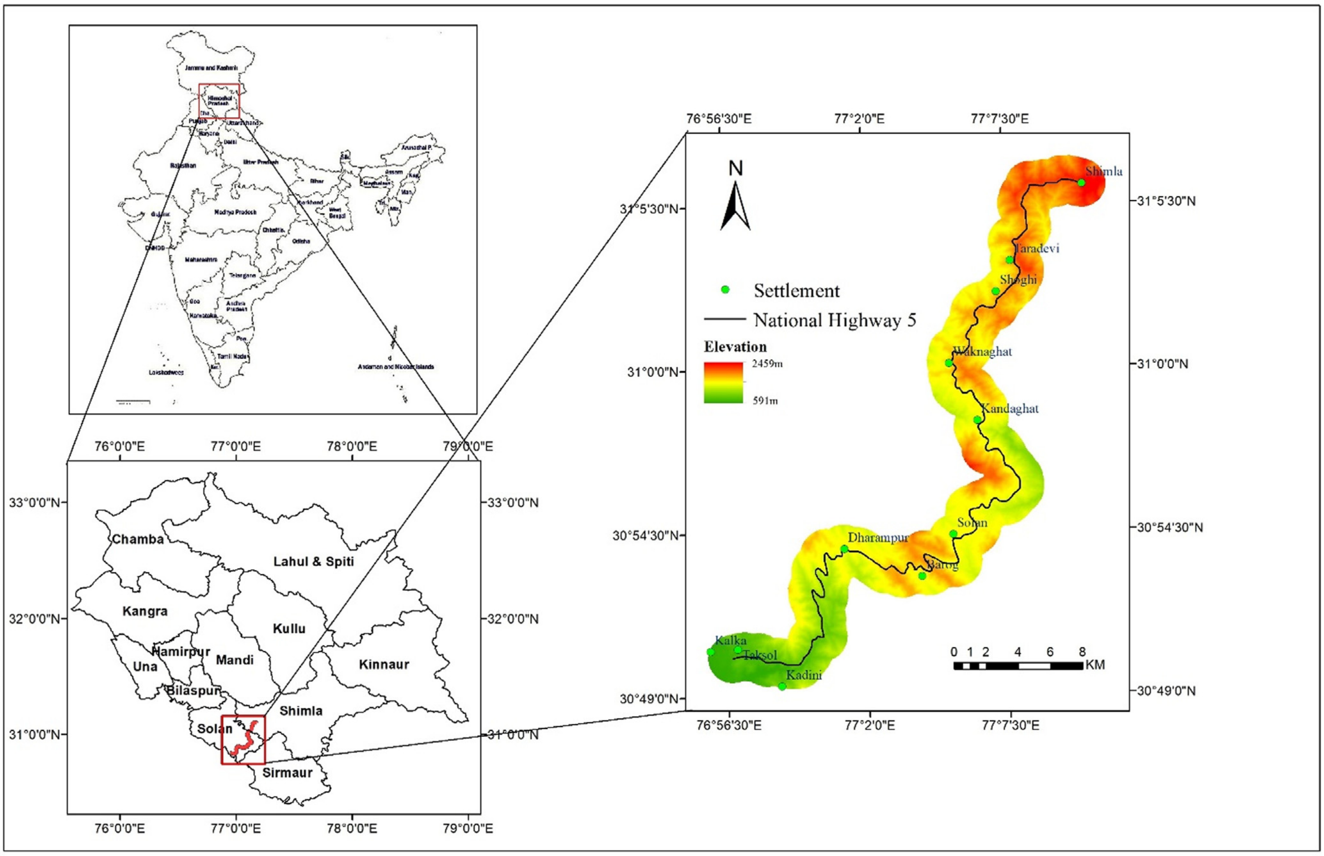

Fig. 1. Study area.

Table 2
Data Used in the Study.

Extracted Data	Scale	Source
Landslide Points		Literature, Field Survey, GSI Practical Sheet, Google Earth
Aspect		Digital Elevation Model (DEM)
Curvature		Digital Elevation Model (DEM)
Relative Relief		Digital Elevation Model (DEM)
Fault Density	1:50,000	Ground Water Prospects Map
Geology	1:500,000	Geology Map of Himachal Pradesh
Lithology	1:50,000	Ground Water Prospects Map
Drainage Density	1:50,000	Survey of India Toposheet
Road	1:250,000	U.S. Army Corps of Engineers

limestone, dolomite, quartzite, phyllite and siltstone. The major deposits of limestone are present in Shimla region. The lithology of the study area belongs to Jutogh group, Rampur group, Shali group and Shimla group [22].

2.2. Landslide inventory

Landslide inventory shows the distribution of the landslide data [13,19]. The landslide inventory in this study is prepared using historical data, google earth and field survey. The landslide information is obtained from the literature, Survey of India sheets and inventories prepared by National Remote Sensing Centre (NRSC). The landslide inventory consists of the information about location of landslide, triggering factor, activity of landslide, type, classification and geology of the failed mass. Landslides are also detected from the google earth from LISS imagery. Landslides are presented in the form of points. A total number of 214 landslides are considered in the study. Fig. 2 shows the images of few landslides occurred in the area. Fig. 2 shows the images of few landslides occurred in the study area.

3. Materials and methods

The data required for this study is obtained from the satellite imagery, Survey of India (SOI) toposheets, field surveys and GSI practical sheets. The digital elevation model (DEM) is obtained from Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER). The digital elevation model has a grid size of 30*30 m. The data related to slope, aspect, curvature and relief is extracted from ASTER DEM. The geology and lithology data is digitized from SOI toposheets. A detailed flow chart is shown in the Fig. 3.

3.1. Causative factors of landslides

Occurrence of the landslides depends upon the various factors. The factors considered in this study are divided into three categories i.e. DEM based factors, drainage and lineament characteristics and geological characteristics of the region. Fig. 4 shows the details of causative factors.

