Research

Slope stability assessment and landslide susceptibility mapping in the Lesser Himalaya, Mussoorie, Uttarakhand

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Abstract

The present study aims to assess slope stability and landslide susceptibility mapping of road-cut slopes along Mussoorie road in the Lesser Himalayan region. A total of 18 suspected unstable slope sites were selected for the investigation, and performed geo-mechanical classification techniques, including Rock Mass Rating (RMR), Slope Mass Rating (SMR), Geological Strength Index (GSI), and kinematic analysis. For the Landslide susceptibility mapping, the Frequency Ratio (FR) method was employed using the weightage of various causative factors which includes slope, aspect, curvature, elevation, distance from streams, distance from lineaments, lithology, and rainfall. The finding indicates that out of 18 selected slopes, 4 slopes are bad slope or unstable, which includes slope 3,4 and 6 in the lower part of the Mussoorie area near Jharipani, while slope 10 near Hathi Paon-Mussoorie Road is also unstable. The slopes around Junu waterfall are stable. Partially unstable slopes may vulnerable to slope failure in the future due to heavy rainfall and unstructured construction. Additionally, the Area Under Curve (AUC) and predictive rate curve values are 61% and 78% respectively, indicating acceptable overall accuracy. This study highlights the landslide issues in Mussoorie region due to rapid urbanization & climate change and demonstrates the effectiveness of the employed methods for future risk analysis.

Keywords Landslide · Rock Mass Rating (RMR) · Slope Mass Rating (SMR) · Geological Strength Index (GSI) · Kinematic analysis · Frequency Ratio (FR)

1 Introduction

Landslides are the most commonly occurring geo-hazard in mountainous terrains—such as the Himalayan region, which significantly cause distress and inconvenience to the inhabitants [1]. They are defined as the mass movement of debris down a slope, one of the most common natural disasters in mountainous regions triggered due to heavy rainfall, earthquakes, tectonic disturbances, and increasing anthropologic activities viz., road widening. These geohazards occur worldwide and can severely impact the natural environment and human settlements.

It has become a reoccurring issue for Mussoorie, a popular tourist hotspot in Dehradun, Uttarakhand. Mussoorie, a small hill station in the Dehradun district of Uttarakhand, has recently faced numerous landslides, both minor and major.

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This situation worsens during the monsoon season. This has led to traffic congestion, and some areas have to restricted due to vulnerable condition of the road.

Recent development activities in the town, including building infrastructure, laying new roads, and widening existing ones to accommodate the rapid influx of tourist and investors, have impacted the stability of slopes along the Dehradun-Mussoorie highway [2–5]. The excavation of slopes for road widening and construction has created geologically unstable steep slopes that are prone to failures [6].

Numerous methods exist to determine slope stability, including rock mass classification methods, numerical methods like limit equilibrium methods, finite element modelling, and others [7–13]. Previous work by the disaster management planning in 2018 has found that landslide in Mussoorie is a "high-risk hazard" mainly due to the presence of steep cut slopes and tectonic discontinuities. Main Boundary Thrust, which separates Shiwalik and Lesser Himalaya, also passes through the area, responsible for the geologically fractured and fragile rocks. Landslide Susceptibility Mapping (LSM) by the Wadia Institute of Himalayan Geology (WIHG) covering 84 km sq. area of Mussoorie also showed that about 29% of the area falls in the moderate landslide susceptible zone while 56% in low to shallow landslide susceptible zones [14]. In the research by Thakur et al., the mitigation of landslide risk management can be achieved by new engineering solutions such as Matrix Laboratory (MATLAB) techniques along with slope stability assessment tools: Rock Mass Rating (RMR), Slope Mass Rating (SMR), and the Limit Equilibrium Method (LEM) [15]. Singh et al., discuss about the various methods to evaluate landslide susceptibility using statistical models, geographic information systems (GIS) and remote sensing. Also, they discuss about the advantages and limitations of these methods and techniques [16]. In the research by Qazi et al., performed in Kinnaur district Himachal Pradesh, the area under curve (AUC) approach was used. The prediction rate of landslides in the region is 88.90%. Also, the landslide susceptibility zone map was prepared [17]. Another research by Bhardwaj et al., predicted the landslide risk zone based on analytical hierarchy process (AHP), and logistic regression (LR) analysis [18].

The study area is located in the Lesser Himalaya and is tectonically deformed, with unfavourable geological lineaments. The subtropical weather conditions further increase the vulnerability of the slopes [19]. The after-effects of heavy rainfall during monsoon season are evident in (Fig. 1), which includes photos of past landslides in the area.

For this study we have used geo-mechanical techniques based on rock mass classification, which are popular for evaluating cut slope's stability when limited field data is available and there is a need to assess stability conditions quickly [20, 21]. Therefore, slope stability evaluation of the selected slopes was done using Kinematic Analysis, Rock Mass Rating (RMR), Geological Strength Index (GSI), and Slope Mass Rating (SMR) techniques. Identifying unstable slopes and implying

| 30.428223, 78.075177 | 30. 445178, 78.061623 | 30.421666, 78.076586 | 30.420345, 78.070782 |
| 30.425011, 78.074037 | 30. 417959, 78.076071 | 30.421704, 78.076650 | 30.421550, 78.076426 |

Fig. 1 Photographs of landslides in the study area depicting the state of the slope during Monsoon season

mitigation can help reduce the risk of landslide related accidents. For mapping purposes, the Frequency Ratio model was later applied, and is commonly used for landslide susceptibility mapping and is known to yield accurate results [22]. Many factors may cause landslides, such as the steepness of a slope, curvature of a slope, aspect, and elevation, which are used in this method by building a correlation between past landslides and estimated into numerical values to prepare a landslide susceptibility map [23].

2 Methodology

2.1 Study area

The hill station Mussoorie is 35 km from Dehradun, the capital of Uttarakhand. It lies at an altitude of ~ 2020 m from the mean sea level. The area is accessible through 3 asphaltic roads: Mussoorie-Dehradun Road, Kimadi Road, and Kyar kulli Bhatta Road. The present study focuses on the area from longitude 30°27′ 30.2″ N to 30° 25′ 11.1″ N and latitude 78° 05′ 06.3″ E to 78° 01′ 54.3″ E of Mussoorie and Hathipaon roads, as shown in (Fig. 2). Since the area falls in the Lesser Himalayan region, the elevation lies between 880 and 2125 m. Major River present in the area is the Tons River, while others are seasonal rivers and tributaries. According to the Köppen climate classification, the climate of Mussoorie is classified into a Cwb category which stands for Highland subtropical variety. The average temperature reaches − 1° in the month of January, the hottest month is May which has an average temperature of 32° Celsius. During the monsoon season, Mussoorie receives a total annual rainfall of ~ 1800 mm. The Lithology and structure determine the strength and permeability of the rock; hence it highly affects the slope movement [24]. Geologically, the Mussoorie group comprises three major formations: The Krol, Blaini, and Tal [25]. The Blaini formation consists of conglomerate, carbonaceous shale, and grey siltstone. It passes upward, forming a girdle into Infra-Krol formation. The Infra-Krol formation consists of two units, i.e., the lower-grey green siltstone, shale, and greywacke, and the upper black-pyritious shale and slate with thin quartzite interbeds. The Tal formation mainly consists of chert, shale, sandy limestone, quartzite, limestone, olive shale, and phyllite. All these formations are susceptible to landslides. The area structure around Mussoorie is a doubly-plunging NW–SE trending syncline. The plunge is at 10–15° towards SE in the NW portion. Main Boundary Thrust (MBT) is also present in Mussoorie between the Shiwalik and Chandpur formations.

