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ORIGINAL PAPER

Increasing risk of cascading hazards in the central Himalayas

Sanjib Sharma[1] · **Rocky Talchabhadel**[2] · **Santosh Nepal**[3,4] · **Ganesh R. Ghimire**[5] · **Biplob Rakhal**[6] · **Jeeban Panthi**[7] · **Basanta R. Adhikari**[8] · **Soni M. Pradhanang**[7] · **Shreedhar Maskey**[9] · **Saurav Kumar**[2]

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Abstract

Cascading hazards are becoming more prevalent in the central Himalayas. Primary hazards (e.g., earthquakes, avalanches, and landslides) often trigger secondary hazards (e.g., landslide dam, debris flow, and flooding), compounding the risks to human settlements, infrastructures, and ecosystems. Risk management strategies are commonly tailored to a single hazard, leaving human and natural systems vulnerable to cascading hazards. In this commentary, we characterize diverse natural hazards in the central Himalayas, including their cascading mechanisms and potential impacts. A scientifically sound understanding of the cascading hazards, underlying mechanisms, and appropriate tools to account for the compounding risks are crucial to informing the design of risk management strategies. We also discuss the need for an integrated modeling framework, reliable prediction and early warning system, and sustainable disaster mitigation and adaptation strategies.

Keywords Central Himalayas · Cascading hazards · Hazard predictions · Risk · Mitigation and adaptation · Risk management

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✉ Rocky Talchabhadel
rocky.talchabhadel@ag.tamu.edu

[1] Earth and Environmental Systems Institute, The Pennsylvania State University, University Park, PA, USA

[2] Texas A&M AgriLife Research, Texas A&M University, El Paso, TX, USA

[3] International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal

[4] International Water Management Institute (IWMI), Nepal Office, Kathmandu, Nepal

[5] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

[6] Engineering-GIS, World Food Programme, Lalitpur, Nepal

[7] Department of Geosciences, University of Rhode Island, Kingston, RI, USA

[8] Department of Civil Engineering, Institute of Engineering, Tribhuvan University, Kirtipur, Nepal

[9] IHE Delft Institute for Water Education, Delft, The Netherlands

1 Introduction

The Himalayan region—also referred to as the water towers of Asia—has the largest concentration of snow and ice reserves outside the polar regions. Several river systems that are critical for human inhabitation in several parts of the continent (e.g., Indus, Ganges, Yangtze, and Brahmaputra) originate here. However, the region is exposed to a range of disruptive hazards and stresses, ranging from extreme weather events to unplanned land-use changes and environmental degradation (Gautam 2017; Kirschbaum et al. 2019; Rakhal et al. 2021; Tellman et al. 2021). Cascading hazards that result from a sequence of hazards and/or their interactions lead to devastating climate-related impacts and human disasters. One hazard often triggers another hazard, and the compounding impacts of these hazards lead to greater damage over the wider area than is expected from a single hazard (Cutter 2018; Raymond et al. 2020). Hazard interactions are highly nonlinear and may surpass a tipping point after which the impacts can amplify substantially even to a small change in the forcing (AghaKouchak et al. 2018; Raymond et al. 2020). A considerable challenge remains to identify a priori the tipping point for a region like the Himalayas.

Sharp elevation gradients, fragile geological features, high seasonal precipitation variability, and frequent seismic activities make the Himalayan region particularly vulnerable to multiple hazards (Vaidya et al. 2019). Moreover, the region is experiencing a strong influence of climate change on precipitation, sediment flux, permafrost thaw, and glacier melt (IPCC 2021; Li et al. 2021; Wijngaard et al. 2017). Human activities, especially the expansion of the built environment and other land-use changes, have altered land-surface characteristics, the river flows, and sediment load, impacting downstream communities, geomorphology, and ecosystems (Whipp and Ehlers 2019). These complex coupled interactions between human and natural systems across a wider scale make hazard and risk management particularly challenging in the Himalayan region.

