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# Preface: Estimating and predicting natural hazards and vulnerabilities in the Himalayan region

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**Abstract.** This special issue focuses on natural hazards and risks in the Himalayan region. Nine research articles address critical gaps in research, from compiling avalanche databases to developing early warning systems for landslides and assessing flood risk and vulnerabilities in urban areas. By fostering interdisciplinary collaboration and leveraging advanced methods, the research presented in this special issue contributes to building safer and more resilient communities in the Himalayan region.

## 1 Introduction

The Himalaya has long fascinated the world's geoscientific community. Stretching across several countries, including India, Nepal, Bhutan, and China, the Earth's highest and youngest mountain range testifies to highly dynamic hydroclimatic, tectonic, and geomorphic processes. At the same time, the Himalaya is also a region teeming with life and cultural heritage. However, amid its physical, ecological, and cultural diversity lies a great challenge – the frequency and magnitude of extreme natural events that repeatedly inflict loss of life and economic damage. This special issue brings together nine research articles on the topic of "estimating and predicting natural hazards and vulnerabilities in the Himalayan region".

Over the past 15 years, the Himalaya has experienced several extreme natural events, highlighting its high seismic, hydrological, and geomorphological hazard potential.

- *2015 Gorkha earthquake ($M_\mathrm{w}$ 7.8).* The earthquake and its aftershocks killed more than 9000 people (Kargel et al., 2016), triggered thousands of landslides (Roback et al., 2017), damaged 30 % of Nepal's hydroelectric projects (Schwanghart et al., 2018), and posed serious challenges with respect to social vulnerabilities (Hülssiep et al., 2021).
- *2013 Indian floods.* Heavy precipitation and a glacier lake outburst flood (GLOF) in Uttarakhand resulted in flash floods, debris flows, and landslides that caused thousands of fatalities (Allen et al., 2016; Chevuturi and Dimri, 2016).
- *2021 flood events in India and Nepal.* The Chamoli flood (Shugar et al., 2021) and the Melamchi flood (Adhikari et al., 2023) represent cascading events of multiple geomorphic and hydrological processes invoking extreme flood and sediment discharge.
- *2023 South Lhonak Lake outburst in Sikkim.* The proglacial lake (Sattar et al., 2019, 2021) drained catastrophically, destroying two hydropower projects located $> 50$ km downstream of the breach and causing fatalities along the Teesta River (Kashyap and Behera, 2024).

- *2023 Himachal Pradesh floods.* Unprecedented extreme precipitation events from 7–10 July 2023 led to flash floods and landslides in Himachal Pradesh, causing widespread destruction. The region received 436 % more rain than normal (734.4 mm), resulting in a total monetary loss of USD 1.27 million and 72 fatalities, with 92 injuries (Raghuvanshi and Agarwal, 2024).

These catastrophic events underscore the urgent need for the comprehensive understanding, quantification, modeling, and prediction of natural hazards and vulnerabilities, especially in the face of climate change and increasing land-use pressure (Ozturk et al., 2022). Data scarcity, due to restricted access, sparse observation networks, and challenging fieldwork conditions, remains a significant obstacle to integrative risk management (e.g., Martha et al., 2021) and, as a consequence, safeguarding mountain livelihoods. The nine papers presented in this special issue address these challenges. The aim of this preface is to provide an overview of, introduction to, and summary of the papers, which we organized according to the predominant physical processes they address.

## 2 Contributions to the special issue

Recognizing the need for a deeper understanding and improved management of natural hazards in the Himalayan region, this special issue presents nine research articles. The contributions are organized as follows:

- *Cryospheric hazards.* Acharya et al. (2023) compile an open-access database of avalanches in the Himalaya, providing essential data for hazard zonation and adaptation measures.

- *Landslides.* Burrows et al. (2022) utilize Sentinel-1 radar data to improve the temporal accuracy of landslide inventories with remote sensing. Dixit et al. (2024) propose a prototype early warning system for rainfall-induced landslides using numerical models. Mey et al. (2024) analyze landslide susceptibility along the NH 7 highway in Uttarakhand.

