

UNCOVERING GEOHAZARDS AFFECTING INFRASTRUCTURE IN THE HIMALAYAS

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ABSTRACT

The Himalayan region, formed by the ongoing collision of the Indian and Eurasian plates, is among the most geologically active zones in the world. Infrastructure development across this mountainous terrain faces severe threats from geohazards such as landslides, earthquakes, glacial lake outburst floods (GLOFs), and Deep-Seated Gravitational Slope Deformations (DGSDs). These hazards, intensified by climate change and poorly planned construction, have resulted in repeated damage to roads, bridges, hydropower plants, and settlements. Events like the 2021 Melamchi flood and persistent ground deformation at Pakyong Airport in India exemplify the vulnerability of infrastructure to complex geomorphological and hydrometeorological processes. Many urban and rural areas across Nepal, India, and Bhutan are situated on DGSDs terrain without proper hazard assessment. This paper highlights the nature and impact of these geohazards, supported by recent case studies, and stresses the need for precise engineering geological investigations, hazard mapping, and risk-informed planning. Without incorporating geohazard science into infrastructure development, the Himalayan region remains exposed to growing disaster risks, leading to increased economic losses and compromised resilience. Strengthening geotechnical solutions, monitoring systems, and regional cooperation are essential steps toward safer infrastructure in this geologically young mountain environment.

1 INTRODUCTION

The Himalayas, a 2,400 km long mountain chain stretching across eight countries from Afghanistan to Myanmar, are the youngest and most tectonically active mountain range in the world. They were formed by the ongoing collision between the Indian and Eurasian tectonic plates. This active tectonic setting has led to complex geological conditions, marked by frequent earthquakes, floods, landslides, and rapidly eroding landscapes in high-altitude regions. Beyond their geological significance, the Himalayas have a major influence on the socio-economic conditions of South Asia, particularly in Pakistan, northern India, Nepal, and Bhutan (Figure 1). The region is home to millions of people and is the source of major rivers that support agriculture, energy generation, and water supply for nearly half of the global population. The presence of key road networks, hydropower projects, and expanding infrastructure reflects the economic importance of the Himalayas, but also reveals high exposure to geohazards of the region.

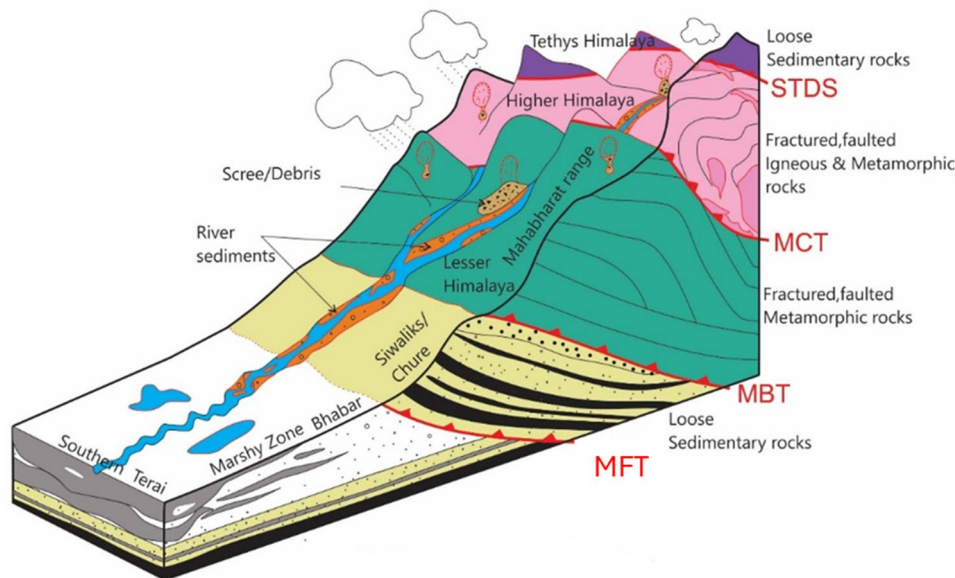


Figure 1: Geological and geomorphological settings of the Himalaya (source: DMG, 2025)

Geohazards in the Himalayas are natural geological and climatic processes that pose serious threats to human lives, livelihoods, and infrastructure. Major hazards include landslides and Deep-Seated Gravitational Slope Deformations (DGSDs), which occur frequently due to steep slopes, earthquakes, intense monsoon rainfall, and ongoing tectonic

activity. Earthquakes, generated by active faults such as the Main Frontal Thrust (MFT) and Main Boundary Thrust (MBT), often cause widespread damage and trigger secondary hazards like landslides. Glacial lake outburst floods (GLOFs) are becoming increasingly common due to the rapid retreat of glaciers and the melting of permafrost, forming unstable glacial lakes dammed by loose moraine. These risks are further intensified by poorly planned development, expanding road construction in both national and rural areas, and the growing impacts of climate change across the Himalayan region.