The most prominent primary triggers of cascading hazards in the Himalayas are earthquakes, rockfall, avalanches, and landslides (Kargel et al. 2016; Veh et al. 2020; Whipp and Ehlers 2019). These primary triggers can initiate secondary hazards such as landslide-dam, debris flow, flash floods, and critical infrastructure failure (Vaidya et al. 2019). For example, landslides can block rivers and expose communities, infrastructures, and ecosystems to backwater inundation, debris flow, and dam-break flooding. Such triggers often begin in a specific location and eventually cascade to cause widespread consequences. The timescale for the primary trigger to initiate secondary hazards is often event-specific. For instance, the time taken by an earthquake initiating a landslide is different from a landslide triggering flash floods and critical infrastructure failure. Also, often a series of seemingly normal hydrometeorological events triggers a chain of events over a long- or short-time scale with disastrous consequences (Cook et al. 2018). For example, days of warm temperatures in the higher altitudes may increase the chances of glacial lake outburst floods, while a series of average rainfall events in regions with altered land use and other anthropogenic disturbances may increase the probability of landslide dam outburst floods. Consequently, the increased likelihoods of glacial lake outbursts and landslide dams and outbursts can exponentially amplify flood risks in the downstream settlements. Therefore, traditional risk management strategies tailored around single hazards fail to withstand multihazard interactions and their cascading impacts under dynamic natural and anthropogenic perturbations. In this commentary, we highlight the increasing risk of cascading hazards causing massive disasters in the central Himalayas with a particular emphasis on characterizing hazards and their propagation through the multisectoral system.

2 How do natural hazards cascade to cause disasters?

We characterize the cascading mechanisms with examples of diverse cascading hazards from the central Himalayas and illustrate the triggering factors, consequent secondary hazards, and multisectoral impacts (Fig. 1).

2012 Seti flash flood High mountains' rock and ice avalanches often trigger cascading hazards to downstream river valleys. A huge landslide due to rock slope failure occurred at Sabque Crique, Annapurna range, Central Nepal on May 05, 2012. The rock mass descended about 2 km from the high mountain (Dwivedi and Neupane 2013). The resulting vibration, pressure, and heat caused the glaciers/ice to melt rapidly. The whole mass descended further downslope to the Seti river leading to flash floods, massive debris flows, ice block flows, and hyper-concentrated slurry flows. These cascading hazards killed over 70 people and impacted the livelihood in several downstream settlements, including in the Sadi Khola and Machhapuchre VDCs of the Kaski district (Dwivedi and Neupane 2013).

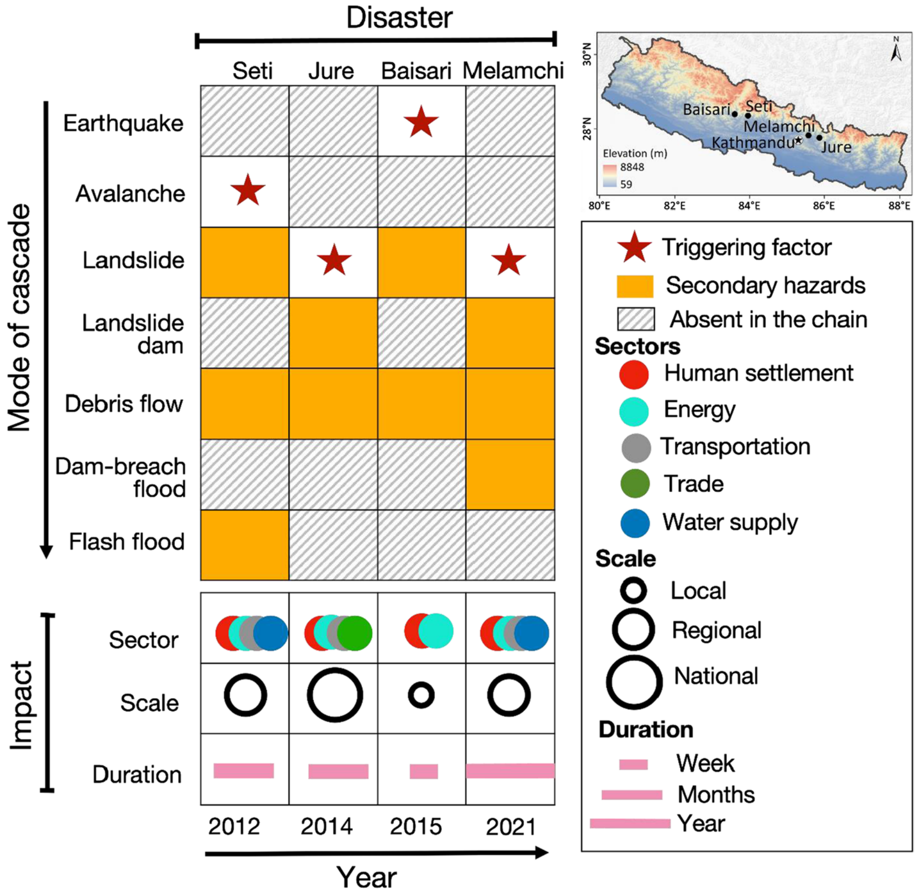

Fig. 1 Recent cascading hazards in the central Himalayas, and their modes of the cascade. These hazards pose substantial damage across different sectors (human settlement, energy, transportation, water supply, and trade), and at a wider range of spatial (local, regional, and national), and temporal (week, month, and year) scales

The flood destroyed agricultural land and interrupted critical infrastructures, including roadways, utility power poles, bridges, and water supply systems. This event is likely not a one-off extreme, instead, a harbinger of what may be expected in the future with the ways mountain hazards (e.g., glacier melt and/or glacier lake outburst flood hazards) are being modulated by the warming climate (Veh et al. 2020).

