



International Journal of Geography, Geology and Environment

ISSN Print: 2706-7483

ISSN Online: 2706-7491

NAAS Rating (2026): 4.5

IJGGE 2026; 8(10): 01-16

www.geojournal.net

Received: 30-07-2026

Accepted: 16-09-2026

Published: 01-10-2026

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Silent forces rising risks: A systematic review of natural hazards, cascading processes and emerging risk in the Himalaya

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DOI: <https://www.doi.org/10.22271/27067483.2026.v8.i10a.886>

ABSTRACT

Background: The Himalaya is the youngest, highest and most tectonically and climatically active mountain belt on Earth. Hazard prone environments create by large human populations. Traditionally, earthquakes, rainfall- and earthquake triggered landslides, debris flows, glacial lake outburst floods (GLOF), permafrost degradation, rock ice avalanches and snow avalanches have been studied as separate hazard classes. Yet field evidence from recent disasters shows that these events are frequently linked in cascading and compounding sequences.

Objective: This review synthesizes peer-reviewed and institutional literature on natural hazards and emerging cascading risk across the Himalayan arc with emphasis on (i) the geological and climatic drivers of individual hazard types (ii) documented cascading and compound hazard pathways, (iii) the growing exposure of settlements and infrastructure and (iv) research and risk management gaps.

Methods: A structured systematic literature review was undertaken. Academic search platforms (Google Scholar, ScienceDirect, SpringerLink, Wiley Online Library, Nature Portfolio journals, Copernicus/NHESS, MDPI, AGU/Wiley, Frontiers) and institutional repositories (ICIMOD/HKH library, USGS, World Bank, UNDP) were searched using combinations of terms relating to Himalayan hazards, cascading and compound risk, glacial lake outburst floods, seismicity, permafrost and disaster risk reduction for literature published mainly between 2000 and 2026. Because this review draws on open-web-indexed academic search rather than paid bibliographic databases. It is presented as a structured systematic analysis; the eligibility screening, source list and limitations of this approach are stated explicitly in the Methods section.

Results: The reviewed literature meets on several consistent findings. The seismogenic Main Himalayan Thrust accumulates strain that is released in infrequent great earthquakes of which the 2015 Mw 7.8 Gorkha earthquake which triggered tens of thousands of landslides. Monsoon rainfall remains the dominant trigger of shallow landslides and debris flows and post-seismic terrain shows elevated landslide susceptibility for years after strong shaking. Cryospheric change glacier retreat, glacial lake expansion and permafrost degradation. Chamoli (Uttarakhand) disaster 2021 generating new and evolving hazard pathways, including GLOFs and rock-ice avalanches. Such event as the 2021 Melamchi flood show that single hazard assessment frequently underestimates real world risk. Exposure is rising fastest in valley bottom and mid-hill corridors, where roads, hydropower infrastructure, and settlements are expanding into hazard prone terrain.

Conclusions: Himalayan disaster risk is increasingly shaped by the interaction of tectonic, climatic, cryospheric and anthropogenic processes rather than by any single hazard acting in isolation. The evidence supports a shift from hazard specific assessment toward integrated, cascading-risk-informed hazard characterization, long-term multi-hazard inventories, expanded early-warning coverage, and hazard-aware infrastructure planning, particularly for hydropower and transport corridors in the middle and high mountains.

Keywords: Himalaya, Cascading hazards, Compound risk, Glacial lake outburst flood, Landslide, Permafrost, Seismic hazard, Disaster risk reduction, Systematic review

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1. Introduction

1.1 The Himalayan region: A dynamic mountain system

The Himalaya extends approximately 2,500 km along the northern margin of the Indian subcontinent from the Nanga Parbat *syntaxis* in the west to the Namche Barwa *syntaxis* in the east. The mountain belt has been built by the ongoing convergence between the Indian and Eurasian plates which began approximately 50 million years ago and continues today at rates of roughly 17-20 mm per year. Positioned mainly along the

Main Himalayan Thrust (MHT), the crustal-scale décollement that divides the underthrusting Indian crust from the overlying Himalayan wedge (Dal Zilio *et al.*, 2021; Sreejith *et al.*, 2025) [1, 2]. This ongoing convergence sustains rapid rock uplift, steep relief and high erosion rates while simultaneously loading the MHT with elastic strain that is periodically released in large-magnitude earthquakes. The tectonic template is one of the most extreme climatic and cryospheric gradients on the planet. The Himalaya intercepts the South Asian monsoon generating intense orographic rainfall on its southern flank while at high elevation it hosts the largest concentration of glaciers and permafrost outside the polar regions a domain often termed the “Third Pole” (Wester *et al.*, 2019; Wester *et al.*, 2023) [3, 4]. Snow ice and monsoon precipitation together sustain the headwaters of major transboundary rivers, including the Indus, Ganges and Brahmaputra systems.

1.1.1 Structural and Lithological Framework

The Himalayan orogen is conventionally divided from south to north. The Sub-Himalaya comprising weakly consolidated Neogene molasse sediments bounded to the south by the Main Frontal Thrust (MFT); the Lesser Himalaya comprising low- to medium-grade metasedimentary and sedimentary rocks bounded to the south by the Main Boundary Thrust (MBT); the Higher Himalaya comprising high-grade gneiss, schist and migmatite bounded to the south by the Main Central Thrust (MCT); and the *Tethys* Himalaya comprising a largely unmetamorphosed Paleozoic–Mesozoic sedimentary sequence north of the South Tibetan Detachment System. This structural associated variation in rock strength, weathering susceptibility and discontinuity fabric. Lesser Himalayan metasediments whereas the Higher Himalayan gneissic terrain more commonly produces structurally controlled rockfalls wedge failures where glacierized or permafrost-affected, rock–ice avalanches of the kind documented at Chamoli Disaster. This lithological and structural control is consistent with and complements. The geotechnical characterization of Lesser Himalayan rock materials (including quartzite ballast-source lithologies) reported in the regional engineering-geology literature (Sharma *et al.*, 2023) [5].

1.2 Natural hazards and their significance

The combination of active tectonics, relief, monsoonal climate and a rapidly changing cryosphere makes the Himalaya one of the most naturally hazardous regions on Earth. Earthquakes co-seismic landslides, rainfall-triggered landslides and debris flows, riverine and flash floods, glacial lake outburst floods, rock–ice avalanches and snow avalanches all recur across the region. The 25 April 2015 Mw 7.8 Gorkha earthquake alone triggered on the order of 25,000–47,000 landslides across more than 30,000 km² of central Nepal, destroyed and damaged hundreds of thousands of structures and killed almost 9,000 people (Roback *et al.*, 2018; Zekkos *et al.*, 2017; Kargel *et al.*, 2016) [6, 7, 8]. More recently the 7 February 2021 Chamoli disaster in Uttarakhand, India. Roughly 27 million m³ of rock and glacier ice detached from the north face of Ronti Peak and transformed into a long-runout debris flow, killed more than 200 people and destroyed two hydropower projects (Shugar *et al.*, 2021) [9].

Multi-hazard exposure assessments indicate that the Hindu Kush Himalaya (HKH) is among the highest-mortality-risk regions globally for hydrological and geophysical hazards and that human settlement is excessively concentrated in zones susceptible to more than one hazard type: nearly half of the regional population lives in areas highly susceptible to multiple overlapping hazards (Rusk *et al.*, 2022) [10].

1.3 Silent and slow-onset processes

The Himalaya undergoing slower less visible transformations that progressively raise background hazard levels. Glacier retreat and the associated expansion of glacial lakes have been documented across

the central and eastern Himalaya with the number of glacial lakes roughly doubling between the 1970s and 2010s in parts of the region and glacier mass loss accelerating markedly over the past two decades (Wester *et al.*, 2023) [4]. The high Himalaya above roughly 5,000 m is degrading in response to rising air temperature, destabilizing previously frozen slopes and providing preparatory conditions for rock and rock–ice avalanches more than 70% of documented rock–ice avalanches in High Mountain Asia originate in probable permafrost terrain (Baral *et al.*, 2023; Rather *et al.*, 2026) [11, 12]. These “silent” processes rarely make headlines individually, yet they progressively reconfigure the susceptibility of Himalayan slopes to sudden failure and they interact with more familiar triggers earthquakes and monsoon rainfall to produce hazard sequences that are more complex and often more damaging.

1.4 Climate and environmental change

Anthropogenic climate change is modifying nearly every hazard relevant process in the Himalaya. Warming is bigger at higher elevations, accelerating glacier mass loss, altering the seasonality and intensity of snowmelt and increasing the frequency of extreme precipitation events even where mean annual rainfall changes little (Wester *et al.*, 2023) [4]. Climate driven shifts in rainfall intensity, duration and seasonal distribution are altering landslide triggering thresholds and spatial susceptibility patterns across the Nepal Himalaya [13].

