International Journal of Aquatic Research and Environmental Studies 6(2) 453-466 2026

Integrated Hazard-Vulnerability-Risk Analysis and Landslide Zonation Mapping in Chamoli District: A Geospatial Approach

Uma Bhattacharya[1]*, Dr. Rajesh Jolly[2]

Abstract

The study is an in-depth analysis of hazards, vulnerability, and risk in disaster management, with a particular focus on the Chamoli district in the Uttarakhand, Central Himalaya. Hazards have been defined by origin, speed of onset, frequency, and spatial characteristics, illustrating how these events transform into disasters when interacting with vulnerable conditions. Vulnerability is thoroughly examined through its components—susceptibility and resilience—and categorized by their physical and environmental dimensions, based on the existing geographical indicators. Furthermore, this study explores risk as the expected loss resulting from the interaction of hazard and vulnerability. A significant portion of the sources then applies these concepts to landslide hazard zonation mapping in Chamoli, integrating geospatial analysis, geological settings, and structural features to assess regional stability for infrastructural development, such as road construction, while considering the area's seismic vulnerability and environmental challenges.

[1] Research Scholar, Department of Geography, Lovely Professional University, Phagwara, Punjab, India
[2] Associate Professor, Department of Geography, Lovely Professional University, Phagwara, Punjab, India
*Corresponding Author: Uma Bhattacharya, Research Scholar, Department of Geography, Lovely Professional University, Phagwara, Punjab, India bhatuma7@gmail.com

Keywords: Hazards, Vulnerability, ASTER DEM, Landslide-zonation

Introduction:

A hazard refers to a rare or extreme event in the natural or human-made environment that adversely impacts human life, property, or activity to the extent that it can potentially lead to a disaster. Hazards are understood as potentially damaging physical events, phenomena, or human actions that can result in fatalities, injuries, property loss, environmental degradation, and socio-economic disruptions (Makoka & Kaplan, 2005; UNISDR, 2009). Hazards are external threats that affect people and assets at risk. They are not disasters in themselves but may lead to one when interacting with vulnerable conditions. In earlier times, hazards were perceived as divine acts or acts of God. This fatalistic perspective lacked recognition of the societal contributions to disasters. A shift towards scientific interpretation emerged post the 1755 Lisbon Earthquake, which highlighted commonalities in structural damage and hinted at underlying human factors (Etkin, 2015). Subsequent academic contributions (Alexander, 2000; Cutter, 1996; Hewitt, 1997) have emphasized that hazards are extreme geophysical or social threats, not necessarily in terms of their probability of occurrence but in their potential to cause harm. Hazards gain significance only in the presence of exposure and vulnerability (Wisner et al., 2003).

Objectives of the Study

The objectives of the current study are as follows:

1. To assess the vulnerability of the study area to the natural hazard based on the analysis of the Geo-environmental setup of the study area
2. To classify the region into different landslide zones using different geo-environmental variables

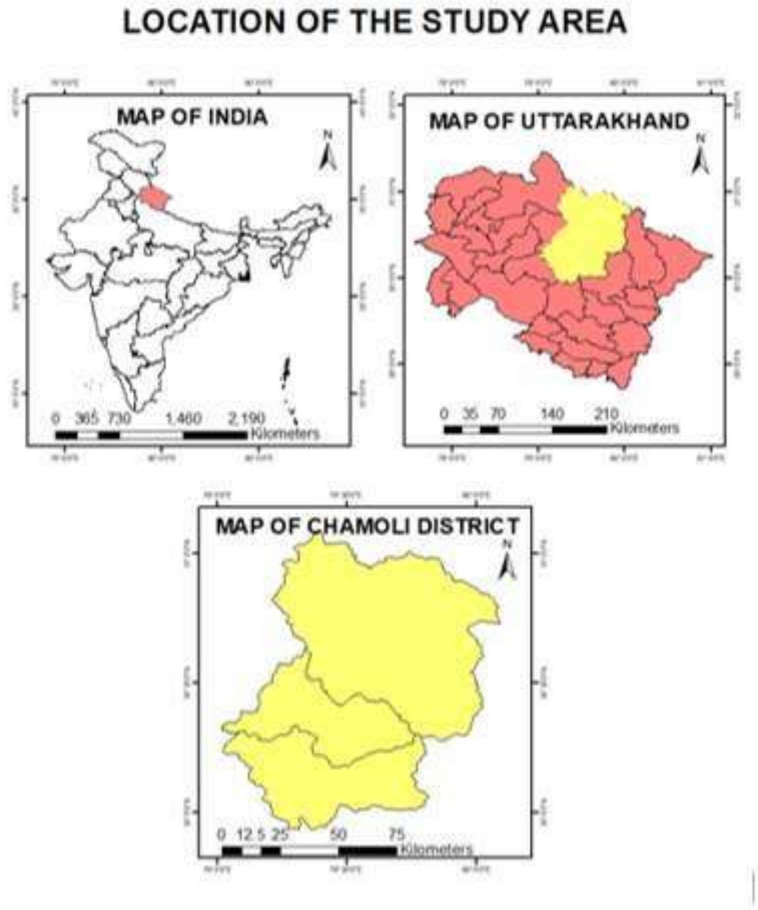
Location of the Study Area:

Chamoli district, located in the state of Uttarakhand, India (Figure 1), is part of the central Himalayas, renowned for its rich biodiversity, cultural heritage, and scenic landscapes. However, the region's rugged terrain and fragile ecosystem also make it particularly vulnerable to natural hazards such as landslides, earthquakes, floods, and glacial lake outburst floods (GLOFs). This chapter examines the geoenvironmental setting of Chamoli and evaluates its susceptibility to these hazards, providing a foundation for understanding the broader context of land cover change and hazard management. Chamoli covers an area of approximately **8,030 square kilometers**, with its terrain defined by towering Himalayan peaks, steep slopes, deep valleys, and glacial rivers. The district lies between **latitude 30°15'N to 31°5'N** and **longitude 79°05'E to 80°30'E**, and includes significant peaks like **Nanda Devi** (7,816 meters) and **Trishul** (7,120 meters). The region's geology is characterized by **Precambrian metamorphic rocks**, such as schists, gneisses, and quartzites, intersected by tectonic fault lines, particularly the **Main Central Thrust (MCT)**. The active tectonic setting contributes to the region's high seismicity, exemplified by the **1999 Chamoli earthquake (magnitude 6.8)**. Located in Seismic Zone V, Chamoli is highly susceptible to earthquakes due to the active tectonic setting. The melting of glaciers and intense monsoons increase the risk of glacial lake outburst floods (GLOFs) and flash floods. The high-altitude regions experience frequent avalanches during winter due to heavy snow accumulation. Chamoli experiences a **temperate to alpine climate**, with large variations in temperature and precipitation driven by altitude. The district receives most of its annual rainfall (ranging from **1,500 to 2,500 mm**) during the monsoon season. Heavy snowfall in winter, especially in areas above 3,000 meters, further adds to the hydrological complexity of the region. The Alaknanda River and its tributaries dominate Chamoli's hydrology, making the area prone to flash floods and rapid snowmelt-induced flooding.