2.2 Methods and data collection

A preliminary field survey was conducted along the road connecting Dehradun to Mussoorie. About 18 landslides were mapped using Google Earth as polygons later converted to points raster layer with projected coordinate system WGS 1984 UTM 44N, using previous landslide data from Bhuvan as a reference and intensive field investigation, since the past landslide's locations can guide to identify the locations of new landslides [26]. These 18 suspected slopes were selected for a slope stability assessment using geo-mechanical classification techniques, including Rock Mass Rating (RMR), Slope Mass Rating (SMR), Geological Strength Index (GSI), and Kinematic Analysis.

2.2.1 Rock Mass Rating (RMR)

The Rock Mass Rating (RMR) method evaluates six parameters: uniaxial compressive strength of rock material, Rock Quality Designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions, and orientation of discontinuities and uses a numerical weighted system where specific ratings are assigned to geological properties such as discontinuities, groundwater condition, roughness, and strength properties of the rock masses. The sum of these ratings is then calculated to determine the RMR value. RMR datasheet is describe in Tables 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 (Appendix 1).

2.2.2 Slope Mass Rating (SMR)

The Slope Mass Rating (SMR) is a rock mass geo-mechanical classification developed by Manuel Romana in 1985 to describe the strength of a rock outcrop or slope, it is based on RMR values. SMR is defined by the formula:
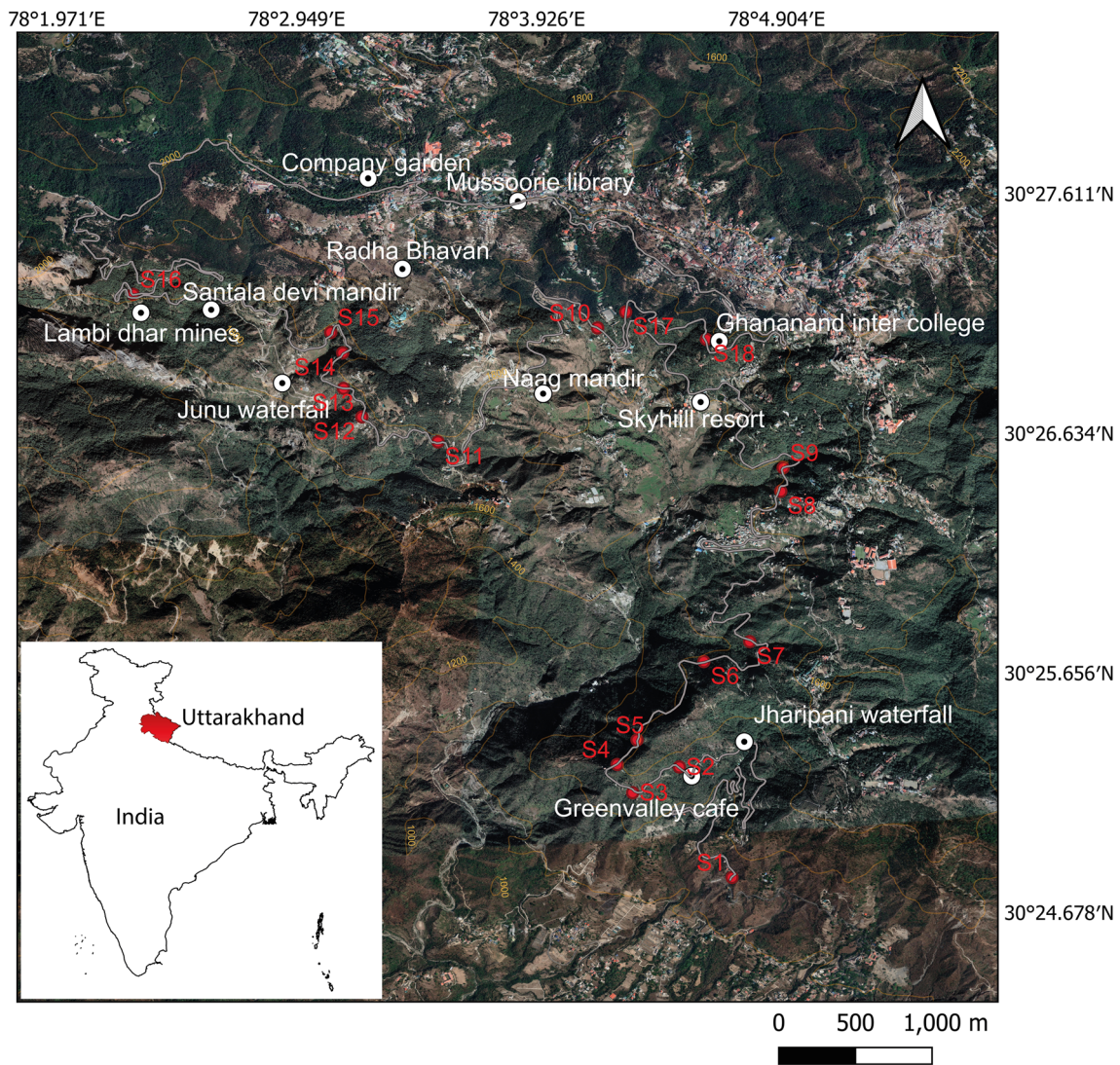
Fig. 2 Location map of the study area highlighting the path followed for field investigation and the location of the studied slopes alongside the road

$$SMR = RMR(b) - (F1 \times F2 \times F3) + F4$$

where RMR(b) is the basic RMR, and F1, F2, F3 are factors based on the type of failure that might occur, such as planar, wedge, or toppling.