2014 Jure landslide Cascading hazards can even occur under moderate meteorological conditions when coupled with geohazards such as a rockslide, making them destructive and challenging to mitigate. An example is the Jure landslide, which occurred 70 km northeast of Kathmandu on August 02, 2014. The landslide (width = 900 m, slope length = 1500 m, and maximum depth = 200 m) was a typical mass failure with massive rock fragments, sand, and soil (Yagi et al. 2021). Debris from the landslide formed a 55 m tall earthen dam that blocked the Sunkoshi River. The debris dam led to the formation of a lake up to 3 km upstream from the base of the landslide. These cascading hazards led to multisectoral impacts, including transportation, trade, and energy (van der Geest 2018). The landslide killed 156 people, submerged dozens of houses, and destroyed critical infrastructures (e.g., school, bridge, and cement industry) (van der Geest 2018). The lake formed due to the landslide-dam, destroyed sections of the national highway linking Nepal and China, and disrupted cross-border trade exchange of nearly US dollar 370,000 per day- for almost two months (Zhang et al. 2017). This event interrupted the operation of Sanima hydropower (2.60 megawatts) and SunKoshi hydropower (10.05 megawatts), causing electricity outages in several locations.

2015 Gorkha earthquake The 7.8 Mw Gorkha Earthquake (April 25, 2015) and subsequent aftershocks triggered over 20,000 landslides over an area of more than 25,000 km^2 (Gnyawali and Adhikari 2017). There is evidence of landslides blocking the river and creating landslide-dam lakes. The Baisari landslide (May 24, 2015) in the northwest of Kathmandu is one of those major seismically induced landslides. The landslide blocked the Kali Gandaki River forming an artificial earthen dam. The water level rose rapidly behind the dam and created a lake extending up to 3 km upstream (Hashash et al. 2015). The landslide buried a human settlement of 25 houses. The operation of the 144 megawatt Kali Gandaki-A Hydropower project, located 45 km downstream of the landslide area, was suspended due to the potential risk of flooding. The water stored in the landslide-dammed lake was released in a controlled manner to avoid downstream disasters. Several landslides were reactivated in the subsequent monsoon season, further adding massive amounts of sediments to the river.

2021 Melamchi flood There are several instances of landslides triggering dam-breach floods. An example is a catastrophic debris flood that struck the Melamchi Bazar, north of Kathmandu, on June 15, 2021. The Melamchi River was blocked upstream of the Melamchi Bazar by a landslide dam (Pandey et al. 2021). Consequent dam breach resulted in a large amount of debris and sediment-laden flow. Heavy debris flow was observed at the high-altitude glacial deposits. This incident cannot be attributed to a single factor rather was the result of multiple processes that occurred at various locations along the Melamchi River (Maharjan et al. 2021). At least 5 people died, 6 were injured, 20 remained missing, and over 500 were displaced from this flood. The flood also caused substantial damage to the Melamchi Drinking Water Supply headworks infrastructure, disrupting the water supply to the nation's capital. After one and half months of the Melamchi flood, there was another episode of the sediment-laden flood. Since the riverbed was already aggravated from the previous one, the later flood severely impacted the built environment, including bridges and settlements. The upstream region of the river experienced further aggradation due to sediments from several landslides and continuous toe-cutting. Such conditions are conducive for similar sediment-laden floods in the monsoon season over the next few years even under moderate hydrometeorological conditions.

Several cascading hazards with diverse mechanisms have been observed in the surrounding region of the central Himalayas. A few such examples are the 2013 Uttarakhand flood (Houze et al. 2017) and the 2021 Chamoli flood in India (Shugar et al. 2021). In high-altitude areas, warming climates are likely to alter temperature, precipitation patterns, and glacier melting characteristics (Hock et al. 2019). Although individual events such as the Melamchi and the Chamoli floods are difficult to directly attribute to climate change, cryosphere-related hazards are expected to increase under a warming climate (Hock et al. 2019; Shugar et al. 2021). Recently observed hazards such as the first-ever recorded supercell thunderstorm/tornado (Pokharel 2021; Meyer et al. 2021) and increasing wildfire incidents (Bhujel et al. 2017) in the central Himalayas raise new concerns on how hazard interactions and cascades might evolve under future climatic conditions. Wildfires destroy vegetation and decrease the soil’s ability to absorb water. Even a normal rainfall on these vulnerable landscapes can easily erode the ground and lead to landslides and flash floods. These interactions can lead to complex behaviors and impacts that are difficult to predict.