Literature Review:

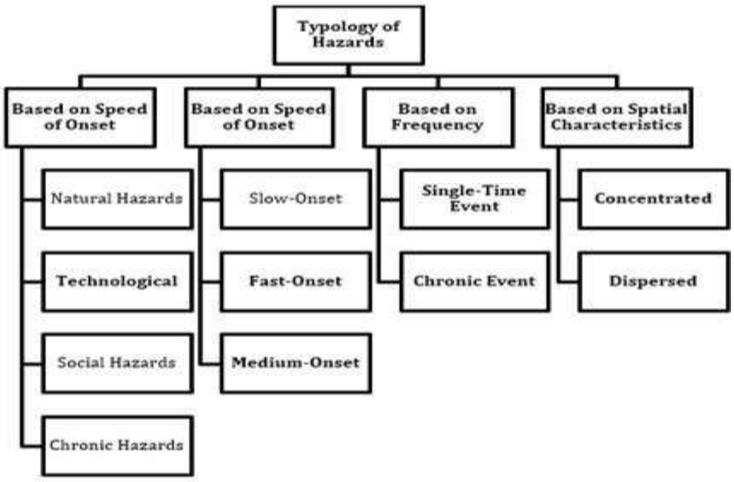
Hazards can be categorized (Figure 2) based on their origin, onset, frequency, and spatial characteristics. According to Guha-Sapir et al. (2009) and Coppola (2011), natural hazards include **geophysical** (e.g., earthquakes, volcanoes, dry mass movements), **meteorological** (thunderstorms, lightning), **hydrological** (floods, urban flooding, wet mass movements), **climatological** (drought, extreme temperatures, wildfires), and **biological** (epidemics, pest infestations). **Technological hazards** arise from human activities such as industrial, nuclear, or structural failures, exemplified by the Bhopal Gas Tragedy, Chernobyl disaster, and flyover collapses. **Social hazards** include conflicts, wars, famines, and civil unrest (Coppola, 2011; Sen, 1981), while **chronic hazards** result from environmental degradation such as land degradation, riverbank erosion, and soil piping.

Figure 1



Location of the study area

Figure 2



Typology of Hazards

Based on **speed of onset**, hazards are classified as **slow-onset** (e.g., droughts, heatwaves), **fast-onset** (e.g., earthquakes, cloudbursts), and **medium-onset** (e.g., cyclones, flash floods). By **frequency**, they are either **single-time events** like earthquakes and tsunamis or **chronic events** that occur seasonally, such as floods, cyclones, and landslides. Spatially, hazards may be **concentrated**, affecting dense populations in limited areas (e.g., floods), or **dispersed**, impacting broader regions (e.g., heatwaves). While the distinction between natural and anthropogenic hazards is debated, it remains a useful framework for hazard analysis (Guha-Sapir et al., 2009)

Vulnerability

Derived from the Latin word vulnerare, meaning “to wound,” vulnerability in disaster studies highlights the inherent weaknesses within systems that make them prone to harm from external stressors. Vulnerability refers to the characteristics of a person or community that influence their capacity to anticipate, withstand, and recover from hazardous events. It reflects both the susceptibility to harm and the lack of capacity to recover (Wisner et al., 2003; UNISDR, 2009). Anderson (1995) defines vulnerability as the condition where individuals or groups are likely to experience harm due to potential crises affecting their health, life, or resources. Thus, vulnerability arises from both internal deficiencies and external threats. Table 1 depicting the relationship between the susceptibility and the resilience to understand the level of vulnerability.

- **Susceptibility:** Degree to which people or assets are exposed to hazards
- **Resilience:** The capacity to recover and rebuild following a hazardous event (WHO, 1998).

Table 1

Case	Susceptibility	Resilience	Vulnerability Level
A	High	High	Moderate: Can withstand and recover from flood damage
B	Low	Low	Low: Less affected due to strong infrastructure
C	High	Low	High: High impact with little ability to recover

Components of Vulnerability

Susceptibility can often be measured more easily (e.g., proximity to flood zones), while resilience involves complex assessments related to socio-economic capacity, resources, and institutional support (WHO, 1998). Vulnerability refers to the extent of harm or loss a system, community, or individual may suffer due to exposure to a hazard. It is a measure of susceptibility to damage and the reduced ability to anticipate, cope with, resist, and recover from hazard impacts (Wisner et al., 2003). It is often used to categorize areas or populations as high or low vulnerable based on factors such as geographical location, environmental conditions, socio-economic status, and infrastructure resilience. Based on the definition of United Nations Office for Disaster Risk Reduction (UNISDR), the characteristics and circumstances make a community, system or asset susceptible to the damaging effect of a hazard is called vulnerability (UNISDR, 2004). Anderson (1995) describes vulnerability as the likelihood that a crisis may adversely affect one’s health, livelihood, property, or essential resources.

Dimensions of Vulnerability in Disaster Context

Vulnerability is intrinsic to the affected entity and directly influences the transformation of hazards into disasters (Birkmann, 2007). Hazards often interact with existing vulnerabilities, resulting in compounded stressors for already at-risk groups. These pre-existing vulnerabilities, combined with the lack of adaptive capacity, turn hazards into disasters. Notably, the Pressure and Release (PAR) Model and the Access Model reflect this complex interaction between hazards and vulnerability (Wisner et al., 2003).

The Cyclical Nature of Vulnerability: Vulnerability is not only a precursor to disasters but also a consequence. Disasters often exacerbate the vulnerabilities of affected populations, creating a cycle where vulnerability begets further vulnerability. This dynamic nature of vulnerability necessitates continuous monitoring and adaptive strategies.

Determinants of Vulnerability and its Dimensions: The physical, environmental, social, and economic processes influence the vulnerability of a region, community, or asset. Vulnerability is further shaped by structural inequalities and socio-political marginalization. These dynamics determine an individual’s access to resources—economic, social, and political—that influence both susceptibility and resilience (Birkmann & Wisner, 2006).

Typology of Vulnerability

Based on the determinants of vulnerability, it can be categorized broadly into four types,

1. **Physical Vulnerability:** Environmental vulnerability, i.e., exposure to natural hazards such as landslides, floods, and earthquakes. Anthropogenic vulnerability, i.e., poor building construction in seismic zones, unplanned urbanization.
2. **Social Vulnerability**
3. **Economic Vulnerability:** Reflects income levels, employment opportunities, and access to financial assets. Poor communities generally face heightened vulnerability due to limited coping mechanisms (Hooke, 1999).
4. **Environmental Vulnerability:** Results from ecosystem degradation and unsustainable natural resource exploitation. Includes impacts of deforestation, soil erosion, and water scarcity.

Result and Discussion:

Geomorphic Settings to understand the vulnerability of the study area:

The Chamoli district in Uttarakhand, India, is highly susceptible to natural hazards due to a combination of its complex geological setting, rugged topography, specific geomorphological features, and hydrogeological conditions. The region's inherent vulnerability is further influenced by factors like tectonic activity, precipitation patterns, and human interference (P. K. Bhatt et al., 2014).