2.2.3 Geological Strength Index (GSI)

The Geological Strength Index (GSI), developed by Hoek & Brown in 1980, estimates the overall rock mass properties and discontinuity characteristics. GSI is a visual assessment of the geological character of rock, considering parameters such as the surface and structural condition of an outcrop. These parameters are crucial for predicting the rock mass strength and deformability of the slope. The rock mass is rated according to predefined characteristics and weighted ratings, categorizing it based on interlocking patterns, weathering, length, and condition of the joints.
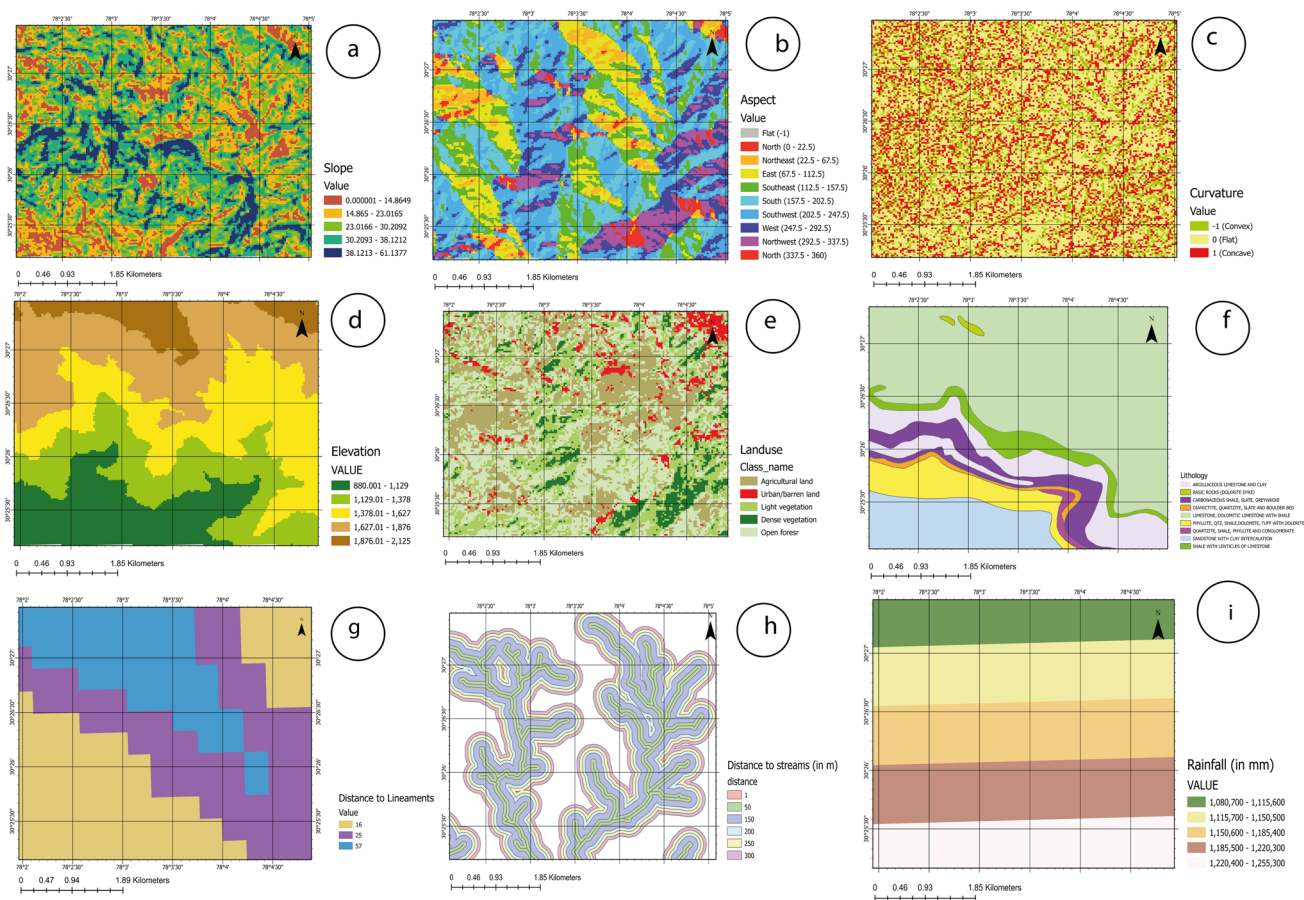
Fig. 3 Causative factors for landslide susceptibility mapping. **a** The slope map of the area with legends depicting different degree of steepness. **b** The aspect showing the different direction of slope angle. **c** The curvature depicting if the slope curvature is concave, flat or convex. **d** The elevation map showing different altitude of the study area **e** the land use map shows the different ways the land of the study area is occupied. **f** The lithology map of the area was prepared using geological data from Bhuvan site. **g** The distance to lineaments depicts the distance of landslide sites from lineaments in the vicinity. **h** The distance to streams depicts the distance of vulnerable landslide sites from the streams present in the area. **i** The rainfall map depicts the amount of rainfall in the area in mm which was prepared using interpolation method

2.2.4 Kinematic analysis

The kinematic analysis is used to determine the probability and type of structural failures that might occur on the slope, such as plane sliding, wedge sliding, and toppling, as depicted in Figs. 8, 9, 10 (Appendix 2). This analysis depends on the orientation of the discontinuities present in the rock mass. The stereonets for this study were prepared using Dips software.

2.2.5 Data collection for Frequency Ratio (FR) method

For the map preparation, nine causative factors were considered: Aspect, Slope, Curvature, Elevation, Rainfall, Distance to Lineaments, Distance to Streams, Lithology, and Land Use, as shown in Fig. 3. The aspect, elevation, slope, streams, and curvature maps were all produced using ResourceSat-2 DEM data at 30 m spatial resolution from the ISRO Bhuvan site. The Lithology and Lineament maps were downloaded from the Bhukosh site. The Land Use map was produced using Landsat 8 data under supervised classification in ArcGIS Pro software. Rainfall data was collected from the Climatic Research Unit (University of East Anglia) and the NCAS website.
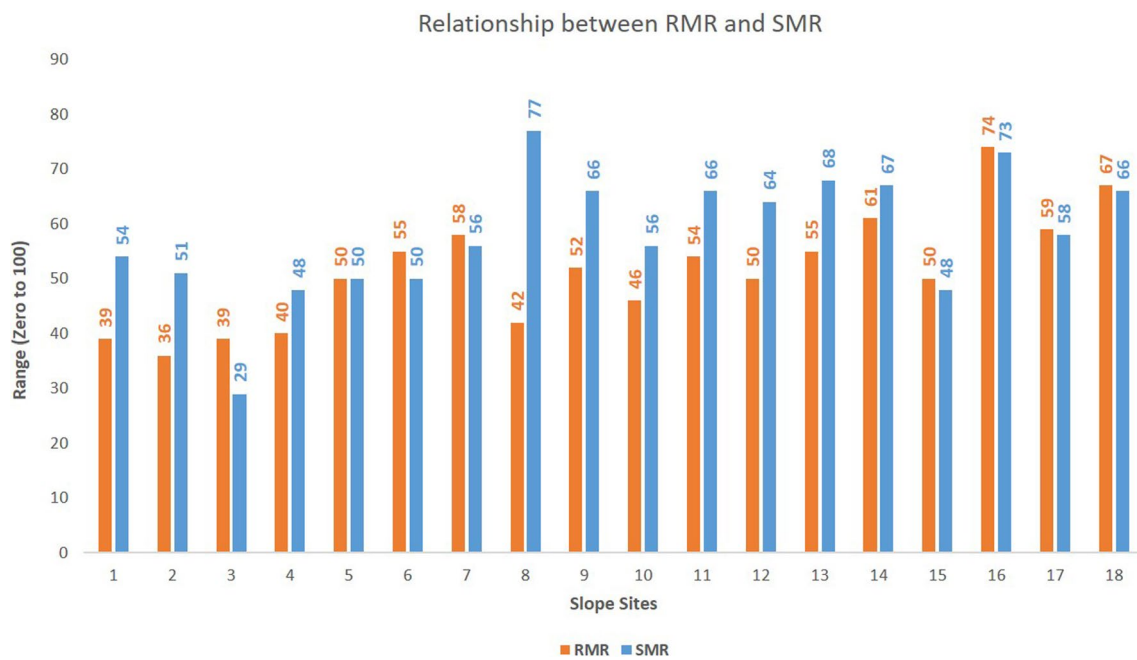
Fig. 4 Graphical representation of RMR and SMR values of the studied slopes

2.2.6 Frequency Ratio (FR) model

The Frequency Ratio (FR) model which is a statistical method, was used in this study to prepare a landslide susceptibility map of the study area. This model creates a landslide susceptibility map based on the spatial relationship between landslides and their causative factors [27]. It calculates the ratio between the area of landslides and the total area of the map, defined as the "probability of landslide occurrence to non-occurrence for a particular attribute". The Frequency Ratio model is intelligible and easily applied, which explains its widespread use in literature [28]. It is expressed:

$$FR = \frac{Nip/N}{Nilp/Nl}$$

where the *Nip* is the number of pixels in each landslide causative factor, *N* is the number of pixels in the total area of the study map, *Nilp* is the number of landslide pixels in each landslide causative factor, *Nl* is the total number of landslide pixels in the study area map.

The first step is to calculate the area of landslide pixels in each causative factor using the tabulate area tool. After that, the area is divided by the total area. The landslides data was divided into 80% training dataset and 20%. Testing dataset to test accuracy based on Area Under Curve (AUC) and Predictive rate curve values. Based on the above concepts we have evaluated the landslide susceptibility in the region.

3 Results and discussion

3.1 Slope stability assessment

The slopes were classified using various rock mass classification techniques. 18 of the most vulnerable slopes were selected and rated based on characteristics such as slope angle, height, structural conditions, weathering conditions, sets and spacing of discontinuities. Most of the rock mass in the area are predominantly deterred and weathered, with 2 or 3 joint sets present in most cases, and spacing between 2 and 15 cm.