1.5 Existing research

Earthquake triggered landsliding associated with the Gorkha earthquake has been mapped, modelled and analysed in exceptional detail (Roback *et al.*, 2018; Gallen *et al.*, 2017; Zekkos *et al.*, 2017; Kincey *et al.*, 2024) [6, 13, 7, 14]. Glacial Lake inventories and GLOF susceptibility have been assessed regionally and at individual high-risk lakes (Shrestha *et al.*, 2007; Veh *et al.*, 2020) [15, 16]. Permafrost distribution and its geomorphic consequences have been reviewed for High Mountain Asia as a whole (Baral *et al.*, 2023) [11]. Rainfall thresholds for landslide initiation have been derived for Nepal and the wider Himalaya (Dahal *et al.*, 2008; Kincey *et al.*, 2024) [17, 14]. Seismic hazard on the Main Himalayan Thrust has been the subject of sustained geophysical and paleo seismological investigation (Bilham, 2019; Dal Zilio *et al.*, 2019; Dal Zilio *et al.*, 2020; Dal Zilio *et al.*, 2021; Sreejith *et al.*, 2025) [18, 19, 20, 1, 2]. Case studies of individual disasters (Chamoli, Melamchi) increasingly show cascading and compound behavior but synthesis across these cases, and connection of that synthesis to the underlying single hazard literature has lagged behind the pace of case-study publication (Maharjan *et al.*, 2021; Shugar *et al.*, 2021) [21, 9].

1.6 Knowledge gap and rationale

Three gaps motivate this review. First, most Himalayan hazard research remains disciplinarily and hazard specifically siloed (seismology, glaciology, geomorphology, hydrology proceeding largely in parallel), even though recent disasters make clear that hazard *interactions* are central to real world impact. Second, the pace of cryospheric change means that hazard susceptibility derived from historical inventories may already be out of date in permafrost and glacierized terrain. Third, exposure is changing rapidly through road construction, hydropower development and settlement expansion into steep and previously marginal terrain in ways that are not always incorporated into hazard assessment. A synthesis that draws these threads together, explicitly organized around the concept of cascading and compound risk can help identify where the existing single hazard. Figure 1 schematic illustration simplified for clarity.

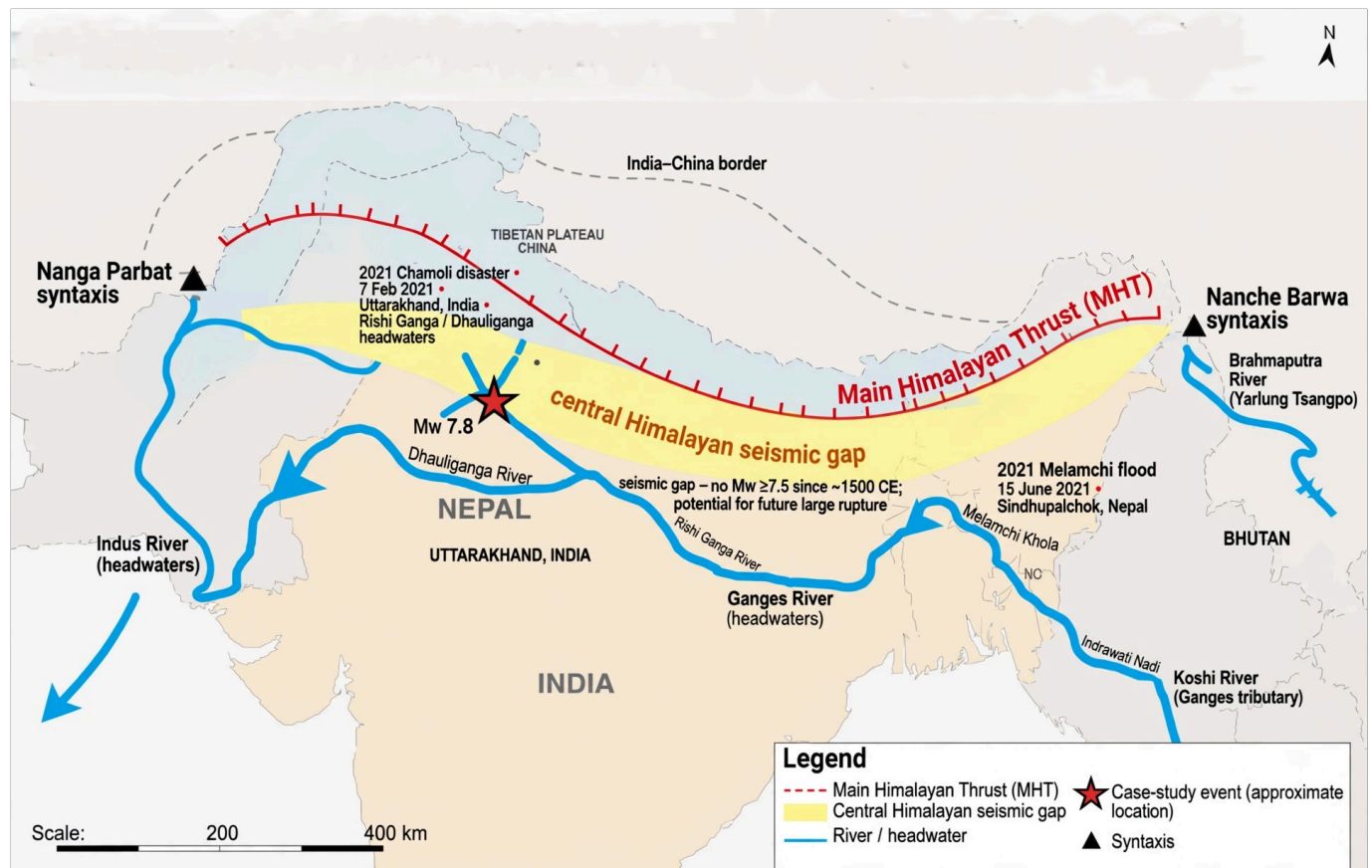


Figure 1. Schematic map of the Himalayan arc showing the MHT, Himalayan seismic gap, the major river (Indus, Ganges, Brahmaputra), and the approximate locations of the three case-study (2015 Gorkha earthquake, central Nepal; 2021 Chamoli disaster, Uttarakhand, India; 2021 Melamchi flood, Sindhupalchowk, Nepal).

1.7 Research questions

This review addresses the following questions:

1. What are the principal natural hazard types documented in the Himalayan region, and what mechanisms drive them?
2. To what extent, and through what pathways, do Himalayan hazards interact to produce cascading or compound events?
3. How is climate change modifying the frequency, magnitude or spatial pattern of these hazards and their interactions?
4. How is exposure of people and infrastructure changing across the region, and where does this exposure most closely intersect with elevated multi-hazard susceptibility?
5. What are the principal gaps in the current evidence base, and what are the resulting priorities for research, monitoring and risk-management practice?

2. Conceptual framework

2.1 The concept of “silent forces”

This review accepts “silent forces” as a conceptual framework for the gradual, cumulative, often underlying or elevated processes like permafrost degradation, glacier mass loss, progressive rock mass weakening, groundwater and pore pressure change and tectonic which, while not disasters in themselves. These processes are frequently invisible to conventional hazard monitoring, which is oriented toward event detection rather than the tracking of preparatory change. The metaphor is intended to complement not replace.

2.2 Hazard, exposure, vulnerability and risk

Consistent with standard disaster risk reduction terminology (UNDRR, 2016; UNISDR, 2009) [22, 23], this review distinguishes between:

- **Hazard:** a potentially damaging physical event, phenomenon or process (e.g., an earthquake, a landslide, a GLOF).
- **Exposure:** the presence of people, infrastructure, or other assets in hazard prone locations;
- **Vulnerability:** the physical, social, economic or environmental factors that increase susceptibility to harm from a given hazard.
- **Risk:** the potential for loss, understood as a function of hazard, exposure and vulnerability interacting together.

A recurring theme across the reviewed literature is that Himalayan disaster risk has risen even in areas where the underlying physical hazard has changed comparatively little, because exposure through road building, hydropower construction, and settlement expansion into valley bottoms and steep slopes has increased substantially (Rusk *et al.*, 2022; Koks *et al.*, 2019) [10, 24].