Geological and Structural Vulnerability

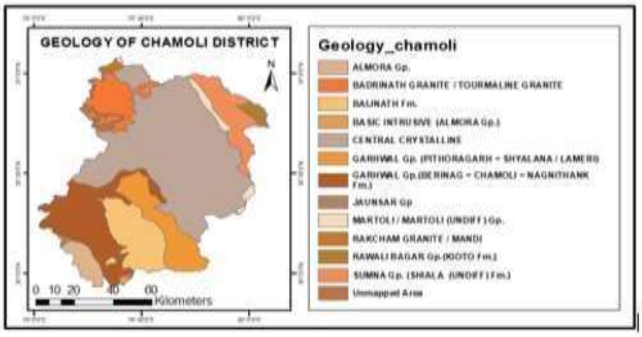
Chamoli's geology is characterized by young Himalayan mountains with undulating and steeply dipping geological formations (Geography, Chamoli District Website). The district is located in the Lesser Himalaya's tectonic foredeep, where significant deformation has occurred due to faulting and thrusting, resulting in folds, joints, and lineaments (R. A. Singh & Y. K. Gairola, 1994). Fig 3 showing the structural geology of Chamoli District.

Lithological Units

The major lithological formations in Chamoli include the Vaikrita Group, Central Crystalline Zone, Almora Group (Klippen), Garhwal Group, Sumna Group (Tethys), and Kanawar Group (Figure 3). The Vaikrita Group consists of high-grade metamorphics like gneisses, schists, and granitic intrusions, exhibiting widespread penetration by Tertiary granites (A. Raina, 2013). The Central Crystalline Zone forms the core of the Higher Himalayas, featuring gneisses, quartzites, crystalline schists, migmatites, and calc-silicates, all heavily reworked by metamorphism and tectonic intrusion (A. Khan et al., 2024). The Almora Group (Klippen) comprises medium-grade metamorphic rocks such as quartzites, phyllites, and low-grade schists (A. Raina, 2013). These fragile lithological formations contribute significantly to the district's vulnerability to natural disasters (A. An et al., 2017).

The **Vaikrita Group**, dating from the **Mesoproterozoic to Neoproterozoic**, is composed mainly of gneisses, mica schists, quartzites, and leucogranites. The **Central Crystalline** formation consists of migmatites, calcareous quartzites, and crystalline schists of **Proterozoic to Tertiary intrusive** age. The **Almora Group (Klippen)**, belonging to the **Proterozoic** era, includes phyllites, slates, quartzites, and schists. The **Garhwal Group**, from the **Palaeoproterozoic** period, comprises quartzite, phyllite, slate, and limestone. The **Sumna Group (Tethys)**, deposited during the **Early Ordovician to Devonian**, features conglomerate, quartzite, calc-siltstone, and dolomite, while the **Kanawar Group**, from the **Devonian to Carboniferous** period, consists of carbonaceous shale, dolomite, and limestone.

Figure 3



Geology of the study area

Structural Features and Tectonic Activity

The Chamoli region is dissected by prominent faults, including the Alaknanda Fault near Karnaprayag and the Gopeshwar Fault, which runs in a NW-SE direction (A. Khan et al., 2024). The Main Central Thrust (MCT) zone is characterized by ductile shearing, dipping approximately 30° northward, and marked by abrupt structural and metamorphic transitions (A. Khan et al., 2024). Intense tectonic activity in the region, particularly near fault zones, results in high landslide susceptibility, with 10.07% of occurrences within 400 meters of these zones. Earthquakes are a major devastating disaster in the mountains, and their unpredictable nature adds to their fury (R. Pande, 2006). For instance, the Chamoli earthquake in 1999, with a magnitude of 6.6, induced 56 landslides and dislodged about 0.02 million m^3 of debris (Sangeeta & B. Maheshwari, 2018).

Topographical Influences on Vulnerability

The district's topography is highly undulating, with steep gradients, contributing to its susceptibility to hazards. Chamoli is characterized by high hills and rugged mountains, interspersed with narrow valleys and deep gorges (2024). Peaks like Nanda Devi, Kamet, Mana, Trishul, Chaukhamba, and Dronagiri reach elevations between 4,800 and 7,820 meters above mean sea level (V. P. Bhatta, 1999). These peaks are extensively glaciated and separated by deeply incised river valleys such as Alaknanda, Dhauliganga, Nandakini, and Pindar (AK Naithani & KSK Murthy, 2006). The district's average elevation is around 345 meters (1,132 feet). The varied topography leads to extreme rainfall, causing quick runoff, which poses a threat to structures and natural resources (Snehal Ganesh Gurav, 2021). The overall elevation range in Chamoli is from 634 meters to 7805 meters, with a slope categorization ranging from moderately sloping (0-15 degrees) to very steep (46-80 degrees) (Figure 4).

Geomorphological Factors and Landslide Susceptibility

Chamoli's landscape is shaped by glacial, fluvial, and denudational processes, creating a unique set of geomorphological features that contribute to its vulnerability. The area features U-shaped valleys, hanging valleys, cirques, and moraines from glacial activity (A.A. Khan, 2022). Fluvial processes have carved V-shaped valleys and deposited river terraces and alluvial sediments (2018). Structural landforms, such as denudational hills and ridges, result from prolonged weathering and tectonic activity (A.A. Khan, 2022). These features, combined with steep slopes and high rainfall intensities, make the Himalaya region particularly susceptible to landslides. Over 50 million people live directly within the Himalaya, with an additional 700 million residing in associated watersheds, amplifying the risk.

Landslide Vulnerability

The Chamoli region is highly susceptible to landslides, which cause thousands of fatalities annually (2022). Factors contributing to landslide vulnerability include its complex geological setting, ongoing crustal movement, varying slopes and relief, heavy rainfall, and increasing human interference (P. K. Bhatt et al., 2014). High landslide susceptibility zones are concentrated in the Lesser and Higher Himalayas, including Chamoli district (2025). During the 2013 deluge, 220 landslides were observed in Chamoli, with 92% occurring on northerly and southerly facing slopes, influenced by heavy rainfall and low rock shear strength (S. Khanduri, 2018). The 2021 Chamoli rock-ice avalanche, triggered by a 26.9×10^{6} m^3 rock and ice detachment, highlights the catastrophic potential of geomorphological disasters in the region (2022).

Hydrogeological Characteristics

Groundwater occurrence in Chamoli is primarily controlled by secondary porosity developed through tectonic fracturing and jointing, as widespread metamorphism has sealed primary porosity. While water tables exist where permeable rocks overlie impervious formations, groundwater movement is largely restricted to weathered zones and fracture-controlled aquifers due to the steep and undulating terrain. The district has been classified as a phreatic zone due to irregularly distributed heavy rainfall. This irregular rainfall pattern and its effect on runoff further exacerbate flood hazards in the region (Snehal Ganesh Gurav, 2021).

