Landslide Susceptibility Mapping in Darjeeling Hills

Passang Sherpa[1], Uttam Lal[1], Rajesh Kumar[1]

Abstract

Landslides are recurrent natural events that pose significant risks to human settlements and infrastructure, particularly in craggy Himalayan terrains like the Darjeeling Hills. This study aims to examine landslide events in the region, analyze their occurrence, underlying factors, and implications for the local community. Various datasets, including landslide point data, geology maps, road networks, rainfall data, slope maps, and physiography maps, were utilized for spatial analysis of landslides. The findings reveal that landslide occurrences are concentrated in the high and middle altitudinal hills, particularly in areas with extremely steep slopes. The high precipitation and weak geology of the region contribute to the vulnerability of these areas to landslides. Rainfall, road density, slope, and geology were utilized for landslide susceptibility mapping using weighted overlay method in GIS environment. The landslide susceptibility zones were divided into four classes i.e., highly unstable, moderately unstable, moderately stable and stable that cover 1%, 45%, 46% and 7% of the total study area (1265.1 km^2*). The findings of the study can be used for mitigation of landslides and land use planning.*

Keywords: *Landslides, Darjeeling Hills, Landslide Susceptibility Zonation, GIS*

1. Introduction

Landslides are - widespread and devastating calamity, particularly in the Himalayas, due to the physical makeup of the terrain and the presence of loose rock and debris materials. They are sporadic and simultaneous natural hazards in mountainous regions, leading to altered landscapes and significant losses (De, 2017; Dikshit et al., 2020). One of the primary factors behind landslides is the gravitational force, causing slopes to shift from stable to unstable condition (Chawla et al., 2018). Landslides

[1] Department of Geography, School of Human Sciences, Sikkim University, Gangtok 737102, Sikkim, India

pose significant hydrogeological and man-made elements, posing risks to human settlements, transportation networks, civil infrastructures, and natural resources such as agricultural land and forests (Nad, 2015).

In the Darjeeling Himalayas, landslides are notably prevalent along overflowing water sources that intersect with roads like the 'Hill Cart Road' and other hill-lowland connections (De, 2017). One particularly vulnerable area is near the Upper and Lower 'Pagal Jhoras', where the road has experienced subsidence up to a depth of approximately 7-9 meters since 1979 (Basu, 2001). The region has a history of significant landslides, with documented occurrences in 1899, 1950 (resulting in 127 fatalities), and 1968 (with 667 fatalities) (Pal et al., 2016). The Darjeeling hills are frequently affected by landslides that cause loss of human lives and damage to public and private properties (District Disaster Management Plan Darjeeling, 2022-23). The present study aims to comprehensively identify the multifaceted factors associated with occurrence of landslides in the Darjeeling Hills and to prepare a landslide susceptibility map.

2. Study Area

Darjeeling Hill comprises the northern part of the Indian state of West Bengal. It is situated in the Eastern Himalayan region which is located at a height of 300 to 12000 feet from mean sea level (DCHB, 2011). Darjeeling Hill includes three hilly subdivisions of Darjeeling Sadar, Kalimpong, and Kurseong, comprising an area of 2476 km^2 and hosting a population of 7,90,591 in 2011. Geographically, the Darjeeling district is divided into two large sub-areas i.e., the hill region and the plains region (Nad, 2015).

Kalimpong is a separate district were carved out from the Darjeeling district in 2017 and has not been considered in the present study. Presently, the Darjeeling Hill region consists of two subdivisions named Darjeeling Sadar and Kurseong, comprising an area of 1265.1 km^2. while the Plain region consist of Siliguri Subdivision, comprising an area of 802.01 km^2.

The Darjeeling Hills are bordered by the state of Sikkim to the north, while in the east, they adjoin the captivating district of Kalimpong. To the south, the boundaries of the Darjeeling Hills extend towards the bustling subdivision of Siliguri, and in the west, they share an international border with Nepal (Figure 1).

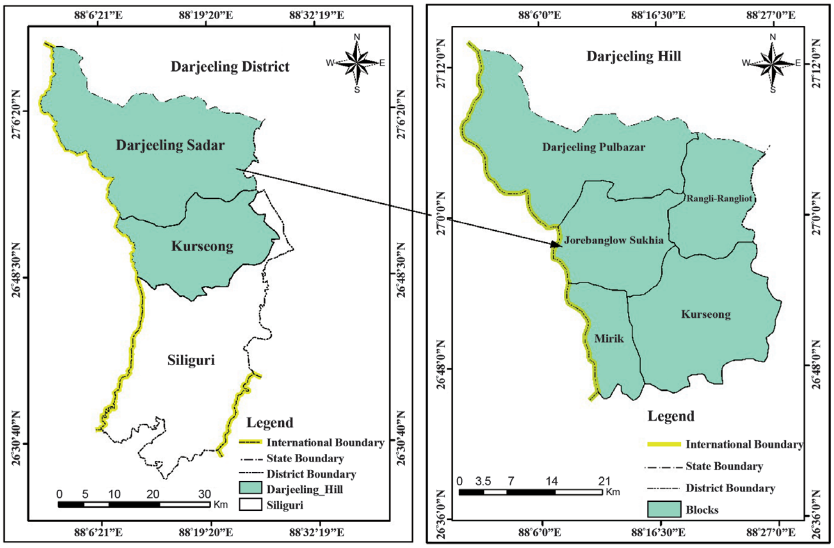

Figure 1: Location Map of the Study Area

Source: District Census Handbook, Darjeeling, 2011.

3. Materials and Methods

The present study focuses on investigating landslides in the Darjeeling Hills, utilizing diverse datasets and information sources. The key datasets employed in the research include landslide point (1991-2017) and geology data were collected from the Geological Survey of India (GSI) Bhukosh platform. Additionally, Road Network Data extracted from Open Street Map is utilized to understand the road infrastructure, including national highways and state highways, connecting the hills to the lowlands. Rainfall Data obtained from the India Water Resource Information System (WRIS) offers annual rainfall expressed in millimeters and records of the normal rainfall over the region. Forest And Buildings removed Copernicus (FAB) digital elevation model (DEM) version 1-0 was obtained from Hawker and Neal (2021). Spatial resolution of DEM is 30m. The Physiography of Darjeeling Hills is collected from Cajee (2018). All the spatial data sets were assimilated at 30 m spatial resolution using UTM 45 N projection system and WGS 84 datum in GIS environment.

Geospatial analysis techniques are then employed to identify the factors associated with landslides. Slope was computed using FAB DEM in GIS environment.

Road density was computed using 1km x 1km mesh size in GIS environment. Datasets related to geology, physiography, slope, road density, and rainfall are integrated and analyzed to assess their influence on landslide occurrences. Subsequently, Landslide susceptibility zonation maps are generated through weighted overlay analysis in GIS environment, considering factors such as slope, rainfall density, road density, and geology. These maps classify areas into highly unstable, moderately unstable, and stable zones, providing valuable insights into the distribution of landslide-prone areas. The study results are visually presented using ArcGIS 10.2, allowing for clear visualization of landslide occurrences, susceptibility zones, and the spatial relationship between influencing factors (Figure 2).

