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ASSESSMENT OF TERRAIN STABILITY ZONES IN THE BIRAHI GANGA RIVER BASIN, GARHWAL HIMALAYA, UTTARAKHAND, USING AHP AND GIS

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Abstract

The Himalayan region is globally recognised for its complex geology, highly dissected terrain, steep slopes, and intense monsoonal rainfall, making it one of the most landslide-prone and geomorphologically dynamic regions in the world. Landslides, slope failures, and flash floods are frequent in this region and severely affect human settlements, transportation infrastructure and natural ecosystems. Therefore, assessing terrain stability is crucial for sustainable habitation and development planning. The present study evaluates terrain stability zones in the Birahi Ganga River Basin using the Analytical Hierarchy Process (AHP) integrated with Geographic Information System (GIS) techniques. Spatial variability in terrain stability is evident across the basin. Eight key parameters—landslide zones, slope, tectonic units, normalised difference snow index (NDSI), dissection index, relative relief, absolute relief and normalised difference vegetation index (NDVI)—were analysed to generate a composite terrain stability map. Based on weighted overlay analysis, the basin was classified into five stability zones: stable, moderately stable, moderately vulnerable, vulnerable and highly vulnerable. The stable terrain covers 11.8% of the basin and is mainly concentrated in the north-western, central, and south-central parts, whereas highly vulnerable terrain accounts for 12% and is predominantly found in the eastern, north-eastern and south-western sections. Moderately stable and moderately vulnerable zones occupy 22% and 27.8% of the basin, respectively. Overall, the results indicate a gradual decrease in terrain vulnerability from the eastern to the western part of the basin. The study identifies suitable stable zones for human habitation and settlement expansion, demonstrating the effectiveness of the AHP–GIS approach for terrain stability assessment in mountainous regions.

Keywords: Birahi Ganga, Terrain Stability zones, Analytical Hierarchy Process (AHP), Geographical Information System (GIS).

1. Introduction

Mountainous regions are characterised by steep slopes, high relief, complex geological structures, and dynamic geomorphic processes which influence terrain instability and various types of geomorphic hazards such as landslides, slope failures, and flash

floods. The Himalayan regions are geologically young, tectonically active, and subjected to intense monsoonal rainfall experience frequent mass-wasting phenomena that significantly affect human settlements and socioeconomic infrastructure. According to the Geological Survey of India (GSI), nearly 12.6% of the total land area in the country is prone to landslides and Uttarakhand is one of the most affected states. The accelerated population growth demanded the use of areas which were not previously used for agricultural, settlement, urban expansion and other purposes, thereby exposing these areas to landslide problems after rainy seasons (Woldearegay, 2013). Both the natural factors such as lithological variation, tectonic activity, slope morphology, and hydrological conditions, along with anthropogenic pressures like deforestation, road construction, and unplanned settlement expansion trigger the terrain instability in the region. Therefore, assessing terrain stability is significant for sustainable land-use planning, disaster mitigation and environmental management in the study area. Terrain stability zones indicate the areas of slope stability with respect to unstable, potentially unstable and stable terrain within a particular landscape outline the zones of slope failure (Forest Practices Code of British Columbia 1999). Different types of terrain units were used (Guzzetti et al., 1999) and each terrain unit is assigned a series of attributes relevant to stability, including elevation, slope relative relief, dissection index, etc.

Though terrain stability assessment plays a significant role in regional development, there remains a significant research gap in evaluating terrain stability zones at the sub-basin level in the Garhwal Himalaya. In the Himalayan region, a number of research works have focused on landslide susceptibility mapping and hazard zonation; among them, a very few have used integrated multiple geomorphic parameters to assess terrain stability zones, particularly using a multi-criteria decision-making approach such as the Analytical Hierarchy Process (AHP) with the combination of Geographical Information System (Saha et al., 2002; Saha et al., 2005; Chauhan et al., 2010; Kundu et al. 2013; Dinesh Pathak, 2016; Khanduri, S., 2018; Nandy, S., 2021)

At present, different types of interdisciplinary decision-making approaches are used to determine the terrain stability zone. Analytical Hierarchy Process (AHP) is one of the prominent GIS based spatial decision support system, first introduced by Saaty in 1980. Nandy (2021) stated that “AHP is an approach using different types of multi-criterion, which focuses on the relative priorities assigned to each criterion to achieve a defined objective.” AHP is widely used to identify environmentally suitable zones, tourism potential areas, landslide susceptibility zones, agricultural suitability areas, land suitability areas, etc.

The present study analyses the geological, geomorphological and environmental parameters which influence terrain stability in the Birahi Ganga river basin. The primary objective of this study is to prepare a terrain stability map using selected parameters and the AHP–GIS techniques, to delineate and classify the basin into different stability zones and to identify potential areas suitable for sustainable human settlement and development planning.