2.3 Compound and cascading hazards

Following usage established in the broader hazards literature (Gill *et al.*, 2014; Pescaroli *et al.*, 2018) [25, 26] and applied specifically to the Himalaya (Rusk *et al.*, 2022) [10], this review distinguishes:

- **Compound hazards:** the combination of multiple hazards or drivers occurring simultaneously or in close succession.
- **Cascading hazards:** sequences in which one hazard event triggers, or substantially increases the likelihood of a subsequent and often different hazard.

- The Chamoli disaster of February 2021 is a widely cited example of a cascading sequence permafrost and glacier conditioned rock ice detachment transforming, within minutes, into a long runout debris flow that struck downstream hydropower infrastructure 15 km away (Shugar *et al.*, 2021) [9]. The 2021 Melamchi flood illustrates compounding behaviour, in which the erosional legacy of the 2015 Gorkha earthquake, antecedent monsoon rainfall and remobilization of glacial and landslide derived sediment combined to produce a debris flood substantially larger than would be expected from rainfall alone (Maharjan *et al.*, 2021; Chen *et al.*, 2025) [21, 27].

2.4 The Himalayan cascading-risk framework used in this review

For the purpose of organizing the synthesis in Sections 4 and 5, this review familiarizes a simple four domain framework:

1. **Geological/tectonic domain** - rock strength, structural fabric, active faulting and seismicity, which condition long-term landscape susceptibility and provide the trigger mechanism for co-seismic mass movement.

2. **Climatic/hydrometeorological domain** - monsoon rainfall intensity and distribution, extreme precipitation events, and their trends under climate change, which are the principal trigger of landslides, debris flows and floods.
3. **Cryospheric domain** - glaciers, snow, permafrost and glacial lakes, which are undergoing rapid, climate-driven transformation and generating new hazard pathways (GLOFs, rock-ice avalanches, permafrost-related slope failure)
4. **Exposure/anthropogenic domain** - settlement patterns, road and hydropower development, and land-use change, which determine how physical hazard translates into human and economic loss.

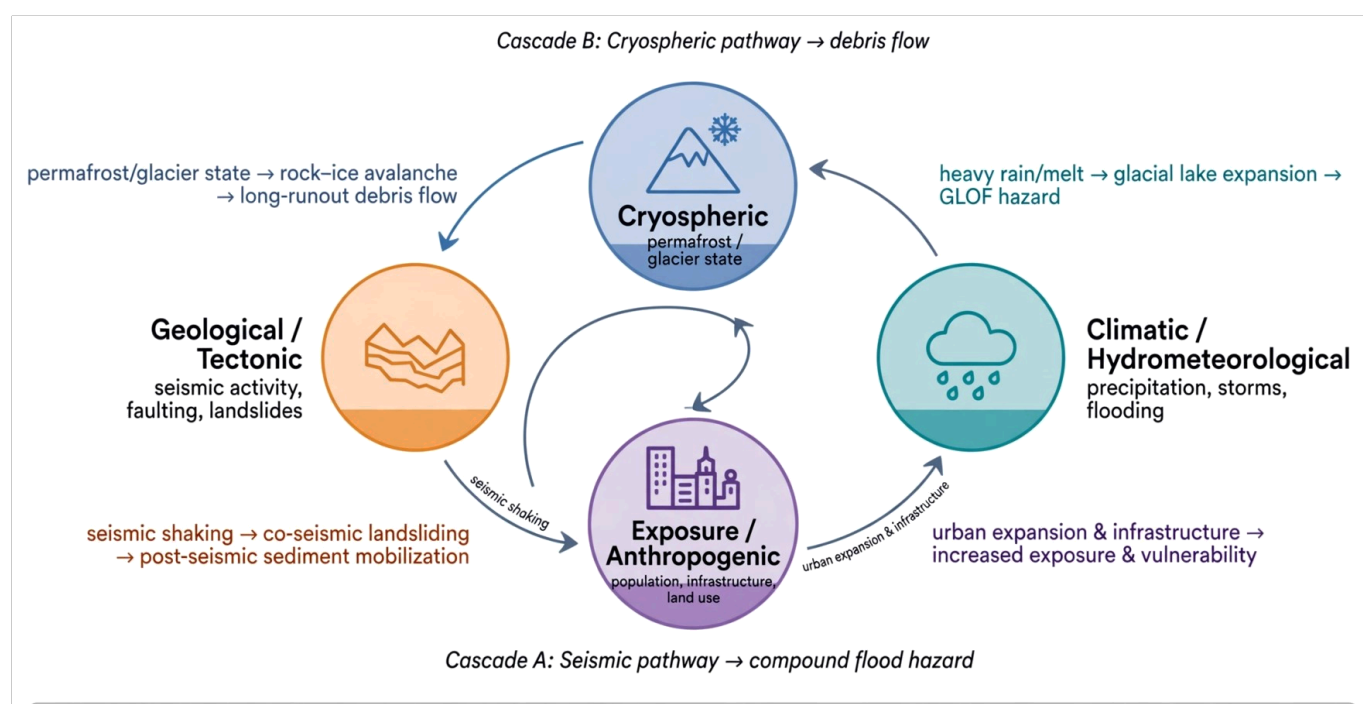


Figure 2. Conceptual diagram of the Himalayan cascading-risk framework

3. Materials and methods

3.1 Review approach and rationale

This review follows a systematic review principle. The present review was conducted using open-web-accessible academic search engines and publisher platforms.

3.2 Search strategy

Searches were conducted using combinations of the following term groups, connected with Boolean operators where the search platform supported them:

- **Region terms:** Himalaya; Himalayan; Hindu Kush Himalaya; HKH; High Mountain Asia; Nepal; Uttarakhand; Sikkim; Bhutan; Tibet/Qinghai-Tibet Plateau.

- **Hazard terms:** earthquake; seismic hazard; landslide; debris flow; rockfall; glacial lake outburst flood (GLOF); permafrost; rock-ice avalanche; snow avalanche; flash flood; cascading hazard; compound hazard; multi-hazard.
- **Driver/process terms:** monsoon rainfall; extreme precipitation; climate change; glacier retreat; cryosphere; tectonics; Main Himalayan Thrust.
- **Impact/management terms:** exposure; vulnerability; infrastructure; hydropower; early warning system; disaster risk reduction.

Table 1. Conceptual framework linking hazard domains, principal processes, and representative hazard types discussed in this review.

Zone	processes	hazard types	references
Geological/tectonic	Continental convergence; strain accumulation on the Main Himalayan Thrust; rock-mass weakening	Earthquakes; co-seismic landslides and rockfalls	Dal Zilio <i>et al.</i> (2021); Bilham (2019); Sreejith <i>et al.</i> (2025)
Climatic/hydrometeorological	Monsoon rainfall; extreme precipitation; rainfall-intensity/duration thresholds	Rainfall-triggered landslides; debris flows; flash floods	Dahal & Hasegawa (2008); Kincey <i>et al.</i> (2024)
Cryospheric	Glacier retreat; glacial lake expansion; permafrost degradation; snowpack change	GLOFs; rock–ice avalanches; permafrost-related slope failure; snow avalanches	Wester <i>et al.</i> (2023); Baral <i>et al.</i> (2023); Voh, Korup & Walz (2020); Acharya <i>et al.</i> (2023)
Exposure/anthropogenic	Road and hydropower construction; settlement expansion; land-use change	Amplified impact of the above hazards on people, infrastructure and livelihoods	Rusk <i>et al.</i> (2022); Koks <i>et al.</i> (2019); Kincey <i>et al.</i> (2024)

Platforms searched included Google Scholar, ScienceDirect (Elsevier), SpringerLink, Wiley Online Library, Nature Portfolio journals (including *Nature*, *Nature Geoscience*, *Scientific Reports*, and *npj Natural Hazards*), Copernicus (*Natural Hazards and Earth System Sciences*), MDPI journals, AGU publications (*Earth's Future*, *Geophysical Research Letters*), Frontiers, and PubMed/PMC. Institutional and grey-literature sources were also consulted, including the International Centre for Integrated Mountain Development (ICIMOD) library and HKH knowledge portal, the United States Geological Survey (USGS), the World Bank, the United Nations Development Programme (UNDP), and the Stockholm Environment Institute (SEI). Searches were conducted in 2026 and prioritized literature published between 2000 and 2026 with an emphasis on the post-2015 period reflecting the substantial expansion of Himalayan hazard research following the Gorkha earthquake.

3.3 Eligibility criteria

Inclusion criteria. A source was (Dal Zilio *et al.*, 2021) [1] addressed a natural hazard, hazard driving process or disaster event located within or directly comparable to the Himalayan region; (Sreejith *et al.*, 2025) [2] presented empirical, observational, remote sensing, modelling or case-study evidence, or was a peer-reviewed or institutionally published review synthesizing such evidence; (Wester *et al.*, 2019) [3] was available in English; and (Wester *et al.*, 2023) [4] was retrievable in full text or via a detailed abstract/summary sufficient to extract verifiable factual content.