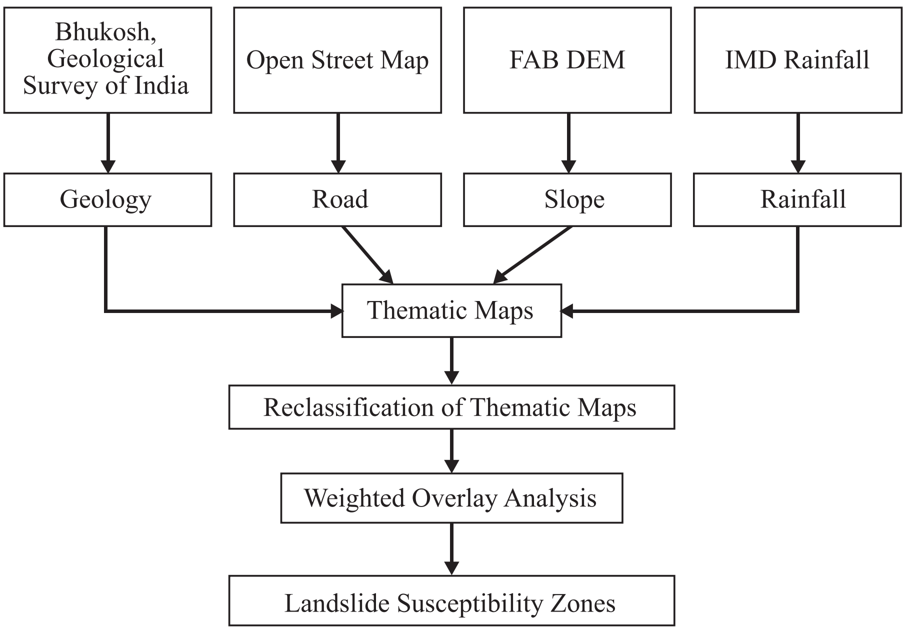

Figure 2: Flow diagram showing Methodology used for Landslide Susceptibility Zonation

4. Results and Discussion

Spatial Analysis of Landslides in Darjeeling Hills

In Darjeeling, a landslide is the more frequently occurring natural disaster and is caused by several factors such as the geological makeup of the area, slope, rainfall, soil, physiography, and by human interventions. To know the past landslide occurrence in Darjeeling a landslide inventory map is prepared, which is a geospatial representation that identifies and documents the location, extent, and characteristics of past landslides in a given area. It serves as a valuable tool for understanding the distribution and frequency of landslides, which can aid in assessing landslide susceptibility zonation and informing land-use planning, disaster management, and mitigation strategies (Martha et al., 2021).

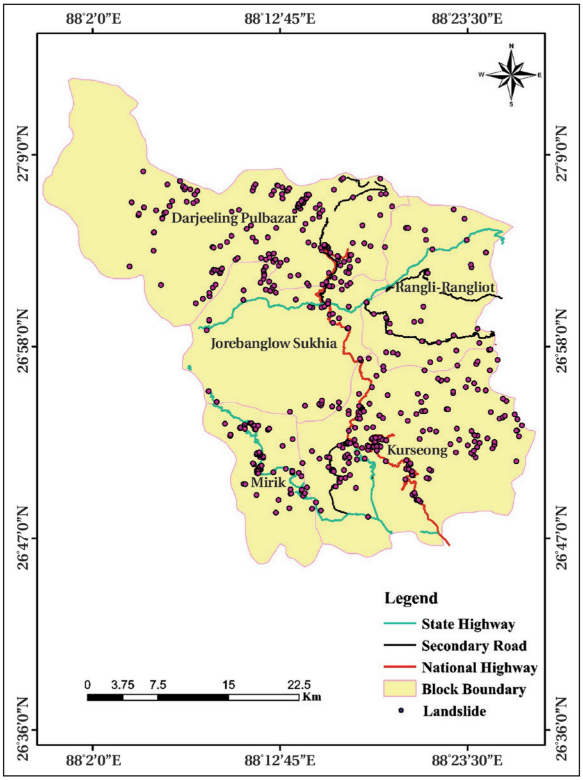

Figure 3: Landslide Inventory Map of Darjeeling Hills (1991-2017)

Source: Bhukosh, Geological Survey of India, extracted on 14/11/2022.

Figure 3 displays landslide occurrences in different blocks of Darjeeling hills from 1991 to 2017, with Kurseong and Darjeeling-Pulbazar areas experiencing a higher frequency of landslides. These occurrences can be attributed to various factors, including geology, slope, rainfall, physiography, soil, and human activities such as road construction and urban development. The high and middle hills are particularly susceptible to landslides, while the lower hills have fewer incidents.

Darjeeling, Kurseong, and Mirik are prominent towns in the region and are composed of soft schists, phyllite, and gneiss, making them prone to landslides due to their complex physical characteristics, high precipitation, and weak geology (Cajee, 2018).

The slope analysis reveals that these areas mainly fall under extremely steep slopes (34°-66°) to steep slopes (24°-33°), contributing to landslide formation. Combined with the high annual rainfall, the presence of such steep slopes enhances the risk of landslides in the region.

The soil in Darjeeling primarily consists of red and clayey soil, which covers most parts of the area. These soil types are highly susceptible to landslides as they are easily eroded during heavy rainfall (Mitra et al., 2018).

Furthermore, the figure demonstrates that landslides have occurred predominantly along or near the presence of roads, including national highways, state highways, and secondary roads. This indicates that the development of road infrastructure in the Darjeeling hills is contributing to the growing number of landslides in the region. The high amount of average rainfall in Darjeeling, which surpasses normal levels, also plays a significant role in the increasing number of landslides on the hill.

In conclusion, the analysis highlights the key factors influencing landslide occurrences in Darjeeling hills, emphasizing the importance of implementing appropriate measures to manage and mitigate landslide risks. Sustainable land-use practices, slope stabilization measures, early warning systems, and close monitoring of vulnerable areas are essential for safeguarding human lives and infrastructure from the devastating impact of landslides (Cajee, 2018; Mitra et al., 2018).

Factors Affecting Landslide

A landslip is a natural event caused by gravity that results in the falling of elements such as rock, soil, mud, and so on (Fayaz et al., 2022). Various underlying environmental and human factors influence the occurrence of landslides in any given location. Natural factors include the area's geological makeup, physiographic layout, soil composition, and rainfall patterns. Human qualities or elements include interventions by humans in the form of huge projects such as infrastructure development in the shape of highways, tunnels, and hydropower constructions. Some of the factors which affect landslides are discussed below:

Geology

The core Himalayan structure consists of massive thrusts formed by the rising Indian continent's basement. The Siwalik rocks are folded sedimentary rocks from the Pliocene-Pleistocene era. The Middle Hills are thrust sheets comprising prehistoric limestone and gneiss from the Indian shield. The Greater Himalayas consist of Precambrian gneisses intruded by Tertiary granites. The Darjeeling Himalaya shares the same geology, with prominent formations like Tertiary and Metamorphized Darjeeling Gneiss, Daling Series, and Damuda Series (Gerrard, 1994; Goscombe, 2000) (Figure 4).

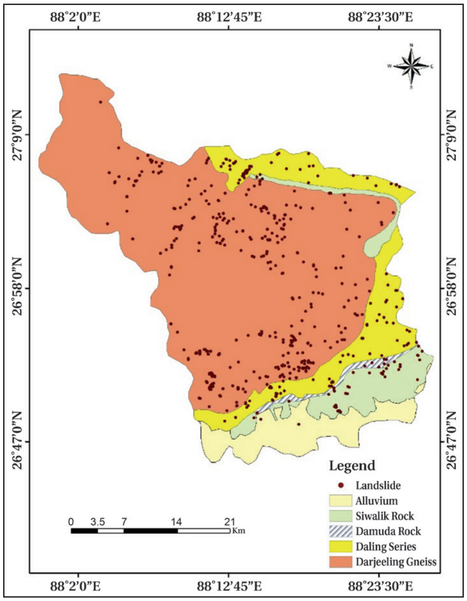

Figure 4: Occurrence of Landslide in different Geology of Darjeeling Hills, (1991-2017).