2. Study area:

The present work is carried out in the Birahi Ganga river basin, located in the Joshimath and Dasholi blocks of Chamoli district of Garhwal division of Uttarakhand. The study area lies between 30º 19´10˝ N to 30º 26´9˝ N and 79º 23´18˝ E to 79º 42´24˝ E. The Birahi Ganga originates from the Nandaghungti glacier of the Nandadevi range at an altitude of about 5600 m and flows east to west direction and meets with the river Alaknanda as a left bank tributary at Jaisal village (30º 24´58˝ N& 79º 23´12˝ E). (Fig.1) The total geographical area of the basin is about 277.27 km² (Patra et al., 2018). Geologically, the study area is characterised by the Pandukeshwar Formation, Munsiyari Formation, Berinag Formation, Tejam Formation and Baijnath Crystalline. (Geological Map of Himalaya, scale 1:1000000, Western sector, Published by Geological Survey of India). In the study area, the presence of Vaikrita Thrust, Munsiyari Thrust, Baijnath Klippe, some minor Thrust and Anticlinal Axis signifies the instability of the area (Valdiya, 1976 & Sharma et al. 2017).

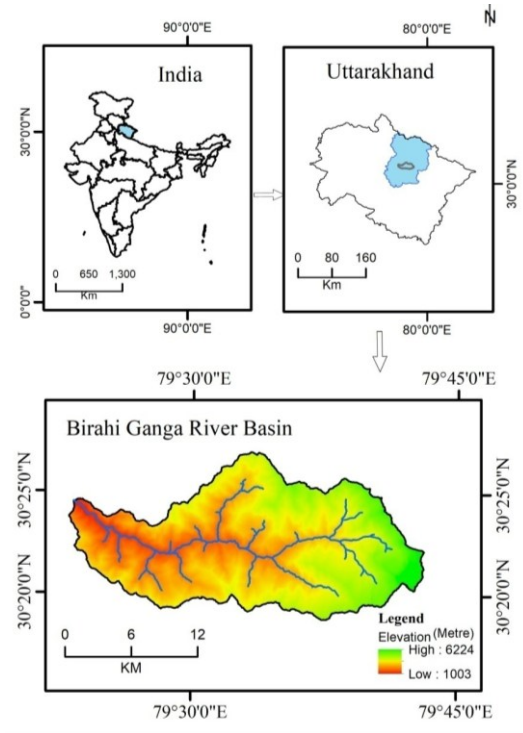


Figure 1: Location map of the study area, Birahi Ganga river basin

The study area is characterised by highly dissected hills and valleys, Altiplanation terraces, valley glaciers, Aretes, Hummocks, Piedmont Alluvial Plain, Piedmont Slope, Ridges, Tellus or Scree, etc. (Survey of India Toposheet 1:50000 and Geomorphological map, Geological Survey of India, Government of India, Kolkata, India). The mean monthly

temperature of the study area varies from 9.39º C in January to 24.53º C in May and the mean monthly rainfall varies from 0.5 mm in October to 454.60 mm in August. (www.imd.gov.in, accessed on 14/04/2019) The Birahi Ganga river basin is fed by Pui Gadhera, Kaliyaghat Gadhera, Shyam Gad, Rogila Gad, Dhadali Gad (right bank tributaries), and Gudiyar Gadhera, Bhori Gadhera, Ghat Gad, Begar Nala (left bank tributaries). The general elevation of the Birahi Ganga river basin varies from 1,000 m (at Jaisal village) to 5,600 m (at Nandaghungti) (Patra et al., 2018).

3. Database:

The main objective of this work is to identify the terrain stability zones in the Birahi Ganga river basin. Firstly, primary data were collected through GPS field surveys, along with interviews and questionnaires administered to experts in relevant disciplines to identify and prioritise the factors essential for demarcating terrain stability zones in the Birahi Ganga river basin. The secondary datasets, like satellite imagery, GIS datasets, articles, and previous records, were collected and are listed in the Table1.

Table 1: Characteristics of the used datasets

Data	Scale/resolution	Date of acquisition	Source	Remarks
Topographical maps	1:50000	-	Survey of India (SOI)	Two Sheets-53N/7 & 53N/11 of the year 1967 7 1985.
ALOS PALSAR DEM	Spatial resolution: 12.5 m	18/11/2018	www.asf.alaska.edu	Radiometrically Terrain Corrected (RTC) data.
Landsat 8-OLI	Spatial resolution: 30 m	17/12/2021	United States Geological Survey (USGS)	-
Landslide data	1: 20,00,000	15/03/2022	National Disaster Management Authority (NDMA), Uttarakhand	
Geology & Tectonic	1:333000	-	Works of Valdiya (1976&1979) & Sharma et al (2017).	-

The selected parameters and their thematic layers were prepared with the help of Microsoft Excel v. 2016 and ArcGIS 10.5 software. Slope, relative relief, absolute relief, and dissection index map have been prepared from ALOS PALSAR DEM by using spatial analysis tools in the ArcGIS environment. The landslide-prone zonation map of the study area has been prepared on the basis of the data provided by the National Disaster Management Authority (NDMA), Uttarakhand. Normalised Difference Vegetation Index (NDVI) maps were prepared from Landsat 8 OLI data with the help of the raster calculator in a GIS environment. Normalised Difference Snow Index (NDSI) was calculated from the Landsat-8 OLI data in ArcGIS 10.5 software.

4. Methodology:

To identify the stable terrain, the first step is the selection of suitable parameters. In this study, eight different parameters such as, landslide prone area, slope, tectonic unit, snow affected area, dissection index, relative relief, absolute relief and normalised difference vegetation index (NDVI) were used. Adequacy of parameters and easy

generation of parameters from related sources for ascertaining the variety of the terrain stable zones are two main causes for selecting these parameters (Nandy,2021).