3.1.1. Slope gradient

Slope gradient is one of the most important factors which affect the occurrence of the landslides. It directly impacts the stability of slopes as it influences the shear force [23]. Steeper the slope more will be the probability of occurrence of the landslides [11]. The slope gradient in the region varies from gentle to very steep. In

Fig. 2. Landslide occurred in the study area [Landslide 1: Long: 77°9′6.893″E, Lat: 31°2′55.57″N, Landslide 2: Long:77°6′44.045″E, Lat:30°58′45.342″N, Landslide 3: Long: 77°4′42.711″E, Lat: 30°53′23.058″N, Landslide 4: Long: 76°56′58.685″E, Lat: 30°51′1.586″N].

57% cases the slope is more than 60°. The instability in the mass is induced due to the steep angle of the slope. Slope gradient also controls the flow of water [35]. The slope has been divided into five categories.

3.1.2. Slope aspect

Aspect represents the direction of the slope. Aspect affects the exposure of sun, erosion characteristics and flow of water [47]. Aspect map is divided into 10 categories.

3.1.3. Curvature

Curvature is defined as slope of slope. It is the second derivative of the surface. The positive value of curvature indicates the convexity of the surface while the negative value shows the concavity of the surface. 0 value of curvature indicates the flat surface. In landslide hazard zonation, curvature indirectly represents the effect of water [28].

3.1.4. Relative relief

Relative relief of the study area shows the variation of the elevation. It affects the natural conditions which affect the occurrence of the landslides [47]. The relative relief varies from 0 m to 254 m.

3.1.5. Geology

The study area has diverse geological characteristics. The region is covered with lower Shivalik formations, Subathu formation, Jaunsar group, Jutogh group, Dharmashala group and Balani formations. Mix of Muree group, Dharmashala group, Dagshai and Kasauli formations are more prone towards landslide incidents while Jaunsar group is relatively less affected by landslides in this study area.

3.1.6. Lithology

Lithology identifies the type of rock in the study area. The erosion and stability of the rocks depend upon the lithology of the area. The rocks are of mixed type in the study area. The study area consists of shale, sandstone, siltstone, phyllite and dolomite in mixed form.

3.1.7. Fault density

Natural faults occur in the study area. The effect of faults is considered in the form of fault density. The faults increase the landslide activities [32].

3.1.8. Drainage density

Drainage characteristics of the region affect the landslide possibility. Drainage density is obtained by digitizing the streams.

3.1.9. Distance from the road

Distance from the road is also an important parameter for occurrence of landslides. During the construction of roads, the cutting activities disturb the natural slopes [46]. The slope near the toe become weak along the highways.

3.1.10. Topographic wetness index (TWI)

Topographic wetness index (TWI) represents the moisture in the soil. The TWI represents the tendency of water accumulation [24]. TWI is calculated using the following formula:

$$Topographic\ Wetness\ Index\ (TWI) = \ln\left(\frac{SCA}{tan\varphi}\right) \quad (1)$$

Here, SCA is specific catchment area and φ is the slope angle. SCA is defined as flow accumulation area per unit contour width. Assuming the properties of soil or rock mass uniform, SCA shows the tendency to receive the water while slope angle shows the tendency of draining of the water [24].

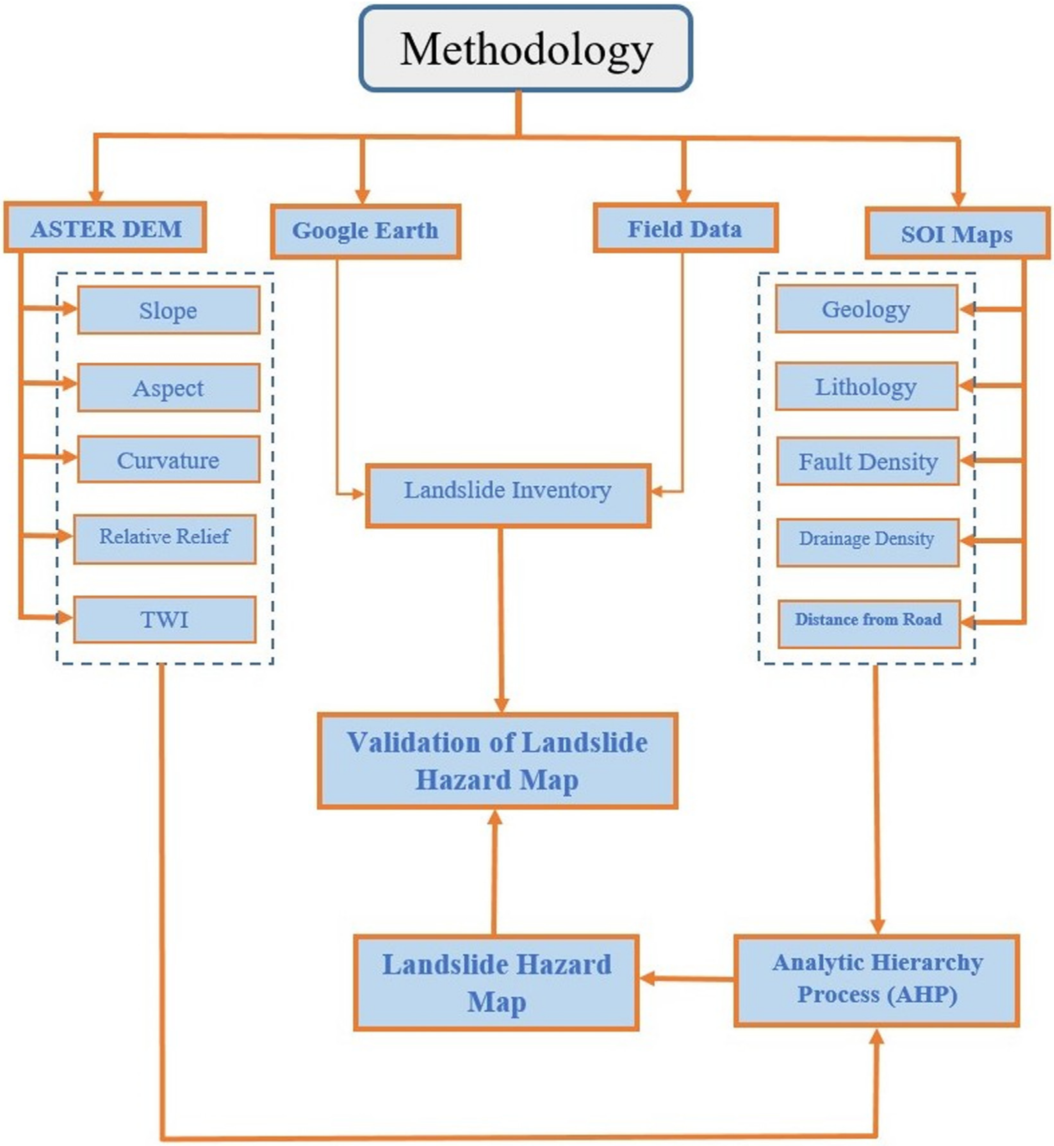

Fig. 3. Flow of the work.