Source: Bhukosh, Geological Survey of India, Extracted on 17/02/2023

Table 1: Area and number of landslides occurrence in different geological structure (1991-2017)

Geological Structure	Area in Sq. km.	No. of Landslide	Percentage
Darjeeling Gneiss	879.9	410	73.2
Daling Series	177.4	103	18.4
Damuda Rock	13.3	9	1.6
Siwalik Rock	98.1	35	6.3
Alluvium	96.4	3	0.5
Total	**1265.1**	**560**	**100**

Source: Bhukosh, Geological Survey of India, Extracted on 17/02/2023.

The table highlights the dominant geological structure, "Darjeeling Gneiss," covering 879.9 sq. km, with the highest landslide frequency of 410 incidents (around 73.2%). The "Daling Series" and "Siwalik Rock" also have significant landslides (103 and 35 incidents) despite their smaller areas. On the other hand, "Damuda Rock" and "Alluvium" are the least prone to landslides, with 9 and 3 incidents, respectively from 1991-2017 (Table 1).

The occurrence of landslides is high in Darjeeling Gneiss due to its composition of weak metamorphic rocks like quartzites, biotite-kyanite, garnetiferous mica-schists, and sillimanite gneiss (Cajee, 2018). These types of rocks are susceptible to landslides, especially when combined with factors such as high precipitation and steep slopes. In contrast, Damuda rocks are less prone to landslides due to their low porosity, sedimentary formation, and weathering resistance. Their stable and well-layered composition reduces water infiltration and maintains strength over time. However, landslides can still occur under certain conditions, influenced by slope angle, geological structure, and external forces like rainfall or earthquakes (Gerrard, 1994).

Physiography

The Darjeeling Hills exhibit a diverse and intricate physical landscape, ranging from plains to the lofty Sandakphu, featuring steep valleys, Jhoras (streams), and springs. The region is characterized by ridges, valleys, spurs, and various micro-topographical units. It can be categorized into lower hills (200-800m altitude) in the central portion, middle hills (800m-1400m) with tea plantations in the western and north-eastern parts, and upper hills (above 1400m) hosting peaks like Sandakphu, Phalut, and Singalila. Eroded tracts, tea estates, and majestic peaks shape the distinct geography of the Darjeeling Hills (Cajee, 2018) (Figure 5).

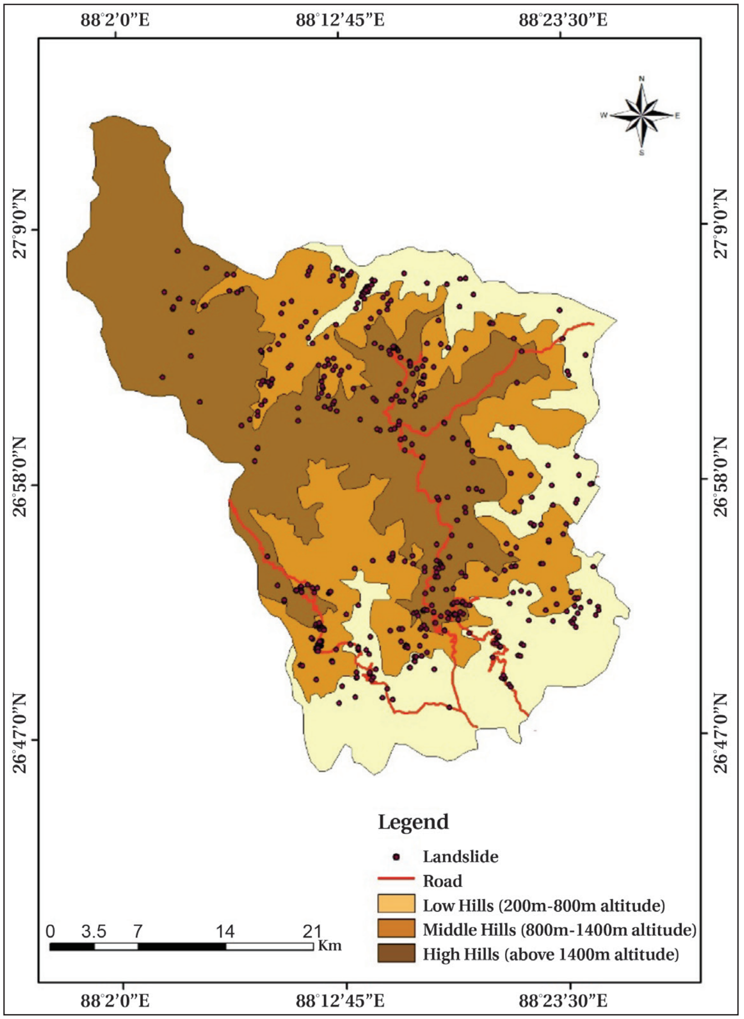

Figure 5: Landslides occurred along different Physiography of Darjeeling Hills (1991-2017)

Source: Adopted & Modified after Cajee, 2018.

Table 2: Area and number of landslides occurrence in different physiography (1991-2017)

Physiography	Area in Sq.km.	No. of Landslide	Percentage
High Hills	528.8	194	34.6
Middle Hills	389.4	233	41.6
Lower Hills	346.9	133	23.8
Total	**1265.1**	**560**	**100**

Source: Bhukosh, Geological Survey of India, Extracted on 17/02/2023.

The table highlights three physiographic zones: "High Hills," "Middle Hills," and "Lower Hills." The "Middle Hills" have the highest landslide frequency (233 incidents) and the highest percentage of landslides (41.6%), indicating greater vulnerability. On the other hand, the "Lower Hills" have the lowest landslide percentage, suggesting they are relatively less prone to landslides during the study period (Table 2).

Areas like Darjeeling, Kurseong, and Mirik, characterized by soft schists, phyllite, and gneiss, are highly susceptible to landslides due to weak geology, high precipitation, and hilly terrain. These factors lead to frequent and significant landslides, causing substantial damage to infrastructure and endangering lives (Dikshit et al., 2020; Sumantra & Ragunathan, 2016).

Rainfall

The landslide has a direct relationship with the structure of the rock formation in the area, the slope of the area, lithology, etc. Darjeeling is composed of relatively new geological formations that are prone to landslides. Though the cause of a landslip varies by location, heavy monsoon rains are frequently to blame in Darjeeling. Precipitation constitutes one of the primary causes of a "geological disaster." The scale of geological disasters and the intensity of rainfall are inversely associated; rain penetration decreases soil strength and friction resistance between soil and bedrock, as well as increasing soil gravity, which causes the geological disaster (Zhang, 2020).

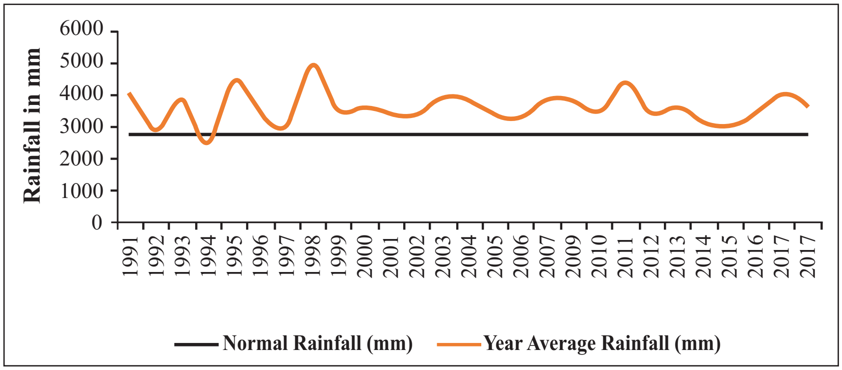

Figure 6: Patterns of rainfall in Darjeeling Hills (1991-2017).

Source: India, Water Resource Information System extracted on 17/04/2023.