The objective of this paper is to examine the nature and extent of geohazards in the Himalayan region and to assess their direct and indirect impacts on critical infrastructure such as roads, bridges, hydropower plants, settlements, and related systems. Given the region's complex tectonic setting and growing human activity, infrastructure is often built in areas highly prone to natural hazards. This study focuses on how geohazards, particularly landslides (including DGSDs), earthquakes, and GLOFs, disrupt essential services, result in economic losses, and pose risks to long-term development. The paper also explores practical strategies to reduce these risks, including geotechnical engineering solutions, hazard mapping, early warning systems, and risk-informed planning. By examining both the challenges and the available mitigation options, the paper supports a more informed and cautious approach to infrastructure development in the Himalayan region.

2 Geohazard Context in the Himalayas

The Himalayas present a hazardous environment for infrastructure due to the interplay of tectonic activity, climate extremes, fragile geology, and human interventions. Historical earthquakes such as the 1934 Bihar–Nepal and the 2015 Gorkha Earthquake events have caused widespread damage to roads, bridges, hydropower facilities, and settlements. Intense monsoonal rainfall, snowmelt, and the rapid retreat of glaciers and permafrost melting (Figure 2a) and rainfall in the higher altitudes contribute to frequent landslides, debris flow, flash floods, and glacial lake outburst floods (GLOFs), threatening downstream infrastructure.

The 2021 Melamchi flood, which struck north of Kathmandu on June 15, was one of the most devastating disasters in central Nepal in recent years. Triggered by intense monsoon rainfall, the flood and debris flow swept through the Melamchi and Indrawati river corridors, causing widespread destruction. The disaster severely damaged the Melamchi Water Supply Project (MWSP), a flagship national project designed to supply 170 million liters of drinking water per day to Kathmandu Valley. Key infrastructure, including the headworks, access roads, tunnels, and intake structures, were either submerged or washed away. The flood also destroyed over a dozen motorable and pedestrian bridges, and inundated several settlements, including parts of Melamchi Bazaar (Figure 2b). More than 260 households were directly affected, and over 500 families had to be evacuated. Agricultural lands, worth millions of rupees, were buried under debris, and numerous fisheries along the riverbanks were completely destroyed. Estimates suggest that the total economic loss exceeded NPR 30 billion (approximately USD 250 million). Recovery and reconstruction efforts have been slow, hindered by the complexity of terrain and recurring monsoon threats. The Melamchi disaster highlighted critical gaps in engineering geological investigation in before the project construction, river basin management, and the resilience of large infrastructure projects to climate-induced disasters.

Likewise, Deep-Seated Gravitational Slope Deformations (DGSDs) are widespread across the Himalayan region but often remain undetected until triggered by external factors such as intense rainfall or seismic events, resulting in large-scale slope failures. A best example is the Pakyong Airport in Sikkim, India (Figure 2c), where progressive ground deformation attributed to DGSDs has caused persistent instability over the past three years. Despite ongoing monitoring efforts, a comprehensive long-term mitigation strategy with specific engineering geological understanding has not yet been implemented. The airport continues to experience creeping slope movements, widespread cracking, and significant structural damage, particularly in the mechanically stabilized earth (MSE) walls and retaining structures. This case exemplifies the critical oversight of engineering geomorphology and engineering geological site characterization in infrastructure development across the Himalayan terrain.