- *Slow-moving landslides.* Sundriyal et al. (2023) investigate the geotechnical stability of slow-moving landslides in urban areas like Joshimath, Uttarakhand, highlighting the need for better management strategies.

- *Hydrological extremes.* Fischer et al. (2022) examine the impact of extreme floods on Pokhara, Nepal, emphasizing the importance of adapting early warning strategies for rapidly growing urban areas.

- *Flood risk.* Mesta et al. (2023) analyze flood risk under various urbanization and climate change scenarios in the Kathmandu Valley, advocating for risk-mitigation strategies to reduce future losses.

- *Multi-hazard risk.* Chouhan and Mukherjee (2023) develop a multi-hazard risk assessment tool tailored for Himalayan communities, addressing the need for comprehensive risk evaluations.

- *Seismic vulnerability.* Fayaz et al. (2023) assess earthquake vulnerability in Srinagar, providing insights and practical measures for reducing seismic risk.

### 2.1 Cryospheric hazards

Cryospheric hazards (Richardson and Reynolds, 2000) in the Himalaya have received considerable attention, in particular as they are affected by changes in heat waves and heavy-precipitation events, glacial retreat, and permafrost degradation (IPCC, 2012). Few studies (e.g., McClung, 2016), however, have targeted avalanches in the Himalaya. In fact, avalanche hazards have evaded a systematic spatial analysis so far despite frequent accidents with mountaineers, hiking groups, and the military. In their review article, Acharya et al. (2023) compile and describe an open-access and version-controlled database of > 680 avalanches causing more than 3000 fatalities. Although the total number of fatalities is lower than in less densely populated mountain regions such as the European Alps (see, for example, Fuchs et al., 2013), the authors emphasize that far more people are affected who – unlike skiers and mountaineers – do not voluntarily expose themselves to the risk of avalanches. The data of Acharya et al. (2023) are an important quantitative and qualitative database for the planning of adaptation measures and creating hazard zonation maps.

### 2.2 Landslides

Landslides belong to the most ubiquitous hazards in the Himalaya (Kirschbaum et al., 2015). To understand their hazard and risk, analyses mostly rely on landslide inventories. In these inventories, however, the timing of the landslides is often poorly documented, if at all. The lack of time stamps is a severe shortcoming because landslide events strongly vary through time due to the high seasonality and/or episodic occurrence of landslide-triggering events such as storms and floods (Jones et al., 2021). To this end, the lack of accurate temporal information limits the development of dynamic hazard and susceptibility models (Ozturk et al., 2021). With the advancement of Earth observation technologies, landslide inventories are routinely compiled from optical and multispectral satellite imagery (e.g., Behling et al., 2016). These inventories quite accurately describe the geometry and location of landslides, but they require cloud-free, daylight images, which may not prevail for weeks to months following landslide-generating events (Williams et al., 2018). To overcome this constraint on retrieving spatiotemporal landslide inventories, Burrows et al. (2022) used Sentinel-1 synthetic-aperture-radar amplitude time series to constrain landslide occurrence to within a few days. Using a landslide inventory from Nepal, they show that their method is able to assign daily time stamps to up to 30 % of landslides with an accuracy of 80 %. The methods developed could open up new avenues for improving the quality of existing landslide inventories, thus ultimately advancing landslide hazard and susceptibility models.

Regarding the short-term prediction of landslides, rainfall intensities measured over various time periods offer important information. Rainfall intensity–duration thresholds are the primary method for issuing early warnings regarding rainfall-induced landslide hazards. Establishing an operational early warning system thus necessitates a thorough examination of the regional hydrometeorological conditions to establish connections between landslides and their triggering rainfall events (Patton et al., 2023). However, in data-sparse regions, available rainfall data relevant to landslide prediction often lack adequate temporal resolution. This limitation is particularly relevant if landslide prediction requires data with sub-daily resolution (Gariano et al., 2023). This challenge is prevalent in the Himalayan region (Dikshit et al., 2020; Gariano et al., 2023; Kanungo and Sharma, 2014; Mathew et al., 2014; Shah et al., 2024), impeding the development of effective early warning systems for rainfall-induced landslides. The framework proposed by Dixit et al. (2024) suggests a prototype early warning system comprising a Weather Research and Forecasting (WRF) model (Srivastava et al., 2022) combined with a spatiotemporal numerical model for debris flows. The initial step involves simulating hourly precipitation time series to serve as input boundary conditions for the debris flow model. The final model demands minimal input from actual observations, with calibration required only at the outset. The use of simulated, model-driven outputs for generating rainfall intensity–duration thresholds may not be the most precise and reliable method, but given the short and incomplete database of debris flows in the region, it serves as a practical solution for hazard and risk assessment.