The relationship and proximity between SMR (Slope Mass Rating) and RMR (Rock Mass Rating) values serve as critical indicators in assessing slope stability (Fig. 4). When these values correlate closely and fall within a similar range, it

generally suggests that the slope may appear stable overall, but maybe vulnerable to failure because of the presence of poor rock mass joint conditions. Moreover, the interpretation of high RMR and SMR values initially implies favourable rock conditions. But in contrast the GSI values are low in these slopes, which indicate the weaknesses that manifest due to weathering, resulting in poor to very poor surface conditions. These conditions can tend to worsen, particularly during periods of monsoon season or when subjected to tectonic disturbances, as noted by [6]. Using the Rock Mass Rating (RMR) system, the classes ranged from 36 to 75. Four slopes (1, 2, 3, and 4) were found to be unstable, while the rest were classified as stable.

The Geological Strength Index (GSI) classification indicates that rock slopes with a GSI value of ≤ 25 are unstable and are vulnerable to failure. According to GSI classification, slopes 3, 4, 10, and 11 are unstable, while the rest are stable (Table 1).

The means of RMR, SMR, and GSI were calculated and categorized into three stability classes: ≤ 40 (bad slope/unstable), 41–50 (normal slope/partially stable), and > 50 (good slope/stable). Slope sites 3, 4, 6, and 10 were found to have bad slope/unstable slope values.

3.2 Landslide susceptibility mapping based on various causative factors

The frequency ratio (FR) data concerning landslides is detailed in (Table 2), revealing various factors influencing slope instability across the study area.

The analysing slope angles reveals that moderate steep slopes, particularly those ranging from 20–30°, exhibit the highest FR values, theses slopes were observed alongside of the road. The aspect map indicates that the North-West direction seems to be the most vulnerable, with an FR value of 2.303, which also highlights slope direction near the road. Hydrological factors such as streams and groundwater also deteriorate slope structure, making it weaker and more susceptible to failure. Elevation in Mussoorie ranges from 880 to 2125 m above sea level, shows the highest FR between 1100 to 1300 m was the most susceptible height for slope failure. Regarding lithology, shale rock with limestone lenticels from the Krol Formation exhibits the highest FR. This lithological composition is fragile due to being weak and fragile by nature, these kinds of rocks are of sedimentary origin and lacks strength, contributing significantly to slope instability. Similarly, due to presence of lineaments and faults such as Main boundary thrust, the study is susceptible to landslides. Lastly, the highest FR values are associated with rainfall, which is the main cause of major mud slides that occur in the area during monsoon season. The landslide susceptibility map indicates that about more than 50% of Very High Hazard Zone lying in the south-western area of the Mussoorie, near the Main Boundary Thrust below Jharipani waterfall (Fig. 5).

Table 1 Numerical rating table of Rock Mass Rating, Slope Mass Rating, and Geological Strength Index, Mean and type of failure from kinematic analysis

Slope no	Type of failure	RMR	SMR	GSI	Mean	Description/Stability
1	Wedge	39	54	45	46	Normal slope or Partially stable
2	Planar	36	51	50	46	Normal slope or Partially stable
3	Direct toppling	39	29	25	31	Bad slope or Unstable
4	Planar	40	48	20	36	Bad slope or Unstable
5	Planar	50	50	45	48	Normal slope or Partially stable
6	Flexural toppling	55	50	30	45	Bad slope or Unstable
7	Wedge	58	56	30	48	Normal slope or Partially stable
8	Planar	42	77	40	53	Good slope or Stable
9	Direct toppling	52	66	55	58	Good slope or Stable
10	Direct toppling	46	56	15	39	Bad slope or Unstable
11	Planar	54	66	20	47	Normal slope or Partially stable
12	Direct toppling	50	64	55	56	Good slope or Stable
13	Direct toppling	55	68	75	66	Good slope or Stable
14	Direct toppling	61	67	55	61	Good slope or Stable
15	Planar	50	48	35	44	Normal slope or Partially stable
16	Wedge	74	73	46	64	Good slope or Stable
17	Direct toppling	59	58	55	57	Good slope or Stable
18	Direct toppling	67	66	65	66	Good slope or Stable

Table 2 Frequency ratio and predictive rate values of the causative factors

S. No	Data layers	Class	Weightage	FR	PR
1	Slope (degree °)	14.865–23.0165	4	1.53	9.00
		23.0166–30.2092	3	1.04	
		30.2093–38.1212	1	0.46	
		38.1213–61.1377	3	1.08	
2	Aspect (degree °)	North (0–22.5)	2	0.97	12.73
		Southeast (112.5–157.5)	1	0.57	
		South (157.5–202.5)	2	0.99	
		West (247.5–292.5)	1	0.63	
		Northwest (292.5–337.5)	4	2.30	
3	Curvature	−1	4	1.07	1.03
		0	3	0.98	
		1	3	0.96	
4	Distance to Streams (m)	1	2	0.68	8.76
		50	1	0.42	
		150	7	2.60	
5	Elevation (m)	880.001–1129	1	0.50	7.44
		1129.01–1378	3	1.03	
		1378.01–1627	4	1.47	
		1627.01–1876	2	0.69	
6	Lithology	Limestone, dolomitic limestone with shale	2	0.50	6.60
		Shale with lenticles of limestone	3	0.97	
		Argillaceous limestone and clay	6	1.81	
7	Land use	Agricultural land	1	0.80	19.55
		Urban/Barren Land	2	1.06	
		Light Vegetation	2	1.41	
		Dense Vegetation	5	3.37	
		Open Forest	1	0.36	
8	Rainfall (mm)	108.07–111.56	3	1.40	7.66
		111.57–115.05	3	1.05	
		115.06–118.54	1	0.53	
		118.55–122.03	3	1.05	
		122.04–125.53	3	1.40	
9	Distance to lineaments	16	2	0.67	6.14
		25	3	1.03	
		57	6	2.40	

The heightened susceptibility could be due to fragile geological condition and urbanization that is taking place in the upper part of the hill station which could make the roots in the lower part of the hill station weaker.

The combination of these causative factors contributes greatly to the vulnerability of the area to landslides. From the field survey it can be concluded that the study area has pre-existent weaker geological formations and this condition is made worse by haphazard building practices in the hill station. The understanding of these causative factors and their negative effects is crucial for landslide risk management and mitigation strategies for the study area. In such vulnerable region there is need of properly built Retaining and Gabion walls with working drainage holes to facilitate surface run off, further increasing biological reinforcement on open slopes could further increase the soil shear strength in case of slopes that pre-dominantly consist of soil.