Similarly, several towns in Nepal, including Tansen, Tamghas, Mangalsen, Baitadi, Ilam, Okhaldhunga, and Gorkha, and in India, such as Darjeeling, Kurseong, Nainital, Joshimath and Pithoragarh, are located on DGSD-prone slopes. The Bhawanijhora Landslide in Bhutan is a prominent example of a transboundary landslide disaster, closely associated with DGSD. The debris flow originates in Bhutan and deposits downstream in India, highlighting the cross-border implications of geomorphological hazards in the Himalayan region (Figure 2d). These areas frequently exhibit symptoms of ground instability, including cracks in buildings, tilting of structures, and progressive ground displacement, especially during the monsoon season and following seismic activity. However, systematic engineering geological investigations and site-specific stabilization measures remain largely inadequate. The lack of understanding and mitigation of DGSD processes continues to pose a serious threat to the sustainability of urban infrastructure and settlements in these vulnerable Himalayan mountainous regions.

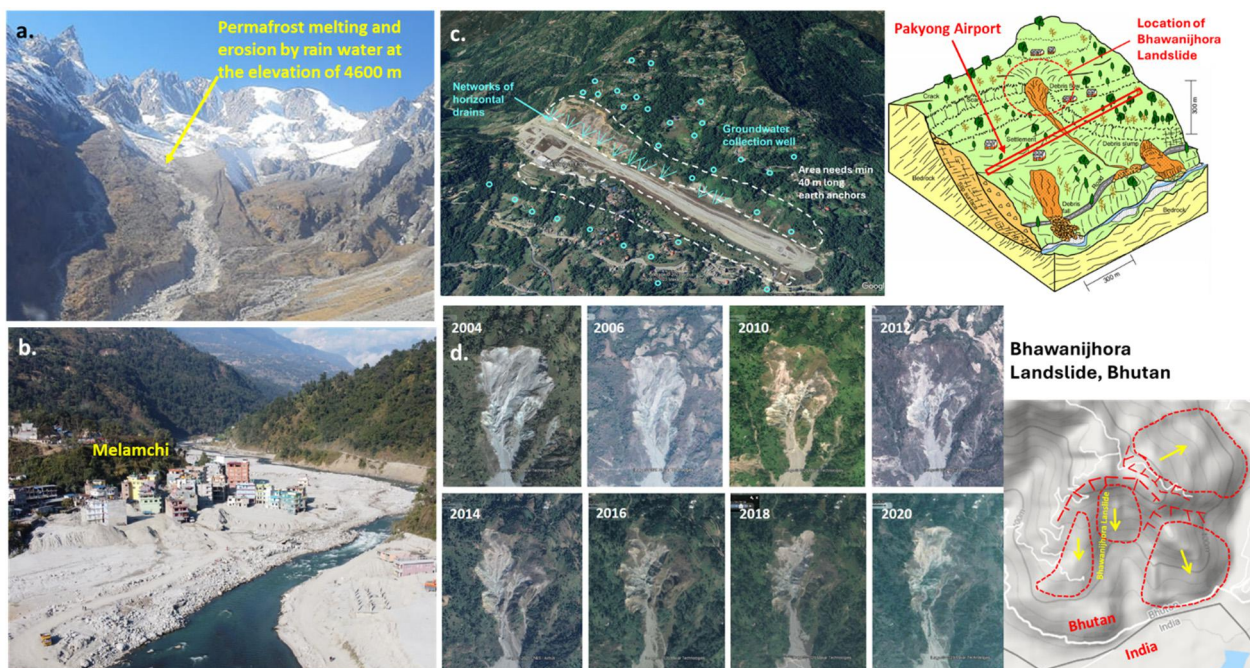


Figure 2: Illustrations of geohazard issues in the Himalaya: a) Permafrost melting and headward erosion – Observed in the Melamchi River basin at an elevation of approximately 4,600 meters, where permafrost degradation is accelerating headward erosion processes. b) Burial of Melamchi Town – Resulting from the catastrophic July 15, 2021 flash flood, triggered by a combination of glacial lake outburst flood (GLOF) and landslide dam outburst flood (LDOF), which buried large sections of the town. c) Pakyong Airport instability – Constructed on a DGSD-affected slope, the site has experienced ongoing ground deformation and structural failures due to creeping slope movements. Suitable mitigation measures needed for the site is also illustrated in the image. d) Bhawanijhora Landslide – A typical transboundary landslide occurring within DGSD terrain, demonstrating complex interactions of gravitational deformation. The geomorphological settings of both the Pakyong Airport and Bhawanijhora landslide sites are consistent with the DGSD model characteristic of the Himalayan region.