These few examples of cascading hazards are more unusual than the typical single hazards. In most of the above examples, there were triggering factors that caused the secondary hazards (Fig. 1). The primary and/or secondary hazards typically have the potential to reach the tipping point to cause a massive impact. As in the case of the Melamchi flood, gradual rise in the upstream water level suddenly surpassed the landslide dam and resulted in the dam breach flood. If the hazard does not reach the tipping point, the impact could be of a lesser degree, as was the case with the Baisari landslide. In the Baisari landslide, the river overtopped the dam and the impact was minimal despite the river being blocked by the landslide. There is often a strong upstream–downstream linkage in cascading hydrologic hazards (Fig. 2). The triggering event often occurs in upstream areas of the mountainous regions and associated cascading hazards unfold subsequently in the downstream regions (Fig. 1).

3 Future directions and priorities

How can we advance the existing capabilities for Earth system modeling to improve cascading hazard and risk prediction? Conventional modeling has focused on estimating the likelihood of single hazards in isolation; emphasizing hazard over risk prediction; and rarely quantifying and communicating prediction uncertainties. The few examples of cascading hazards discussed here point to the need for integrated models, modeling frameworks, and analyses that can account for the dynamic interactions among natural and human systems in the context of multiple interacting stresses and over a wide range of spatiotemporal scales (Gill and Malamud 2016). We identify the research need in two broad areas: (1) understanding multistressor multiscale drivers of cascading hazards, their interactions and failure modes, and (2) understanding how human and natural systems respond to the failure in one or multiple systems. Understanding the dynamics of cascading hazards in the central Himalayas requires considering interconnected processes that occur in high mountains, mid-hills, and low-lying lands, as well as external stresses that influence extreme events, geomorphology, and settlement patterns (Fig. 2). Recent advances in global change research, unprecedented availability of novel datasets (i.e., remote sensing from satellites, small unmanned aircraft systems, and citizen science), big data analytics,

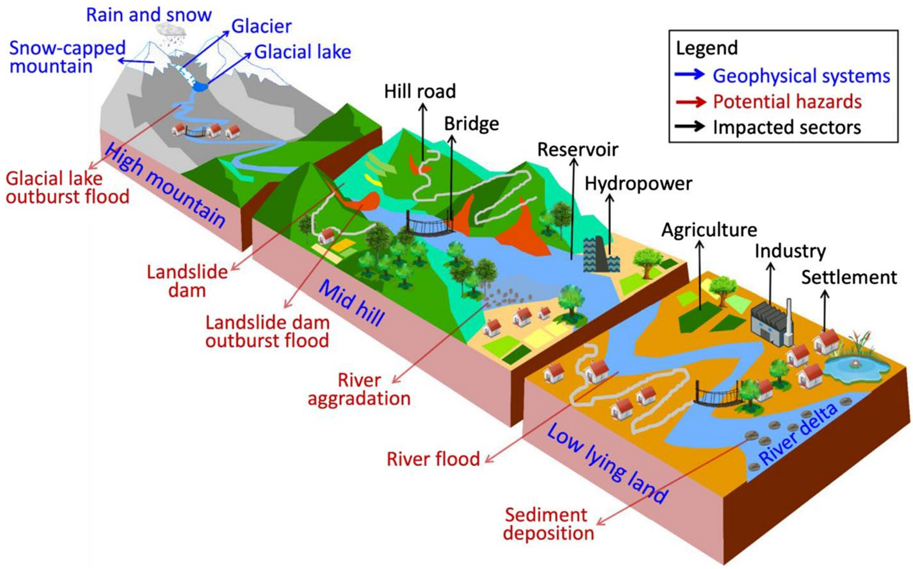

Fig. 2 A schematic diagram of the major water/sediment-related hazards across the Himalayan River from upstream to downstream areas (adapted from Nepal et al. (2018)). The major water/sediment-related hazards are overlaid at respective zones. For example, under a warming climate, the melting of the glacier, ice, and snow would increase, and the volume of the glacial lake will rise, increasing the chances of glacial lake outburst floods (GLOFs). Similarly, under haphazard road construction, land use changes or/and altered rainfall extremes, the landslide occurrence would increase, and the landslide volume could block the river forming a dammed lake which, in turn, could result in landslide dam outburst flood (LDOF). Sometimes, these GLOF and LDOF events can occur one after another in a single watershed, amplifying the magnitude of damage to the lives and livelihoods located at downstream floodplains across scales

and high-performance computing resources present substantial opportunities to develop interconnected systems of data, model, analysis, and decision support capabilities that could help improve mountain hazard and risk prediction capabilities (Maskey 2019).