The Himalayan road network ensures access to remote mountain places and provides the basic infrastructure for any kind of economic development (Rawat and Sharma, 1997). However, roads traversing the steep Himalayan landscape are frequently affected by landslides (Hearn and Shakya, 2017). To understand the interplay of several predisposing factors of road-blocking landslides, Mey et al. (2024) analyze the spatial distribution of landslides along the NH 7 between Rishikesh and Joshimath, Uttarakhand. Based on a Bayesian point pattern model, they find that, corrected for the influence of terrain and lithology, road sections widened during the last decade exhibit twice the probability of road-blocking landslides compared to non-widened road sections. Their research highlights malpractices and challenges in road construction and maintenance, emphasizing the need for improved management of geohazards and road design with reference to established manuals and guidelines.

## 2.3 Slow-moving landslides

Much of the attention paid to landslide hazard has focused on rapid or catastrophic slope failures. Deep-seated, slow-moving landslides and their interaction with urban areas, in contrast, have rarely been studied (e.g., Dille et al., 2022). In January 2023, Joshimath, Uttarakhand, made headlines when sectors of the town experienced extensive damage due to an increase in the landslide deformation rate (Gahalaut et al., 2023). The crisis led to intense discussion about the potential causes of this deformation and its management, calling for reliable studies of the phenomenon. Sundriyal et al. (2023) address the issue from a geotechnical perspective, presenting slope stability analyses for Joshimath and Bhatwari, another NW Himalayan town located on a slow-moving landslide. In addition to natural causes like the extreme rainfall events of 2010 and 2021, as well as the fact that both towns are situated on areas with a history of landslides, Sundriyal et al. (2023) emphasize that the lack of sewage management plans in these towns is a critical factor. They highlight that human activities, such as the discharge of liquid waste from homes and the added weight of buildings, cannot be ruled out as contributors to landslide movements. This is further supported by modeled displacements, which are concentrated in the hillslope segments aligned with the settlements. Their results demonstrate the critical state of these hillslopes and their high potential for slope displacement in the event of a major earthquake in the region. These findings highlight the need for more comprehensive assessment of slow-moving landslide hazards in the Himalaya and the development of more effective management strategies for this type of hazard.

## 2.4 Hydrological extremes

Hydrological extremes such as droughts, floods, and heavy-rain-triggered mass movements account for 45 % of the fatalities and 74 % of the economic losses caused by natural hazards (IPCC, 2021). In particular, the mountain regions of Asia exhibit an elevated susceptibility to various flood hazards, including sub-glacial outburst floods, glacial-surge-induced damming of valleys, outbursts from potentially landslide-dammed lakes, and transformed avalanches of ice and rock, presenting a greater frequency and severity of such events compared to other regions globally. The hydrological disasters in this region are due to its unique hydro-climatological, geological, and topographical conditions, and partly due to seismic activity (Korup and Clague, 2009). Previous research emphasizes the significance of a global perspective on mountain floods (Kron, 2015), acknowledging their widespread occurrence and impacts. Nevertheless, local studies are also required to deliver the much-needed detailed and fine-scale insights for the development of improved early warning strategies and adaptation measures (IPCC, 2023). In their study, Fischer et al. (2022) analyzed the potential impacts of such floods on the mountain city of Pokhara, Nepal, a city that hosts an impressive archive of past floods and debris flows (Fort, 1987; Schwanghart et al., 2016). Based on simulations of physically plausible flood scenarios, they report that extreme floods primarily affect squatter settlements, which have expanded rapidly by a factor of up to 20 since 2008 and straddle the Seti River. These results strongly highlight the need to adapt early warning strategies in Nepal's second-largest city, whose rapid and often unregulated growth constantly modifies its exposure and vulnerability to extreme hydrological and geomorphic events.