3.3 Validation by AUC (Area Under Curve)

Validation of a map is necessary to check its accuracy so that it can be used in the future. The validation curve or Area Under Curve (AUC) is the relation between the percentage of landslide susceptibility map used for training and the
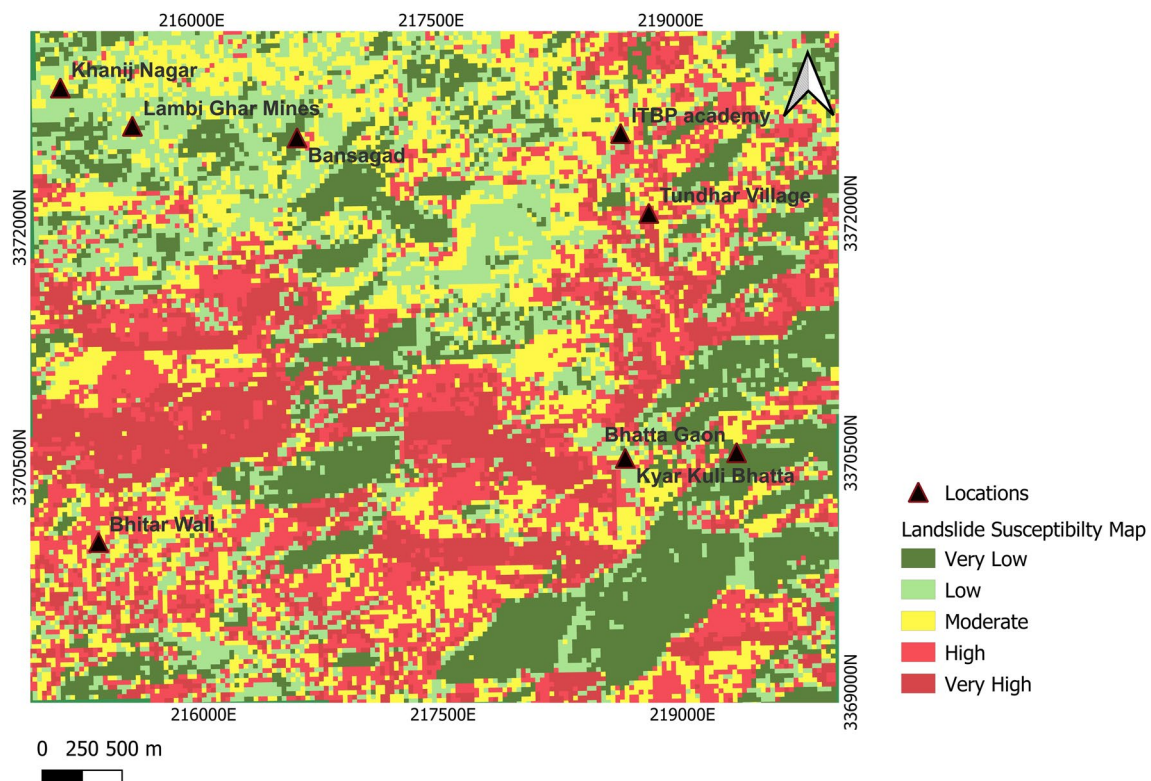
Fig. 5 Landslide susceptibility map with important locations/places of Mussoorie constructed using Frequency Ratio (FR) method

Fig. 6 AUC (Area under curve) graph
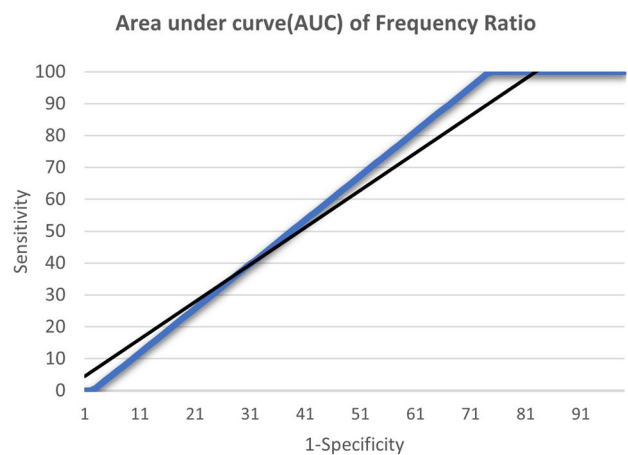
percentage of pixels of the landslide. In contrast, the predictive rate curve is the relationship between the percentage of landslide susceptibility map and the percentage of landslide pixels used for testing [29]. To check accuracy, the landslide data was divided into 80% training data and the rest 20% for testing purposes. The AUC for the map using the tabulate area tool and landslide testing layer came out to be 0.61 or 61% (Fig. 6), which falls under the satisfactory category. The predictive rate curve value is 0.78 or 78% (Fig. 7).

4 Conclusion

This study highlights the critical issue of landslides in Mussoorie region, driven by rapid urbanization, heavy rainfall and haphazard construction. An effective approach for assessing landslide risks is demonstrated by the integration of comprehensive geo-mechanical classification approaches for slope stability assessment and the Frequency Ratio (FR) method for

Fig. 7 Predictive rate graph
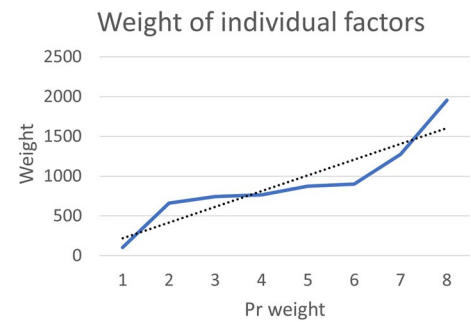
landslide susceptibility mapping. The findings reveal that four of the eighteen slopes that were selected are expected to be unstable, specifically slopes 3, 4, and 6 in the lower part of the Mussoorie area near Jharipani, and slope 10 near Hathi Paon-Mussoorie Road. On the other hand, it was discovered that the area near the Junu waterfall was having stable slope. But future slope failure is highly probable on the partially unstable slopes, mainly because of excessive rainfall and uncontrolled construction activities. The Area Under Curve (AUC) and predictive rate curve values were determined to be 61% and 78%, respectively, indicating an acceptable overall accuracy for the methods used. The results highlight the need for continuous monitoring and assessment of slope stability, especially in a region experiencing significant anthropogenic stresses and climatic variability. The predictive insights provided by this study are vital for local authorities and urban planners in Mussoorie region. By identifying high-risk areas, appropriate mitigation measures can be implemented to reduce the potential impact of landslides on infrastructure and human safety. The landslide susceptibility map can aid decision-makers, land use planners, and engineers in optimal management to reduce losses from current and future landslides through appropriate preventive measures and mitigation strategies [30]. The study also demonstrates the necessity for structured construction practices and improved land use planning to mitigate the adverse effects of urbanization on slope stability. Furthermore, landslide activities near water resources such as rivers, lakes, and waterfalls in the region pose a risk to biodiversity [31]. Future studies should focus on incorporating more advanced modelling techniques and real-time monitoring systems to improve the precision and reliability of landslide susceptibility assessments. Additionally, engaging local communities in data collection and awareness programs can foster a proactive approach to landslide risk management. Overall, this study contributes significantly to the understanding of landslide dynamics in the Lesser Himalayan region and sets a precedent for similar assessments in other vulnerable areas.

Declarations

Competing interests The authors declare no competing interests.

Appendices

Appendix 1

Table 3 Datasheet for Rock Mass Rating (RMR) values of Slope Site 1

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-1			
Location			30° 27′ 04.1″ N 78° 04′ 54.2″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			60°	74°	42°	
Dip Direction			355°	268°	170°	
Joint description	Persistence (m)		0.5–2.5	1–3	3–10	2–4
	Spacing (cm)		4–10	5–20	6–20	15
	Aperture (mm)		1–2	1–2	1–2	4
	Roughness		sm-un	Sm-un	Sm-un	1
	Alteration		Iron stained			
	Type of Filling		Soil			2
Rock Mass Description	Rock Type		Slate			
	Strength		Weak			2
	Degree of Weathering		MW			3
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD-45.7%			8
Remarks	Slope angle—75–80°, slope direction—310°, slope height—6–8 m, road strike—050°				RMR Basic = 39, Class-IV Poor Rock Mass	

Table 4 Datasheet for Rock Mass Rating (RMR) values of Slope Site 2

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-2			
Coordinates			30° 25′ 16.3″ N 78° 04′ 30.5″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			30°	51°	30°	
Dip Direction			25°	115°	275°	
joint description	Persistence (m)		1–2 m	30 m	30 m	4
	Spacing (cm)		1–4 cm	3 cm	1–2 cm	5
	Aperture (mm)		< 1–2 mm	1–5 mm	1–2 mm	1
	Roughness		Ro-pl	Ro-pl	Ro-pl	3
	Alteration		None			
	Type of Filling		Soil	Soil	Soil	2
Rock Mass Description	Rock Type		Slate			
	Strength		Weak rock			
	Degree of Weathering		MW			3
	Geological Structure		IFA			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD < 25%			3
Remarks	Slope direction—210° Slope angle—83–87° Slope height—17–20 m Road strike—110°				RMR Basic = 36, Class-IV Poor Rock Mass	