Figure 6 indicates a significant deviation of average rainfall in Darjeeling from normal conditions. High rainfall is a critical factor contributing to landslides on steep slopes. In subtropical and tropical climates, such slopes may remain stable until intense rainstorms trigger failures (Tsaparas et al., 2002). Throughout the study period, Darjeeling experienced above-normal rainfall, leading to increased soil moisture and elevated pore pressures, resulting in slope failure and devastating landslides (Dai & Lee, 2001).

Slope

The slope is crucial for researching the formation, progress, and vulnerability of landslides. The horizontal distance across two points is expressed by this topographic feature. The slope is an aspect of the digital elevation model that is studied in the topographical parameter classification. In landslide susceptibility investigations, slopes with the highest landslip frequency are determined by classifying slopes (Cellek, 2020).

Slope, along with other variables such as physiography, geology, and drainage, determines the formation of landslides in any place. Darjeeling is a steep terrain with a slope ranging from 0° to 66°. The Fabdem is used to categorise the slope, based on the natural break (Jenks), the slope has been categorised into four distinct categories: Gentle slopes range from 0° to 11°, moderate slopes range from 12° to 23°, steep slopes range from 24° to 33°, and extremely steep slopes range from 34° to 66° (Figure 7).

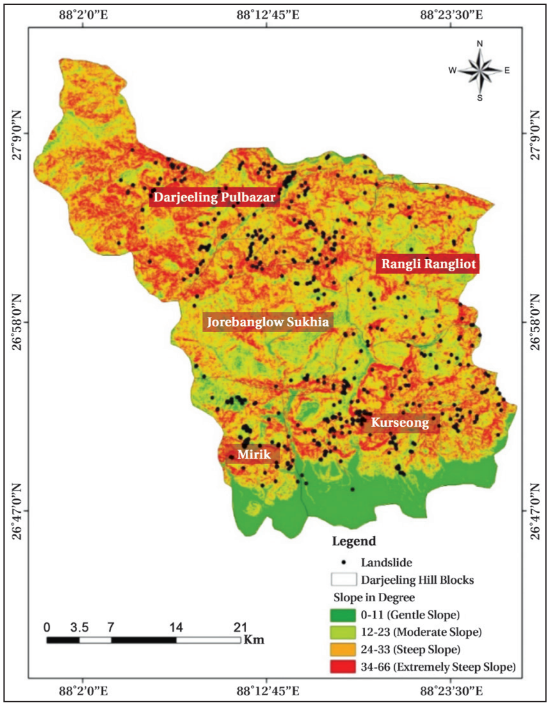

Figure 7: Landslides occurred along different Slopes of Darjeeling Hills, (1991-2017).

Source: Forest and Building removed Copernicus DEM, Extracted on 04/05/2023.

Table 3: Area and number of landslides occurrence along different slope (1991-2017)

Slope	Area in Sq.km.	No. of Landslides	Percentage
Gentle Slope	172	11	3.9
Moderate Slope	371.5	112	20
Steep Slope	454.3	224	40
Extremely Steep Slope	267.3	202	36.1
Total	**1265.1**	**560**	**100**

Source: Bhukosh, Geological Survey of India, Extracted on 17/02/2023.

The data reveals a clear relationship between slope steepness and landslide occurrences. Gentle slopes, covering 172 sq. km, experienced 11 landslides (3.9% of the total), indicating lower vulnerability. Moderate slopes, spanning 371.5 sq. km, had 112 landslides (20% of the total), showing a higher percentage of landslides. Steep slopes, covering 454.3 sq. km, had 224 landslides (40% of the total), indicating significant vulnerability. Extremely steep slopes, covering 267.3 sq. km, had 202 landslides (36.1% of the total), suggesting the highest vulnerability during 1991-2017 (Table 3). Notably, Darjeeling-Pulbazar and Kurseong blocks, classified as having steep to extremely steep slopes, experienced high landslide occurrences, while Jorebunglow-Sukhia and Rangli-Rangliot blocks, with moderate to gentle slopes, had fewer landslide cases. The occurrence of landslides in Darjeeling is directly related to the slope of the area. Slope characteristics play a critical role in landslide initiation when forces exceed material resilience, leading to collapse and downhill slipping. In addition to slope parameters, natural conditions, weathering, soil moisture, vegetation, and human activity also contribute to landslides (Dong et al., 2021). Understanding these factors is crucial for effective landslide mitigation and disaster management strategies, particularly in areas with steeper terrain.

Soil

Darjeeling hills soils have been formed by both river activity and lithological deterioration. The soils that have formed in the Kalimpong region are primarily reddish due to the abundance presence of phyllites and schist, black soils are encountered rarely. Soils in the district's highlands, which span from west to east along most of the interfluvial zones, are primarily mixed sandy loam and loamy, but those on the southern slopes of Mirik and Kurseong are primarily clayey loam and reddish. Sandy soils are mostly found to the east of the Tista River (Mitra et al., 2018).

Darjeeling has soil types such as sandy and sandy clay (which are generally prone to erosion and instability), and due to the presence of slopes along with the high amount of rainfall in the area, the occurrence of landslides is a continuous phenomenon. In the Darjeeling hills, there has been a high amount of deforestation due to the rapid increase in population leading to build-up area increase due to loss of vegetation and exposure of grounds leading to erosion and subsequent landslides.

Human Intervention in Landslide Events

Human activities have been identified as a significant initiating cause for numerous landslides. Human-caused landslides typically occur on excavated slopes, causing several deaths and extensive damage. Numerous investigations have discovered that breakdowns on cut slopes are connected with stress release caused by excavation (Zhang, 2012).

Human-induced landslides refer to landslides that are directly caused or significantly influenced by human activities. These activities can directly alter the stability of slopes and trigger landslide events. Here are some examples of human-induced factors that can lead to landslides:

Construction of Road Network

Engineering structures connected with road networks possess a significant influence in generating landslides (Wang et al., 2014). In Darjeeling Hills, during the study period if focused it shows that the landslide is more frequent in the areas where there is a high and medium density of road networks. It explains how in Darjeeling hills landslides are influenced by the road network. In the building of roads, large slopes or tracts were cleared which can lead to greater exposure to rain and leading to slope failure due to the presence of a high amount of infiltration and saturation with the presence of high slopes.

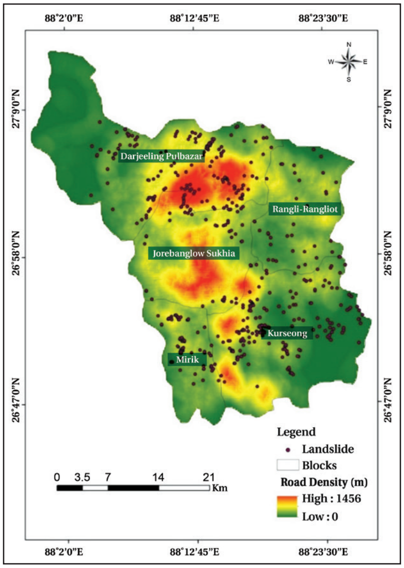

Figure 8: Relationship between Road Networks and Landslides (1991-2017).
Source: Open Street Map, extracted on 06/04/2023.

Table 4: Area and number of landslides occurrence along different road density (1991-2017)

Road Density (m/km)	No. of Landslides	Percentage
0-142	88	15.7
142-331	185	33
331-576	195	34.8
576-879	47	8.4
879-1455	45	8
Total	**560**	**100**

Source: Bhukosh, Geological Survey of India, Extracted on 17/02/2023.