3.2. Analytic hierarchy process (AHP)

Analytic hierarchy process (AHP) is a decision making tool which helps in breaking the complex problem in simple criteria. AHP is based upon three principles i.e. decomposition of problem, comparative judgment and synthesis of relative importance or rankings [49,50,39]. In AHP, the problem is broken in hierarchical criteria. These criteria are compared to each other. This process of relative comparison is called pair-wise comparison. Eigen vector method is used to calculate the rankings and after that consistency of the solution is also checked by using consistency ratio [49,50]. Table 3 shows the scale of pairwise comparison given by Saaty.

The consistency of the weights for relative importance assigned during the pairwise comparison can be checked using the equation given below.

$$ConsistencyRatio(CR) = \frac{CI}{RI} \quad (2)$$

Here, CI is consistency index while RI is randomness index.

CI is calculated as follows:

$$consistency\,index(CI) = \frac{\lambda \max - n}{n - 1} \quad (3)$$

Here, λmax = Major Eigen value and n = order of matrix

Randomness index values are given by Saaty which depends on the value of n. RI is the result of extensive experimentation on the large sample of dataset. Table 4 shows the randomness index (RI) for different values of n. If CR values are less than 10%, the pairwise comparison is considered as consistent. If the CR value is more than 10%, the solution is considered inconsistent and weights are reassigned in pairwise comparison matrix. The weightage of causative factors and sub-factors are shown in Table 5.

4. Results and discussion

Analytic hierarchy process (AHP) is implemented for landslide susceptibility mapping along highway corridors in GIS environment. A landslide inventory of 215 landslides is prepared from Google earth, previous literature and GSI practical sheet. 70% of the landslides from the inventory are randomly selected as training data while the rest 30% are used for testing. The relative comparison of the causative factors is done based on the landslide inventory. The weightage of the factors and sub-factors is calculated using AHP and the results are checked for consistency. The consistency ratio is kept below 10%. The consistency ratio is obtained

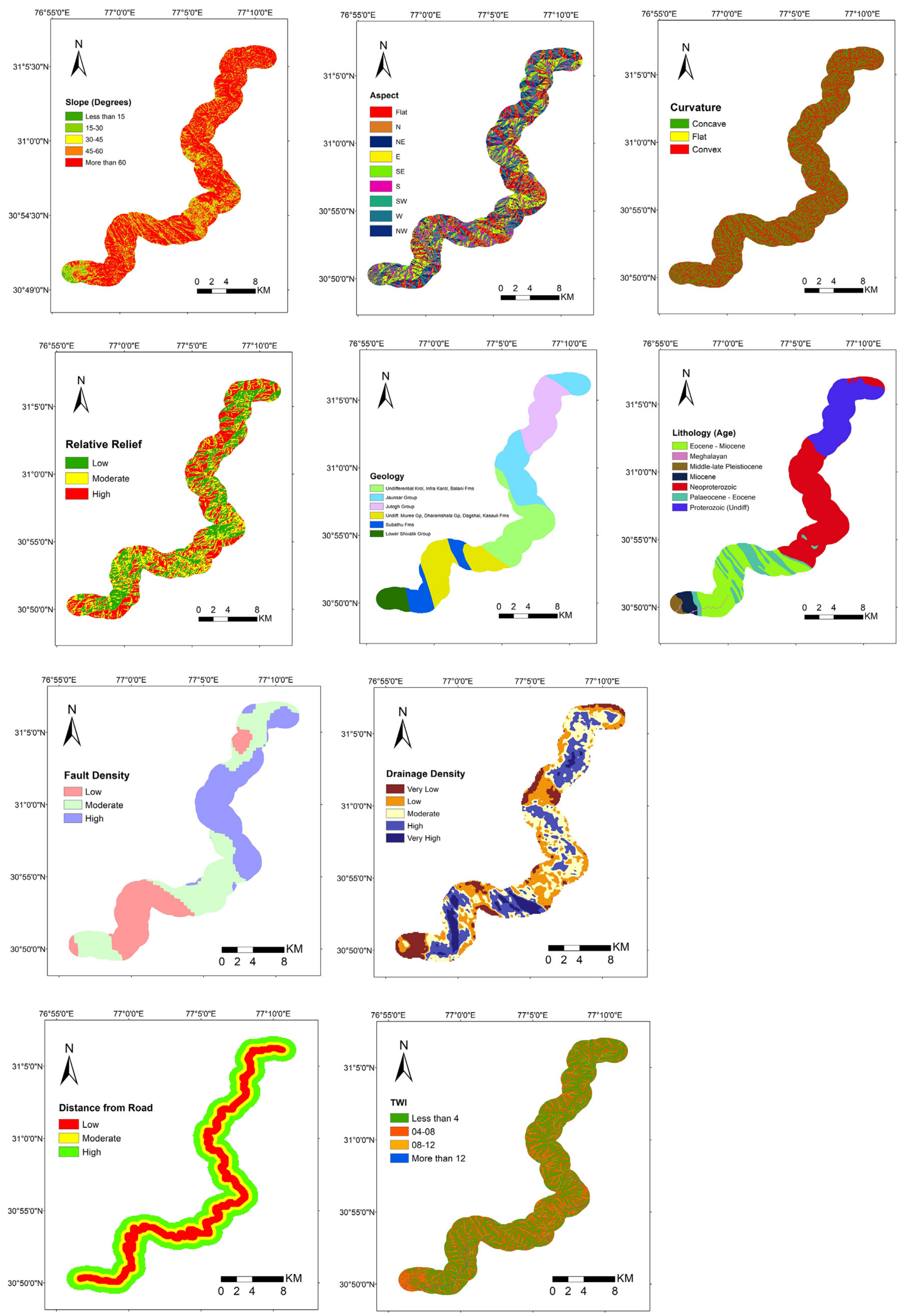

Fig. 4. Causative factors of landslides a) Slope b) Aspect c) Curvature d) Relative relief e) Geology f) Lithology g) Fault density h) Drainage density i) Distance from the road k) Topographic wetness index (TWI).