Table 5 Datasheet for Rock Mass Rating (RMR) values of Slope Site 3

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-3			
Coordinates			30°25′10.0″N 78°04′19.1″E			
Set Number			J0	J1	J2	Ratings
Dip Amount			45°	83°	65°	
Dip Direction			170°	225°	125°	
Joint description	Persistence (m)		3–12	< 1 m	1	2–6
	Spacing (cm)		1–15	5–30	1–10	8
	Aperture (mm)		0.25–0.55	0	0	5
	Roughness		Smooth-planar			1
	Alteration		None			
	Type of Filling		Soil			2
Rock Mass Description	Rock Type		Slate			
	Strength		Weak			2
	Degree of Weathering		Highly			1
	Geological Structure		Intensely jointed			
	Water Inflow		Dry			15
	Jv	Block Dimension No. of Joints/M^3	RQD < 25%			3
Remarks	Slope angle—75–80°, slope direction—350°, slope height—10–12 m, road strike—85°					RMR Basic = 39, Class-IV Poor Rock Mass

Table 6 Datasheet for Rock Mass Rating (RMR) values of Slope Site 4

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-4			
Coordinates			30°25′ 16.9″ N 78° 04′ 15.3″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			68°	45°	75°	
Dip Direction			190°	160°	210°	
joint description	Persistence (m)		10–20	1–3	1–2	1–4
	Spacing (cm)		1–30	0.5–10	1–3	5
	Aperture (mm)		0	0	0	6
	Roughness		Rough-planar			3
	Alteration		None			
	Type of Filling		soil			2
Rock Mass Description	Rock Type		Quartzite			
	Strength		Weak			2
	Degree of Weathering		Moderate			3
	Geological Structure		IJ			
	Water Inflow		Dry			15
	Jv	Block Dimension No. of Joints/M^3	< 25%			3
Remarks	Slope angle—755°, slope direction—1350°, slope height—8–9 m, road strike—0350°					RMR Basic = 40, Class-IV Poor Rock Mass

Table 7 Datasheet for Rock Mass Rating (RMR) values of Slope Site 5

Datasheet for Rock Mass Rating					
Project	Mussoorie road		Location: Spot-5		
Coordinates:			30.423030° N 78.072268° E		
Set Number			J0	J1	J2	Ratings
Dip Amount			75º	30º		
Dip Direction			265º	100º		
Joint description	Persistence (m)		10–12	> 20		1
	Spacing (cm)		2–12	2–5		5–8
	Aperture (mm)		0.55–1	0.25–2.5		4–5
	Roughness		Ro-pl	ro-pl		3
	Alteration		None			
	Type of Filling		PFC	PFC		4
Rock Mass Description	Rock Type		Quartzite			
	Strength		Strong rock			13
	Degree of Weathering		SW			5
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M³	RQD < 25%			3
Remarks	Slope angle—85° slope direction—S275° W road strike—180° slope height—5 to 7 m				RMR (Basic) = 50, Class-III Fair Rock Mass

Table 8 Datasheet for Rock Mass Rating (RMR) values of Slope Site 6

Datasheet for Rock Mass Rating					
Project	Mussoorie road		Location: Spot-6		
Coordinates:			30.423030° N78.072268° E		
Set Number			J0	J1	J2	Ratings
Dip Amount			75º	30º		
Dip Direction			265º	100º		
joint description	Persistence (m)		10–12	> 20		1
	Spacing (cm)		2–12	2–5		5–8
	Aperture (mm)		0.55–1	0.25–2.5		4–5
	Roughness		Ro-pl	ro-pl		3
	Alteration		None			
	Type of Filling		PFC	PFC		4
Rock Mass Description	Rock Type		Quartzite			
	Strength		Strong rock			13
	Degree of Weathering		SW			5
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M³	RQD < 25%			3
Remarks	Slope angle—85° slope direction—S275ºW road strike—180° slope height—5 to 7 m				RMR Basic = 55, Class-III Fair Rock Mass

Table 9 Datasheet for Rock Mass Rating (RMR) values of Slope Site 7

Datasheet for Rock Mass Rating

Project	Mussoorie road		Location: Spot-7			
Coordinates			30° 25′ 47.0″ N 78° 04′ 47.7″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			54°	64°	40°	
Dip Direction			40°	350°	220°	
Joint description	Persistence (m)		3–10	3–10	3–10	2
	Spacing (cm)		1–30	0.5–30	0.6–2 m	13–17
	Aperture (mm)		0	0	0.25–0.55	5
	Roughness		Sm-st	Sm-st	Sm-st	1
	Alteration		None			
	Type of Filling		Soil			2
Rock Mass Description	Rock Type		Dolomite			
	Strength		Strong			13
	Degree of Weathering		MW			3
	Geological Structure		SFO			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	< 25%			3
Remarks	Slope angle—60°, slope direction—060°, slope height—14–15 m, road strike—330°				RMR Basic = 58,Class-III Fair Rock Mass	

Table 10 Datasheet for Rock Mass Rating (RMR) values of Slope Site 8

Datasheet for Rock Mass Rating

Project	Mussoorie road		Location: Spot-8			
Coordinates			30° 26′ 23.8″ N 78° 04′ 55.3″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			40°	77°		
Dip Direction			340°	155°		
joint description	Persistence (m)		5–25	1–2		4
	Spacing (cm)		5–30	3–15		8
	Aperture (mm)		Tight	0.25–0.1		5
	Roughness		Sm-st	Sm-st		1
	Alteration		None			6
	Type of Filling		Soil	–		2
Rock Mass Description	Rock Type		Limestone			
	Strength		Medium Strong rock			8
	Degree of Weathering		SW			5
	Geological Structure		SFO			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD-25–50%			8
Remarks	Slope angle—85°, slope direction—085°, slope height—5–7 m, road strike—170°				RMR Basic = 42, Class-IV Poor Rock Mass	

Table 11 Datasheet for Rock Mass Rating (RMR) values of Slope Site 9

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-9			
Coordinates			30° 26′ 46.0″ N 78° 04′ 45.2″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			26	77	29	
Dip Direction			40	160	260	
Joint description	Persistence (m)		> 10	3	1–3	1–4
	Spacing (cm)		2–10	1–3	6–20	8
	Aperture (mm)		< 0.25	0.25–0.5	0.25–0.55	5
	Roughness		Ro-pl	Ro-pl	Ro-pl	3
	Alteration		None			
	Type of Filling		Clay	Clay	Clay	6
Rock Mass Description	Rock Type		Quartzite			
	Strength		Strong rock			8
	Degree of Weathering		MW			3
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M³	RQD < 25%			3
Remarks	Slope angle—85°, slope direction—015°, slope height—5–7 m, road strike—300°			RMR Basic = 52, Class-III Fair Rock Mass		

Table 12 Datasheet for Rock Mass Rating (RMR) values of Slope Site 10

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-10			
Coordinates			30° 27′ 03.8″ N 78° 04′ 10.5″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			20°	80°	55°	
Dip Direction			110°	150°	310°	
Joint description	Persistence (m)		3–10	1–2	1	2–4
	Spacing (cm)		2–30	1–5	0.5–8	8–10
	Aperture (mm)		0.25–1	0.5–1.5	10–50	1–5
	Roughness		Ro-pl	Ro-pl	Ro-pl	3
	Alteration		None			
	Type of Filling		Clay			2
Rock Mass Description	Rock Type		Limestone			
	Strength		Medium strong rock			8
	Degree of Weathering		HW			3
	Geological Structure		Sfo			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M³	RQD < 25%			3
Remarks	Slope angle—75°, slope height—18–20 m, slope direction—45°, road strike—310°			RMR Basic = 46, Class- III Fair Rock Mass		