Exclusion criteria. Sources were excluded (Dal Zilio *et al.*, 2021) [1] were opinion pieces, blog commentary, or news reports without an identifiable underlying study (used only sparingly, and only for well-documented recent disaster narratives, (Sreejith *et al.*, 2025) [2] addressed hazards entirely outside the Himalaya/High Mountain Asia with no regionally transferable content (Wester *et al.*, 2019) [3] could not be attributed to identifiable authorship or a verifiable institutional source; or (Wester *et al.*, 2023) [4] duplicated content already captured from a primary source.

3.4 Source selection

Candidate sources identified through the search strategy were screened by title and abstract/summary for topical and regional relevance, then read in more detail to confirm eligibility and extract content. Sources were organized thematically according to the framework. Within each theme, findings were synthesized, cross checked.

3.5 Data extraction

For each included source, the following information was extracted where available: hazard type addressed; geographic location/extent; data type and method (field survey, remote sensing, numerical modelling, statistical analysis, literature review); principal quantitative or qualitative findings; documented hazard interactions or cascading pathways and stated limitations or research gaps. Table 2 presents a representative, non-exhaustive sample of included studies.

4. Results

4.1 Overview of the evidence base

This review span geophysics and seismology, glaciology and permafrost science, engineering geology and geomorphology, hydrology, remote sensing and disaster risk management, published mainly in international journals. Table 2 presents a representative sample of the included literature, organized by theme to illustrate the range of methods and evidence synthesized in this review.

4.2 Tectonic setting and seismic hazard

The Himalayan orogen is underlain by the Main Himalayan Thrust (MHT), a low-angle décollement along which the Indian plate is being underthrust beneath the Himalaya and southern Tibet (Dal Zilio *et al.*, 2021) [1]. Geodetic and paleoseismological studies converge on the finding that the central Himalayan seismic gap spanning the Himachal-Garhwal-Kumaon. Mw ≥ 8 earthquake in at least the past

five centuries has accumulated sufficient strain to sustain one or more earthquakes of approximately Mw 8.8 (Sreejith *et al.*, 2025) [2]. Physics based earthquake cycle simulations of the MHT similarly identify along strike segmentation with low-coupling zones acting as rupture barriers that bound the plausible maximum magnitude near Mw 8.9 (Niroula *et al.*, 2026) [28]. Imaging studies in the Garhwal-Kumaon Himalaya independently confirm lateral variation in MHT geometry flat-ramp-flat structure (Kanauija *et al.*, 2025) [29]. The 25 April 2015 Mw 7.8 Gorkha earthquake, though it did not fully close the central seismic gap. Independent satellite-based mapping efforts converge on a landslide count in the tens of thousands approximately 24,900 landslides mapped by (Roback *et al.*) [6] across more than 30,000 km², with subsequent, methodologically distinct inventories reporting totals exceeding 47,000 once aftershock-triggered and delayed failures are included (Zekkos *et al.*, 2017; Tian *et al.*, 2020) [7, 30]. The single largest failure, the Langtang landslide in Rasuwa district, buried the village of Langtang and killed more than 200 people in one event (Tian *et al.*, 2020) [30]. Rapid-response Newmark-type landslide models, evaluated against the observed inventory, captured the broad spatial pattern of landsliding reasonably well under moderate-to-high assumed rock strength, underscoring the practical difficulty of forecasting co-seismic landslide hazard in real time even with a well-characterized triggering earthquake (Gallen *et al.*, 2017) [13].

4.3 Rainfall as the dominant landslide trigger

Independently of seismicity, monsoon rainfall is consistently identified across the reviewed literature as the principal trigger of shallow landslides and debris flows in the Himalaya. Analysis of landslide inventories in Nepal indicates that more than 70% of recorded landslide events cluster within the southwest monsoon season, and representative rainfall intensity duration thresholds for example, cumulative rainfall exceeding roughly 250 mm over a 15-day period in parts of the Sikkim Himalaya have been proposed to characterize landslide-triggering conditions (Dahal *et al.*, 2008) [17]. A recent national-scale assessment combining rainfall-triggered landslide susceptibility with population exposure data found that the ten Nepali districts. The highest landslide susceptibility is concentrated in the High Himalaya. Northern border with Tibet with Manang district recording the single highest mean susceptibility value. Population exposure is generally lower in these high-susceptibility districts than in the more densely settled Middle Hills, but the potential for locally catastrophic impact illustrated by events in Uttarakhand, Chamoli and Melamchi remains substantial wherever people, roads or infrastructure are present in these high-susceptibility zones (Kincey *et al.*, 2024) [14]. A growing body of literature further links climate change to shifting landslide-triggering thresholds. Because the hydrological cycle intensifies under a warmer atmosphere, extreme-precipitation. Annual precipitation changes comparatively little and this is beginning to alter both the timing and spatial pattern of landslide susceptibility across the Nepal Himalaya (Bhattarai *et al.*, 2026) [31].

4.4 Cryospheric change: Glacier retreat and glacial lake outburst floods

The Himalayan cryosphere is undergoing rapid, largely irreversible change. ICIMOD Hindu Kush Himalaya Assessment and its 2023 [4] HI-WISE follow-up report document accelerating glacier mass loss across the region with glacier mass loss in the 2010s roughly 65% faster than in the preceding decade in parts of High Mountain. Asia alongside declining snow cover, increasing permafrost thaw, and more erratic snowfall (Wester *et al.*, 2019; Wester *et al.*, 2023) [3, 4]. Between 1990 and 2020, the central and eastern Himalaya lost close to 30% of snow cover extent, while the regional inventory of glacial lakes almost doubled between 1977 and 2010; the Karakoram sector, by contrast, shows relative glacier stability, a pattern attributed to the so-called Karakoram anomaly (Banerjee *et al.*, 2026) [32]. Expanding and destabilizing glacial lakes translate directly into GLOF hazard. Nepal alone has recorded 26 GLOF events since the 1970, eleven of which originated across the border in Tibet, underscoring the trans

boundary character of this hazard (Davis *et al.*, 2021; World Bank, 2011) [33, 34]. The 5 July 2016 Bhote Koshi GLOF, triggered by the breach of Gongbatongshacuo Lake in the Tibet Autonomous Region, destroyed sections of a major highway linking Nepal and China and severely damaged a hydropower plant, with total economic losses estimated near US\$70 million (Davis *et al.*, 2021) [33]. More recent regional assessments identify dozens of “potentially dangerous” glacial lakes across Nepal, India and Bhutan. A Green Climate Fund-supported project targets four priority lakes in Nepal (Thulagi, Lower Barun, Lumding Tsho and Hongu 2) for water-level lowering and early-warning investment, reflecting the scale of anticipated exposure (UNDP, 2025) [35]. In the eastern Himalaya, transboundary GLOF exposure assessments have identified 27 high-risk glacial lakes across five districts of Arunachal Pradesh alone, with associated risk to hydroelectric infrastructure shared between India and Bhutan (Dwivedi *et al.*, 2026) [36]. A 2025 ice-snow avalanche-triggered outburst at Birendra Lake in the Nepal Himalaya further illustrates how mass-movement processes, rather than gradual moraine-dam degradation alone, can generate GLOF events even at comparatively small, previously lower-priority lakes (Khadka *et al.*, 2025) [37]. GLOF hazard is itself frequently the product of an upstream mass-movement trigger rather than a purely hydrological or thermal process. High Mountain Asia, roughly 54% of documented GLOF are triggered by mass movements including ice and rock avalanches, landslides and debris flows entering a glacial lake rather than by gradual moraine-dam degradation alone (Rather *et al.*, 2026) [38]. This finding is central to the cascading-hazard framing. GLOF risk cannot, in many cases, be assessed independently of slope-stability and permafrost conditions in the lake contributing catchment.