Human activities such as slope-cutting for road construction, and poor drainage design further aggravate geohazards in the rural areas. Many major infrastructure projects are implemented without adequate engineering geological studies or long-term hazard planning. The under construction Kathmandu–Terai Madhesh Fast Track has encountered repeated slope failures, tunnel deformation, and drainage issues, partly due to DGSDs. Key road networks like the Prithvi Highway, B.P. Highway, and Mid-Hill Highway, along with several hydropower projects, suffer frequent disruptions from monsoon-triggered landslides and erosion. In many cases, reactive maintenance replaces preventive measures without proper understanding of engineering geological settings of the site, resulting in escalating costs and further vulnerability.

3 Major Geohazards Affecting Infrastructure

3.1. LANDSLIDES

In Nepal, landslides are among the most frequent and destructive natural disasters, occurring annually and causing substantial social and economic losses, particularly in mountainous regions (Dahal and Hasegawa, 2008). Fatalities due to landslides remain consistently high. Figure 4 illustrates the multi-hazard landscape of Nepal, where landslides are identified as a recurring threat. An analysis of data from the past 50 years reveals that landslides have caused an average of 110 deaths per year, with annual fatalities reaching as high as 1,350 in extreme cases.

For instance, during the early monsoon period in 2021 (June 10 to June 16), landslides and floods claimed at least 20 lives. Numerous villages and settlements along river basins were severely affected by landslide dam outburst floods (LDOFs), highlighting the urgent need for proactive measures.

In late September 2024, central Nepal experienced one of its most devastating natural disasters in recent history, as unprecedented monsoon rainfall triggered widespread flooding and landslides across the region.

Between September 26 and 30, the Kathmandu Valley received over 700 mm of rain, nearly half its annual average—over just three days. This deluge caused the Bagmati River to overflow, inundating large parts of Kathmandu and Patan. The resulting floods and landslides led to at least 246 confirmed deaths nationwide, with over 4,000 people rescued and more than 1,200 homes destroyed or severely damaged. Infrastructure damage was extensive: 25 bridges, 37 highways, and 11 hydropower stations were impacted, while seven major highways leading out of Kathmandu were blocked by debris. The disaster also disrupted power, water, and telecommunications services across multiple districts. In the Kathmandu Valley alone, at least 73 fatalities were reported. Rescue operations were hampered by blocked roads and ongoing landslides, with entire vehicles, including buses, buried under debris.



Figure 3: Damage and loss scenario during extreme rainfall of September 26 and 30, 2024. Red box is official data of National Disaster Risk Reduction and Management (NDRRMA), Government of Nepal.

To reduce the impacts of future disasters, it is crucial to identify and monitor areas that are highly susceptible to landslides in advance. Landslide hazard assessment is fundamental for understanding the geomorphological and geotechnical characteristics of vulnerable terrain, especially under the stress of extreme climatic events. These assessments support systematic data collection, risk evaluation, and the development of site-specific mitigation strategies. In particular, landslide hazard maps provide essential insights into the spatial distribution of susceptibility across different regions. They serve as critical tools for local communities and government agencies, enabling evidence-based planning and the implementation of targeted, action-oriented disaster risk reduction interventions.