Table 13 Datasheet for Rock Mass Rating (RMR) values of Slope Site 11

Datasheet for Rock Mass Rating						
PROJECT	Mussoorie road		LOCATION: Spot-11			
Coordinates			30° 26' 35.9" N 78° 03' 31.5" E			
Set Number			J0	J1	J2	Ratings
Dip Amount			5°	90°		
Dip Direction			180°	95°		
Joint description	Persistence (m)		3–10	1–3		2–4
	Spacing (cm)		60	5–10		8–10
	Aperture (mm)		0	< 1		5–6
	Roughness		ro-pl	Ro-pl		3
	Alteration		None			
	Type of Filling		Pcf	Pcf		4
Rock Mass Description	Rock Type		Quartzite/dolomite			
	Strength		Moderately strong			8
	Degree of Weathering		MW			3
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD < 25%			3
Remarks	Slope angle—75°, slope height—8–11 m, slope direction—10°, road strike—90°				RMR Basic = 54, Class-III Fair Rock Mass	

Table 14 Datasheet for Rock Mass Rating (RMR) values of Slope Site 12

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-12			
Coordinates			30° 26' 42.0" N 78° 03' 12.9" E			
Set Number			J0	J1	J2	Ratings
Dip Amount			10°	75°	66°	
Dip Direction			120°	210°	210°	
joint description	Persistence (m)		5–7	1–3	1–3	2–4
	Spacing (cm)		1–20	1–5	0.5–10	8
	Aperture (mm)		0	0	0.25–1	5
	Roughness		Ro-pl	Ro-pl	Ro-pl	3
	Alteration		Iron stain			
	Type of Filling		Pcf			4
Rock Mass Description	Rock Type		Limestone			
	Strength		strong rock			8
	Degree of Weathering		HW			1
	Geological Structure		Sfo			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD < 25%			3
Remarks	Slope angle—85–90°, slope direction—310°, slope height—15–18 m, road strike—065°				RMR Basic = 50, Class-III Fair Rock Mass	

Table 15 Datasheet for Rock Mass Rating (RMR) values of Slope Site 13

Datasheet for Rock Mass Rating						
PROJECT	Mussoorie road		Location: Spot-13			
Coordinates			30° 26′ 49.0″ N 78° 03′ 08.4″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			22°	65°		
Dip Direction			60°	28°		
Joint description	Persistence (m)		3–10	1–13		
	Spacing (cm)		1–30	1–30		8
	Aperture (mm)		0	10–20		6
	Roughness		Ro-pl	Ro-pl		3–5
	Alteration		None			
	Type of Filling		Clay			2
Rock Mass Description	Rock Type		Quartzite			
	Strength		Strong rock			8
	Degree of Weathering		MW			3
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M³	RQD < 25%			3
Remarks	Slope angle—75°, slope direction—000°, slope height—12–15 m, road strike—270°					RMR Basic = 55, Class-III Fair Rock Mass

Table 16 Datasheet for Rock Mass Rating (RMR) values of Slope Site 14

Datasheet for Rock Mass Rating						
Project	Mussoorie road		Location: Spot-14			
Coordinates			30° 26′ 57.7″ N 78° 03′ 08.2″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			68°	45°	75°	
Dip Direction			190°	160°	210°	
Joint description	Persistence (m)		10–20	1–3	1–2	1–4
	Spacing (cm)		1–30	0.5–10	1–3	8–10
	Aperture (mm)		0	0	0	6
	Roughness		Ro-pl	Ro-pl	Ro-pl	3
	Alteration		None			
	Type of Filling		Clay	–	–	4
Rock Mass Description	Rock Type		Quartzite			
	Strength		Medium strong rock			8
	Degree of Weathering		MW			3
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M³	RQD-50%			8
Remarks	Slope angle—90° Slope direction—N320°W Slope Height—4–6 m Road Strike—230°					RMR Basic = 61, Class-III Fair Rock Mass

Table 17 Datasheet for Rock Mass Rating (RMR) values of Slope Site 15

Datasheet for Rock Mass Rating

Project	Mussoorie road		Location: Spot-15			
Coordinates			30° 27′ 02.7″ N 78° 03′ 05.3″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			35°	55°	77°	
Dip Direction			155°	95°	75°	
Joint description	Persistence (m)		1–3	1–2	3–10	2–4
	Spacing (cm)		1–30	0.5–40	60 cm–2 m	10–15
	Aperture (mm)		0	0.25–1	0	5
	Roughness		Ro-Pl	Ro-pl	Ro-pl	3
	Alteration		None			
	Type of Filling		Soil	Soil	Soil	2
Rock Mass Description	Rock Type		Slate			
	Strength		weak rock			2
	Degree of Weathering		Hw			1
	Geological Structure		MJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD—25–50%			8
Remarks	Slope angle—75 Slope Direction—45 Slope height—18–20 m Road strike—310°		RMR Basic = 50, Class-III Fair Rock Mass			

Table 18 Datasheet for Rock Mass Rating (RMR) values of Slope Site 16

Datasheet for Rock Mass Rating

Project	Mussoorie road		Location: Spot-16			
Coordinates			30° 27′ 12.0″ N 78° 02′ 17.0″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			79°	45°		
Dip Direction			285°	35°		
joint description	Persistence (m)		1–3	1–3		4
	Spacing (cm)		5–30	10–60		10
	Aperture (mm)		0	0		6
	Roughness		Ro-pl	Ro-pl		3–5
	Alteration		Iron stained			
	Type of Filling		Soil	soil	Soil	2
Rock Mass Description	Rock Type		Quartzite			
	Strength		Strong rock			13
	Degree of Weathering		Mw			3
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	RQD-75–90%			17
Remarks	Slope angle—90°, slope direction—320°, slope height—4–6 m, road strike—230°		RMR Basic = 74, Class- II Good Rock Mass			

Table 19 Datasheet for Rock Mass Rating (RMR) values of Slope Site 17

Datasheet for Rock Mass Rating

Project	Mussoorie road		Location: Spot-17			
Coordinates			30° 27′ 07.7″ N 78° 04′ 17.4″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			27°	70°		
Dip Direction			210°	30°		
joint description	Persistence (m)		3–10	1–3		2–4
	Spacing (cm)		0.5–10	0.5–15		8
	Aperture (mm)		0	0.25–1		5
	Roughness		Ro-pl	Ro-pl		3–5
	Alteration		None			
	Type of Filling		Pcf	Pcf		4
Rock Mass Description	Rock Type		Dolomite			
	Strength		Very strong			13
	Degree of Weathering		SW			5
	Geological Structure		IJ			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	Rqd < 25%			3
Remarks	Slope angle—88°, slope height—3 m, slope direction—270°, road strike—180°				RMR Basic = 59, Class-III Fair Rock Mass	

Table 20 Datasheet for Rock Mass Rating (RMR) values of Slope Site 18

Datasheet for Rock Mass Rating

Project	Mussoorie road		Location: Spot-18			
Coordinates			30° 27′ 01.0″ N 78° 04′ 37.1″ E			
Set Number			J0	J1	J2	Ratings
Dip Amount			15°	87°	20°	
Dip Direction			155°	125°	255°	
Joint description	Persistence (m)		2–3	1–2	40	4
	Spacing (cm)		42–45	20–40	18–60	10
	Aperture (mm)		0	0.1–10	< 0.1	4–5
	Roughness		Sm-pl	Sm-pl	Sm-pl	1
	Alteration		None			
	Type of Filling		None	None	None	6
Rock Mass Description	Rock Type		Dolomite			
	Strength		Strong			13
	Degree of Weathering		SW			5
	Geological Structure		IFA			
	Water Inflow		CD			15
	Jv	Block Dimension No. of Joints/M^3	Rqd-25–50%			8
Remarks	Slope angle—85°, slope direction—40°, slope height—15–18 m, road strike—315°				RMR Basic = 67, Class-III Fair Rock Mass	

Appendix 2

See Figs. 8, 9, 10.