Landslide occurrence is more prevalent in areas with medium and high road network areas compared to low road networks. The occurrence of landslide is frequent in high road density areas (879-1455m) with 45 cases within 63.6 km^2, whereas the occurrence of landslide is less in low road network areas (0-142m) with 88 cases within 413.5 km^2 (Figure 8 and Table 4). This suggests that landslides are commonly observed in hills near road networks, and road construction plays a significant role in their incidence in Darjeeling hills. The construction of roads is widely recognized for its potential to exacerbate landslip activity through the creation of steep and rapidly weathering roadcut cliffs, removal of basal support from hill slopes, increased burden on unstable surfaces, concentration of seepage and runoff, use of blasting during construction causing disturbances, and subsequent vibrations from heavy traffic (Haigh et al., 1995).

Population Growth

Darjeeling Hills' population has grown since the British took it from the Raja (King) of Sikkim and promoted it as a hill resort. When the East India Company initially acquired the area in 1835, it was said to have a population of barely 100 individuals. The Company's decision to develop Darjeeling as a hill resort created an opportunity for people to move and participate in the development process. The indigenous population, predominantly Lepchas, was quickly outnumbered by settlers from Nepal and Sikkim. The population of the Darjeeling Hills has fluctuated over time. However, the Darjeeling Hills have supported a growth rate of more than 20% every decade on average. Since 1970, the Darjeeling Hills' growth rate has greatly surpassed the district's growth rate (Chhetri & Tamang, 2013).

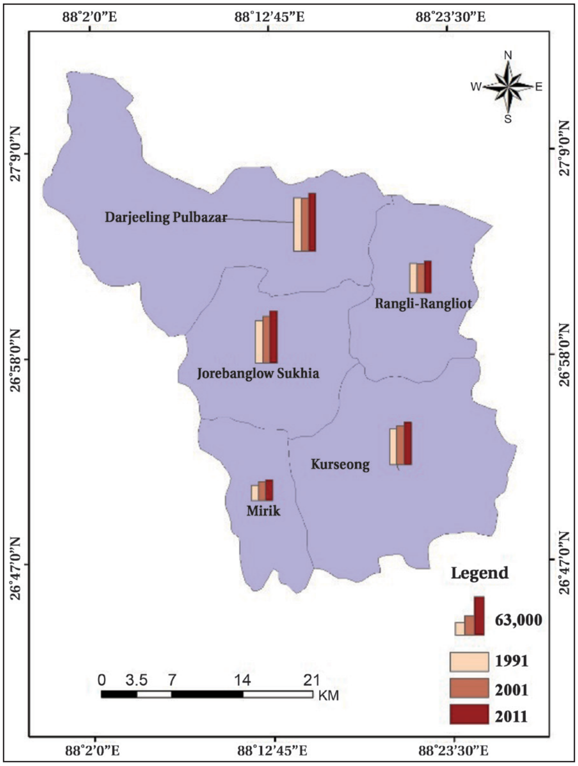

Figure 9: Block-wise Population Growth in Darjeeling Hills (1991, 2001 & 2011)

Source: District Census Handbook, 1991, 2001 & 2011.

Figure 9 shows the block-wise population growth of the Darjeeling Hills. The population in each of the blocks of the Darjeeling Hills is increasing from 1991-2011. Population growth can have an impact on the occurrence of landslides, particularly in areas with steep slopes or unstable terrain. Population growth increases housing and infrastructure demand, causing construction on slopes or landslide-prone areas. Excavation, deforestation, and natural drainage patterns weaken land stability, increasing landslide risk (Crozier et al., 2005). Population growth necessitates land use changes, converting agricultural areas into residential zones, and improper planning can lead to hazardous construction (Carrara et al., 1999).

Categories of landslides

A landslide is the most prevalent natural disaster. Landslides comprise all sorts of mass wasting, funneling, and descending made up of debris, rocks, dirt, and material from the earth sometimes mixed or alone. Landslides are categorized into five types based on the volume of water present: "falling", "toppling", "sliding", "spreading", and "flowing" (Alimohammadlou et al., 2013) (Table 5).

According to Cruden and Varnes, 1996, the following five types of landslides are depicted and described:

a. **Falls**: Falls are sudden movements of geologic masses such as boulders and stones that get separated from upward slopes or mountains. Separation happens at discontinuities like breaks, ligaments, and deposited surfaces, while movement happens via free fall, jumping, and tumbling. The force of gravity, weathering by mechanical means, and the presence of interstitial water all have a major impact on falls.

b. **Topples**: Toppling failures can be defined by the forward motion of the components about some essential point, either below or down along the unit, caused by the forces of gravitation and surrounding units or fluids in cracks.

c. **Slides**: 'Mass wasting' that involves the movement of the materials downward of a 'cohesive block' of soil or rock is referred to as a slide. The factors which trigger the Slide landslide are 'saturation' of the soils with water in the slope and loss of 'shearing strength'. It is often been referred to as 'Slumping'. Rotational slides and longitudinal slides are the two major kinds of slides.

d. **Spread**: The different slides include lateral/horizontal movement over the fairly mild ground. Rapid ground motion, such as an earthquake, induces instability of the damages, cohesionless sediments below a harder, stronger lithological layer.

e. **Flow**: Flow is the landslide that moves the materials downslope in the form of liquid materials.

Table 5: Types of landslides based on 'Varnes' classification of slope movements (Varnes, 1978)

<table>
<tr><th colspan="2" rowspan="3">Types of Movement</th><th colspan="3">Types of Material</th></tr>
<tr><th>Bedrock</th><th colspan="2">Engineering Soils</th></tr>
<tr><th></th><th>Predominantly coarse</th><th>Predominantly Fine</th></tr>
<tr><td colspan="2">Falls</td><td>Rock Fall</td><td>Debris Fall</td><td>Earth Fall</td></tr>
<tr><td colspan="2">Topples</td><td>Rock Topple</td><td>Debris Topple</td><td>Earth Topple</td></tr>
<tr><td rowspan="2">Slides</td><td>Rotational</td><td rowspan="2">Rock Slide</td><td rowspan="2">Debris Slide</td><td rowspan="2">Earth Slide</td></tr>
<tr><td>Translational</td></tr>
<tr><td colspan="2">Lateral Spreads</td><td>Rock Spread</td><td>Debris Spread</td><td>Earth Spread</td></tr>
<tr><td colspan="2">Flows</td><td>Rock Flow</td><td>Debris Flow</td><td>Earth Flow</td></tr>
<tr><td colspan="2">Complex</td><td colspan="3">Combination of two or more principal types of movement</td></tr>
</table>

Table 6: Landslides based on different attributes in Darjeeling Hills (1991-2017)

Landslide Occurred from 1991-2017 Based on different attributes							
Movement	**No. of Land-slide**	**Material**	**No. of Land-slide**	**Activity**	**No. of Land-slide**	**Distribution**	**No. of Land-slide**
Fall	4	Debris	386	Active	329	Widening	58
Flow	18	Rockfall	145	Dormant	68	Retrogressive	93
Slide	477	Rock cum Debris	29	Reactivated	77	Enlarging	43
Subsid-ence	61			Stabilised	8	Diminishing	20
				Suspended	76	Confined	315
				Relict	2	Advancing	31

Source: Bhukosh, Geological Survey of India, extracted on 14/11/2022.

Table 6 represents the categories of landslide based on the different attributes in Darjeeling Hills as given by Bhukosh, Geological Survey of India.