Table 3
Scale of Analytic Hierarchy Process (AHP) [49].

Degree of Preference [49]	Definition	Explanation
1	Equally Important	Both criteria are equally important or both the factors have same effect on occurrence of landslides
3	Moderately Important	One factor is more effective as compared to the other factor
5	Highly Important	One factor affects highly as compared to the other factor
7	Very Highly Important	A factor is highly dominated over other
9	Extremely Important	A factor has highest possibility of affecting the occurrence of landslide over other factor
2,4,6,8	Intermediate Values	If a compromise between two factors is required, intermediate values can be used

using the highest Eigen value and randomness index is obtained from the Table 4. Fig. 4 shows the causative factors of the landslides.

The weightage of individual factors is given in Table 5. Distance from the road had the highest impact on the occurrence of landslides and got the weightage 0.325 in AHP matrix while lithology is the second dominating causative factor with weightage of 0.208. Geology had weightage of 0.114 while aspect is the least important causative factor with AHP weightage of 0.019.

It is observed that the instability in slopes increases as the slope gradient increases. There are no landslides for the slope angles below 30°. Only 20% of the study area consists of slopes with slope angle less than 60°. The slopes which are more than 60° covers around 80% of the study area and 57% of the total landslides occur in regions with slope more than 60°. 15% of the study area is covered with the slopes with slope angle from 45° to 60°, and 28% of the total landslides occur in such regions. No landslide is observed in the area with slopes 0–15°.

Slope aspect represents the direction of slope with respect to magnetic north. It is observed that south-west, west and north-west aspects have more impact on the occurrence of the landslides due to more erosion. 22.85% of the total landslides occur in north-west aspect while south west and west direction face 14.28% and 17.15% of the total landslide event respectively.

Concave curvature has more probability of occurrence of landslides due to impact of water. Flat curvature has no event of landslides. Concave surface faces 54.54% landslide while convex surface faced 45.46% land-sliding events.

Relative relief shows the impact of changes in the vegetation with respect to the elevation. Lower relative relief values in the study area faced more landslide events as compared to the higher relative relief values. The regions with 0–76 m relative relief faced 42.42% of the total landslides while it covers only 30.62% of the total area. The region with highest relative relief i.e. 172–254 m faced only 27.27% landslides while it covers 36.30% of the total area.

Six group of geological formations are encountered in the study area. Undifferential muree group, Dharmashala group, Dagshai and Kasauli formations have highest evidences of landslides in the study area. This geological group covers 20.74% of the total area but 35.53% of the total landslides occurred in this geological formation. Balani formations, un-differential and Infra Krol are also highly susceptible to landslides as this type of formation covers 22.88% area but faced 29.21% of total landslides. Jaunsar group has least susceptibility towards landslides as it faces only 6% of total landslides in the study area.

The lithology of the region is mixed type. The lithological deposits are classified based on their age. Eocene-miocene deposits are highly prone towards landslide events. These deposits faced 42.85% of the total landslides while they cover 22.77% of the total area. Middle late Palaeocene and Meghalayan formation cover very less area and faced only one landslide event. Palaeocene-eocene deposits cover around 10% of the total area and faces around 15% of the total landslides which shows their high proneness towards landslides.

Fault density had a significant impact on the occurrence of landslides. The moderate fault density covers 39.12% of the area but responsible for the occurrence of 50% of the total landslides. The low fault density covers 27% of the total study area while 38.23% of total landslides occurred in these regions.

Drainage density had a linear impact on occurrence of landslides. As the drainage density increases, the proneness towards landslide occurrence increases. 6.83% of the total area is covered with very high drainage density while such type of the region faced 15.83% of the total landslides. There was 24.07% of the total area covered with high drainage density which faced 30.77% of the total landslides. 11.30% of the total area is covered with very low drainage density which faced only 3.84% of the total landslides.

The road considered in this study has been upgraded to four lanes recently. So, landslide events have been increased due to disturbance of natural slopes. Distance from the road is another important causative factor of landslides. The region which has low distance to road covers 30.55% of the total area but faced

Table 4
Randomness Index (R.I.) Table [49].

Number of Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.0	0.0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

Table 5
Weightage of Major Causative Factors.

Factors	Slope	Aspect	Curvature	Relative Relief	Geology	Lithology	Drainage Density	Fault Density	TWI	Road Distance	Weightage
Slope	1										0.058
Aspect	0.2	1									0.019
Curvature	0.5	3	1								0.038
Relative Relief	0.5	2	0.5	1							0.027
Geology	3	5	2	4	1						0.114
Lithology	5	7	5	6	3	1					0.208
Drainage Density	3	5	4	3	0.5	0.25	1				0.095
Fault Density	2	6	2	4	0.5	0.33	0.5	1			0.073
Topographic Wetness Index (TWI)	0.33	2	2	2	0.25	0.2	0.33	1	1		0.042
Distance from Road	5	7	6	7	4	3	7	4	7	1	0.325