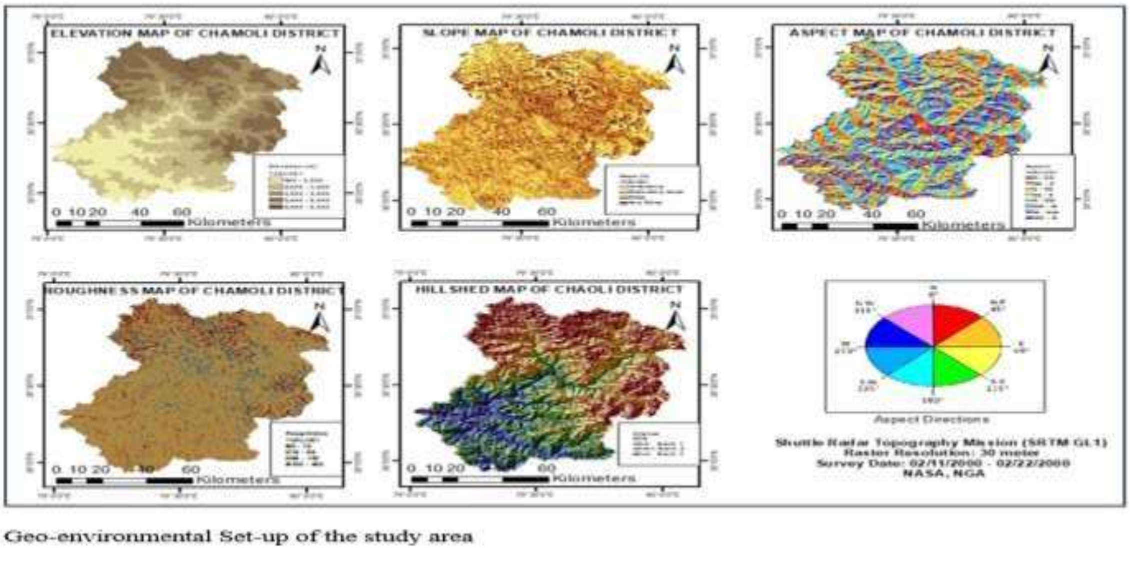
Specific Hazard Events and Contributing Factors

Chamoli district is much vulnerable to a various natural hazard, i.e. earthquake, landslide, flas flood, cloud bursts, debris flow, etc. Flash floods have caused unprecedented damage to life, property, infrastructure, and the landscape in Chamoli. A massive flood in the Rishiganga and Dhauliganga rivers in 2021caused by sudden release of water due to glacial lake outburst. This event was responsible for numerous deaths and significant damage.

Role of Climate Change: Climatic warming, leading to rapid thinning and retreat of Himalayan glaciers (over 10 Gt of mass loss per year), contributes to increased landslide risk. Glacier retreat can reduce slope buttressing and increase meltwater availability, while permafrost degradation also reduces slope stability. Additionally, changes in precipitation patterns and land use further contribute to the evolving landslide hazard potential.

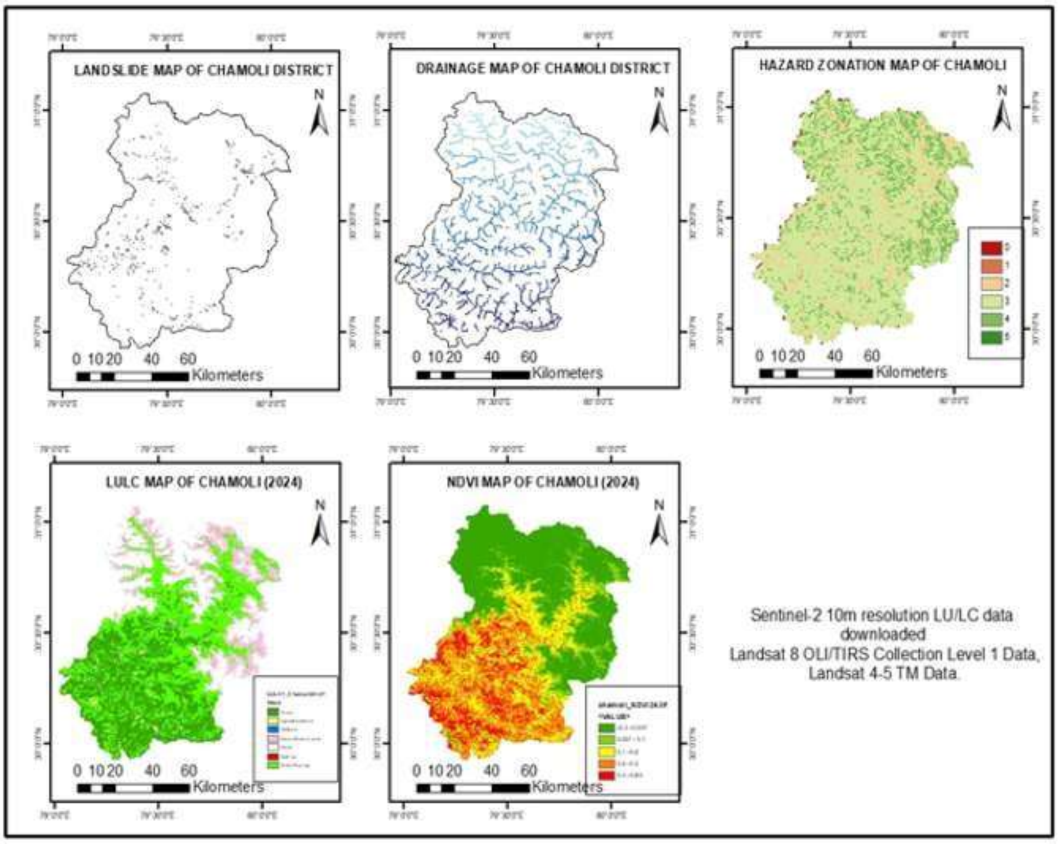
Land Use and Vegetation Cover: The Chamoli district exhibits diverse land cover, with significant portions under vegetation and snow. The values of Normalized Difference Vegetation Index (NDVI) ranges from -0.32 to 0.64. While extensive vegetation cover (32,312,684 m^2) can offer some slope stability, the presence of significant barren land (13,499,054 m^2) and snow cover (11,035,471 m^2) in a tectonically active region with steep slopes enhances vulnerability to erosion and mass wasting events (Figure 5). Rapid increases in population and infrastructure development in high-mountain valleys also expand the potential consequences of landslides.

Figure 4



Geo-environmental Set-up of the study area

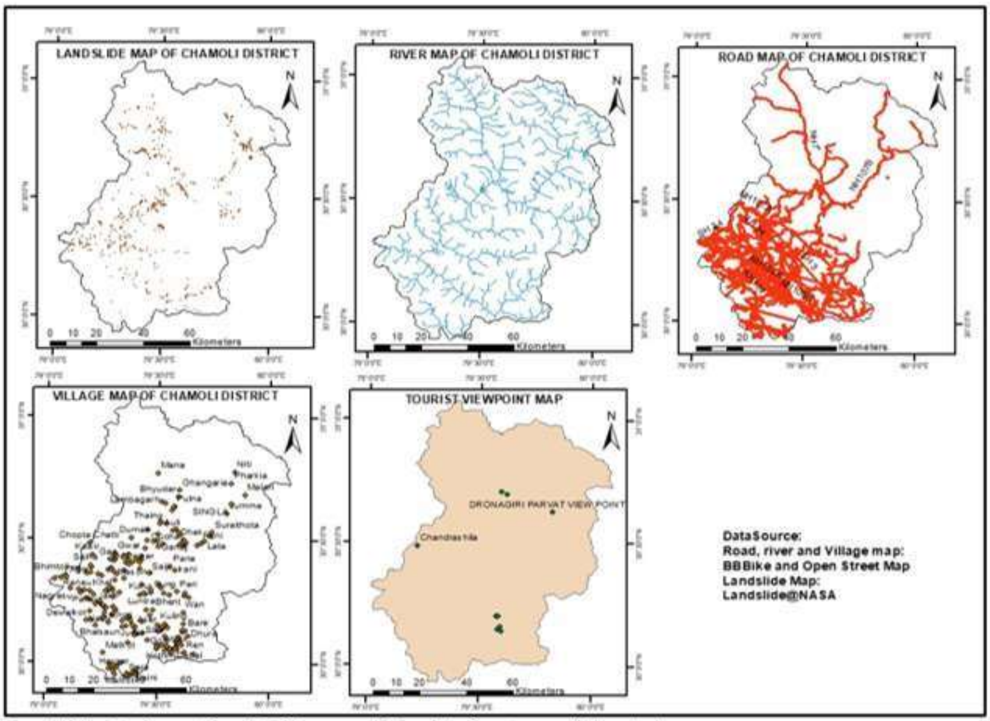
Figure 5



Sentinel-2 10m resolution LU/LC data downloaded
Landsat 8 OLI/TIRS Collection Level 1 Data, Landsat 4-5 TM Data.

