Bulletin of Pure and Applied Sciences
Geology, Vol.45F, No.1,
January-June 2026: P.1-9
Original Article

Print version ISSN 0970 4639
Online version ISSN 2320 3234

Available online at www.bpasjournals.com

Integrated Landslide Process Analysis for Sustainable Hazard Management in the Bhagirathi Valley

Vikas Kumar*

Author's Affiliations:
Amity School of Earth and Environmental Sciences, Amity University Gurugram, Haryana India

*Corresponding Author: Vikas Kumar, Amity School of Earth and Environmental Sciences, Amity University Gurugram, Haryana India
E-mail: vkrajpoot96@gmail.com

Received on 04.01.2026, Revised on 20.02.2026, Accepted on 07.03.2026

How to cite this article: Kumar V. (2026). Integrated Landslide Process Analysis for Sustainable Hazard Management in the Bhagirathi Valley. *Bulletin of Pure and Applied Sciences- Geology*, 45F (1), 1-9.

Abstract:
Landslides are among the most widespread and destructive natural hazards in the Himalayan region, where intricate geological formations, rugged terrain, heavy precipitation, and growing human activities collectively contribute to slope instability. The Bhagirathi Valley, situated in the tectonically dynamic Garhwal Himalaya, is particularly vulnerable to frequent landslide events that interrupt transportation networks, impair hydropower facilities, endanger settlements, and disturb delicate mountain ecosystems. This study seeks to provide a comprehensive analysis of landslide mechanisms and triggering factors in the Bhagirathi Valley through an integrated and sustainability-focused framework. Detailed field-based geological and geomorphological surveys are integrated with GIS and remote sensing techniques to evaluate lithology, structural features, slope characteristics, drainage patterns, land-use transformations, and anthropogenic influences. The findings reveal that landslide activity in the region is controlled by a combination of highly weathered and weak rock formations, ongoing tectonic movements, steep gradients, intense monsoonal rainfall, riverbank erosion, and unplanned developmental activities such as road excavation and hydropower projects. The study underscores that landslides in the valley are not merely natural occurrences but are shaped by complex interactions between environmental and human factors. To address this challenge, a sustainability-oriented framework emphasizing ecosystem-based mitigation strategies, hazard-sensitive land-use planning, and active community involvement is proposed to minimize future risks. The results offer valuable insights for disaster risk reduction policies and sustainable development initiatives in Himalayan mountainous regions.

Keywords: *Landslide processes; Causative factors; GIS and remote sensing; Himalayan hazards; Sustainability; Disaster risk reduction*

1. INTRODUCTION

Mountain environments are inherently dynamic systems governed by the ongoing interplay of tectonic forces, climatic fluctuations, and surface geomorphic processes. In such terrains, landslides represent one of the most significant geomorphic mechanisms, playing a dual role in shaping long-term landscape evolution while simultaneously posing serious risks to human populations (Cruden & Varnes, 1996; Guzzetti et al., 2005). Globally, landslides are responsible for thousands of deaths annually and cause substantial economic damage, especially in developing countries where rapid population growth, expanding infrastructure, and changing land-use patterns increasingly extend into vulnerable mountainous areas (Petley, 2012).

Within the Indian Himalayan region, landslides rank among the most recurrent and destructive natural hazards, disrupting transportation networks, hydropower projects, agricultural systems, and settlements. The state of Uttarakhand in the central Himalaya is particularly prone to landslide activity due to its steep and dissected terrain, weak and highly weathered rock formations, active tectonic conditions, significant seismic activity, and intense monsoon rainfall (Sundriyal et al., 2015). The Bhagirathi Valley, a crucial segment of the upper Ganga basin, has witnessed numerous landslide incidents in recent decades, some of which have resulted in severe socio-economic and environmental impacts, especially during episodes of extreme precipitation (Martha et al., 2013).