The final terrain stability map has been prepared through the AHP method in ArcGIS 10.5 software by calculation of the weight of each criterion and sub-criterion (Figure 2).

4.1. Landslide-prone areas

Landslide-prone zones play an important role in marking unstable and vulnerable areas. The landslide-prone zonation map of the study area has been prepared on the basis of the data provided by the National Disaster Management Authority (NDMA), Uttarakhand. At first, the main map was converted into WGS-84 datum and UTM projection, then digitised the map in ArcGIS 10.5 software to trace out three landslide prone zones-moderate to low, high and severe to very high with in the Birahi Ganga valley (Figure 3) and ranked them according to the terrain stability.

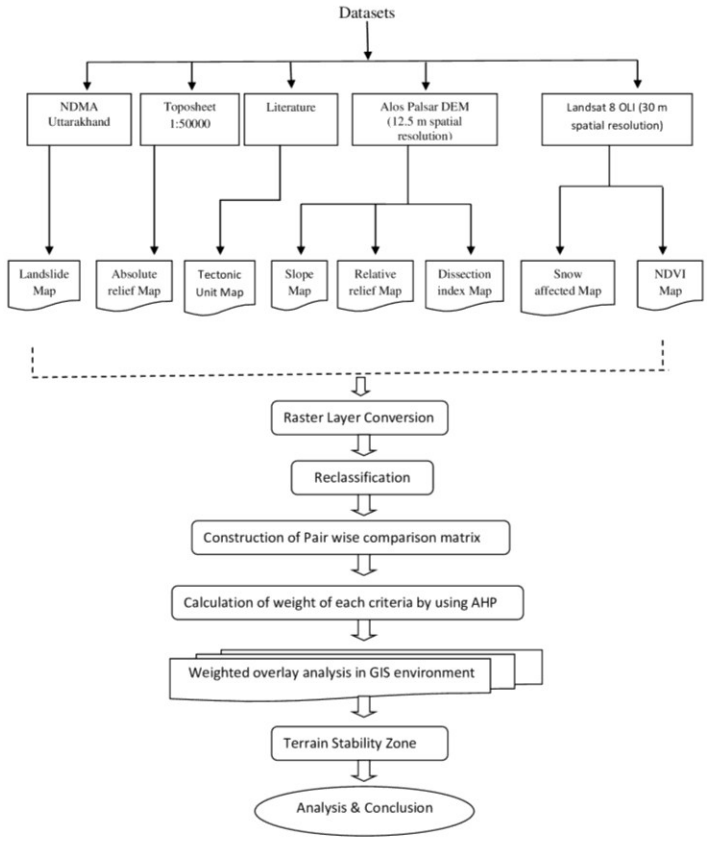


Figure 2: Flow chart of the terrain stability mapping for the study area

4.2. Slope

To determine the stability of a region, slope is a very important landform element (Saha et al., 2005) because the angle of slope show tendency of the slope materials to slide under the force of gravity, nullifying the shearing strength of the component materials in situ. There is a positive relation between slope and erosion (Bhattacharya, 2018). The larger number of landslides occurs in the case of the steeper slope angle of the slope (Youssef et al.,2021).“The stability of the slope against failure can be defined by the relationship between shear forces and the resistance to shear (safety factor), where the driving force of mass movement increases with increasing slope angle” (Guillard and Zezere, 2012). It is an important parameter to determine the terrain stability zones in the study area. It is the first procurement of elevation, with each pixel denoting the angle of slope at a particular location (Saha et al. 2005). Slope gradient directly controls the run-off and indirectly the presence of the soil moisture, which are influenced to the landslide occurrence. In the Himalayan terrain, due to the lack of vegetation or scantily vegetated of, the south-facing slopes are generally more susceptible to slope failure as compared to north-facing slopes (Sinha et al,1975). The slope map of the study area was prepared from ALOS PALSAR DEM (12.5) by using the spatial analysis tool in ArcGIS 10.5 software. The slope angle of the study area ranged from 0º to 82º, which were categorised into five classes at an equal interval of 10º (Fig. 3).