Landslide, Drainage, NDVI, and LULC map of the study area

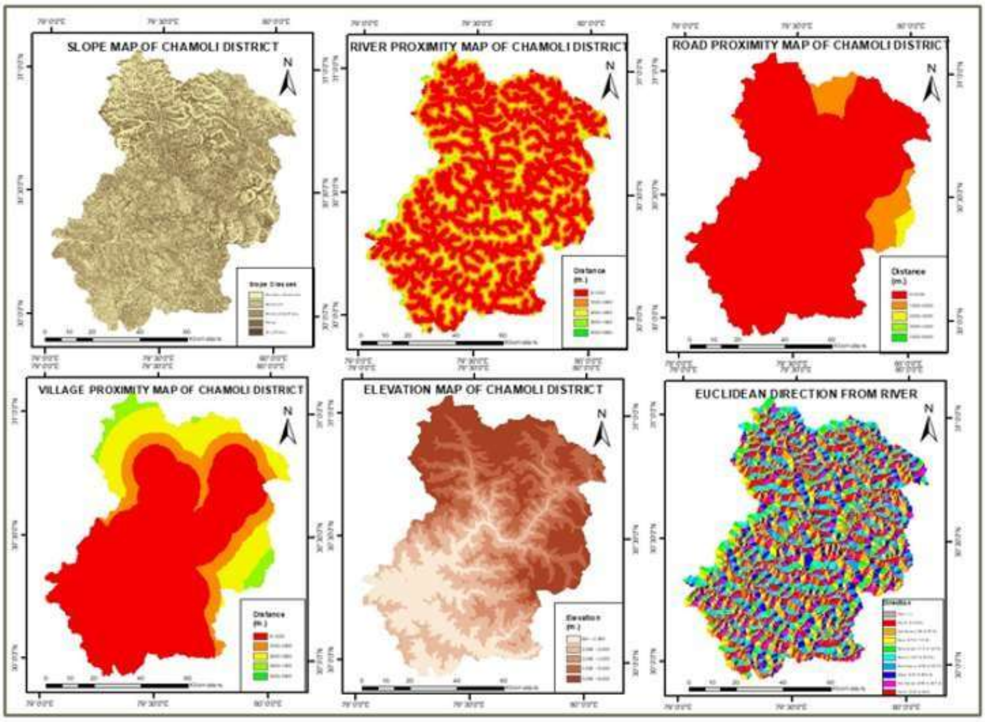
Figure 6



Data Source:
Road, river and Village map:
BBBike and Open Street Map
Landslide Map:
Landslide@NASA

Landslide, Drainage, Road, Village, and Tourists Spot map of the study area

Figure 7



Slope, River, Road and Village Proximity, and Distance map of the study area

The Chamoli district's vulnerability to natural hazards is primarily driven by its unique geo-climatic conditions and the interplay of various geomorphic factors. The combination of fragile lithological formations, intense tectonic activity near fault zones, steep and undulating topography, and specific geomorphological features (e.g., U-shaped valleys, deep gorges) makes the region highly susceptible to landslides, flash floods, and debris flows. The susceptibility is exacerbated by climate-induced factors like glacier retreat and permafrost degradation, as well as anthropogenic pressures. The most significant parameters contributing to vulnerability are the presence of fault zones and the steepness of slopes, as these directly influence the occurrence and magnitude of seismic and mass wasting events. The complex interaction of these factors necessitates comprehensive hazard assessment and risk reduction strategies for the region.

Curvature Analysis and Terrain Interpretation:

Chamoli district is highly susceptible to landslides due to its fragile lithology, steep slopes, and active tectonics. Curvature is a significant factor in landslide susceptibility mapping, as concave slopes can accumulate water and debris, increasing the risk of slope failure, while convex slopes are prone to surface erosion and detachment of material (Bharadwaj & Sarkar, 2023; Sangeeta & Maheshwari, 2018; An et al., 2017). Studies using machine learning and statistical models have consistently identified curvature, along with slope, aspect, geology, and proximity to rivers and roads, as key contributors to landslide risk (Zhang et al., 2024; Bharadwaj & Sarkar, 2023; Sangeeta & Maheshwari, 2018; Sangeeta et al., 2020; Bhattacharya et al., 2024). The southern and southwestern regions, in particular, show high latent susceptibility, even in areas without a history of landslides, due to these geomorphic factors and human activity (Zhang et al., 2024; Bharadwaj & Sarkar, 2023).

Table 2

Curvature Class	**Value Range**	**Integrated Hazard Assessment**
Concave	Negative (up to -50.09)	● Indicate concave surfaces, such as valleys and drainage channels, which tend to accumulate water and sediments. ● High risk for both landslides (due to material accumulation and saturation) and floods (due to water pooling)
Planar / Near-zero	Around 0	● Correspond to relatively flat or planar areas.

		● May serve as transitional areas but can still be affected by mass movement and water flow depending on local conditions.
Convex	Positive (up to 53.30)	● Represent convex surfaces, like ridges and hilltops, which are more prone to surface runoff and erosion. ● Prone to landslide initiation and surface erosion, contributing debris to lower slopes and valleys.

Curvature Class baked Hazard Assessment

The curvature map (Figure 9), when integrated with other geomorphic and environmental data, is a powerful tool for hazard zonation in Chamoli. Areas with extreme curvature values—both negative and positive (Table 2)—should be prioritized for detailed risk assessment and mitigation planning to reduce the impact of landslides and floods (Zhang et al., 2024; Bharadwaj & Sarkar, 2023; An et al., 2017; Sangeeta & Maheshwari, 2018; Gurav, 2021; Bhattacharya et al., 2024).