4.5 Permafrost degradation and rock ice avalanches

Mountain permafrost across High Mountain Asia is degrading in response to warming, with consequences that extend well beyond the immediate zone of thaw. A permafrost change across the region documents substantial reductions in permafrost extent and a range of associated geomorphic impacts. Outburst floods, landslides, debris flows, rockfalls, ice and rock avalanches and ground subsidence. Several of which “can have catastrophic consequences that extend far downstream” of the point of initial failure (Baral *et al.*, 2023) [11]. Machine-learning-based permafrost probability mapping in the western Himalaya (Kinnaur district, Himachal Pradesh) similarly finds that more than 70% of documented rock-ice avalanches in High Mountain Asia originate within probable permafrost terrain, and that roughly 65% of such events initiate at ground temperatures above 1.5 °C evidence, the authors argue, of active permafrost warming rather than failure confined to already-marginal, near-0 °C ground (Rather *et al.*, 2026) [12]. The clearest recent illustration of this hazard pathway is the 7 February 2021 Chamoli disaster in Uttarakhand India. Approximately 27×10^6 m³ of rock and glacier ice detached

from the steep north face of Ronti Peak and rapidly transformed into an exceptionally large and mobile debris flow. Which transported boulders exceeding 20 m in diameter, scoured valley walls up to 220 m above the valley floor and travelled with a total elevation drop of roughly 4,300 m and a horizontal run-out exceeding 17.6 km before reaching populated areas (Shugar *et al.*, 2021; Zhang *et al.*, 2023) [9, 39]. The event killed more than 200 people and destroyed two hydropower projects under construction and the multidisciplinary reconstruction of the disaster. Satellite imagery, seismic records, numerical modelling and eyewitness video has become a reference case for the argument that permafrost and glacier conditioned high-elevation slope failure represents an emerging and previously under-assessed, hazard pathway for downstream Himalayan infrastructure (Shugar *et al.*, 2021) [9]. Broader regional analysis of rock and ice avalanches (RIA) across High Mountain Asia has documented 60 well-recorded large events causing at least 1,366 fatalities. Identified 23 potential driving factors spanning topography, climate, glacier state, permafrost condition and seismicity, providing a basis for improved regional hazard modelling of this comparatively poorly monitored hazard class (Zhong *et al.*, 2025) [40].

4.6 Snow avalanches

Snow and ice avalanches constitute a further significant, if geographically and seasonally concentrated Himalayan hazard. A systematic literature- and database-compilation covering the late twentieth century to 2022 documents more than 3,100 avalanche fatalities across High Mountain Asia. The majority in Afghanistan and India, making avalanches a considerably deadlier hazard, in aggregate, than GLOFs across the wider region (Acharya *et al.*, 2023) [41]. Within this same study mountaineering specific subset, locally hired personnel porters and high-altitude guides, including so-called “icefall doctors” on Himalayan 8,000 m peaks bear a disproportionate share of avalanche risk, accounting for roughly a third of all recorded expedition-related avalanche deaths (Acharya *et al.*, 2023) [41]. Outside mountaineering contexts, avalanches also threaten resident populations and infrastructure in the Western Himalaya: India alone recorded 1,883 avalanche deaths between 1970 and 2016, the majority occurring during or immediately after snowfall, with damage extending to roads, bridges and hydroelectric infrastructure (Abhinav *et al.*, 2025) [42]. Machine-learning-based susceptibility and numerical run-out modelling is increasingly being applied to characterize avalanche-prone terrain at the basin scale in the Western Himalaya, reflecting growing recognition of avalanches as a quantifiable, mappable hazard rather than a purely stochastic mountaineering risk (Abhinav *et al.*, 2025) [42]. A multi-decadal remote-sensing record from the Annapurna II glacier in the central Himalaya similarly documents an increasing frequency and size of ice-snow avalanche events in recent decades, consistent with a climate-linked trend in this hazard class [43].

Table 2. Representative studies

Title	Author	Region	Method	finding
Tectonics/seismic hazard	Dal Zilio <i>et al.</i> , 2021	Himalayan arc	Synthesis/review	Reviews the tectonic-to-earthquake-scale processes governing Himalayan seismogenesis
Tectonics/seismic hazard	Sreejith <i>et al.</i> , 2025	Central Himalayan seismic gap	Geodetic modelling	500–700 years of accumulated strain could require ~Mw 8.8 rupture(s) to release
Tectonics/seismic hazard	Seismica/RSQSim study, 2026	Main Himalayan Thrust	Physics-based earthquake simulation	10,000-year synthetic catalogue bounds maximum magnitude near Mw 8.9
Co-seismic landslides	Roback <i>et al.</i> , 2018	Gorkha earthquake, Nepal	Satellite mapping	Documented ~24,900 landslides across > 30,000 km ²
Co-seismic landslides	Zekkos <i>et al.</i> , 2017	Gorkha earthquake, Nepal	UAV + satellite + field	Refined mapping and mobility analysis in three affected valleys
Co-seismic landslides	Gallen <i>et al.</i> , 2017	Gorkha earthquake, Nepal	Newmark-based modelling	Rapid-response landslide model evaluated against observed inventory
Rainfall-triggered landslides	Dahal & Hasegawa, 2008	Nepal Himalaya	Statistical/threshold analysis	Derived representative rainfall intensity–duration thresholds for landsliding
Rainfall-triggered landslides	Kincey <i>et al.</i> , 2024	Nepal (national)	Susceptibility + exposure modelling	High landslide susceptibility concentrated in High Himalayan districts, compounding exposure risk
Cryosphere/GLOF	Wester <i>et al.</i> , 2019, 2023	Hindu Kush Himalaya	Regional assessment (ICIMOD/HIMAP)	Documents accelerating glacier mass loss and cascading water-cycle impacts
Cryosphere/GLOF	Veh, Korup & Walz, 2020	Himalaya (regional)	Remote sensing/statistical	Establishes hazard trends for Himalayan glacial lake outburst floods
Cryosphere/GLOF	Shrestha, Mool & Bajracharya, 2007	Nepal & Bhutan	Inventory/case study	Early comprehensive GLOF case-study compendium for the region
Permafrost/rock–ice avalanche	Baral <i>et al.</i> , 2023	High Mountain Asia	Comprehensive review	Synthesizes permafrost degradation and cascading mass-movement risk
Permafrost/rock–ice avalanche	Shugar <i>et al.</i> , 2021	Chamoli, Uttarakhand	Multi-sensor remote sensing	Reconstructs the 2021 rock–ice avalanche and downstream debris-flow cascade
Compound flood/erosion	Maharjan <i>et al.</i> , 2021 (ICIMOD)	Melamchi, Nepal	Field + remote sensing assessment	Frames the 2021 Melamchi flood as a cascading, multi-causal hazard event
Compound flood/erosion	Chen <i>et al.</i> , 2025	Melamchi, Nepal	Satellite time-series	Quantifies distributed headwater erosion contributing to the 2021 flood
Snow/ice avalanche	Acharya <i>et al.</i> , 2023 (NHES)	High Mountain Asia	Historical compilation	> 3,100 avalanche deaths (1982–2022); mountaineering exposure a key factor
Multi-hazard exposure	Rusk <i>et al.</i> , 2022	Hindu Kush Himalaya	Maxent susceptibility modelling	Nearly half the regional population lives in areas susceptible to multiple hazards
Early warning	Thapa & Adhikari, 2019	Dolakha, Nepal	Pilot deployment + evaluation	Community-based landslide early-warning system credited with protecting ~495 people

4.7 Cascading and compound hazard events: Detailed case evidence

Three well documented recent events anchor the cascading- and compound-hazard evidence synthesized in this review; their key characteristics are summarized in Table 3.

The Gorkha earthquake illustrates a cascading pathway in which a single tectonic trigger produced a hazard whose consequences unfolded over years rather than seconds. Elevated landslide susceptibility persisted well beyond the initial event, and earthquake-mobilized sediment continued to be reworked by subsequent monsoon seasons, materially contributing to the later Melamchi disaster (Maharjan *et al.*, 2021) [21]. The Chamoli disaster illustrates a cryosphere-conditioned cascade in which permafrost and glacier state, rather than a discrete external trigger, appear to have played the dominant preparatory role, with the initiating rock–ice detachment transforming into a debris flow with sufficient speed and volume that downstream infrastructure had essentially no warning time (Shugar *et al.*, 2021) [9]. The Melamchi flood illustrates compounding behaviour detailed sediment-budget reconstruction using satellite time-series shows that roughly three-quarters of the mass movement contributing to the flood originated from distributed headwater gully, low-order debris flows and incision of glacial deposits source, indicating that the event severity reflected the combined, simultaneous mobilization of multiple sediment sources across the catchment rather than one dominant process (Chen *et al.*, 2025) [27], a finding corroborated by independent multiperspective post-event field reconnaissance (Pandey *et al.*, 2021) [44]. Beyond these three headline cases, the wider 2021 monsoon season in Nepal produced multiple, smaller debris-flow and flash-flood events in Mustang and Manang districts within days of the Melamchi disaster, indicating that compound rainfall terrain hazard was operating at a national, not merely local, scale during that period (Maharjan *et al.*, 2021) [21]. A consistent finding is that exposure not hazard alone is a major and rapidly changing determinant of Himalayan disaster risk. Multi-hazard susceptibility and exposure modelling of the Hindu Kush Himalaya finds that human settlement is disproportionately concentrated in areas susceptible to more than one hazard. Warm, low-altitude foothill areas with perennially moist soils comprise only about 31% of the study region but are home to roughly 49% of its population, and nearly half of the regional population lives in areas highly susceptible to multiple overlapping hazards (Rusk *et al.*, 2022) [10]. The same study finds that areas of high multi-hazard susceptibility are also major corridors of current migration and urban expansion, implying that exposure is likely to continue rising even where the underlying physical hazard does not (Rusk *et al.*, 2022) [10].