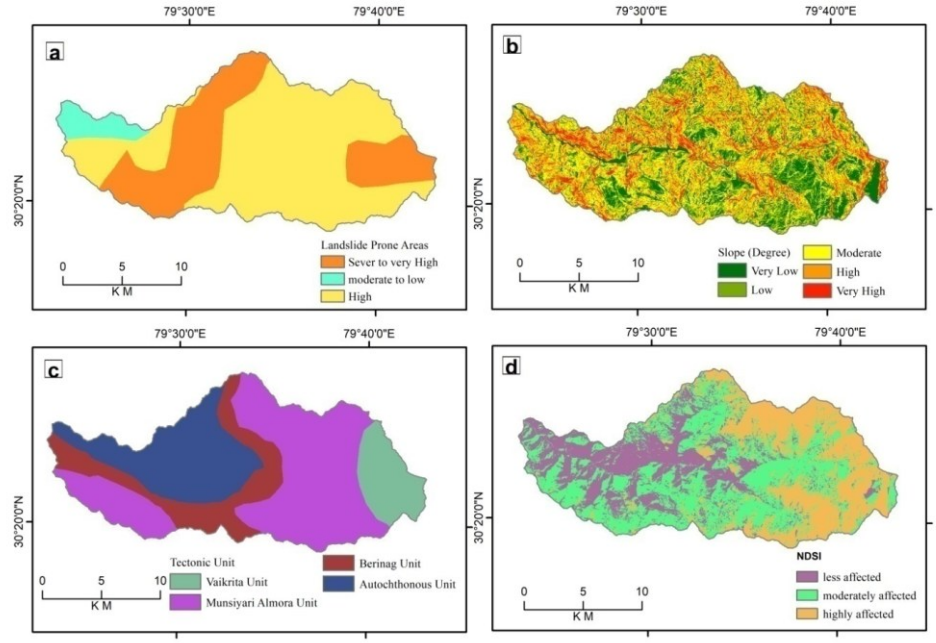


Figure 3: Reclassified parameters: a) Landslide-prone areas, b) Slope, c) Tectonic Unit and d) Snow-affected area

4.3. Tectonic Unit

Terrain stability greatly depends on the bedrock geology of an area, on which geomorphic processes design the landscape (Bhattacharya, 2018). The structural lines and geological formations affect the occurrence of landslides as well as the terrain stability (Bhattacharya 2018). In the study area, four tectonic units have been identified, these are Autochthonous unit, Berinag unit, Munsiyari-Almora unit and Vaikrita unit. Among them Autochthonous unit is comparatively stable, occupying about 26.71% of the total area; on the other hand Vaikrita unit is comparatively highly vulnerable due to the presence of the Vaikrita thrust, and occupied 11.43% of the total area. The tectonic map of the Birahi Ganga river basin had been prepared on the basis of the work of Valdiya (1976). At first, the main map is georeferenced and converted into the WGS 84 datum and UTM projection, and then four tectonic units were digitised (Figure 3).

4.4. Snow-affected area

Snow covers or glaciers, increase instability and vulnerability through physical weathering, erosion, and avalanches. To identify the snow-covered area in the Birahi Ganga river basin, the Normalised Difference Snow Index (NDSI) was calculated from the Landsat-8 OLI data in ArcGIS 10.5 software. Hall et al. (2011) defined Normalised-Difference Snow Index (NDSI) as the normalized difference of two bands (one in the visible and one in the near-infrared or short-wave infrared) and primarily used to map snow cover. The major advantages of NDSI are its elasticity to atmospheric effects and influences caused by viewing geometry (Sibandjeet al., 2014). The NDSI formula is Green-SWIR/Green+SWIR

A greater value (>0.00) of NDSI indicates the presence of snow, whereas a low NDSI value (≤0.0) indicates a snow-free land surface (Riggs et al.,2016). On the basis of the NDSI value, the study area was divided into three zones: less affected, moderately affected, and highly affected. (Fig. 3)

4.5. Dissection Index (DI)

DI plays a very important role in knowing the terrain configuration resulting from the prevalent processes such as the mass movement and fluvial dynamics and also the structural instability exhibited in the form of faulting, tilting, thrusting, and folding (Bhattacharya, 2018). Dissection index is determined for understanding the magnitude of dissection of terrain, morphometry, and physiographic attributes (Singh, 2000). The dissection index helps to identify the stable and unstable terrain. The high value of the Dissection index indicates high relief energy and a high propensity for slope failure when associated with geologically weak and deformed rock strata, and hence the dissection index is closely associated with the stability of the terrain of a region. The dissection index map of the study area was prepared from ALOS PALSAR DEM (of 12.5 m spatial resolution) in ArcGIS 10.5 software by using cartographic and spatial analysis tools. The

value of the dissection index in the study area ranged from 0.0345 to 0.489 and which has been further classified into five classes at 0.1 interval. (Fig. 4)

4.6. Relative relief

The difference between the highest altitude and the lowest altitude in a unit area is called relative relief. There is a close relationship between relative relief and slope and it is more revealing about the localised variation of the magnitude of landform and thus very much beneficial in understanding the potential energy of the landform associated with erosional drainage systems and instability of the slopes (Bhattacharya, 2018). In general, high relative relief indicates steep slope, high erosion probability and landslide potentiality, on the other hand, low relative relief indicates gentle slope and comparatively stable zone (Bhattacharya, 2018). Due to this, relative relief shall be an effective parameter for determing terrain stability zones. The relative relief map of the study area has been prepared from ALOS PALSAR DEM in ArcGIS 10.5 software by using cartographic and spatial analysis tools. The value of relative relief in the study area ranges from 194.61 m to 1231.94 m, which has been classified in five zones at a 200 m interval. (Fig. 4)