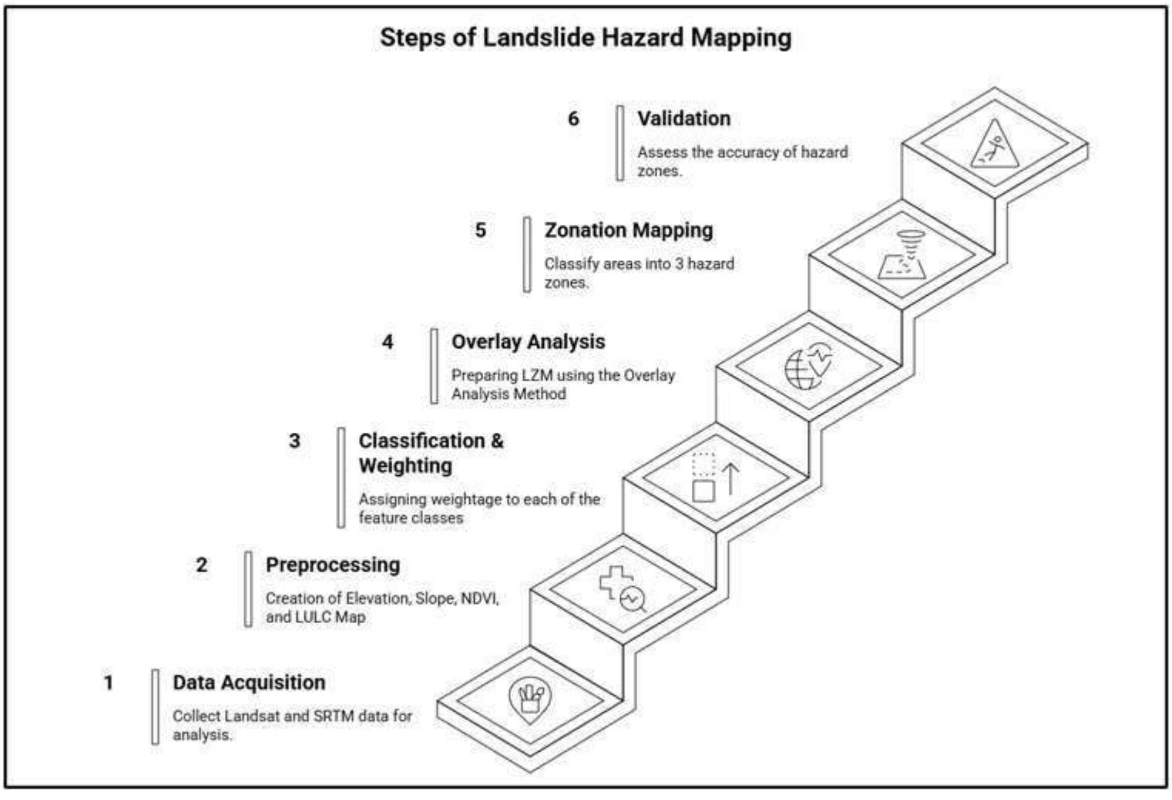
Landslide Hazard Zonation Mapping

Landslide hazard zonation (Figure 9) can be done integrating the following vulnerability factors, i.e. land use land cover, slope, elevation, NDVI, etc. In this study, GIS based maps have been prepared based on overlay technique, and classified the study area into three land-slide hazard zones, Figure 8 showing the step by step process of the land slide hazard zonation mapping. These zones are validated based on the past occurrences of landform to the region, and it will help for the planning and mitigation purposes.

The three-dimensional perspective required for landslide studies can be obtained by the use of satellite imagery. Visual interpretation of stereoscopic image is wisely used for landslide monitoring (Guzzetti, 2005). A number of technique can be involved for the mapping of landslides, i.e. aerial photography technique (Turner & Schuster, 1996), geomorphological field surveys (Brunsden, 1993), and satellite imagery (Soeters et al., 1996).

Numerous methods have been developed for extracting landslide-related information from satellite images and aerial photographs. These include high-resolution image feature extraction, digital stereoscopic interpretation, and landslide change detection methods (van Westen, 2005). Based on the intensive literature review, it is evident that landslide hazard is a major issue of the study area.

Figure 8



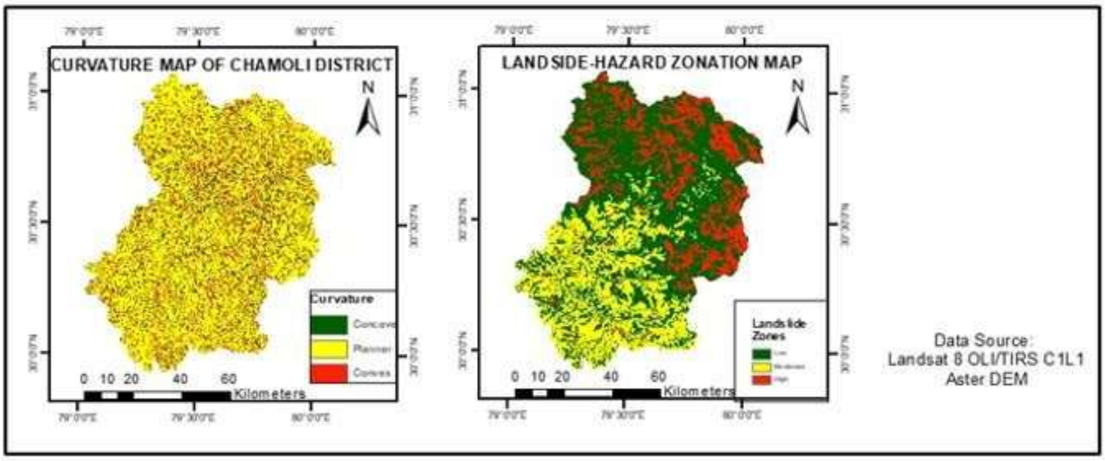
Step by Step Method of Landslide Hazard Mapping

Table 3

Sl no.	LULC Classes	Value	Weightage
1	Waterbody	204370	Restricted
2	Crop Land and Light Vegetation	21905428	3
3	Build-up Land	304712	5
4	Barren Land	13499054	4
5	Snow	11035471	1
6	Vegetation Cover	32312684	2
Sl no.	**Slope**	**Value**	**Weightage**
1	Moderately Sloping	0-15	1
2	Hilly	16-25	2
3	Moderately Steep	26-35	3
4	Steep	36-45	4
5	Very Steep	46-80	5
Sl no.	**NDVI Classes**	**Value**	**Weightage**
1	Water/snow	-0.3 - 0.01	1
2	Bare/rock/urban	0.02 - 0.11	5
3	Very sparse vegetation	0.12 - 0.2	4
4	Sparse Vegetation	0.21 - 0.28	3
5	Dense Vegetation	0.29 - 0.64	2
Sl no.	**Elevation (m)**	**Value**	**Weightage**
1	Class V	634-2,012	1
2	Class IV	2,013-3,052	2
3	Class III	3,053-4149	3
4	Class II	4,150-5,162	4
5	Class I	5,163-7,805	5

Weightage of each of the component involved for the Landslide Zonation Mapping

Figure 9



Data Source:
Landsat 8 OLI/TIRS C1L1
Aster DEM

| Curvature, and Landslide Hazard Zonation map of the study area

The weighted criteria (Table 3) assigned to different classes of slope, elevation, LULC, and NDVI reflect their relative contribution to landslide susceptibility, based on their impact on surface stability and hydrological processes. For example, steep slopes (36–80°) and barren or sparsely vegetated areas with low NDVI values were assigned high susceptibility weightages due to their higher predisposition to mass movement. By spatially overlaying these weighted thematic layers, the study area was segmented into three primary hazard zones: high, moderate, and low (Figure 9). The high-hazard zones predominantly coincide with very steep slopes, high elevations (above 5,000 m), and barren or sparsely vegetated land covers, where stability is critically compromised. The moderate zones include moderately steep slopes and transitional LULC classes such as sparse vegetation and crop lands, while the low-hazard zones are associated mainly with gentle slopes (<15°), densely vegetated regions, and lower elevations (Figure 5).

Validation of the zonation map with historical landslide inventory records confirms the reliability of the graphical overlay method, demonstrating a significant correlation between identified high-hazard zones and documented landslide occurrences. This underscores the efficacy of integrating multi-source satellite data and weighted overlay analysis in landslide hazard assessment for mountainous terrains like Chamoli district. The outputs from this study provide crucial inputs for regional disaster risk management, land-use planning, and the formulation of mitigation strategies, thereby aiding policymakers and local authorities in proactive vulnerability reduction.