Hydropower and transport infrastructure are particularly exposed. Global multi-hazard risk analysis of transport infrastructure finds that approximately 27% of road and rail assets worldwide are exposed to at least one hazard, with flooding the dominant contributor to expected annual damages (Koks *et al.*, 2019) [24]. Himalayan-specific evidence supports substantially elevated local exposure. In Himachal Pradesh, susceptibility-overlay analysis identifies more than 1,450 km of national and state highways, including major sections of the

Manali–Leh and Shimla–Khab corridors, and nearly 2,800 mapped bridges, falling within high or very-high flash-flood susceptibility zones, alongside at least four major hydroelectric installations partially or fully within these zones (Sharma *et al.*, 2026) [45]. GLOF-specific exposure assessment in the India–Bhutan transboundary region similarly finds that several hydroelectric project sites and downstream settlements lie directly within the potential inundation footprint of high-risk glacial lakes (Dwivedi *et al.*, 2026) [36]. Commentary on Eastern Himalayan hydropower development further argues that, absent careful hazard-aware siting, large hydropower infrastructure can itself function as a form of climate maladaptation. High-value assets, and the communities that depend on them, in valley-bottom locations that are structurally the most exposed to compound flood, landslide and GLOF hazard (Sharma *et al.*, 2023) [46].

4.9 Early warning and community-based risk reduction

Community-based landslide early-warning systems (LEWS) have been piloted with documented success in the Nepal Himalaya. A low-cost LEWS installed at Sundrawati village, Kalinchowk rural municipality, Dolakha district. 2015 Gorkha earthquake combines rainfall, soil-moisture and slope-displacement sensors with a GSM-based alert system, and is credited with protecting 495 people across 117 households during a 2018 monsoon warning event (Thapa *et al.*, 2019) [47]. Landslide early-warning system design across the wider Himalaya and adjacent Indian ranges emphasize that effective systems require the integration of monitoring, modelling, warning dissemination and community response capacity, and that the dissemination and response components not sensor technology frequently the weakest link in practice (Ramesh *et al.*, 2023) [48]. At the transboundary and national scale, GLOF early-warning coverage remains markedly incomplete. Commentary on India Himalayan disaster-risk-reduction infrastructure notes that more than 100 dams across six Himalayan states may be vulnerable to GLOF impacts, yet integrated, catchment-scale early-warning coverage remains patchy, with many remote valleys lacking reliable last-mile alerting capacity (Veh *et al.*, 2020) [49]. Site-specific glacial lake monitoring and mitigation systems (GLMS). Including water-level-lowering interventions at lakes such as Tsho Rolpa and Imja in Nepal demonstrate technical feasibility at the individual-lake scale, but region-wide, systematically monitored GLOF early-warning coverage across the full population of “potentially dangerous” lakes identified in regional inventories has not yet been achieved (Rather *et al.*, 2026; Wang *et al.*, 2026) [38, 50].

4.10 Synthesis: Relative monitoring maturity across hazard types

Drawing together the evidence presented in Sections 4.2–4.9, Table 5 offers the present authors qualitative synthesis of the relative monitoring and hazard-assessment maturity of each major Himalayan hazard type. The density and recency of the reviewed literature. The existence of regional inventories and the documented presence or absence of operational early-warning capacity. This table reflects the authors assessment of the reviewed evidence base and is offered as a synthesis aid rather than as a quantitative index drawn from any single cited source.

Table 3. Documented cascading and compound hazard events referenced in this review.

Event	Date	Location	Trigger/initiating process	Cascade pathway	Impact	References
Gorkha earthquake and co-seismic landsliding	25 Apr 2015	Central Nepal (Gorkha–Sindhupalchowk–Rasuwa corridor)	Mw 7.8 rupture on the Main Himalayan Thrust	Strong ground motion → widespread co-seismic landsliding → sediment loading of river systems, elevated post-seismic landslide susceptibility	~25,000–47,000 landslides; ~9,000 deaths; >500,000 structures destroyed/damaged; multi-year elevated landslide hazard	Roback <i>et al.</i> (2018); Zekkos <i>et al.</i> (2017); Kargel <i>et al.</i> (2016)
Chamoli disaster	7 Feb 2021	Ronti Gad–Rishiganga–Dhauliganga valleys, Uttarakhand, India	Detachment of ~27 × 10 ⁶ m ³ rock and glacier ice from Ronti Peak	Rock–ice avalanche → rapid transformation into long-runout debris flow → destruction of downstream hydropower infrastructure	> 200 deaths/missing; two hydropower projects destroyed; 17.6 km run-out	Shugar <i>et al.</i> (2021)
Melamchi flood	14–15 Jun 2021	Melamchi Bazar, Sindhupalchowk district, Nepal	Intense monsoon rainfall onto terrain destabilized by the 2015 Gorkha earthquake	Headwater gullying, debris flows and remobilization of Gorkha-triggered landslide deposits and glacial sediment → cascading erosional and sediment flux → downstream debris flood	5–21 deaths (sources vary), up to ~23 missing; >500 people displaced; Melamchi water-supply infrastructure severely damaged	Maharjan <i>et al.</i> (2021, ICIMOD); Pandey <i>et al.</i> (2021); Chen <i>et al.</i> (2025)

Table 5. Qualitative synthesis of hazard-monitoring maturity across major Himalayan hazard types based on the evidence

	Regional inventory/catalogue maturity	Early-warning operational status	Key limiting factor
Co-seismic landsliding	High for major events (e.g., Gorkha 2015 comprehensively mapped)	Not applicable at the earthquake-trigger stage; relevant to post-event rapid response	Real-time forecasting of the <i>detailed</i> spatial pattern remains limited (Gallen <i>et al.</i> , 2017)
Rainfall-triggered landslides	Moderate-high; national-scale susceptibility models exist for Nepal	Piloted at community/village scale with documented success	Coverage limited to isolated pilot sites; not yet scaled regionally
GLOF	Moderate; regional lake inventories exist, priority lakes identified	Site-specific systems exist at a small number of high-risk lakes (e.g., Tsho Rolpa, Imja)	Majority of “potentially dangerous” lakes lack monitoring; transboundary coordination incomplete
Permafrost/rock–ice avalanche	Low–moderate; permafrost extent inferred via modelling rather than direct observation	Effectively absent at the regional scale	Permafrost not directly observable via routine satellite monitoring
Snow avalanche	Moderate; historical fatality databases exist for mountaineering contexts	Present in some Western Himalayan/Indian military and infrastructure corridors	Limited coverage outside high-value transport and defence corridors
Seismic hazard (Main Himalayan Thrust)	High for long-term probabilistic hazard; low for short-term prediction	Not applicable (no operational earthquake early-warning system identified in the reviewed literature for this region)	Fundamental unpredictability of earthquake timing; segmentation uncertainty

In Table 5 reinforces the research-gap findings. Monitoring maturity is systematically lower for hazard types whose preparatory conditions are not directly observable from routine remote sensing (permafrost). Whose operational deployment remains confined to isolated pilot sites (community landslide early warning) rather than being symptomatic of any lack of underlying scientific understanding.

4.11 Research gaps identified in the reviewed literature

1. Fragmented, hazard-specific monitoring. (Baral *et al.*) [11] note that permafrost, unlike glaciers, cannot be directly observed from standard satellite imagery. This observational asymmetry has produced comparatively limited understanding of permafrost distribution and change relative to glacier monitoring. Permafrost demonstrated role in rock–ice avalanche initiation.
2. Limited cross-hazard interaction modelling. (Rusk *et al.*) [10] explicitly note that, while their pairwise hazard-interaction matrix identifies linkages between hazards. The mechanisms for compounding or cascading hazards in the HKH are neither comprehensively describe nor comprehensively understood. And call for further study as climate change increases the incidence of complex hazard interactions.
3. Incomplete regional GLOF and rock–ice avalanche inventories. Several sources note that hazard assessment for rock–ice avalanches and GLOF. Remains constrained by incomplete historical event catalogues, particularly for remote, sparsely populated high-elevation catchments where events may go undocumented (Baral *et al.*, 2023; Zhong *et al.*, 2025) [11, 40].
4. Under-representation of non-English and sub-national literature. Because much of the internationally indexed literature synthesized here is published in English-language international journal. Region-specific studies published in Nepali, Hindi or Chinese, or in national/sub-national grey literature are likely under-represented in this and comparable reviews.
5. Weak integration of exposure dynamics into hazard maps. (Kincey *et al.*) [14] and (Rusk *et al.*) [10] both note that population and infrastructure exposure is changing rapidly (through migration, urbanization and infrastructure development) in ways that static, historically calibrated hazard maps do not automatically capture, creating a persistent lag between mapped hazard and actual present-day risk.