Table 6
Pairwise comparison matrix

Causative Factors/Sub-factors	1	2	3	4	5	6	7	8	9	AHP Weightage
Slope Gradient										
0-<15	1									0.033
15-<30	3	1								0.063
30-<45	5	3	1							0.129
45-<60	7	5	3	1						0.262
More than 60	9	7	5	3	1					0.513
CR	0.053									
Aspect										
Flat	1									0.023
North	2	1								0.047
Northeast	7	4	1							0.204
East	4	2	0.33	1						0.082
South East	9	8	3	4	1					0.362
South	5	3	0.5	2	0.25	1				0.125
South West	4	2	0.25	1	0.2	0.5	1			0.078
West	3	0.5	0.25	0.5	0.14	0.33	0.5	1		0.046
North West	2	1	0.14	0.33	0.12	0.25	0.33	0.5	1	0.033
CR	0.025									
Curvature										
Flat	1									0.072
Concave	7	1								0.649
Convex	5	0.33	1							0.279
CR	0.068									
Relative Relief										
0-<76	1									0.637
76-<172	0.33	1								0.258
172–254	0.2	0.33	1							0.105
CR	0.04									
Geology										
Undifferential Krol, Infra Krol, Blani Fms	1									0.043
Jaunsar Group	2	1								0.064
Jutogh Group	4	3	1							0.132
Undiff Muree Group, Dharamshal Group, Dagshai and Kasauli Fms	8	7	5	1						0.474
Subathu Fms	6	5	3	0.33	1					0.256
Lower Shivalik Group	0.5	0.33	0.2	0.11	0.14	1				0.031
CR	0.043									
Lithology										
Eocence-Miocene	1									0.135
Meghalayan	0.12	1								0.01
Middle late Pleistiocene	0.11	0.50	1							0.08
Miocene	0.17	4	4	1						0.028
Neoproterozoic	0.25	6	6	4	1					0.076
Palaeocene-Eocene	2	8	9	6	4	1				0.144
Proterozoic (Undiff)	0.25	4	5	5	0.33	0.25	1			0.066
CR	0.085									
Fault Density										
Low	1									0.072
Moderate	5	1								0.279
High	7	3	1							0.649
CR	0.068									
Drainage Density										
Low	1									0.105
Moderate	3	1								0.258
High	5	3	1							0.637
CR	0.04									
Distance from Road										
Low	1									0.804
Moderate	0.12	1								0.122
High	0.11	0.5	1							0.074
CR	0.039									
Topographic Wetness Index (TWI)										
Less than 4	1									0.671
4-<8	0.2	1								0.178
8-<12	0.14	0.5	1							0.096
More than 12	0.11	0.25	0.5	1						0.055
CR	0.022									

40% of the total landslides while the region which has high distance to road covered 45.23% of the total area but faced only 33.12% of the total landslide events.

Lower values of topographic wetness index (TWI) had more impact on occurrence of landslides while higher values had very less effect on occurrence of landslides. 52.6% of the total area is covered with TWI less than 4 while 38% of the total area is covered with TWI between 4 and 8. The region covered TWI value less than 4 faces 61.76% of total landslides while area covered with TWI (from 4 to 8) faced 35.29% of the total landslides. The area with TWI values more than 12 covers 0.5% of the total area and faced no landslide event. Table 6 shows the details of pairwise comparison matrix of the sub-factors, consistency ratio and weightage of sub-factors.

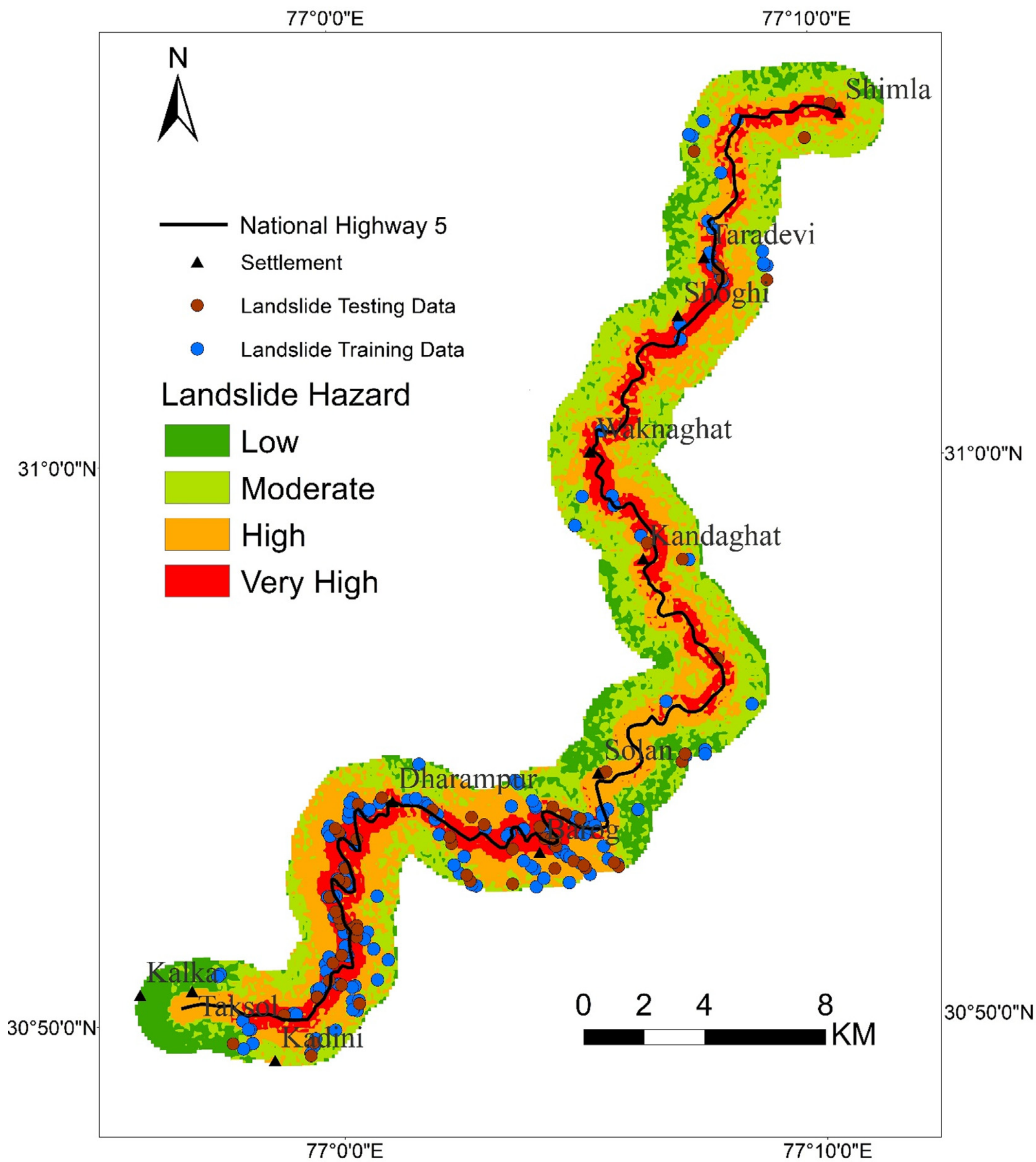

Fig. 5. Landslide Hazard Map.