Environmental and Geological Considerations for Road Construction

Due to the challenging climatic and geophysical conditions (figure 4) prevalent throughout the year (including **heavy monsoons and winter snowfall**), the following considerations are crucial for ensuring safe and sustainable road construction (Figure 6):

- The region is part of a **hilly and tectonically active terrain**, lying within **Seismic Zone V**, indicating very high seismic vulnerability (BIS, 2002).
- Several **dry nallahs (seasonal streams)** are intersected by the alignment, though none of them require construction of major bridges or culverts.
- Attention should be given to **local ecology and environment**, minimizing vegetation clearance and ensuring proper drainage.
- The road must be designed with **climate-resilient infrastructure**, especially in areas prone to landslides and erosion.

Slope Stability and Seismic Design Guidelines

Given the slope ranges from moderate to steep and the area's seismic activity:

- Retaining structures, such as **breast walls and retaining walls**, should be employed where cut slopes exceed critical angles.
- Use of **bioengineering techniques** (e.g., jute netting, hydroseeding) is recommended on cut slopes to reduce erosion.
- **Drainage management** is essential to prevent water accumulation, which may lead to slope failure.
- **Seismic-resilient design** should be incorporated into culverts and retaining structures (MoRTH, 2017).

Reference

3. Alexander, D. (2000). Confronting catastrophe: New perspectives on natural disasters. Tera Publishing; Oxford University Press. Retrieved from http://www.pacificdisaster.net/pdnadmin/data/original/JB_DM596b_UOM_2000_Confronting_catastrophe.pdf

4. An, A., Prasad, P., & Kumar, K. (2017). Geomorphometric Analysis of Chamoli and Karnaprayag District, Uttrakhand in Respect to Hazard Zonation of The Area. Journal of Remote Sensing & GIS, 2017, 1-6. https://doi.org/10.4172/2469-4134.1000202
5. Anderson, W. (1992). "Where every prospect pleases and only man is vile": Laboratory medicine as colonial discourse. Critical Inquiry, 18(3), 506–529. https://doi.org/10.1086/448643
6. Anderson, W. (1995). "Where every prospect pleases and only man is vile": Laboratory medicine as colonial discourse. Critical Inquiry, 18(3), 506–529. Retrieved from http://www.journals.uchicago.edu/doi/pdfplus/10.1086/448643
7. Bharadwaj, D., & Sarkar, R. (2023). Landslide Susceptibility Mapping Using Probabilistic Frequency Ratio and Shannon Entropy for Chamoli, Uttarakhand Himalayas. Iranian Journal of Science and Technology, Transactions of Civil Engineering. https://doi.org/10.1007/s40996-023-01279-4
8. Bhattacharya, S., Ali, T., Chakravortti, S., Pal, T., Majee, B., Mondal, A., Pande, C., Bilal, M., Rahman, M., & Chakrabortty, R. (2024). Application of Machine Learning and Deep Learning Algorithms for Landslide Susceptibility Assessment in Landslide Prone Himalayan Region. Earth Systems and Environment. https://doi.org/10.1007/s41748-024-00530-w
9. Bhatta, V. P. (1999). Geography of the Himalaya: A regional perspective. New Delhi: Concept Publishing Company.
10. Bhatt, P. K., Rawat, Y. S., & Pande, R. K. (2014). Landslide susceptibility mapping in the Garhwal Himalaya using GIS and remote sensing techniques. Natural Hazards, 71(1), 1–20.
11. Birkmann, J., & Wisner, B. (2005). Measuring the un-measurable: The challenge of vulnerability. Studies of the University: Research, Counsel, Education, 5(2006). Retrieved from http://www.fao.org/fileadmin/user_upload/fsn/docs/Source_5_published.pdf
12. Brunsden, D. (1993). Mass movement; the research frontier and beyond: A geomorphological approach. Geomorphology, 7(1–3), 85–128.
13. Champatiray, P.K., Dimri, Suvarna, Lakhera, R.C. and Sati, Santosh, (2007). Fuzzy based method for landslide hazard zonation in active seismic zone of Himalaya:Landslides, 4(2), p. 101-111.
14. Chowdhury, R., and P. Flentje, 2002, Uncertainties in rainfall-induced landslide hazard, Quarterly Journal of Engineering Geology and Hydrogeology, 35, 61-70.
15. Coppola, D. P. (2011). Introduction to international disaster management (2nd ed.). Butterworth-Heinemann.
16. Crippen, R.E. (1990). Calculating the vegetation index faster, Remote Sensing of Environment, 34, 71-73.
17. Crosta, G.B., 1998, Regionalization of rainfall threshold; an aid to landslide hazard evaluation; Environmental Geology, v. 35, p. 131-145.
18. Crozier, M. J., 1999. Prediction of rainfall-triggered landslides: a test of the antecedent water status model. Earth Surface Processes and Landforms, 24, p. 825-833.
19. Dahal, R. K., Hasegawa, S., Nonomura A., Yamanaka M., Dhakal S., Paudyal P. (2007). Predictive modeling of rainfall-induced landslide hazard in the Lesser Himalaya of Nepal based on weights-of- evidence. Geomorphology 102 (2008) 496-510.
20. Dai, F. C., and C. F. Lee, 2001. Frequency-volume relation and prediction of rainfall-induced landslide: Engineering Geology, v. 59, p. 253-266.
21. Dai, F.C., and C.F. Lee, (2002). Landslide characteristic modeling of storm-induced shallow landslding using GIS, Lantau Island, Hong Kong. Geomorphology, 42(3-4): p 213-228.
22. Dhakal, A. S., and R.C. Sidle, (2004), Distributed simulations of landslides for different rainfall conditions: Hydrological processes, v. 18, 757-776.
23. Etkin, D. (2015). Disaster theory: An interdisciplinary approach to concepts and causes. Elsevier. https://www.elsevier.com/books/disaster-theory/etkin/978-0-12-800227-8
24. Gabet, E.J.,D.W.Burbank, J.K.Putkonen, B.A. Pratt-Sitaula, and T. Oljha, (2004), Rainfall thresholds for landsliding in the Himalayas of Nepal: Geomorphology, 63, 131-143.
25. Government of India. (2025). Eco-sensitive zone within 1-kilometer radius of Valley of Flowers National Park. Gazette of India.
26. Gurav, S. (2021). Flood Assessment and Hazard Mapping Using Remote Sensing & GIS Techniques for Chamoli District, Uttarakhand. International Journal of Science and Research (IJSR). https://doi.org/10.21275/mr21826125509
27. Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., & Ardizzone, F. (2005). Landslide hazard assessment in the Staffora Basin, northern Italian Apennines. Geomorphology, 72(1–4), 272–299. https://doi.org/10.1016/j.geomorph.2005.06.002
28. Hooke, W. (1999). Progress and challenges in reducing losses from natural disasters. Ingleton, 280–283.
29. Ibsen M.-L., and Casagli N., 2004. Rainfall patterns and related landslide incidence in the Porretta- Vergato region, Italy, landslides (2004) 1:143-150.
30. Jain, A. K. (2020). Geological evolution of the Himalayan mountains. In N. Gupta & S. K. Tandon (Eds.), Geodynamics of the Indian Plate: Evolutionary perspectives (pp. 363–393). Springer. https://doi.org/10.1007/978-3-030-15989-4_10