Previous investigations of landslides in the Himalayan region have predominantly focused on susceptibility mapping and hazard zonation through GIS-based statistical, heuristic, and machine-learning techniques (Pradhan, 2010). While these approaches are valuable for spatial prediction and regional planning, they frequently offer limited understanding of the fundamental physical mechanisms responsible for slope instability. In addition, many hazard assessments are undertaken without adequately integrating broader sustainability dimensions, including ecosystem integrity, land-use governance, and the resilience of local communities.

In the context of intensifying climate variability and accelerated infrastructure expansion across Himalayan terrains, there is an urgent need for comprehensive, interdisciplinary studies that directly connect landslide dynamics with their driving factors and sustainable development frameworks. Developing a process-oriented understanding of landslide initiation, progression, and triggering mechanisms is crucial for formulating mitigation strategies that effectively reduce risk while preserving fragile mountain ecosystems and ensuring long-term environmental sustainability.

This study addresses this need by adopting a process-based and sustainability-oriented approach to landslide analysis in the Bhagirathi Valley. The specific objectives are to:
(i) examine the dominant landslide processes operating in the valley,
(ii) identify and evaluate natural and anthropogenic causative factors, and
(iii) propose a sustainable framework for landslide risk reduction and land-use planning.

2. REGIONAL SETTING AND STUDY AREA CHARACTERISTICS

2.1 Physiography and Topography

The Bhagirathi Valley displays marked topographic variability, with elevations rising from about 1,000 m in the lower segments to more than 6,000 m above mean sea level in the higher Himalayan reaches. Geomorphologically, the valley is defined by narrow, deeply entrenched gorges, precipitous valley walls, sharp ridges, and confined river channels, all indicative of vigorous fluvial incision and ongoing tectonic uplift. This rugged landscape generates substantial gravitational stress on slope materials, making the region intrinsically vulnerable to slope failures and mass wasting processes (Sundriyal et al., 2015; Guzzetti et al., 2005).

Slope angles in the Bhagirathi Valley frequently surpass 30–45°, particularly along riverbanks, road cuts, and inhabited areas. The presence of steep gradients, coupled with thin or patchy soil cover, highly jointed and fractured bedrock, and intense weathering, considerably weakens slope resistance. Consequently, the region is highly susceptible to various types of landslides, including shallow translational slides, rockfalls, rock slides, and debris flows, particularly during episodes of intense or prolonged monsoonal precipitation (Cruden & Varnes, 1996; Pradhan, 2010). Furthermore, the concentration of infrastructure along steep valley flanks amplifies instability by altering natural slope geometry and disrupting drainage systems, thereby increasing both the frequency and magnitude of landslide occurrences.