The landslide hazard index (LHI) is calculated using the following equation:

$$\begin{aligned} Landslide\ Hazard\ Index\ (LHI) = {} & 0.058 \times Slope + 0.019 \\ & \times Aspect + 0.038 \\ & \times Curvature + 0.027 \\ & \times Relative\ Relief + 0.114 \\ & \times Geology + 0.208 \\ & \times Lithology + 0.095 \\ & \times Drainage\ Density + 0.073 \\ & \times Fault\ Density + 0.042 \\ & \times TWI + 0.325 \\ & \times Distance\ from\ Road \end{aligned} \quad (4)$$

Based on LHI, landslide hazard map for the study area is shown in Fig. 5. The landslide hazard index (LHI) varies from 0.00839 to 0.5211. The landslide hazard map is divided into four categories using natural breaks i.e. low (0.00839–0.1317), moderate (0.1317–0.1961), high (0.1961–0.3969) and very high (0.3969–0.5211). It is found that 21.56% of the total area lies under very high landslide hazard zone which faced 46.51% of the total landslides. 29.05% of the total region lies under high landslide hazard zone which faced 32.56% of the total landslide events. 39.85% of the total study area lies under moderate landslide hazard zone while it faced only 18.60% of total landslide events. 9.52% of the region lies under low landslide hazard zone and only 2.32% of the landslides occurred in this region.

The output of the study is validated with receiver operation characteristics (ROC) curve. The ROC curve is plotted between area of landslide hazard class and area of landslides. The prediction rate for training data is found to be 0.874 while the prediction rate for

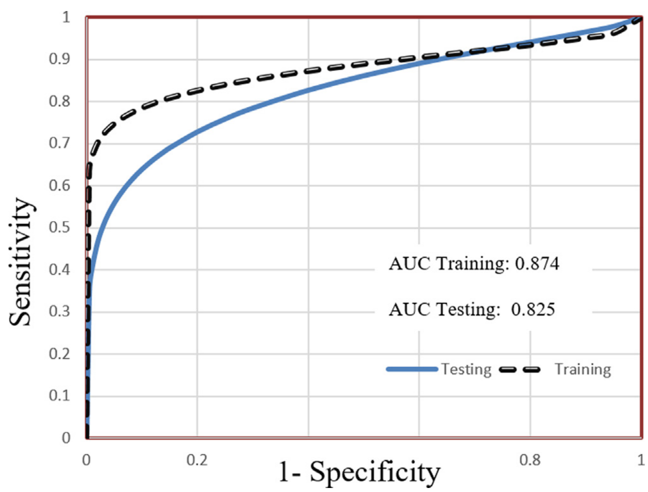

Fig. 6. ROC curve for validation.

testing data is found to be 0.825. Fig. 6 shows the prediction curve for the output.

5. Conclusion

The highway stretch considered in this study is subjected to the landslide disaster frequently. So, landslide hazard assessment is required for planning and execution of construction activities along the highway corridor. Analytic hierarchy process (AHP) has been implemented for preparation of landslide hazard map. There were 10 causative factors which are considered in this study. Distance from road, lithology and geology are the major contributing factors in landslide occurrence according to the weightage assigned using AHP. A landslide inventory containing details of 215 landslides was used to train and test the final output. The landslide inventory had also helped in deciding the pairwise comparison of the different causative factors and sub-factors. 70% of the landslides were used for training and 30% landslide data is used for testing purpose. The landslide hazard map was divided into four zones. It is found that around 79% of landslides lies in high and very high landslide hazard zones. The prediction rate observed for the landslide hazard map is found to be 0.825. The output of the study depends on the causative factors considered and their weightage. The prediction rate can be increased by varying the causative factors and their weightage. The output of the study can be used by the project planners, environmental engineers, construction managers and risk engineers. The landslide hazard map can be used for planning the construction and maintenance operations of the highway.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Ali S, Biermans P, Haider R, Reicherter K. Landslide susceptibility mapping by using a geographic information system (GIS) along the China-Pakistan Economic Corridor (Karakoram Highway), Pakistan. Nat Hazards Earth Syst Sci 2019;19:999–1022. doi: https://doi.org/10.5194/nhess-19-999-2019.

[2] Akgun A, Erkan O. Landslide susceptibility mapping by geographical information system-based multivariate statistical and deterministic models: in an artificial reservoir area at Northern Turkey. Arabian J Geosci 2016;9 (2):1–15. doi: https://doi.org/10.1007/s12517-015-2142-7.

[3] Aleotti P, Chowdhury R. Landslide hazard assessment: Summary review and new perspectives. Bull Eng Geol Environ 1999;58(1):21–44. doi: https://doi.org/10.1007/s100640050066.

[4] Altın TB, Gökkaya E. Landslide-Triggering Factors in Korucak Subbasin, North Anatolian, Turkey. Procedia Earth Planet Sci 2015;15:566–72. doi: https://doi.org/10.1016/j.proeps.2015.08.104.

[5] Bozzano F, Mazzanti P, Prestininzi A, Mugnozza GS. Research and development of advance technologies for landslide hazard analysis in Italy. Landslides 2010;7(3):381–5. doi: https://doi.org/10.1007/s10346-010-0208-x.