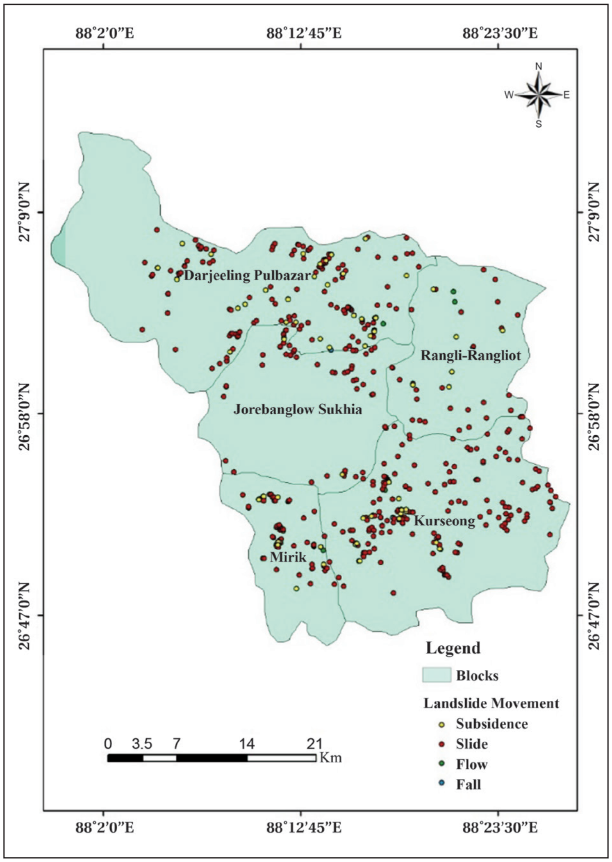

Figure 10: Movement of Landslide occurred in Darjeeling Hills (1991-2017)

Source: Bhukosh, Geological Survey of India, extracted on 14/11/2022.

Figure 10 shows the landslide categories based on movement in Darjeeling hills from 1991-2017. Based on the category of movement, falls in Darjeeling hills have very less occurrence with 4 cases. Whereas slide is the highest occurring landslide type in the Darjeeling hills with 477 cases followed by the subsidence landslide with 61 cases. The maximum of the landslides has occurred due to slide failure and subsidence, which occurs when the soil gets saturated with water and losses its strength to hold.

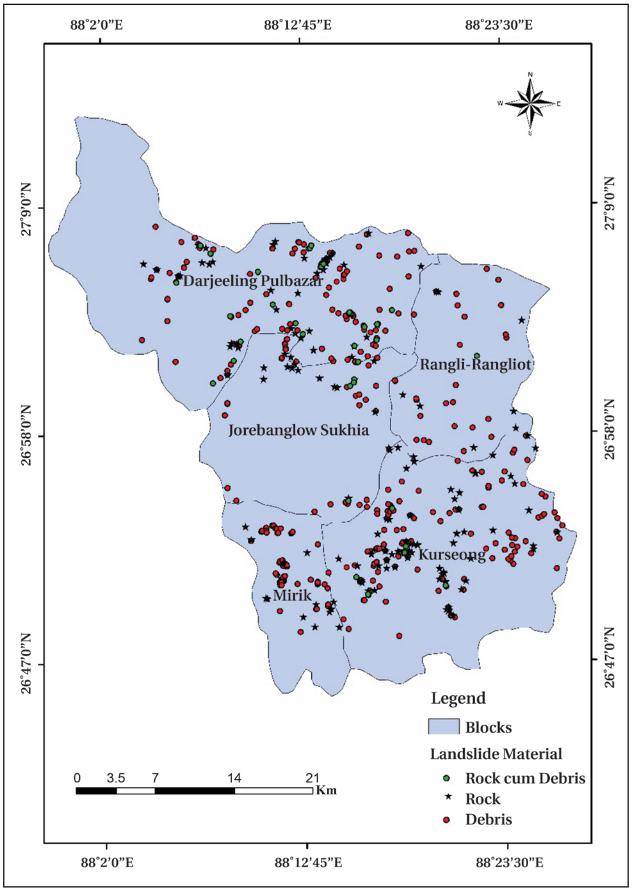

Figure 11: Material of Landslide occurred in Darjeeling Hill (1991-2017)

Source: Bhukosh, Geological Survey of India, extracted on 14/11/2022.

If the material-wise occurrence of the landslide was examined it shows that the Debris slide with 386 cases is the highest occurring landslide in the classification based on material, followed by rockfall with 145 cases and fewer cases of rock cum debris. Most of the debris fall cases can be found in Darjeeling-Pulbazar, Kurseong, and Mirik as these areas fall under extremely steep to moderate slopes which along with the mixture of other factors like rain and geology of the area. Based on Varnes' classification of landslide, it shows that slope failure causes the debris slide, which is mainly induced by rainfall occurrence (Figure 11).

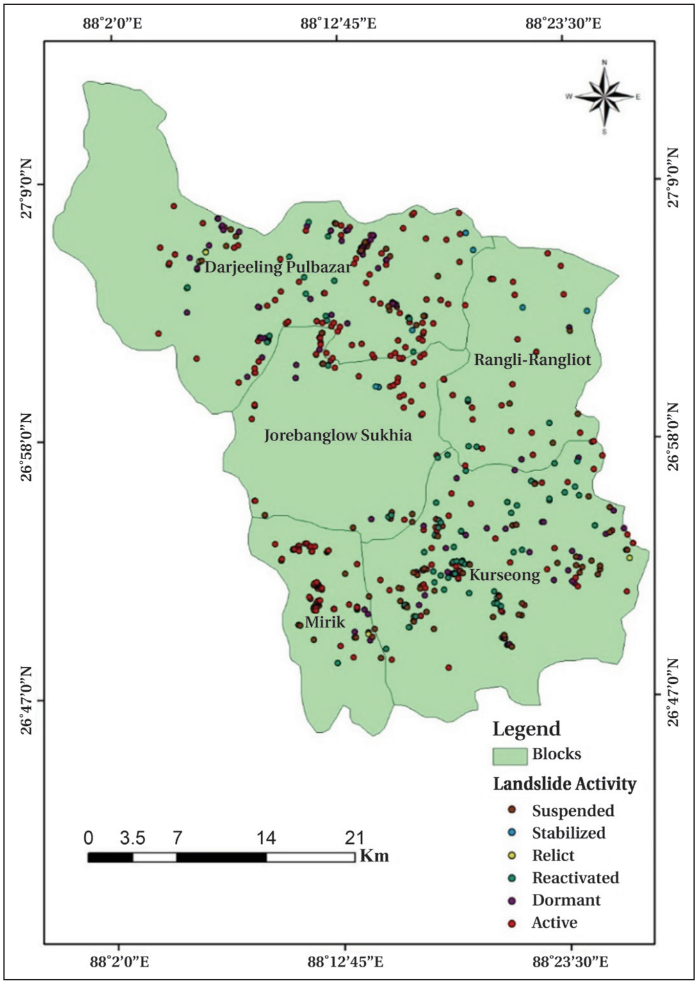

Figure 12: Activity of Landslide occurred in Darjeeling Hills (1991-2017)

Source: Bhukosh, Geological Survey of India, extracted on 14/11/2022.

Figure 12 shows the activity of landslides in the Darjeeling hills from 1991 to 2017. The different categories of landslides and their respective counts are as follows:

Active Landslides (329 cases): These are landslides that are currently occurring or showing signs of movement and pose an ongoing hazard to the area. The reason for the high number of active landslides could be attributed to various factors, such as heavy and prolonged rainfall, geological conditions, steep slopes, and human activities like deforestation and construction.

Reactivated Landslides (77 cases): Reactivated landslides are those that have experienced movement again after being dormant or stable for some time. The reasons for landslides reactivating could be additional rainfall or seismic activity that destabilizes the slope, leading to movement.

Suspended Landslides (76 cases): Suspended landslides are those where movement has ceased for the time being, but there is a possibility of reactivation in the future. The reasons for the suspension could be reduced rainfall or a temporary change in slope stability conditions.

Stabilised Landslides (8 cases): Stabilized landslides are those where some measures or natural processes have helped to prevent further movement or reduce the landslide's activity. The reason for stabilization could be the implementation of engineering measures like retaining walls or drainage systems.