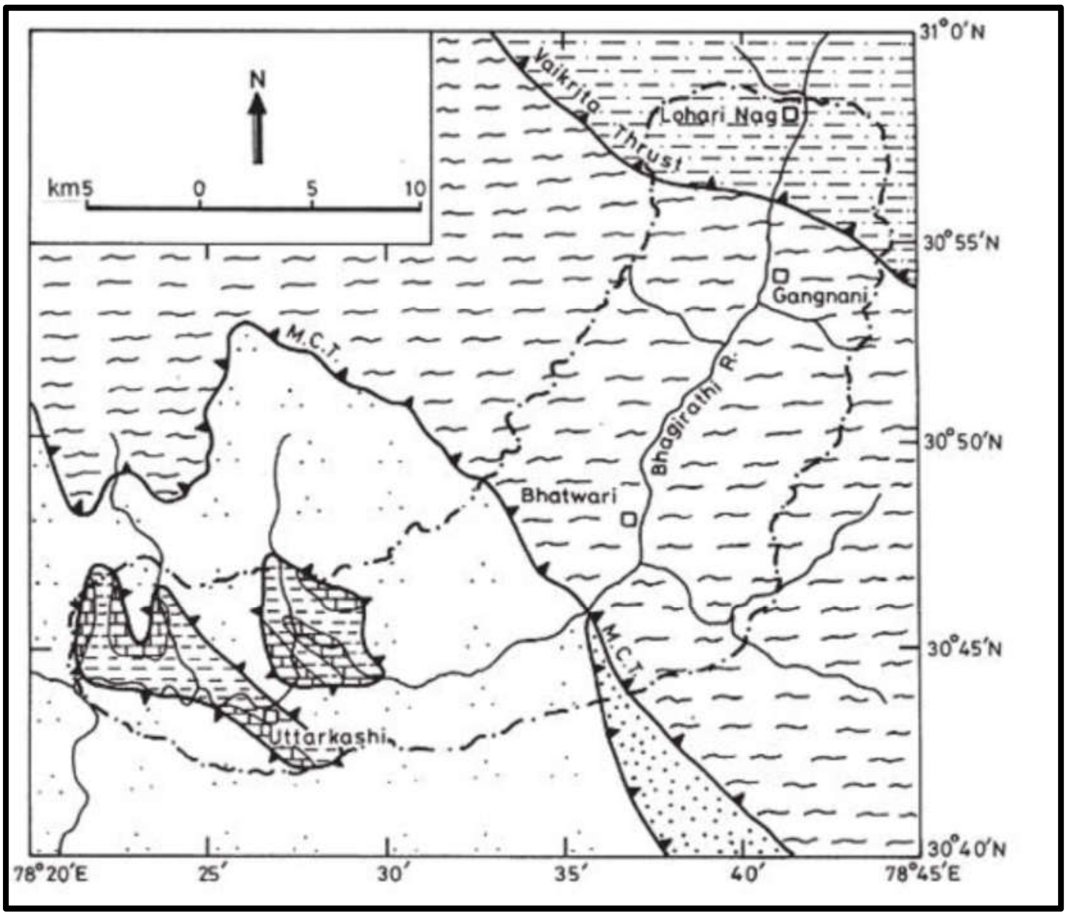

Figure 1: Geology Map of the Area (Saha et al., 2002)

2.2 Geological Framework

Geologically, the Bhagirathi Valley constitutes a significant segment of the Lesser and Higher Himalayan tectonic provinces and is characterized by a heterogeneous assemblage of metamorphic and sedimentary rocks, including phyllites, schists, quartzites, gneisses, and granites. These lithological units exhibit marked differences in mechanical competence and weathering behaviour, which strongly influence slope stability conditions. Fine-grained, foliated rocks such as phyllites and schists are especially vulnerable to rapid weathering and reduction in shear strength, rendering them highly susceptible to slope failures. In contrast, relatively competent rocks such as quartzites and granites generally experience failure along pre-existing structural discontinuities rather than through pervasive weathering (Valdiya, 1980; Gansser, 1964).

The geological setting is further complicated by major tectonic structures, particularly the Main Central Thrust (MCT) and its associated shear and fracture zones that dissect the Bhagirathi Valley. Sustained tectonic movements along these zones have produced intense rock mass deformation, manifested in closely spaced joints, foliations, faults, and shear planes. Such structural discontinuities function as potential slip surfaces for both shallow and deep-seated landslides, especially where their orientation is unfavourable relative to slope geometry (Searle et al., 2008). Consequently, the legacy of tectonic deformation, together with ongoing crustal activity within the Himalayan orogen, exerts a fundamental control over landslide mechanisms and the spatial distribution of slope instability across the region.

Figure 2: Field photograph of the study area

2.3 Climate and Hydrology

The study area experiences a monsoon-dominated climate, with approximately 70–80% of the total annual rainfall occurring during the southwest monsoon season from June to September. This highly concentrated and intense precipitation significantly contributes to slope instability by promoting infiltration, elevating pore-water pressure, and reducing the effective shear strength of slope-forming materials. Extreme rainfall events, such as cloudbursts and extended wet periods, are especially influential in initiating both shallow and deep-seated landslides in the Himalayan region. These events rapidly saturate weathered rock masses and soil cover, while also reactivating pre-existing structural weaknesses (Guzzetti et al., 2005; Sundriyal et al., 2015).