[6] Chaiyaphan C, Ransikarbum K, Sriariyanun M, Cheng YS, Rattanaporn K, Yasurin P, et al. Criteria Analysis of Food Safety using the Analytic Hierarchy Process (AHP) - A Case study of Thailand's Fresh Markets. E3S Web Conferences 2020;141:02001. doi: https://doi.org/10.1051/e3sconf/202014102001.

[7] Chen W, Xie X, Peng J, Wang J, Duan Z, Hong H. GIS-based landslide susceptibility modelling: a comparative assessment of kernel logistic regression, Naïve-Bayes tree, and alternating decision tree models, Geomatics, Natural Hazards Risk 2017;8(2):950-973 10.1080/19475705.2017.1289250

[8] Demir G, Aytekin M, Akgun A. Landslide susceptibility mapping by frequency ratio and logistic regression methods: an example from Niksar-Resadiye (Tokat, Turkey). Arabian J Geosci 2015;8(3):1801–12. doi: https://doi.org/10.1007/s12517-014-1332-z.

[9] Ding Q, Chen W, Hong H. Application of frequency ratio, weights of evidence and evidential belief function models in landslide susceptibility mapping, Geocarto Int 2016;32 (6):619-639, 10.1080/10106049.2016.1165294 District Survey Document Shimla, accessed on 03/05/2021 available on https://emerginghimachal.hp.gov.in/miningstone/survay_docs/shimla.pdf

[11] Donnarumma A, Revellino P, Grelle G, Guadagno FM. Slope angle as indicator parameter of landslide susceptibility in a geologically complex area. In: Margottini C, Canuti P, Sassa K, editors. Landslide Science and Practice. Berlin, Heidelberg: Springer; 2013. p. 425–33. doi: https://doi.org/10.1007/978-3-642-31325-7_56.

[12] Fan W, Wei X, Cao Y, Zheng B. Landslide susceptibility assessment using the certainty factor and analytic hierarchy process. J Mountain Sci 2017;14 (5):906–25. doi: https://doi.org/10.1007/s11629-016-4068-2.

[13] Guzzetti F, Mondini AC, Kardinali M, Fiorucci F, Santangelo M, Chang K. Landslide inventory maps: new solution to old problems. Earth-Sci Rev 2012;112:42–66. doi: https://doi.org/10.1016/j.earscirev.2012.02.001.

[14] Hasekioğulları GD, Ercanoglu M. A new approach to use AHP in landslide susceptibility mapping: a case study at Yenice (Karabuk, NW Turkey). Nat Hazards 2012;63:1157–79. doi: https://doi.org/10.1007/s11069-012-0218-1.

[15] Ilia I, Tsangaratos P. Applying weight of evidence method and sensitivity analysis to produce a landslide susceptibility map. Landslides 2015;13 (2):379–97. doi: https://doi.org/10.1007/s10346-015-0576-3.

[16] Jazouli AE, Barakat A, Khelloud R. GIS-multicriteria evaluation using AHP for landslide susceptibility mapping in Oum Er Rbia high basin (Morocco). Geoenviron Disasters 2009;6:1–12. doi: https://doi.org/10.1186/s40677-019-0119-7.

[17] Khamhong P, Yingviwatanapong C, Ransikarbum K. December). Fuzzy Analytic Hierarchy Process (AHP)-based Criteria Analysis for 3D Printer Selection in Additive Manufacturing. Res, Invent, Innovat Cong (RI2C) 2019:1–5. doi: https://doi.org/10.1109/RI2C48728.2019.8999950.

[18] Kayastha P, Dhital MR, Smedt FD. Application of the analytical hierarchy process (AHP) for landslide susceptibility mapping: A case study from the Tinau watershed, West Nepal. Computers Geosci 2012;52:398–408. doi: https://doi.org/10.1016/j.cageo.2012.11.003.

[19] Kreuzer TM, Wilde M, Terhorst B, Damm B. A landslide inventory system as a base for automated process and risk analyses. Earth Sci Inf 2017;10:507–15. doi: https://doi.org/10.1007/s12145-017-0307-5.

[20] Kavzoglu T, Kutlug Sahin E, Colkesen I. An assessment of multivariate and bivariate approaches in landslide susceptibility mapping: a case study of Duzkoy district. Nat Hazards 2015;76(1):471–96. doi: https://doi.org/10.1007/s11069-014-1506-8.

[21] Kumar R, Anbalagan R. Landslide susceptibility mapping using analytic hierarchy process (AHP) in Tehri Reservoir Rim Region, Uttrakhand. J Geol Soc India 2016;87:1–16. doi: https://doi.org/10.1007/s12594-016-0395-8.

[22] Kumar R, Brookfield ME. Sedimentary environments of the Simla Group (Upper Precambrian), Lesser Himalaya, and their palaeotectonic significance. Sed Geol 1987;52(1–2):27–43. doi: https://doi.org/10.1016/0037-0738(87)90015-7.

[23] Lee S, Min K. Statistical analysis of landslide susceptibility at Yongin. Korea Environ Geol 2001;40(9):1095–113. doi: https://doi.org/10.1007/s002540100310.

[24] Mattivi P, Franci F, Lambertini A, Bitelli G. TWI computation: a comparison of different open source GISs, Open Geospatial Data, Software and Standards 2019;4(6). 10.1186/s40965-019-0066-y Map of India downloaded from https://d-maps.com/, accessed on 02/06/2021

[26] Milevski I, Dragićević S, Zorn M. Statistical and expert-based landslide susceptibility modeling on a national scale applied to North Macedonia. Open Geosci 2019;11(1):750–64. doi: https://doi.org/10.1515/geo-2019-0059.

[27] Myronidis D, Papageorgiou C, Theophanous S. Landslide susceptibility mapping based on landslide history and analytic hierarchy process (AHP). Nat Hazards 2015;81:245–63. doi: https://doi.org/10.1007/s11069-015-2075-1.