5. Discussion

5.1 Himalayan hazards as a networked system, not a catalogue

Treating Himalayan natural hazards as a catalogue of independent phenomena to be assessed and managed one at a time. Instead, the three anchor case studies Gorkha (2015) [6], Chamoli (2021) [9] and Melamchi (2021) [21] together with the broader GLOF, permafrost and exposure literature, depict a networked system. The geological, climatic, cryospheric and anthropogenic domains continuously exchange influence. Tectonic strain release (an earthquake) reshapes hillslope stability for years that reshaped instability interacts with subsequent monsoon rainfall to produce compound sediment mobilization. The resulting sediment together with independently evolving cryospheric hazard (glacier retreat, permafrost thaw), determines flood and debris-flow magnitude in downstream valleys. Exposure is simultaneously increasing through infrastructure development. No single-hazard assessment framework captures this full chain (Rusk *et al.*, 2022; Shugar *et al.*, 2021; Maharjan *et al.*, 2021) [10, 9, 21].

5.2 Earthquake landslide interaction and delayed risk

The Gorkha–Melamchi evidence chain is that co-seismic hazard does not end when shaking stops. The persistence of elevated landslide susceptibility for years after the 2015 earthquake. The direct contribution of Gorkha-mobilized sediment to the 2021 Melamchi disaster six years later. Post-seismic hazard assessment windows commonly used

in engineering practice (often calibrated to the first one to two years after an event) may be too short for Himalayan terrain. Sediment continues to be reworked and remobilized across multiple subsequent monsoon seasons (Maharjan *et al.*, 2021) [21]. A hydropower intake or bridge design based on pre-earthquake sediment-yield assumptions may significantly underestimate debris and sediment loading for years, if not decades, following a major regional earthquake.

5.3 Cryospheric change is creating new, less predictable hazard pathways

The Chamoli disaster is frequently cited in the reviewed literature not because rock–ice avalanches were previously unknown in the Himalaya. How quickly a permafrost- and glacier-conditioned slope failure at extreme elevation can translate into catastrophic downstream impact with essentially no warning time (Shugar *et al.*, 2021) [9]. Satellite monitoring in the way glacier extent can, the preparatory conditions for this class of event are comparatively poorly tracked at a regional scale (Baral *et al.*, 2023) [11]. This creates an asymmetry in the current Himalayan hazard-monitoring landscape. Glacier-related hazard (direct GLOF risk from visibly expanding lakes) is comparatively well inventoried, while permafrost-related rock–ice avalanche hazard, which the evidence indicates triggers a majority of documented High Mountain Asia GLOF in any case, remains comparatively under-monitored (Rather *et al.*, 2026) [12].

5.4 Rainfall, landslides and infrastructure

The rainfall-triggered landslide demonstrates that monsoon precipitation remains, quantitatively, the single most frequent hazard trigger in the Himalaya. Cryospheric and seismic hazards attract disproportionate international research and media attention following high-profile events such as Chamoli. The national-scale susceptibility-exposure analysis of (Kincey *et al.*) [14] is particularly informative. The districts with the highest raw landslide susceptibility (concentrated in the High Himalaya) are not necessarily those with the highest population exposure (concentrated in the Middle Hills), but that catastrophic, low-probability, high-consequence impacts as at Chamoli and in past events such as the 2013 Uttarakhand floods (Ziegler *et al.*, 2014; Kincey *et al.*, 2024) [51, 14].

5.5 Increasing exposure is itself a major component of emerging risk

A recurring finding across the multi-hazard exposure literature (Rusk *et al.*, 2022; Koks *et al.*, 2019) [10, 24]. The infrastructure-specific case evidence (Himachal Pradesh flash-flood exposure overlay. India–Bhutan transboundary GLOF exposure assessment) is that Himalayan disaster risk is rising substantially through exposure growth, independent of any change in the underlying physical hazard. Road and hydropower construction, and the settlement growth that typically follows improved access is disproportionately occurring in valley-bottom and mid-hill corridors that are structurally the most exposed to compound flood, landslide and GLOF hazard (Sharma *et al.*, 2023) [46]. This finding has an important corollary for climate adaptation policy. Infrastructure intended to support development and, in the case of hydropower, low-carbon energy transition can simultaneously function as a vector of maladaptation if sited without explicit reference to multi-hazard and cascading-risk assessment, rather than single-hazard flood or landslide screening alone.

5.6 Implications for hazard assessment practice

The evidence supports three practical shifts in Himalayan hazard-assessment practice. First, hazard assessment for critical infrastructure (hydropower, major highways, water-supply systems such as at Melamchi). Should explicitly incorporate upstream catchment-scale cryospheric and slope-stability conditions, not only local-reach flood or landslide susceptibility, given the demonstrated role of upstream rock–ice avalanche and cascading sediment mobilization in the Chamoli and Melamchi disasters respectively. Second, post-seismic hazard windows should be extended beyond the one-to-two-year horizons common in current practice, in recognition of the multi-year sed

iment-reworking dynamics documented following the Gorkha earthquake. Third, hazard maps and susceptibility models should be paired with exposure-change monitoring (tracking road, hydropower and settlement expansion) rather than treated as static products, given the documented pace of exposure growth in exactly the terrain classes identified as most hazard-prone.

5.7 Implications for early-warning systems

The demonstrated success of low-cost, community-based landslide early-warning systems at the village scale (Thapa *et al.*, 2019) [47]. In contrast to the substantial gaps in catchment- and regional-scale GLOF early-warning coverage. This suggests that the technical building blocks for effective Himalayan early warning are reasonably well established at the local scale. The outstanding challenge is one of coverage, financing and institutional coordination particularly for transboundary glacial lakes. The contributing catchment and the exposed downstream population may lie in different countries as documented for GLOF hazard originating in Tibet and affecting communities in Nepal, and for lakes shared across the India–Bhutan border (Davis *et al.*, 2021; Dwivedi *et al.*, 2026) [33, 36].

5.8 Implications for climate adaptation

cryospheric change is on the timescales relevant to infrastructure planning effectively irreversible even under aggressive emissions mitigation (Wester *et al.*, 2023) [4]. Climate adaptation in the Himalaya cannot rely solely on slowing the rate of hazard change. The evidence suggests that adaptation strategies focused narrowly on individual glacial lakes (water-level lowering, individual-lake early warning) are necessary but, on their own, insufficient, given that a majority of documented regional GLOFs are triggered by upstream mass-movement processes that individual-lake interventions do not address (Rather *et al.*, 2026) [38].

5.9 Implications for engineering geology and geotechnical practice

The cascading-hazard evidence reviewed here has direct relevance for engineering-geological practice in the Himalaya. Particular relevance given the region dependence on rock-cut slopes, tunnels and quarried aggregate and ballast material for road, railway and hydropower construction. Three implications stand out. First, because rock-mass strength and weathering susceptibility vary systematically across the Sub-Himalaya, Lesser Himalaya, Higher Himalaya and *Tethys* Himalaya. Slope-stability and foundation assessment for linear infrastructure (roads, railways, transmission corridors) should be explicitly stratified by structural unit rather than treated as spatially uniform, given the documented concentration of both co-seismic landsliding (Roback *et al.*, 2018) [6] and rainfall-triggered failure (Kincey *et al.*, 2024) [14]. Second, the multi-year post-seismic sediment-reworking dynamics the Gorkha earthquake have direct implications for aggregate and ballast durability assessment. Earthquake-disturbed rock masses in the Lesser Himalaya may continue to shed weathering-susceptible material into stream and quarry sources for years after the triggering event, which is relevant to slake-durability and strength testing protocols for construction and ballast aggregate sourced from these units. Third, the permafrost- and glacier-conditioning of high-elevation rock–ice avalanche hazard argues for extending geotechnical site characterization for high-altitude infrastructure (hydropower intakes, high-mountain roads). A conventional slope-stability and seismic assessment, given that the Chamoli disaster demonstrated that a structurally sound valley floor location can nonetheless be catastrophically exposed to a source area many kilometres upstream and thousands of metres higher in elevation.