Beyond rainfall-driven processes, fluvial dynamics play a crucial role in controlling landslide occurrences within the valley. The Bhagirathi River and its tributaries actively incise both vertically and laterally, resulting in toe erosion and progressive over-steepening of adjoining slopes. The removal of basal support enhances slope susceptibility to failure, particularly during peak discharge phases associated with monsoonal rainfall (Schwanghart et al., 2016). In the higher altitudes, seasonal snowmelt and glacial meltwater further aggravate hydrological instability by increasing subsurface flow and promoting slope saturation during the pre-monsoon and early monsoon periods. Together, intense rainfall, river incision, and meltwater contributions create a highly dynamic hydrological system that governs the initiation and reactivation of landslides in the Bhagirathi Valley (Sati et al., 2011).

2.4 Land Use and Human Activities

Land use in the Bhagirathi Valley consists of a diverse mix of forested hill slopes, terraced farmlands, growing rural and urban settlements, road networks, and major hydropower installations. Over recent decades, rapid development fueled by population increase, tourism expansion, and rising energy requirements has significantly altered the natural terrain. Large-scale slope cutting for road construction, along with tunneling and blasting activities linked to hydropower projects, and the steady growth of built-up areas have extensively modified slope morphology and disrupted the underlying lithological and structural framework.

At the same time, widespread clearing of natural vegetation has diminished root cohesion and intensified surface runoff, contributing to slope instability. Development interventions have also disturbed natural drainage systems, resulting in irregular surface and subsurface water movement that increases pore-water pressure during periods of heavy rainfall. The lack of detailed geotechnical assessments and insufficient adoption of slope stabilization measures have further heightened landslide vulnerability in the valley. Studies conducted in the Himalayan region similarly indicate that poorly planned infrastructure expansion and land-use transformations function as major anthropogenic triggers, aggravating existing geological and climatic fragility and converting natural slope adjustments into recurrent hazard events (Owen et al., 2008; Martha et al., 2013).

3. REVIEW OF LITERATURE

Landslide research has undergone substantial transformation over recent decades, shifting from predominantly descriptive geomorphological approaches to advanced quantitative modeling and comprehensive risk assessment frameworks. The classification system proposed by Cruden and Varnes remains one of the most widely recognized foundations for process-based landslide analysis, emphasizing the critical role of material characteristics and movement mechanisms in evaluating slope hazards.

In mountainous terrains, numerous investigations have consistently identified lithology, geological structure, slope gradient, and rainfall as primary factors influencing landslide initiation. Within the Himalaya, active tectonic processes combined with intense monsoonal precipitation are considered dominant drivers of slope instability, significantly increasing hazard susceptibility.

The integration of Geographic Information Systems (GIS) and remote sensing technologies has revolutionized landslide research by facilitating large-scale susceptibility mapping and systematic inventory development. Analytical approaches such as frequency ratio, logistic regression, fuzzy logic, and machine learning models have been extensively employed to enhance predictive accuracy. Nevertheless, some scholars contend that many susceptibility assessments prioritize spatial prediction performance over a deeper understanding of underlying geomorphic processes.

More recent studies increasingly highlight the influence of anthropogenic activities in intensifying landslide risks. In regions such as Uttarakhand, infrastructure expansion—including road construction, deforestation, and hydropower projects—has been identified as a significant contributor to slope destabilization. These findings emphasize the importance of incorporating sustainability principles and responsible land-use planning into landslide research, mitigation strategies, and hazard management practices.