[28] Ohlmacher GC. Plan curvature and landslide probability in regions dominated by earth flows and earth slides. Eng Geol 2007;91(1–2):117–34. doi: https://doi.org/10.1016/j.enggeo.2007.01.005.
[29] Panchal S, Shrivastava AK. Application of analytic hierarchy process in landslide susceptibility mapping at regional scale in GIS environment. J Statist Manage Syst 2020;23(2):199–206. doi: https://doi.org/10.1080/09720510.2020.1724620.
[30] Panchal S, Shrivastava AK. A Comparative Study of Frequency Ratio, Shannon's Entropy and Analytic Hierarchy Process (AHP) Models for Landslide Susceptibility Assessment. ISPRS Int J Geo-Inf 2021;10(9):1–20. doi: https://doi.org/10.3390/ijgi10090603.
[31] Pardeshi SD, Autade SE, Pardeshi SS. Landslide hazard assessment: recent trends and techniques. SpringerPlus 2013;2(523):1–11. doi: https://doi.org/10.1186/2193-1801-2-523.
[32] Pathak D. Knowledge based landslide susceptibility mapping in the Himalayas. Geoenviron Disasters 2016;3(8):1–11. doi: https://doi.org/10.1186/s40677-016-0042-0.
[33] Park S, Choi C, Kim B, Kim J. Landslide susceptibility mapping using frequency ratio, analytic hierarchy process, logistic regression, and artificial neural network methods at the Inje area, Korea. Environ Earth Sci 2013:1443–1464. 10.1007/s12665-012-1842-5
[34] Polykretis C, Chalkias C. Comparison and evaluation of landslide susceptibility maps obtained from weight of evidence, logistic regression, and artificial neural network models. Nat Hazards 2018;93(1):249–74. doi: https://doi.org/10.1007/s11069-018-3299-7.
[35] Pourghasemi HR, Mohammady M, Pradhan B. Landslide susceptibility mapping using index of entropy and conditional probability models in GIS: Safarood Basin. Iran Catena 2012;97:71–84. doi: https://doi.org/10.1016/j.catena.2012.05.005.
[36] Pradhan B. Landslide susceptibility mapping of a catchment area using frequency ratio, fuzzy logic and multivariate logistic regression approaches. J Indian Soc Remote Sens 2010;38(2):301–20. doi: https://doi.org/10.1007/s12524-010-0020-z.
[37] Ram P, Gupta V, Devi M, Vishwakarma N. Landslide susceptibility mapping using bivariate statistical method for the hilly township of Mussoorie and its surrounding areas, Uttarakhand Himalaya. J Earth Syst Sci 2020;129(1):1–18. doi: https://doi.org/10.1007/s12040-020-01428-7.
[38] Ransikarbum K, Mason SJ. Multiple-objective analysis of integrated relief supply and network restoration in humanitarian logistics operations. Int J Prod Res 2016;54(1):49–68. doi: https://doi.org/10.1080/00207543.2014.977458.
[39] Ransikarbum K, Mason SJ. Goal programming-based post-disaster decision making for integrated relief distribution and early-stage network restoration. Int J Prod Econ 2016;182:324–41. doi: https://doi.org/10.1016/j.ijpe.2016.08.030.
[40] Ransikarbum K, Pitakaso R, Kim N, Ma J. Multicriteria decision analysis framework for part orientation analysis in additive manufacturing. J Comput Des Eng 2021;8(4):1141–57. doi: https://doi.org/10.1093/jcde/qwab037.
[41] Regmi AD, Yoshida K, Pourghasemi HR, DhitaL MR, Pradhan B. Landslide susceptibility mapping along Bhalubang — Shiwapur area of mid-Western Nepal using frequency ratio and conditional probability models. J Mountain Sci 2014;11(5):1266–85. doi: https://doi.org/10.1007/s11629-013-2847-6.
[42] Reichnenbach P, Rossi M, Malamud BD, Mihir M, Guzzetti F. A review of statistically based landslide susceptibility models. Earth-Sci Rev 2018;180:60–91. doi: https://doi.org/10.1016/j.earscirev.2018.03.001.
[43] Sarkar S, Roy AK, Martha TR. Landslide susceptibility assessment using Information Value Method in parts of the Darjeeling Himalayas. J Geol Soc India 2013;82(4):351–62. doi: https://doi.org/10.1007/s12594-013-0162-z.
[44] Senouci R, Taibi N-E, Teodoro AC, Duarte L, Mansour H, Yahia Meddah R. GIS-Based Expert Knowledge for Landslide Susceptibility Mapping (LSM): Case of Mostaganem Coast District, West of Algeria. Sustainability 2021;13(2):1–21. doi: https://doi.org/10.3390/su13020630.
[45] Shahabi H, Ahmad BB, Khezri S. Evaluation and comparison of bivariate and multivariate statistical methods for landslide susceptibility mapping (case study: Zab basin). Arabian J Geosci 2013;6(10):3885–907. doi: https://doi.org/10.1007/s12517-012-0650-2.
[46] Siddique T, Pradhan SP, Vishal V, Mondal MEA, Singh TN. Stability assessment of Himalayan road cut slopes along National Highway 58. India Environ Earth Sci 2017;76(22). doi: https://doi.org/10.1007/s12665-017-7091-x.
[47] Singh K, Kumar V. Hazard assessment of landslide disaster using information value method and analytical hierarchy process in highly tectonic Chamba region in bosom of Himalaya. J Mountain Sci 2018;15(4):808–24. doi: https://doi.org/10.1007/s11629-017-4634-2.
[48] Shano L, Raghuvanshi TK, Meten M. Landslide susceptibility evaluation and hazard zonation techniques – a review. Geoenviron Disasters 2020;7(18):1–19. doi: https://doi.org/10.1186/s40677-020-00152-0.
[49] Saaty TL. The analytic hierarchy process. New York: McGraw-Hill; 1980.
[50] Saaty RW. The analytic hierarchy process—what it is and how it is used. Math Modell 1987;9:161–76. doi: https://doi.org/10.1016/0270-0255(87)90473-8.
[51] Tanyaş H, van Westen CJ, Persello C, Alvioli M. Rapid prediction of the magnitude scale of landslide events triggered by an earthquake. Landslides 2019;16:661–76. doi: https://doi.org/10.1007/s10346-019-01136-4.

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