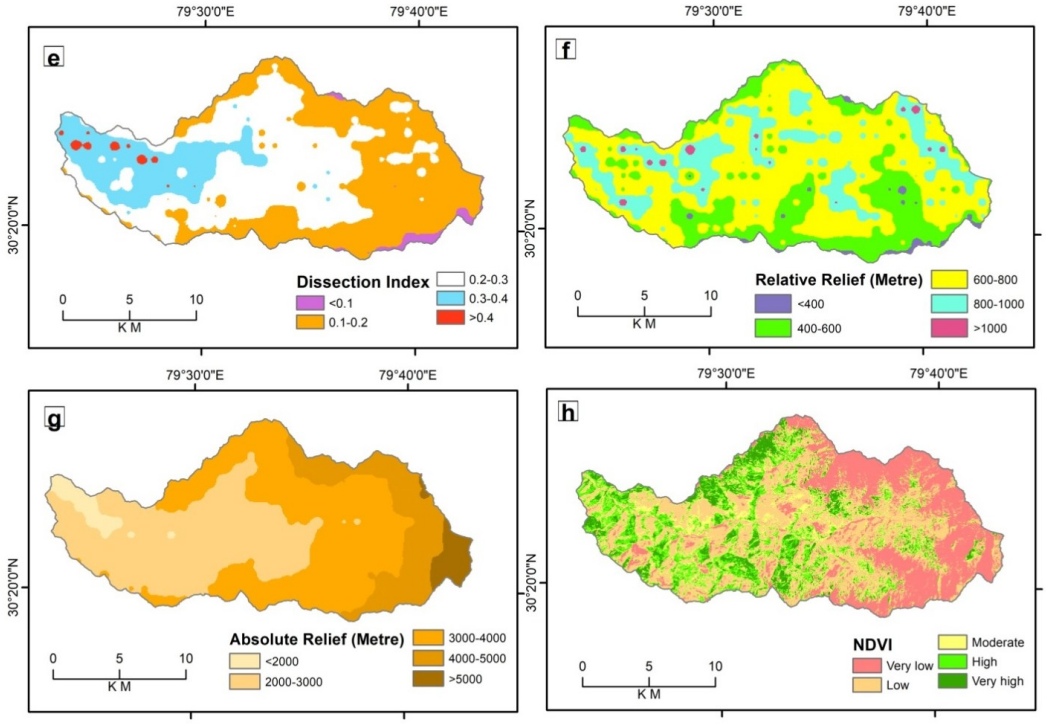


Figure 4: Reclassified parameters: e) Dissection Index, f) Relative relief, g) Absolute relief and h) NDVI

4.7. Absolute relief

Elevation plays a vital role in the terrain sensibility since the higher the elevation higher the relief energy, which responds to the impact of gravity (Bhattacharya, 2018). Generally, altitudinal zones play an important role in the determination of terrain stable zones. Different geological, geomorphological, and meteorological factors such as lithological units, weathering, wind action and precipitation determined the altitude of a region. Altitude is a topographic factor that influences slope instability. It has been mostly used in almost all landslide susceptibility analyses. It was found that increasing elevation decreases the balance of the terrain, similar to the theory of Archdeacon Pratt in the concept of isostasy, the rocks of more elevated objects are made by low-density material and vice versa, which in turn easily destroys the stability of the terrain (Nandy, 2021). The absolute relief map of the study area has been prepared based on some major contour lines by using the digitised method in a GIS environment from SOI Toposheet 1:50,000. The altitude of the basin varies from 1000 m (Jaisal village) to 5600 m (Nandaghungti). The absolute relief of the study area has been classified into five zones at 1000 m intervals. (Fig. 4)

4.8. Normalised Difference Vegetation Index (NDVI)

The Normalised Difference Vegetation Index (NDVI) helps to analyse the vegetation cover of the study area. In the twenty-first century, many researchers used NDVI for vegetation-related monitoring in numerous studies. The vegetation cover plays a vital role in immobilising huge amounts of water through absorption and raising the shear resistance and soil cohesion of the lithological mass (Sidle and Ochiai, 2006). The Normalised Difference Vegetation Index (NDVI) calculation was performed from Landsat 8 OLI imagery of NASA in ArcGIS 10.5 m software based on the following formula-

NDVI = NIR-RED/NIR+RED

Near Infrared (NIR) indicate the wavelength (0.85-0.88) from band 5 and Red indicates the wavelength (0.64-0.67) from band 4 of Landsat 8 OLI satellite imagery. Low NDVI value (<0.18) indicates barren land, built-up area, water body, whereas high NDVI value (>0.18) indicates shrub to dense vegetation. For vegetation, the threshold range is between 0 and 1, with 1 corresponding to very healthy vegetation and 0 reflecting dry and withered plants (Patra et al. 2022). The entire basin is divided into five zones on the basis of NDVI value, these are Very high NDVI value (covers 9.36% area), High NDVI value (covers 17.01%), Moderate NDVI value (covers 10.43%), Low NDVI value (coves 37.41%) and very low NDVI value (covers 25.79% area) (Fig. 4).

4.9. Calculation of Weight for each criterion

To solve any kind of decision-making problem through the AHP model, prioritisation of the criteria by ‘pair-wise comparison’ of all the selected layers is taken into consideration”

(Nandi, 2021). “An excellent and well-known weight evaluation method is the analytical hierarchy process (AHP) proposed by Saaty (1977), which—with regard to the development of weights—has already been called one of the most promising techniques” (Eastman et al.,1998). “To be able to develop criteria weights, the AHP calculates the eigenvalues and the eigenvectors of a square preference matrix which contains the quantified preference information of all possible pairwise criteria constellations” (Marinoni, 2004). “The AHP, as a multi-objective multi-criteria decision making approach, uses a pairwise criteria comparison to arrive at a scale of preferences among sets of alternatives” (Saaty and Vargas, 1991). Here, every parameter is compared to the others by imposing a relative value between 1 and 9. In the present study, Saaty’s fundamental scale for the degree of importance has been used.