4. MATERIALS AND METHODS

4.1 Conceptual Framework

This study adopts an integrated conceptual framework that links landslide processes, causative factors, and sustainability. Rather than treating landslides solely as natural hazards, the framework recognizes them as socio-environmental phenomena influenced by human decisions and development pathways.

4.2 Field-Based Investigations

Extensive field surveys were conducted across representative sections of the valley. Observations included:

- Identification of landslide types and dimensions
- Characterization of slope geometry and failure surfaces
- Measurement of discontinuity orientations
- Assessment of weathering profiles and soil thickness
- Documentation of drainage conditions and human interventions

Field evidence of past landslide activity, such as scarps, displaced material, and damaged infrastructure, was systematically recorded.

4.3 Remote Sensing and GIS Analysis

Multispectral satellite imagery (Landsat and Sentinel) and digital elevation models were used to derive thematic layers, including slope, aspect, curvature, drainage density, and land-use/land-cover. A landslide inventory was prepared using visual interpretation and field validation.

4.4 Evaluation of Causative Factors

Causative factors were grouped into natural and anthropogenic categories. Their influence on landslide occurrence was assessed through spatial overlay analysis and qualitative interpretation based on field evidence.

5. LANDSLIDE PROCESSES IN THE BHAGIRATHI VALLEY

5.1 Types of Landslides

The valley exhibits a wide range of landslide types, reflecting diverse materials and triggering mechanisms. Shallow debris slides are common on weathered slopes during monsoon rainfall, while rock falls and rock slides occur along steep, jointed rock faces. Debris flows are particularly destructive, mobilizing large volumes of saturated material along narrow channels.

5.2 Geological and Structural Controls

Lithology and structure exert a fundamental control on landslide processes. Foliation planes in schists and phyllites often dip parallel to slope faces, creating planar failure conditions. Shear zones associated with major thrusts act as zones of weakness where deep-seated failures may develop.

5.3 Hydrological Processes

Rainfall infiltration increases pore-water pressure, reduces shear strength, and initiates slope failure. Prolonged rainfall events are particularly effective in triggering landslides by saturating soil and rock masses. River undercutting further destabilizes slopes by removing lateral support.

5.4 Seismic Influence

Although earthquakes may not directly trigger every landslide, seismic shaking contributes to long-term slope weakening by opening fractures and reducing rock mass strength. The cumulative effect of repeated seismic events enhances landslide susceptibility.

6. CAUSATIVE FACTORS OF LANDSLIDES

6.1 Natural Factors

Natural causative factors include steep slopes, fragile lithology, active tectonics, intense rainfall, and fluvial erosion. These factors establish a baseline level of susceptibility across the valley.

6.2 Anthropogenic Factors

Anthropogenic interventions often act as direct catalysts for landslides in mountainous environments. Infrastructure development, particularly road construction and slope excavation, commonly results in excessive steepening of natural gradients and insufficient drainage management, thereby disrupting slope stability and intensifying the likelihood of failure (Sarkar & Kanungo, 2004). Large-scale deforestation further contributes to instability by eliminating root reinforcement, lowering soil cohesion, and enhancing surface runoff and erosional processes during heavy rainfall episodes (Sidle & Ochiai, 2006). Moreover, hydropower projects—especially tunneling and blasting operations—substantially alter subsurface stress regimes and natural groundwater circulation patterns, progressively weakening rock formations and adjacent slopes (Gupta & Sah, 2008).

The interaction between intrinsic natural vulnerability—governed by weak lithology, steep topography, and intense precipitation—and human-induced disturbances significantly increases both the occurrence and severity of landslides. These combined effects convert inherently sensitive slopes into high-risk zones, elevating the chances of repeated failures and consequent socio-economic damage (Petley, 2012). Collectively, these observations highlight the urgent necessity for sustainable land-use planning and hazard-responsive development strategies in landslide-prone Himalayan regions.