Relict Cases (2 cases): Relict landslides are old landslide deposits that are no longer active. The reason for their inactivity could be the natural process of erosion and weathering, which has led to the stabilization of the slope over time.

If the landslide classification based on distribution is examined it shows that the cases of confined landslides are maximum in numbers with 315 cases, followed by retrogressive landslides with 93 cases and widening with 58 cases. Once a landslide occurs in a specific area, it often alters the landscape and slope conditions. Confined cases are high in numbers due to the different physical and human factors like slope failure, road cutting, and high intensity of rainfall.

Landslide Susceptibility Zones: Landslide susceptibility zonation (LSZ) maps are extremely useful to policymakers and field engineers when deciding where to execute development plans in hilly terrain, as well as when implementing suitable mitigation strategies in unstable hazard-prone geographic areas (Anbalagan, 1992). Landslide susceptibility mapping/zonation is the classification of terrain into zones based on the time and space likelihood of landslide incident, which includes an overview of the setting, volume, and forecast of future landslip incidence in a region (Shano et al., 2020).

Table 7: Rank and Weightages of Parameters for Landslide Susceptibility Zonation

Sl. No.	Parameters	Classes	Rank	Weightage (%)
1.	Rainfall (in mm)	455-563	1	30
		563-625	2	
		625-687	3	
		687-740	4	
		740-846	5	
2.	Road density (m/km)	0-142	1	20
		142-331	2	
		331-576	3	
		576-879	4	
		879-1455	5	
3.	Slope (in degree)	<11°	1	20
		12°-23°	2	
		24°-33°	3	
		33°-66°	4	
4.	Geology	Alluvial	1	30
		Siwalikh	2	
		Lower Gondwana	3	
		Daling Series	4	
		Darjeeling Gneiss	5	

This study used the four major factors which mainly affect the landslide in the Darjeeling hills. Rainfall, Road density, Slope, and Geology are used to analyze the Landslide Susceptibility Zonation (LSZ) of Darjeeling Hills (Table 7). The main triggering factor of landslides found in Darjeeling is Rain as the mean average rainfall during the study period is 3480 mm along with the presence of extremely steep slopes ranging from 33°-66°. Rainfall serves as one of the strongest and most prominent causative factors that cause slope failure in various parts of the world (Zhang et al., 2011).

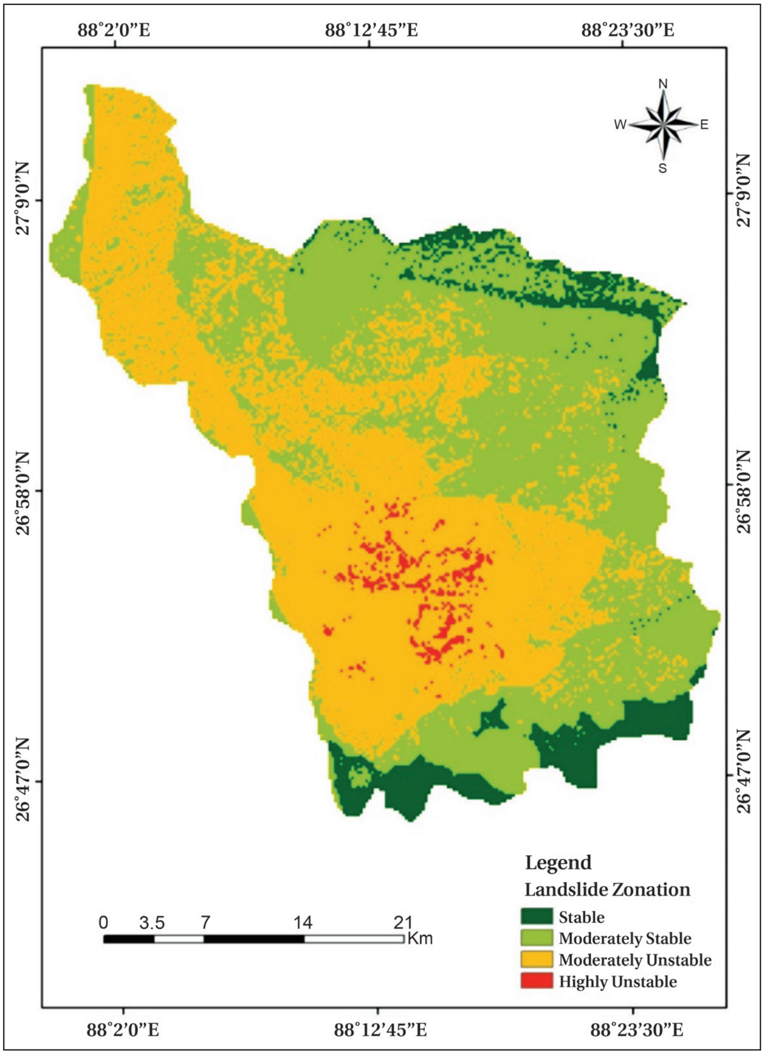

Figure 13: Landslide Susceptibility Zonation Map of Darjeeling Hills

Source: Prepared after data extracted from Bhukosh, Geological Survey of India (GSI)

Landslide susceptibility zonation map of Darjeeling hills was created using four major landslide triggering factors which include rainfall, slope, road density, and geology of the study area (Figure 13).

From the analysis, it is found that about 15.39 km^2 of land is highly unstable. This highly unstable zone lies mostly in the north-western part of the Kurseong block, as this part falls under the extremely steep slope category. Approximately 573.26 km^2 of the area falls under a moderately unstable zone, as these areas are dominated by built-up areas along with high road density. Around 582.88 km^2 falls under a moderately stable zone, covering most of the remaining areas, as this region has low road density, as shown in Figure 8, indicating low human settlement. The remaining 93.57 km^2 area falls under the stable zone, as it encompasses the foothills of the Darjeeling hills.

From the above Landslide Susceptibility Zonation map, it can be observed that landslides are more prone to steeper slopes that receive a high amount of average rainfall. The southern frontier of the Darjeeling-Bhutan Himalaya receives among the highest yearly precipitation (3000-6000 mm) and frequently experiences severe rains (up to 800 mm per day) throughout the entire southern Himalayan edge due to multi-scale interaction between monsoonal airflow and regional terrain (Prokop, 2017).

5. Findings and Conclusions

This study reveals that landslide occurrence is most frequent in the Darjeeling Gneiss geological formation with 410 cases, followed by the Daling series with 103 cases, Siwalik rocks with 35 cases, Damuda rocks with 9 cases, and alluvium with only 3 cases during the study period from 1991-2017 Darjeeling hills.

The "Middle Hills" have the highest landslide frequency with 233 incidents. The "High Hills" rank second with 194 landslides, and the "Lower Hills" have the lowest landslide count, 133 incidents. "Middle Hills" are the most vulnerable to landslides, while the "Lower Hills" are relatively less prone during the study period. These findings are crucial for effective disaster management and mitigation in the region.

Landslide occurrences were most frequent on steep slopes (24° - 33°) with 224 cases, followed by extremely steep slopes (34°- 66°) with 202 cases, moderate slopes (12° - 23°) with 112 cases, and gentle slopes (0° - 11°) with only 22 cases during the study period from 1991-2017 in Darjeeling hills.

Landslide occurrence is more prevalent in areas with medium and high road network areas compared to low road networks. The occurrence of landslide is frequent in high road density areas (879-1455m) with 45 cases within 63.6 km^2, whereas the occurrence of landslide is less in low road network areas (0-142m) with 88 cases within 413.5 km^2.

The research highlights the crucial role of rainfall in triggering landslides in Darjeeling Hills. Higher-than-normal rainfall during the study period increased the moisture content in the soil, exceeding the threshold for slope stability, and leading to devastating landslides.