Table 2: The fundamental scale for the degree of importance

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one activity over another
5	Essential or Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

In the ‘pair-wise comparison matrix’, each criterion is related to another criterion in the hierarchical order between 1 and 9 (where the criteria of row become important over column) and between 1/2 and 1/9 (where the criteria of column become important over row). Using the pair-wise, the analytical hierarchy process calculates comparative weights for individual criterion layers (Yalew, et al.2016).

Acceptability of the matrix table has been checked through the Consistency Ratio (CR). The value of the CR is measured through the following formula –

$$CR = CI/RI$$

Where, CI is the Consistency Index and RI is the Random Index of hierarchical order of the matrix. The formula of the CI is

$$CI = (\lambda max - n) / (n - 1)$$

Where λmax is the principal or highest eigenvalue of the matrix and n indicates the order of the matrix. For a significant result, the value of CR must be less than 0.10 (Saaty, 1977). Weights or priorities are decided by normalising the pairwise comparison matrix (Akinci, *et al.*2013, p. 6)

Table 3: Pairwise comparison matrix of 12 stability prospecting factors for the AHP process

Criteria/parameters	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Landslide zones [1]	1	2	3	4	5	7	8	9
Slope [2]	1/2	1	2	4	4	6	7	8
Tectonic Unit [3]	1/3	1/2	1	3	4	5	6	7
Snow-affected area [4]	1/4	1/4	1/3	1	2	4	5	7
Dissection Index [5]	1/5	1/4	1/4	1/2	1	2	4	5
Relative Relief [6]	1/7	1/6	1/5	1/4	1/2	1	2	3
Absolute Relief [7]	1/8	1/7	1/6	1/5	1/4	1/2	1	2
NDVI [8]	1/9	1/8	1/7	1/7	1/5	1/3	1/2	1

Max. Eigenvalue (λmax) = 8.437; n = 8
Consistency Index (CI) = (8.437–8)/(8–1) = 0.0624
Random Index (RI) = 1.404
Consistency ratio (CR) = (0.0624/1.404) = 0.044; Consistency check = 4%

Table 4: Saaty's Random Index for different values of n

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.525	0.882	1.115	1252	1.341	1.404	1.452	1.484	1.513	1.535	1.555	1.570	1.583

Table 5: Normalised value of cumulative weight (Cw) for each parameter

Criteria/parameters	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	Normalised Weight
Landslide zones [1]	0.38	0.45	0.42	0.31	0.29	0.27	0.24	0.21	0.317
Slope [2]	0.18	0.23	0.28	0.31	0.24	0.23	0.21	0.19	0.233
Tectonic Unit [3]	0.12	0.11	0.14	0.23	0.24	0.19	0.18	0.17	0.172
Snow-affected area [4]	0.09	0.06	0.05	0.08	0.12	0.15	0.15	0.17	0.108
Dissection Index [5]	0.08	0.06	0.04	0.04	0.06	0.08	0.12	0.12	0.076
Relative Relief [6]	0.05	0.04	0.03	0.02	0.03	0.04	0.06	0.07	0.045
Absolute Relief [7]	0.05	0.03	0.02	0.01	0.01	0.02	0.03	0.05	0.028
NDVI [8]	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.016

The normalised weight of every thematic layer has been derived by calculating the eigenvector. According to Table 5, landslide zones, which occupies 31.7% weightage is the most important parameter to identify stability. Similarly, Slope (23.5%), Tectonic unit (17.5%), Snow affected area (10.8%), Dissection Index (7.6%), Absolute Relief (2.8%) and NDVI (1.6%) respectively, occupy their weightage and position regarding the influence of terrain stability. The normalised value of each sub-criterion of every parameter has been calculated through rank normalisation. Determination of the rank score of every sub-criterion based on a 'Likert scale' where rank is assigned within 5 responses in numerical value to measure the characteristics of stability of sub-criteria under investigation. Here, the highest rank represents greater terrain stability and vice versa. At last rank normalisation value is multiplied by the parameter weight to get the normalised value of each sub-criterion. After getting the normalised value of each sub-criterion, add the values in the attribute table and prepared terrain stability map by using the weighted overlay tool in ArcGIS 10.5.