7. SUSTAINABILITY PERSPECTIVE ON LANDSLIDE RISK

A sustainability-driven framework for landslide management emphasizes enduring resilience and proactive risk minimization rather than relying solely on short-term, infrastructure-focused engineering interventions. While conventional mechanical stabilization methods may provide immediate protection, they frequently overlook the deeper environmental and socio-ecological factors that contribute to slope failure. In contrast, ecosystem-based approaches—such as bioengineering applications and afforestation with indigenous, deep-rooted plant species—enhance slope stability by strengthening soil structure, moderating runoff, and sustaining hydrological equilibrium, while also preserving ecological balance (Gray & Sotir, 1996; Stokes et al., 2014).

Integrating hazard-sensitive land-use planning into broader regional development strategies is equally critical. Regulating or limiting construction in areas identified as high-risk through scientific hazard assessments substantially reduces exposure and potential damage (Guzzetti et al., 2005). Such planning ensures that infrastructure growth remains compatible with the ecological limits of fragile mountainous landscapes. Moreover, community engagement and awareness initiatives are vital components of sustainable risk reduction. Educated and prepared communities can better identify early warning indicators, implement appropriate land management practices, and respond effectively during landslide events (UNDRR, 2015). Collectively, ecosystem-based solutions, risk-informed spatial planning, and active community participation constitute the foundation of sustainable landslide risk management in mountain regions.

The integrated assessment further reveals that landslides in the Bhagirathi Valley arise from the interaction between natural processes and human activities. Unsustainable developmental interventions intensify pre-existing geological vulnerabilities, converting natural slope dynamics into hazardous events. Comparisons with findings from other Himalayan investigations underscore the broader applicability of integrated, process-oriented methodologies. Embedding sustainability principles within landslide research and management thus offers a strategic pathway toward resilient and environmentally responsible mountain development.

8. CONCLUSIONS

This study offers a comprehensive, process-oriented insight into the causes of landslides in the Bhagirathi Valley by adopting an integrated and sustainability-focused framework. The findings reveal that landslides in the Himalayan terrain are not the result of a single factor but emerge from the dynamic interaction of geological fragility, hydrological triggers such as intense rainfall and slope saturation, and increasing anthropogenic pressures including road construction, deforestation, and unplanned settlements. These interconnected drivers amplify slope instability and heighten disaster vulnerability in the region. The study emphasizes that effective risk reduction requires a multidimensional strategy that combines scientific assessment with sustainable land-use planning, ecosystem-based mitigation measures, and active community participation. Strengthening environmental governance, promoting resilient infrastructure, and encouraging local awareness are critical steps toward minimizing future landslide hazards and ensuring long-term ecological and socio-economic stability in fragile Himalayan landscapes.

9. POLICY IMPLICATIONS AND MANAGEMENT STRATEGIES

The study underscores important policy measures for managing landslide risks in ecologically fragile mountain regions. It emphasizes the need to make landslide hazard assessments compulsory before approving infrastructure projects so that development aligns with local geological and geomorphological conditions. Incorporating GIS-based hazard and susceptibility maps into regional and local planning systems can significantly improve decision-making by helping authorities identify high-risk areas and regulate land use more effectively (Guzzetti et al., 2005). The findings also advocate for eco-friendly, nature-based slope stabilization approaches, including bioengineering and vegetation-based techniques, which enhance slope stability while reducing environmental damage (Gray & Sotir, 1996). Furthermore, stronger coordination among geological departments, disaster management agencies, and local governance institutions is essential. Such collaboration promotes efficient data sharing, timely early warning dissemination, and the implementation of integrated mitigation strategies aligned with sustainable development principles (UNDRR, 2015).

The study underscores the need for:

- Mandatory landslide hazard assessment prior to infrastructure development
- Integration of GIS-based hazard maps into regional planning
- Promotion of eco-friendly slope stabilization techniques
- Strengthening institutional coordination for disaster risk reduction

REFERENCES

Cruden, D. M., & Varnes, D. J. (1996). Landslide types and processes. *Transportation Research Board Special Report*, *247*, 36–75.