Fig. 8 Stereonets and Kinematic Analysis of Slope 1 to 6

Fig. 9 Stereonets and Kinematic Analysis of Slope 7 to 12

Fig. 10 Stereonets and Kinematic Analysis of Slope 13 to 18

References

1. Landslide Hazard around Mussoorie: The Lesser Himalayan Tourist Destination of Uttarakhand, India. (n.d.). https://www.researchgate.net/publication/317818754_Landslide_Hazard_around_Mussoorie_The_Lesser_Himalayan_Tourist_Destination_of_Uttarakhand_India. Accessed 29 June 2024.
2. Rautela P. Traditional practices of the people of Uttarakhand Himalaya in India and relevance of these in disaster risk reduction in present times. International Journal of Disaster Risk Reduction. 2015;13:281–90. https://doi.org/10.1016/j.ijdrr.2015.07.004.
3. Mani A, Kumari M, Badola R. Morphometric analysis of Suswa River Basin using geospatial techniques. Engi Proc. 2022;27(1):65.
4. Mani A, Kumari M, Badola R. Evaluating urban topography and land use changes for urban river management using geospatial techniques. Eng Proc. 2023;58(1):12.
5. Mani A, Kumari M, Badola R (2023) A GIS-Based Assessment of Asan River Basin for Watershed Management. In Proceedings of 42nd INCA International Congress on Digital Cartography to Harness Blue Economy. INCA: Dehradun, India.
6. Sati SP, Sundriyal Y, Rana N, Dangwal S. Recent landslides in Uttarakhand: nature's fury or human folly. Curr Sci. 2011;100:1617–20.
7. Singh K, Khaidem S, Gupta SK, Sharma A. Assessment of landslide occurrence and prediction of susceptible zone based on GIS along national highway 37, Manipur, India. Sadhana. 2024;49:74. https://doi.org/10.1007/s12046-023-02422-7.
8. Magray AA, Singh K, Sharma S. Comparative analysis of certainty factor and analytic hierarchy process for landslide susceptibility zonation in parts of Solan, Himachal Pradesh, India. Quaestiones Geographicae. 2023;42(3):5–18. https://doi.org/10.14746/Quageo-2023-0020.
9. Qazi A, Singh K. Rock mass classification techniques and parameters: a review. J Mining Environ. 2023;14(1):155–78.
10. Bhardwaj V, Singh K. Landslide susceptibility assessment using remote sensing and GIS-a review. J Mining Environ. 2023;14(1):133–54.
11. Singh K, Sharma A. Road cut slope stability analysis at Kotropi Landslide Zone Along NH-154 in Himachal Pradesh, India. J Geol Soc India. 2022;98:379–86. https://doi.org/10.1007/s12594-022-1989-y.
12. Singh K, Kumar V. Slope stability analysis of landslide zones in the part of Himalaya, Chamba, Himachal Pradesh, India. Environ Earth Sci. 2021;80:332. https://doi.org/10.1007/s12665-021-09629-z.
13. Singh K, Kumar V. Road cut slope stability assessment along Himalayan National Highway NH-154A, India. J Geol Soc India. 2020;9(5):491–8.
14. 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):167. https://doi.org/10.1007/s12040-020-01428-7.
15. Thakur T, Singh K, Sharma A (2024) A review on analysis and mitigation strategies for landslide risk management: case studies of Nainital, Satluj Valley, Pipalkoti, Jhakri, Panjpiri in Indian Himalayan Region, India. J Mining Environ.
16. Singh K, Bhardwaj V, Sharma A, Thakur S. A comprehensive review on landslide susceptibility zonation techniques. Quaestiones Geographicae. 2024;43(1):79–91.
17. Qazi A, Singh K, Vishwakarma DK, Abdo HG. GIS based landslide susceptibility zonation mapping using frequency ratio, information value and weight of evidence: a case study in Kinnaur District HP India. Bull Eng Geol Environ. 2023;82(332):1–24. https://doi.org/10.1007/s10064-023-03344-8.
18. Bhardwaj V, Singh K. Assessment of landslide susceptibility of Pithoragarh, Uttarakhand (India) using logistic regression and multi-criteria decision-based analysis by analytical hierarchy process. Appl Earth Sci. 2023;32(3–4):1–9. https://doi.org/10.1080/25726838.2023.2237370.
19. Joshi B, Singh B, Dikshit V. Study of landslide occurrence along main boundary thrust and its impact in Dehradun Region -A Report. INDOROCK: Third Indian Rock Conference by ISRMTT. 2011
20. Sarkar S, Kanungo DP, Kumar S. Rock mass classification and slope stability assessment of road cut slopes in Garhwal Himalaya, India. Geotech Geol Eng. 2012;30(4):827–40. https://doi.org/10.1007/s10706-012-9501-x.
21. Anbalagan R, Kohli A, Chakraborty D. Stability Analysis of Harmony Landslide in Garhwal Himalaya, Uttarakhand State, India. In: 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG) at: Goa, India. 2008
22. Thanh DQ, Nguyen DH, Prakash I, Jaafari A, Nguyen V-T, Phong TV, Pham BT. GIS based frequency ratio method for landslide susceptibility mapping at Da Lat City, Lam Dong province, Vietnam. Vietnam J Earth Sci. 2020;42(1):55–66. https://doi.org/10.15625/0866-7187/42/1/14758.
23. Choi J, Oh H-J, Lee H-J, Lee C, Lee S. Combining landslide susceptibility maps obtained from frequency ratio, logistic regression, and artificial neural network models using ASTER images and GIS. Eng Geol. 2012;124:12–23. https://doi.org/10.1016/j.enggeo.2011.09.011.
24. Ayalew L, Yamagishi H. The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains, Central Japan. Geomorphology. 2005;65(1):15–31. https://doi.org/10.1016/j.geomorph.2004.06.010.
25. Kanungo D, Mehrotra GS, Sarkar S. Lithotectonic evaluation of landslide and mass movements in Garhwal Himalaya. J Ind Soc Eng Geol. 1993;22:19–33.
26. Lee S, Talib JA. Probabilistic landslide susceptibility and factor effect analysis. Environ Geol. 2005;47(7):982–90. https://doi.org/10.1007/s00254-005-1228-z.
27. Gholami M, Ghachkanlu EN, Khosravi K, Pirasteh S. Landslide prediction capability by comparison of frequency ratio, fuzzy gamma and landslide index method. J Earth Syst Sci. 2019;128(2):42. https://doi.org/10.1007/s12040-018-1047-8.
28. Akinci H, Dogan S, Kılıçoğlu C, Temiz M. Production of landslide susceptibility map of Samsun (Turkey) City Center by using frequency ratio method. Int J Phys Sci. 2011;6:1015–25.
29. Pham BT, Phong TV, Nguyen-Thoi T, Parial K, Singh SK, Ly H-B, Nguyen KT, Ho LS, Le HV, Prakash I. Ensemble modeling of landslide susceptibility using random subspace learner and different decision tree classifiers. Geocarto Int. 2020;37(3):735.
30. Shahabi H, Hashim M. Landslide susceptibility mapping using GIS-based statistical models and Remote sensing data in tropical environment. Sci Rep. 2015;5:9899. https://doi.org/10.1038/srep09899.

31.   Mani A, Bansal D, Kumari M, Kumar D. Land use land cover changes and climate change impact on the water resources: a study of Uttarakhand State. In river conservation and water resource management (pp. 1–16). Singapore: Springer Nature Singapore; 2023.

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