Table 6: Normalised value of each sub-criterion of different parameters

Criteria/parameters	Sub-criteria	Parameter weight	Rank	Rank normalization	Normalised value	Area in km2	Area in %
Landslide zones	Moderate to low	0.317	1	0.1667	0.053	14.55	5.25
	High		2	0.3333	0.1056	167.18	60.30
	Severe to very high		3	0.5000	0.1585	95.54	34.45
Slope	<20°	0.235	1	0.0667	0.0156	45.19	16.30
	20° - 30°		2	0.1333	0.0313	70.80	25.53
	30° - 40°		3	0.2000	0.0474	70.69	25.50
	40° - 50°		4	0.2667	0.0626	59.09	21.31
	>50°		5	0.3333	0.0783	31.50	11.36
Tectonic Unit	Autochthonous Unit	0.175	1	0.1000	0.0175	74.07	26.71
	Berinag Unit		2	0.2000	0.0350	52.14	18.80
	Munsiari Almora Unit		3	0.3000	0.0525	119.38	43.06
	Vaikrita Unit		4	0.4000	0.0700	31.68	11.43
Snow-affected area	Less affected	0.108	1	0.1667	0.0180	81.13	29.26
	Moderately affected		2	0.3333	0.0359	110.38	39.81
	Highly affected		3	0.5000	0.0541	85.76	30.93
Dissection Index	<0.1	0.076	1	0.0667	0.005	4.42	1.59
	0.1 – 0.2		2	0.1333	0.010	117.51	42.38
	0.2 – 0.3		3	0.2000	0.015	105.82	38.16
	0.3 – 0.4		4	0.2667	0.020	47.44	17.12
	>0.4		5	0.3333	0.025	2.08	0.75
Relative Relief	<400	0.045	1	0.0667	0.003	3.45	1.24
	400 – 600		2	0.1333	0.005	70.56	25.45
	600 – 800		3	0.2000	0.009	142.17	51.27
	800 – 1000		4	0.2667	0.012	58.91	21.25
	>1000		5	0.3333	0.014	2.18	0.79
Absolute Relief	<2000	0.028	1	0.0667	0.0018	9.33	3.36
	2000 - 3000		2	0.1333	0.0037	110.41	39.82
	3000 - 4000		3	0.2000	0.0056	100.12	36.11
	4000 - 5000		4	0.2667	0.0074	46.95	16.93
	>5000		5	0.3333	0.0093	10.46	3.77
NDVI	Very Low	0.016	1	0.0667	0.0010	25.95	9.36
	Low		2	0.1333	0.0021	47.16	17.01
	Moderate		3	0.2000	0.0032	28.93	10.43
	High		4	0.2667	0.0042	93.72	33.80
	Very High		5	0.3333	0.0053	81.51	29.40

5. Results and Discussion

5.1. Terrain stability map

The predicted terrain stability map of the study area has been prepared with the help of eight parameters, i.e. landslide-prone area, slope, tectonic unit, snow-affected area, dissection index, relative relief, absolute relief, and Normalised Difference Vegetation Index. Among the parameters, Landslide prone area is considered the foremost and the terrain stability is directly regulated by this parameter (Escape et al, 2015). The landslide-prone zonation map is classified into three vulnerability zones: i) moderate to low, ii) high and iii) severe to very high. Among them high landslide-prone area covers the maximum area (60.30%), followed by the middle, the middle-east and one patch in the western side of the basin. Severe to very high landslide-prone area (unstable terrain) is observed in the extreme eastern (upper part of the basin) and the middle-western portion of the study area. Landslide, slope failure, rock creep, and soil erosion are directly related to slope. The total area of the basin is classified into five slope categories, these are: i) Very low (<20º), ii) Low (20º -30º), iii) Moderate (30º -40º), iv) High (40º -50º), and v) Very High (>50º). These slope zones are unevenly distributed in the different parts of the basin. Among them, 20º to 30º, and 30º to 40º slope zones occupied 51.03% of the study area. Very low (<20º) and very high slope zone (>50º) covers 16.30% & 11.36% respectively. In the study area, four major tectonic units are identified: i) Vaikrita Unit, ii) Munsiyari Almora Unit, iii) Berinag Unit and iv) Autochthonous Unit. The Munsiyari-Almora Unit is observed in the middle-east and south-western part has spread over 43.6%, followed by Autochthonous Unit, Berinag Unit and Vaikrita Unit covers 26.71%, 18.80% and 11.43%, respectively. Snow directly controls weathering phenomena, and the study area is classified into less affected, moderately affected, and highly affected snow cover zones. The highly affected snow cover area occupied 30.93% of the study area, noted in the eastern part of the basin and the less affected snow cover area cover 29.26% of the study area and was observed in the western part of the basin.

The roughness of terrain is clearly identified by the dissection index. On the basis of the dissection index value, the total area is divided into five zones: i) <0.1, ii) 0.1-0.2, iii) 0.2-0.3, iv) 0.3-0.4, and v) >0.4. The lowest category observed in the southern, northern, north-eastern and eastern parts of the basin occupied 43.97% of the study area and the high category observed in the middle and western parts of the basin occupied 17.87% of the study area. Direct relation with slope encourages relative relief to be an effective parameter for estimating terrain stability (Bhattacharya, 2018). The relative relief of the Birahi Ganga river basin has been classified into five groups: i) <400 m, ii) 400-600 m, iii) 600-800 m, iv) 800-1000 m and v) >100 m. Very low (<400 m) to low (400-550 m) relative relief classes occupied 74.01 km² (26.69%), whereas moderate (600 800 m) to high (800 1000 m) relative relief classes occupied 218.71 km² (78.87%) and were unevenly distributed in the basin.