Gansser, A. (1964). *Geology of the Himalayas*. Interscience Publishers.

Gray, D. H., & Sotir, R. B. (1996). *Biotechnical and soil bioengineering slope stabilization: A practical guide for erosion control*. John Wiley & Sons.

Gupta, V., & Sah, M. P. (2008). Impact of the Tehri Dam on landslide incidence in the Tehri Garhwal Himalaya, India. *Environmental Geology*, *55*(8), 1631–1645. https://doi.org/10.1007/s00254-007-1101-4

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., & Ardizzone, F. (2005). Probabilistic landslide hazard assessment at the basin scale. *Geomorphology*, *72*(1–4), 272–299. https://doi.org/10.1016/j.geomorph.2005.06.002

Martha, T. R., Roy, P., Mazumdar, R., Govindharaj, K. B., & Kumar, K. V. (2013). Landslides triggered by the June 2013 extreme rainfall event in Uttarakhand. *Current Science*, *105*(2), 236–243.

Owen, L. A., Kamp, U., Khattak, G. A., Harp, E. L., Keefer, D. K., & Bauer, M. A. (2008). Landslides triggered by the 8 October 2005 Kashmir earthquake. *Geomorphology*, *94*(1–2), 1–9. https://doi.org/10.1016/j.geomorph.2007.04.007

Petley, D. (2012). Global patterns of loss of life from landslides. *Geology*, *40*(10), 927–930. https://doi.org/10.1130/G33217.1

Pradhan, B. (2010). Landslide susceptibility mapping using GIS-based approaches. *Journal of the Indian Society of Remote Sensing*, *38*(2), 301–320. https://doi.org/10.1007/s12524-010-0020-z

Sarkar, S., & Kanungo, D. P. (2004). An integrated approach for landslide susceptibility mapping using remote sensing and GIS. *Photogrammetric Engineering & Remote Sensing*, *70*(5), 617–625.

Saha, A.K., Gupta, R.P. and Arora, M.K., 2002. GIS-based landslide hazard zonation in the Bhagirathi (Ganga) valley, Himalayas. *International journal of remote sensing*, *23*(2), pp.357-369.

Sati, S. P., Sundriyal, Y. P., Rana, N., & Dangwal, S. (2011). Recent landslides in Uttarakhand: Nature's fury or human folly. *Current Science*, *100*(11), 1617–1620.

Schwanghart, W., Wulf, H., & Scherler, D. (2016). Heterogeneity in Himalayan erosion patterns: Insights from river profile analysis. *Tectonics*, *35*(8), 1873–1893. https://doi.org/10.1002/2016TC004163

Searle, M. P., Law, R. D., Jessup, M. J., & Godin, L. (2008). Structural geology of the Himalayan–Tibetan orogen. *Journal of the Geological Society*, *165*(1), 3–21. https://doi.org/10.1144/0016-76492007-047

Sidle, R. C., & Ochiai, H. (2006). *Landslides: Processes, prediction, and land use*. American Geophysical Union.

Stokes, A., Douglas, G. B., Fourcaud, T., et al. (2014). Ecological mitigation of hillslope instability: Ten key issues facing researchers and practitioners. *Plant and Soil*, *377*(1–2), 1–23. https://doi.org/10.1007/s11104-014-2044-6

Sundriyal, Y. P., Shukla, A. D., Rana, N., & Juyal, N. (2015). Terrain response to climate variability in the Himalaya. *Quaternary International*, *371*, 1–14. https://doi.org/10.1016/j.quaint.2014.10.046

United Nations Office for Disaster Risk Reduction (UNDRR). (2015). *Sendai framework for disaster risk reduction 2015–2030*. United Nations.

Valdiya, K. S. (1980). *Geology of Kumaun Lesser Himalaya*. Wadia Institute of Himalayan Geology.