Reliable early warning systems are critical for disaster preparedness and management (Li et al. 2020; Mishra et al. 2019; Thapa and Adhikari 2019). In the central Himalayas, early warning systems for natural hazards have not yet been well developed. There has been some progress in flood early warning systems, but these are mostly for relatively large rivers in the lower valleys/plains (DHM 2018). Early warning systems configured to a specific hazard in isolation can substantially underestimate the risk, distort disaster response priorities, and increase vulnerability to cascading hazards. New capabilities are, therefore, needed for multihazard- and cascading hazard-risk communication to facilitate proactive planning and management, focusing on the vulnerable communities (Vaidya et al. 2019). Warning communication in the central Himalayas is often difficult due to the lack of automated measurements, computing resources, and communication infrastructure. More research, operational efforts, and resources need to be mobilized to develop, expand, and automatize early warning systems for potential hazards, such as earthquake, avalanche, landslide, and debris flow to communicate the risk associated with their interactions and cascading phenomena.

A key challenge remains in developing a resilient infrastructure system that can withstand the risk of cascading hazards. The current infrastructure design specification primarily relies on observed hydroclimatic records, often overlooking climate uncertainty and nonstationary hydroclimatic extremes. In addition, infrastructure design specification typically neglects the impacts of cascading hazards and their interaction with climatic and socioeconomic changes. There is a pressing need to update infrastructure design guidelines to account the potential impacts of cascading hazards over a range of potential future scenarios, including climate and socioeconomic uncertainties (Wijngaard et al. 2017). Building resilient infrastructure systems is often expensive and requires strategic investment policies that are long-term and cross-sectoral. Analytical frameworks such as robust decision making (Lempert et al. 2006) and infrastructure design under deep uncertainty (Chester et al. 2020; Lempert 2002) facilitate the identification of potential robust strategies, characterize the vulnerabilities of such strategies, and evaluate trade-offs among them.

Risk management requires reliable mitigation and adaptation strategies (Srivastava et al. 2020; Sekhri et al. 2020). There is a growing need to establish robust policies and actions that can be implemented over the long-term to reduce the risk. Adaptation strategies could involve large-scale infrastructures (e.g., appropriate basin management practices to enhance land stability and reduce soil erosion, flood control works, evacuation roads, and facilities) as well as soft strategies (e.g., risk mapping, hazard zoning, and land use planning). Adaptation responses can differ based on hazard characteristics (slow-paced and sudden-onset hazards, and their frequency and magnitude), locations (high mountains, mid hills, and low-lying land) as well as socioeconomic conditions (Rasul et al. 2020). Implementing these strategies requires a sound understanding of current and future risks, strengthening governance across administrative levels, and promoting risk-informed private and public investments (Abe et al. 2019). Risk management strategies should prioritize equity and inclusion as a fundamental objective of hazard management by directing resources to those who face disproportionate risks of harm to achieve more equitable and inclusive outcomes. More mission-oriented fundamental research is needed to identify the equitable and inclusive disaster adaptation and mitigation strategies, and to evaluate their performance under different institutional and governance constraints.

Risks from natural hazards are dynamic and are expected to increase with changing environmental conditions, unplanned settlement patterns, and unbalanced socioeconomic developments (Hock et al. 2019; Ragettli et al. 2016; Wijngaard et al. 2017; IPCC 2021). Comprehensive understanding of natural hazards, cascading mechanisms, and associated disasters are critical to enhancing potential adaptation measures, risk management strategies, and prediction capabilities across the Himalayan region. Risk management demands convergence research that is driven by deep scientific questions or pressing societal needs, and requires meaningful integration among academic disciplines, stakeholders, and decision-makers (NSF 2019; Peek et al. 2020). Disaster mitigation plans and policies should take a holistic approach to better characterize and integrate multihazard interactions and cascading phenomena (Vaidya et al. 2019). We emphasize the need for an integrated multihazard multiscale modeling framework, reliable prediction and early warning systems, and sustainable disaster mitigation and adaptation plans under an equitable framework to cope with the cascading hazards and risk in the central Himalayas.

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Declarations

Competing interests The authors declare no competing interests.

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