5.10 Transboundary governance and data-sharing challenges

A distinct implication running through the GLOF and cryospheric hazard evidence is that a substantial share of Himalayan hazard exposure is inherently transboundary. Glacial lakes in the Tibet

Autonomous Region have generated outburst floods affecting downstream communities and infrastructure in Nepal (Davis *et al.*, 2021) [33]. Glacial lakes in Arunachal Pradesh, India, pose shared exposure to hydropower infrastructure across the India–Bhutan border. Effective hazard monitoring, early warning and risk communication for these hazard pathways cannot be achieved through purely national institutional arrangements. The evidence reviewed here suggests that regional institutions with an established transboundary mandate ICIMOD being the clearest example, through its HKH Assessment and HI-WISE reporting processes occupy a structurally necessary role in Himalayan disaster risk reduction.

5.11 Strengths and limitations of this review

This review principal strength is that it draws together, in a single systematic synthesis, hazard-specific literatures (seismology, glaciology, geomorphology, hydrology) that are frequently reviewed separately. It anchors that synthesis in three of the most thoroughly documented recent Himalayan disasters, allowing direct evaluation of cascading- and compound-hazard mechanisms against real event evidence rather than purely theoretical hazard-interaction matrices. Its principal limitation, stated transparently. Its findings should be treated as a rigorous but non-exhaustive account of the current evidence base, and any translation of this review into a formal, database-verified systematic review or *meta-analysis* (for example, for submission to a journal that specifically requires PRISMA reporting) would require supplementary screening of *Scopus*, Web of Science and regional-language databases beyond the scope of the present synthesis.

6. Research gaps and recommendations

6.1 Priority research areas

- 1. Long-term, multi-hazard event inventories.** Regionally consistent, multi-decadal inventories that log landslides, GLOF. Rock–ice avalanches and floods together, with consistent meta-data, would allow the kind of cross-hazard interaction analysis that individual, hazard-specific catalogues cannot support.
- 2. Expanded permafrost monitoring.** Because permafrost cannot be directly observed from standard optical or radar satellite imagery. Glacier extent can, targeted in-situ and geophysical monitoring networks, combined with machine-learning-based probability mapping of the kind piloted in Kinnaur district (Rather *et al.*, 2026) [12].
- 3. Cross-hazard interaction and cascading-pathway modelling.** Building on the pairwise hazard-interaction matrices developed for the wider Hindu Kush Himalaya (Rusk *et al.*, 2022) [10]. Detailed, catchment-specific cascading-pathway models of the kind reconstructed after the fact for Chamoli and Melamchi should be developed prospectively for other catchments with similar cryospheric and geomorphic conditions.
- 4. Post-seismic sediment and hazard monitoring extended beyond one to two years.** Given the documented multi-year contribution of Gorkha-earthquake-mobilized sediment to the 2021 Melamchi disaster. Post-seismic monitoring and hazard-assessment protocols should explicitly plan for multi-year, multi-monsoon-season sediment reworking rather than treating the immediate post-earthquake period as the primary hazard window.
- 5. Exposure-dynamic hazard mapping.** Hazard and susceptibility maps should be linked to regularly updated infrastructure and settlement datasets (road networks, hydropower project registries, census/settlement data). Exposure growth in high-susceptibility terrain can be tracked over time rather than assessed only at the time of initial hazard mapping.

6. Broader linguistic and institutional inclusion. Future systematic reviews of Himalayan hazards should explicitly include Nepali-, Hindi- and Chinese-language literature and national/sub-national grey literature (departmental reports, university theses, NGO field assessments). Ideally through formal database access (*Scopus*, Web of Science, regional academic repositories) and, where relevant, direct collaboration with in-country research institutions, to reduce the English-language bias inherent in the present and comparable international reviews.

6.2 Recommendations for risk-management practice

- **For infrastructure planning agencies (hydropower developers, road authorities):** incorporate upstream catchment-scale cryospheric and slope-stability screening into environmental and hazard impact assessment. Local-reach flood and landslide screening, particularly for infrastructure sited within valleys draining glacierized or permafrost-affected catchments.
- **For national disaster-management authorities:** extend post-earthquake hazard-monitoring windows to cover multiple subsequent monsoon seasons, and prioritize sediment and debris-flow monitoring in earthquake-affected catchments beyond the immediate emergency-response period.
- **For early-warning system investment:** prioritize expansion of transboundary institutional coordination mechanisms for GLOF early warning. Continued technical investment in low-cost, community-based landslide early-warning systems, given the demonstrated local-scale effectiveness of the latter.
- **For research funders and academic institutions:** support the development of regionally consistent, multi-hazard event databases and permafrost-monitoring infrastructure. Regional research assets, given that individual national or institutional efforts to date remain fragmented.
- **For regional cooperation bodies (e.g., ICIMOD and its member-country institutions):** continue and expand the transboundary hazard-assessment and data-sharing role already demonstrated in the HKH Assessment. HI-WISE reporting processes given the explicitly transboundary character of major hazard pathways (upstream glacial lakes in Tibet affecting downstream communities in Nepal; shared lakes and hydropower exposure across the India–Bhutan border).

Table 4. Priority research areas identified in this review, mapped to the evidence gap that motivates each priority and an indicative responsible actor.

Priority research area	Evidence gap identified	Indicative responsible actor(s)
Long-term, multi-hazard event inventories	Hazard-specific catalogues (landslide, GLOF, avalanche) are maintained largely independently, limiting cross-hazard interaction analysis	National geological surveys; ICIMOD; university research departments
Expanded permafrost monitoring	Permafrost cannot be directly observed by routine satellite monitoring, unlike glacier extent, leaving rock–ice avalanche preconditioning poorly tracked	National meteorological/geological agencies; international cryosphere research consortia
Cross-hazard interaction and cascading-pathway modelling	Existing hazard–interaction matrices for the HKH remain descriptive rather than predictive at catchment scale	Academic research groups; ICIMOD regional programmes
Extended post-seismic hazard monitoring (multi-year)	Post-seismic hazard windows in current practice are frequently limited to 1–2 years, despite multi-year sediment reworking documented after Gorkha	National disaster management authorities; infrastructure owners
Exposure-dynamic hazard mapping	Static hazard maps do not track rapid road, hydropower and settlement expansion into hazard-prone terrain	Land-use planning authorities; infrastructure regulators
Broader linguistic and institutional inclusion in future reviews	English-language, internationally indexed literature likely under-represents regional-language and grey literature	Academic journals; regional universities; national research councils

7. Conclusion

The Himalaya disaster risk profile cannot be adequately understood, or managed, through hazard-specific assessment alone. The evidence reviewed here spanning the tectonic setting of the Main Himalayan Thrust. Monsoon-driven landslide triggering, rapid cryospheric change and its cascading hazard consequences and the well-documented case evidence from the 2015 Gorkha earthquake, the 2021 Chamoli disaster and the 2021 Melamchi flood. Himalayan hazards interact across geological, climatic, cryospheric and anthropogenic domains, and these interactions, rather than any single hazard type in isolation, increasingly determine real-world disaster outcomes. At the same time, rising exposure through road, hydropower and settlement expansion into precisely the terrain identified as most hazard-prone means that disaster risk is growing even in locations where the underlying physical hazard is changing comparatively little. This review has been conducted as a transparent, systematic synthesis literature review and its findings and reference list should be understood and used, within that framework. Long-term, cross-hazard event inventories expanded permafrost monitoring; prospective, catchment-specific cascading-hazard modelling. Extended post-seismic hazard-monitoring windows exposure-dynamic hazard mapping; and continued, strengthened transboundary cooperation on early warning and hazard data-sharing. Advancing these priorities will require sustained collaboration among geoscientists, hydrologists, engineers, disaster-risk-management practitioners and the regional and national institutions.

Acknowledgements

The author thanks colleagues at the Central Department of Geology, Tribhuvan University, for discussion during the development of this review.

Conflicts of interest

The author declares no conflict of interest.

Data availability statement

This review synthesizes previously published, publicly available literature; no new primary data were generated. Full source details are provided in the reference list below, including DOIs and source URLs where available.

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How to cite this article: Tomar APS, Sharma DR. Silent forces rising risks: A systematic review of natural hazards, cascading processes and emerging risk in the Himalaya. *International Journal of Geography, Geology and Environment*. 2026;8(10):01-16. doi: <https://www.doi.org/10.22271/27067483.2026.v8.i10a.886>