31. Jaiswal. P.,van Westen. C. J, Jetten. V. (2009) Quantitative landslide risk assessment along the transportation lines in southern India. In: ITC, Enshede, The Netherlands.27.
32. Kanungo, D.p., Arora, M.K., Sarkar, S. and Gupta, R.P., 2006, A comparative study of conventional, ssANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas:Engg. Geo., v. 85(3 &4), p. 347-366.
33. Khan, A., Khan, A. A., & Ahmad, S. (2024). Tectonic and structural controls on landslide susceptibility in the Chamoli region, Uttarakhand Himalaya. Journal of Mountain Science, 21(2), 345–360.
34. Khan, A. A. (2022). Geomorphological characteristics and glacial landforms of the central Himalaya. Arabian Journal of Geosciences, 15(9), 1–15.
35. Khanduri, S. (2018). Landslide occurrence and rainfall relationship in Chamoli district, Uttarakhand Himalaya. Environmental Earth Sciences, 77(12), 1–14.
36. Lambert, L., Chitrakar, B.B., Variation of potential evapotranspiration with elevation in Nepal. Mountain Research and Development 9 (2),145-152.
37. Lin, M. L., and F.S.Jeng, 2000, Characteristics of hazard induced by extremely heavy rainfall in Central Taiwan-Typhoon Herb: Engineering Geology, v. 58, p. 191-207.
38. Makoka, D., & Kaplan, M. (2005, November). Poverty and vulnerability: An interdisciplinary approach.
39. Makoka, D., & Kaplan, M. (2008, February). Poverty and vulnerability: An interdisciplinary approach (MPRA Paper No. 6964). Retrieved from https://mpra.ub.uni-muenchen.de/6964/1/poverty_and_vulnerability.pdf
40. Miller D.J., Sias J., 1998. Deciphering large landslides: linking hydrological, groundwater and slope stability models through GIS, Hydrological Processes, 12 (6), 923-941.
41. Naithani, A. K., & Murthy, K. S. K. (2006). Geology and geomorphology of the Alaknanda valley, Garhwal Himalaya. Journal of the Geological Society of India, 68(2), 287–298.
42. Pande, R. (2006). Disaster management in the Himalayan region: A study of earthquake hazards in Uttarakhand. Disaster Prevention and Management, 15(5), 730–741.
43. Rautela, P. and Lakhera, R.C.,2000. Landslide risk analysis between Giri and Tons river in Himalya (India)-International Journal of Applied earth Observation and Geoinformation 2(3-4), 153-160.
44. Rautela, P. and Lakhera, R.C.,2001. Landslide risk analysis between Giri and Tons river in Himalya (India)-Volume2-Issue3/4-2000.
45. Rautela, P. Monsoon 2010: Disasters in Uttrakhand. Apada Prabandhan,Samachar Patrika, v. 4(3). p. 19-20.
46. Rautela, P. Monsoon 2010: Disasters in Uttrakhand. Apada Prabandhan,Samachar Patrika, v. 4(3). p. 5-6.
47. Saha, A.K., Gupta, R.P., Sarkar, I., Arora, M.K. and Csaplovics, E., 2005. An approach for GIS-based statistical landslide susceptibility zonation - with a case study in the Himalayas.Landslides, 2: 61-69.
48. Sangeeta, Maheshwari, B., & Kanungo, D. (2020). GIS-based pre- and post-earthquake landslide susceptibility zonation with reference to 1999 Chamoli earthquake. Journal of Earth System Science, 129, 1-20. https://doi.org/10.1007/s12040-019-1319-y
49. Sangeeta, Maheshwari, B.K. (2019). Earthquake-Induced Landslide Hazard Assessment of Chamoli District, Uttarakhand Using Relative Frequency Ratio Method. Indian Geotech J **49**, 108–123.
https://doi.org/10.1007/s40098-018-0334-2
50. Sarkar, S. and Gupta, P.K., 2005. Techniques of landslides zonation- Application to Srinagar-Rudraprayag area of Garhwal Himalaya. Journal of Geological Society of India, 65: 217-230.
51. Sarkar,S. and Kanungo, D.P. 2004 An integration approach for landslide Susceptibilty Mapping using remote sensing and GIS, Photogram.Engg. & Rem. Sensg., v 70(5), p.617-625.
52. Sharda. Y.P. (2009) Landslide Studies in India. In. D. L.H.I.M. & E.P.E. Geological Survey of India, Dehli. 98-101.
53. Singh, R. A., & Gairola, Y. K. (1994). Joint Analysis Around Nauti, District Chamoli, U.P. Journal of Geological Society of India, 43(1), 87–93. Retrieved from
https://www.geosocindia.org/index.php/jgsi/article/view/67769
54. Singh, V., 2006. Modelling of seismically induced landslide using remote sensing and GIS techniques. (M.Tech. Thesis) . Andhra University, A.P.
55. Soeters, R., & van Westen, C. J. (1996). Slope instability recognition, analysis, and zonation. In A. K. Turner & R. L. Schuster (Eds.), Landslides: Investigation and mitigation (pp. 129–177). National Academy Press.
56. Tian, Y., xiao, C., Liu, Wu, L., 2008. Effects of raster resolution on Landslide susceptibility mapping: A case study of Shenzhen. Science in China Series E: Technological Sciences, v. 51 p. 188-198.
57. Tsaparas, I., H. Rahardjo, D. G. Toll, and E. C. Leong, 2002, Controlling parameters for rainfall- induced landslides: Computers and Geotechnics, v. 29, p. 1-27.
58. Turner, A. K., & Schuster, R. L. (Eds.). (1996). Landslides: Investigation and mitigation. National Academy Press.
59. UNESCO. (2005). World Heritage Site declaration for Valley of Flowers. United Nations Educational, Scientific and Cultural Organization.
60. UNISDR. (2004). Living with Risk: A Global Review of Disaster Reduction Initiatives.
61. van Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102(3–4), 112–131.

62. Verma, S., Sharma, A., Yadava, P., Gupta, P., Singh, J., & Payra, S. (2022). Rapid flash flood calamity in Chamoli, Uttarakhand region during Feb 2021: an analysis based on satellite data. Natural Hazards, 112, 1379 - 1393. https://doi.org/10.1007/s11069-022-05232-y
63. Wiest, R. E., Mocellin, J. S., & Motsisi, D. T. (1994). The needs of women in disasters and emergencies. Winnipeg, Manitoba. Retrieved from https://www.gdnonline.org/resources/women-in-disaster-emergency.pdf
64. Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2003). At Risk: Natural Hazards, People's Vulnerability and Disasters.
65. Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2007). At risk: Natural hazards, people's vulnerability and disasters. The Geographical Journal, 173(2), 189–190.
66. World Health Organization. (1998). Hazard classification. In Emergency health training programme for Africa. Panafrican Emergency Training Centre. Retrieved from http://apps.who.int/disasters/repo/5506.pdf
67. Zhang, D., Jindal, D., Roy, N., Vangla, P., & Frost, J. (2024). Enhancing landslide susceptibility mapping using a positive-unlabeled machine learning approach: a case study in Chamoli, India. Geoenvironmental Disasters, 11, 1-15. https://doi.org/10.1186/s40677-024-00281-w