The study provides valuable insights into the occurrence, frequency, and patterns of landslides in the Darjeeling Hills. Landslides pose significant risks to human settlements and infrastructure in this hilly terrain. Understanding the underlying factors, such as slope characteristics and rainfall, is essential for effective disaster preparedness and infrastructure planning. To enhance community resilience and reduce the impact of landslides, policymakers and disaster management authorities must prioritize the implementation of early warning systems and comprehensive disaster management plans. Institutional arrangements, such as the District Disaster Management Authority, play a crucial role in coordinating response and relief efforts during landslide events. By incorporating findings of the study into decision-making processes, the region can be better equipped to mitigate the impact of landslides on lives and livelihoods. Proactive measures and investments in disaster management strategies are vital to safeguarding the local community and infrastructure from the recurrent and devastating effects of landslides in the Darjeeling Hills.

References

1. Alimohammadlou, Y., Najafi, A., & Yalcin, A. (2013). Landslide process and impacts: A proposed classification method. *Catena*, 104, 219-232.
2. Anbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. *Engineering geology*, 32(4), 269-277.
3. Basu, S. R. (2001, December). A systematic study of landslides along the arterial routes to Darjeeling and their control. In *Geotechnical Engineering–Meeting Society's Needs, Proceedings of the 14th Southeast Asian Geotechnical Conference* (pp. 10-14).
4. Cajee, L. (2018). Physical aspects of the Darjeeling Himalaya: understanding from a geographical perspective. *IOSR Journal of Humanities and Social Science*, 2(3), 66-79.
5. Carrara, A., Cardinali, M., Guzzetti, F., & Reichenbach, P. (1999). Use of GIS technology in the prediction and monitoring of landslide hazards. *Natural Hazards*, 20(2-3), 117-135.
6. Cellek, S. (2020). Effect of the slope angle and its classification on a landslide. *Natural Hazards and Earth System Sciences Discussions*, 1-23.
7. Chawla, A., Chawla, S., Pasupaleti, S., Rao, A. C. S., Sarkar, K., & Dwivedi, R. (2018). Landslide Susceptibility Mapping in Darjeeling Himalayas, India. *Advances in Civil Engineering, 2018*, 1-17.
8. Chhetri, B., & Tamang, L. (2013). Population growth and associated problems: a case study of Darjeeling Town. *International Journal of Humanities and Social Science Invention*, 2(5), 63-67.

9. Crozier, M. J., & Glade, T. (2005). Landslide hazard and risk: issues, concepts, and approach. *Landslide hazard and risk*, 1-40.
10. Dai, F. C., & Lee, C. F. (2001). Frequency–volume relation and prediction of rainfall-induced landslides. *Engineering geology*, 59(3-4), 253-266.
11. De, S.K. (2017). Landslides and human interference in Darjiling Himalayas, India. *Revista de Geomorfologie*, 19, 44-57.
12. Dikshit, A., Sarkar, R., Pradhan, B., Segoni, S., & Alamri, A. M. (2020). Rainfall induced landslide studies in Indian Himalayan region: a critical review. *Applied Sciences*, 10(7), 2466.
13. District Disaster Management Plan Darjeeling (2022-2023). District disaster management plan Darjeeling. Govt. of West Bengal, 1-229.
14. Dong, J., Wang, C., Huang, Z., Yang, J., & Xue, L. (2021). Dynamic response characteristics and instability criteria of a slope with a middle-locked segment. *Soil Dynamics and Earthquake Engineering*, 150, 106899.
15. Fayaz, M., Khader, S. A., & Rafiq, M. (2022). Landslides in the Himalayas: Causes, Evolution, and Mitigation—A Case Study of National Highway 44, India. In Disaster Management in the Complex Himalayan Terrains: Natural Hazard Management, Methodologies and Policy Implications (pp. 43-58). *Cham: Springer International Publishing*.
16. Gerrard, J. (1994). The landslide hazard in the Himalayas: geological control and human action. In *Geomorphology and natural hazards* (pp. 221-230). Elsevier.
17. Goscombe, B. E. N., & HAND, M. (2000). Contrasting P–T paths in the Eastern Himalaya, Nepal: inverted isograds in a paired metamorphic mountain belt. *Journal of Petrology*, 41(12), 1673-1719.
18. Government of West Bengal Office of District Magistrate, District Disaster Management Plan, Darjeeling (2022). Retrieved on 30.06.2023 from https://darjeeling.gov.in/notice/district-disaster-management-plan-darjeeling-2023-24/
19. Government of West Bengal Office of District Magistrate, District Disaster Management Plan, Darjeeling (2023). Retrieved on 30.06.2023 from https://darjeeling.gov.in/notice/district-disaster-management-plan-darjeeling-2023-24/
20. Haigh, M. J., Rawat, J. S., Rawat, M. S., Bartarya, S. K., & Rai, S. P. (1995). Interactions between forest and landslide activity along new highways in the Kumaun Himalaya. *Forest Ecology and Management*, 78(1-3), 173-189.
21. Martha, T. R., Roy, P., Jain, N., Khanna, K., Mrinalini, K., Kumar, K. V., & Rao, P. V. N. (2021). Geospatial landslide inventory of India—an insight into occurrence and exposure on a national scale. *Engineering geology*, 18(6), 2125-2141.
22. Mitra, D., Bhandery, C., Mukhopadhyay, A., Chanda, A., & Hazra, S. (2018). Landslide risk assessment in Darjeeling hills using multi-criteria decision support system: a Bayesian network approach. *Disaster risk governance in India and cross cutting issues*, 361-386.
23. Nad, C. (2015). Landslide Hazard Management of Darjeeling Hill-A Critical Need for Inhabited. *International Journal of Humanities and Social Science Invention, 4(3)*, 48-60.
24. Pal, R., Biswas, S.S., Modal, B., & Pramanik, M.K. (2016). Landslides and Floods in the Tista Basin (Darjeeling and Jalpaiguri Districts): Historical Evidence, Causes and Consequences. The Journal of Indian Geophysical Union, 20(2), 209-215.
25. Prokop, P., & Walanus, A. (2017). Impact of the Darjeeling–Bhutan Himalayan front on rainfall hazard pattern. *Natural Hazards, 89*, 387-404.
26. Shano, L., Raghuvanshi, T. K., & Meten, M. (2020). Landslide susceptibility evaluation and hazard zonation techniques–a review. *Geo-environmental Disasters*, 7(1), 1-19.
27. Sumantra, S. B., & Raghunath, P. (2016). Causes of Landslides in Darjeeling Himalayas during June-July, 2015. Journal of Geography and Natural Disasters, 6(173), 2167-0587.
28. Tsaparas, I., Rahardjo, H., Toll, D. G., & Leong, E. C. (2002). Controlling parameters for rainfall-induced landslides. *Computers and geotechnics*, 29(1), 1-27.
29. Wang, X., Zhang, L., Wang, S., & Lari, S. (2014). Regional landslide susceptibility zoning with considering the aggregation of landslide points and the weights of factors. *Landslides*, 11, 399-409.
30. Zhang, F., Liu, G., Chen, W., Liang, S., Chen, R., & Han, W. (2012). Human-induced landslide on a high cut slope: a case of repeated failures due to multi-excavation. *Journal of Rock Mechanics and Geotechnical Engineering*, 4(4), 367-374.
31. Zhang, L. L., Zhang, J., Zhang, L. M., & Tang, W. H. (2011). Stability analysis of rainfall-induced slope failure: a review. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 164(5), 299-316.
32. Zhang, Y. (2020). Research on the relationship between precipitation and landslide. *In E3S Web of Conferences* (Vol. 198, p. 04027).
33. Hawker, L. & Neal, J. (2021). FABDEM V1-0. https://doi.org/10.5523/bris.25wfy0f9ukoge2gs7a5mqpq2j7