### 2.5 Flood risk

Flood risk is a growing concern globally, fueled by rapid urbanization and the effects of climate change (Rentschler et al., 2022). Previous flood risk assessments have primarily focused on high-income countries and large economic centers in developing countries, leveraging high-resolution flood, asset, and population maps but neglecting the lack of such data in less developed countries (Malgwi et al., 2020). Additionally, researchers have explored the impact of flood adaptation measures and urban development on flood risk trajectories. However, there is a notable gap in the literature regarding multi-hazard-prone areas, particularly in mountain regions (Rusk et al., 2022). Mesta et al. (2023) address this challenge by providing a comprehensive analysis of flood risk under various urbanization and climate change scenarios. The study employs four exposure scenarios, representing both the current urban system and potential near-future development trajectories in the Kathmandu Basin. The study reveals that a significant proportion of the current building stock in the Kathmandu Basin is situated within 100- and 1000-year inundation areas, indicating potential substantial losses. However, employing risk-mitigation strategies, such as building elevation and flood-hazard-informed land-use planning, can considerably reduce losses in the future. In addition, high-income populations, with a larger concentration of buildings in floodplains, experience the highest mean loss ratios. This contrasts with earthquake-related risks, emphasizing the need for tailored risk-mitigation measures. Importantly, the study demonstrates that risk-informed policies uniformly targeting flood risk across different income levels provide the most significant benefits for low-income populations, offering valuable insights to decision-makers.

### 2.6 Multi-hazard risk

The multifaceted nature of the Himalayan hazardscape calls for an integrated approach to evaluate the full range of risks for communities, buildings, and infrastructure. Chouhan and Mukherjee (2023) emphasize that risk assessment surveys for buildings typically focus only on single hazards, largely due to a lack of survey instruments that are specifically designed to cover the range of hazards in mountain communities. Their study aims to fill this gap through the design and testing of a survey form for rapid risk assessment crafted to address the multi-hazard risk environment of Himalayan communities. With this contribution, Chouhan and Mukherjee (2023) provide a ready-to-use tool for a more complete assessment of the risks posed by the range of hazards discussed in this special issue.

### 2.7 Seismic vulnerability

Finally, the study by Fayaz et al. (2023) helps in identifying the vulnerability patterns at the municipal ward level in Srinagar. Their study identifies spatial hotspots of vulnerability due to factors like high population density, building density, pounding potential, and narrow streets, reflecting potential challenges in other Himalayan urban centers. The study highlights how masonry construction and irregular building geometry contribute to the understanding of seismic vulnerability, offering a template for similar studies in other Himalayan cities. Finally, the study discusses practical measures such as the strict implementation of building codes, retrofitting vulnerable structures, and fostering earthquake awareness, adaptable to diverse socio-cultural and economic contexts in the Himalayan region. In addition, the authors suggest a roadmap for setting up the context for future studies in the Himalayan region to help in understanding localized vulnerability assessment and to acknowledge the settlement pattern and diverse topography. The parameters used in the study include building materials and construction practices. The parameters can be adapted and transferred to other Himalaya regions to support vulnerability studies. Moreover, the study helps in aligning policymaking with specific regions, which will ultimately promote new development ideas across the Himalayan regions. Collaborative research initiatives are very important to establish standardized approaches to vulnerability assessment and risk management.

## 3 Conclusions

The studies presented in this special issue cover a wide spectrum of natural hazards, ranging from cryospheric hazards to hydrological extremes, and address critical gaps in research related to landslides, floods, and earthquakes. Key findings underscore the urgent need for comprehensive risk assessment and management strategies tailored to the unique challenges posed by the Himalayan hazardscapes. Overall, this special issue highlights the importance of interdisciplinary collaboration and the adoption of innovative methods to address the challenges posed by natural extreme events. Moving forward, concerted efforts are urgently needed to address problems of data scarcity, to implement evidence-based policies, and to develop and conduct practices that enhance resilience across the Himalayan landscape. By leveraging the insights gained from this research, we can strive towards building safer and more resilient communities in one of the world's most hazard-prone regions.

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