The proportionate relationship between altitude and stability acquires an assured situation in the examination of terrain stability analysis (Pack et al, 2001). Based on altitude, the study area was divided into five classes: i) <2000 m (3.36%), ii) 2000-3000 m (39.82%), iii) 3000-4000 m (36.11%), iv) 4000-5000 m (16.93%) and v) >5000 m (3.77%). The elevation of the study area increases from west to east and instability also increases proportionally. There is a positive relationship between vegetation cover and terrain stability. On the basis of NDVI, the study area was classified into five zones: i) Very low (9.36%), ii) Low (17.01%), iii) Moderate (10.43%), iv) High (33.80%) and v) very high (29.40%). High to very high NDVI zones are mainly observed in the western, northern, southern and south-western parts of the study area and low to very low NDVI zones are observed in the middle, north-eastern, eastern and south-eastern portions of the study area.

5.2. Assessment of Terrain stability zones

The terrain stability map of the study area has been prepared on the basis of the weight of the different thematic layers and their classes in a GIS environment. The final map of the terrain stability has been classified into five zones using the quintile classification method. The study area is classified into five terrain stability zones: stable, moderately stable, moderately vulnerable, vulnerable, and highly vulnerable. The stable terrain zone observed in the middle and north of the north western part of the basin occupied 32.84 km². The highly vulnerable zone identified in the middle to eastern part and the south western to western part of the basin occupied 33.51 km².

Table 7: Area of different terrain stability zones

Terrain stability zones	Area (in km²)	Area (in %)
Very stable	32.84	11.84
Stable	61.18	22.07
Moderate stable	77.03	27.78
Unstable	72.71	26.22
Severely unstable	33.51	12.09

Table 7 shows that the area under the very stable zone occupied 11.84% of the total area and is noted mainly in the north-western, western, middle, and middle-southern portions of the basin. The village, namely Birahi, Garigaon, Sainj, Gauna, Pagnamalla, Irani, Jhinji, GengKharak, BodnaKharak, MerumKharak, etc., fall under this zone. The stable zone covers 22.07 % of the study area and is observed in the south-eastern, southern, and mid-western portions of the study area. The stable zone was found around the Soti, Thala, Tuna, Durmi, Semkharak, Taraktal, Madura, Nijmulaetc villages. Among the five zones, these two zones are suitable for human habitation. The moderately stable zone covers 27.78% of the study area, and is mainly observed in the south-western, northern, north-eastern, and south-western portions of the study area (Fig 5).

Due to the presence of steep slopes, lofty mountains, snow cover, rocky outcrops, and glaciers in the south-western, eastern, north-eastern, and south-eastern portions of the study area make unstable to severely unstable.

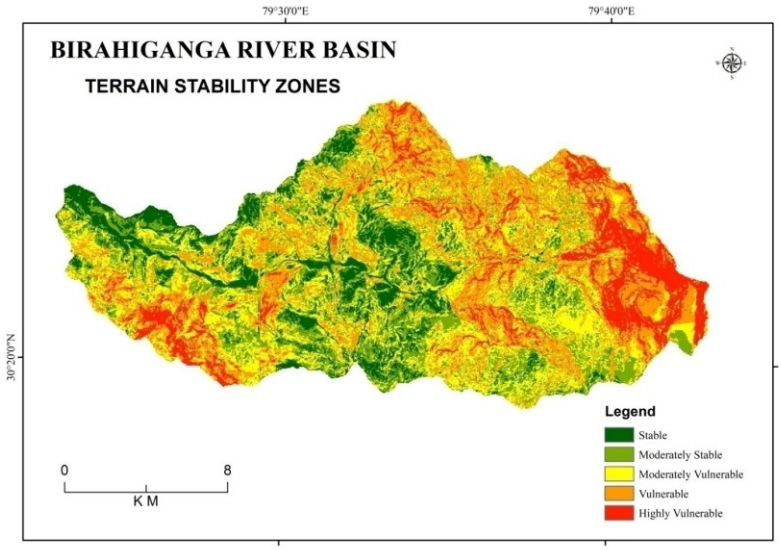


Figure 5: Terrain stability zones of the Birahi Ganga river basin

6. Conclusion

The present work elucidates the integration of Analytical Hierarchy Process (AHP) and Geographical Information System (GIS) techniques for assessing terrain stability zones in the Birahi Ganga river basin of the Garhwal Himalaya. Based on the eight key variables of geological, geomorphological, and environmental conditions, the terrain stability map of the study area was prepared and classified into distinct stability zones: stable, moderately stable, moderately vulnerable, vulnerable and highly vulnerable. The study found that stable (11.84%) and moderately stable (22.07%) zones are primarily distributed in the north-western, middle, and southern portions of the study area. These areas are relatively less affected by tectonic activity, slope instability and snow cover, making them suitable for settlement and associated anthropogenic activities like farming, marketplaces, places of worship, transport, and communication networks. On the other hand, the eastern, north-eastern, and south-western portions of the basin are characterised as highly vulnerable (12.09%) zones due to high relative relief, steep slopes and increased landslide susceptibility. A gradual decrease in terrain vulnerability from the eastern to the western part of the basin has been observed, reflecting the influence of topographic gradient and lithological variation. The study highlights that slope, landslide susceptibility and tectonic structures are the most influential factors controlling terrain stability in the Himalayan environment.

The integration of AHP and GIS helps to evaluate terrain stability and identify suitable zones for infrastructure development and disaster risk reduction. The results of the present study help engineers, policy makers, and regional planning authorities to implement sustainable land-use strategies and minimise geomorphic hazards in the Birahi Ganga river basin and other similar Himalayan terrains.

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