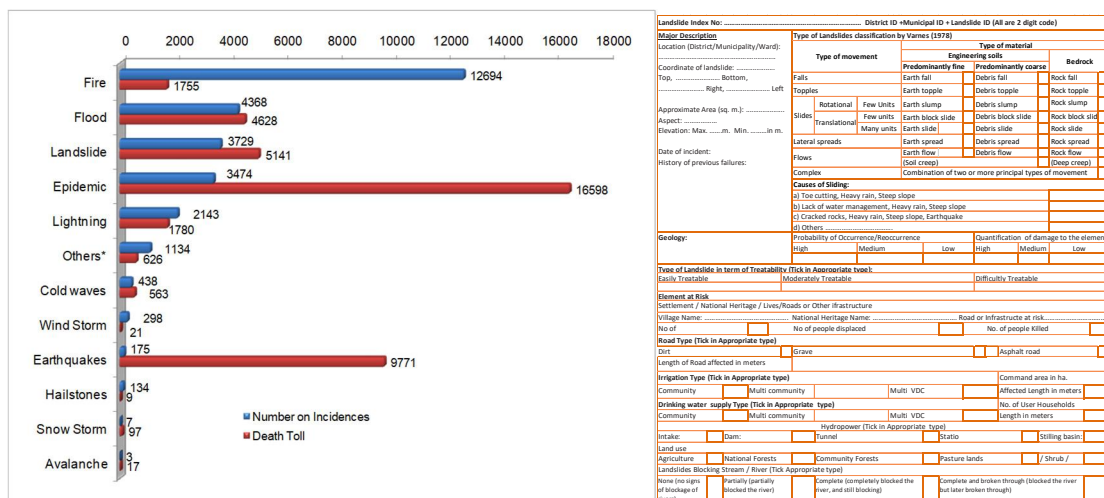


Figure 4: Multi-hazard scenario of Nepal by its number of incidences and death toll, 1971-2018 (Source: MoHA, 2018) and table on right is a recommended sheet for landslide data collection in after the disaster.

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3.2. EARTHQUAKES

Nepal lies in one of the most seismically active regions in the world due to the ongoing subduction of the Indian Plate beneath the Eurasian Plate along the Himalayan arc. The convergence rate of approximately 45 mm/year has led to the formation of a series of major thrust faults—namely, the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and the highly seismogenic Main Frontal Thrust (MFT). These active tectonic structures continuously accumulate strain, which is periodically released through large-magnitude earthquakes (Lavé and Avouac, 2000; Bilham, 2004).

Nepal has experienced several significant seismic events over the past century, including the devastating 1934 Mw 8.0 Bihar-Nepal Earthquake and the 2015 Gorkha Earthquake of Mw 7.8. These events demonstrate the country's high vulnerability to seismic hazards, particularly due to the concentration of population and infrastructure along the thrust zones.

In addition to ground shaking and surface rupture, earthquake-induced landslides represent a major secondary hazard. Though not comprehensively documented, historical earthquakes such as the 1934 Bihar-Nepal, 1950 Assam, and 2005 Kashmir earthquakes triggered numerous landslides across the Himalaya. The 2015 Gorkha Earthquake alone resulted in thousands of co-seismic landslides that caused extensive damage to settlements, transportation networks, and natural river systems (Roback et al., 2018; Dahal, 2015).

Despite the well-established relationship between seismicity and Himalayan tectonics, the systematic study and documentation of earthquake-induced landslides in Nepal remain limited. These landslides often cause more widespread and prolonged damage than the seismic shaking itself, underscoring the need for integrated seismic and landslide risk assessment and preparedness.

3.3. GLACIAL LAKE OUTBURST FLOODS AND FLASH FLOODS

Glacial Lake Outburst Floods (GLOFs) represent one of the most serious climate-induced hazards in Nepal. As glaciers are retreating rapidly, leading to the formation and expansion of glacial lakes, many of which are dammed by unstable terminal moraines. Dams of glacial lake usually fail due to icefalls, rockfall into the lake, landslides into the lake, heavy rainfall in high altitude, or internal pressure build up they release massive volumes of water and debris downstream in a sudden and highly destructive manner. Nepal currently has over a thousand identified glacial lakes, with more than two dozen considered potentially dangerous. Historic events like the 1985 Dig Tsho GLOF or Thame GLOF of 2024 in eastern Nepal highlight the scale of destruction such events can cause, including loss of infrastructure, disruption of livelihoods, and degradation of river ecosystems. GLOFs pose a direct threat to mountain communities, hydroelectric plants, roads, bridges, and agricultural lands situated along river valleys. Despite their high risk, monitoring and mitigation systems for GLOFs in Nepal remain limited.

Riverbank failures due to flash floods are a widespread and recurring hazard in Nepal, especially during the monsoon season when rivers experience high discharge and increased erosive power. These failures are driven by river undercutting, saturation of banks, and the collapse of loosely consolidated alluvial materials. In mountainous regions, steep gradients and unregulated river systems exacerbate the risk of lateral erosion, leading to the loss of settlements, roads, and agricultural land. In the Terai and Middle hills, human activities such as gravel mining and construction too close to riverbanks further destabilize these fragile areas. Addressing riverbank failures in Nepal requires a combination of engineering measures (such as revetments and check dams), ecological approaches (such as riparian vegetation and bioengineering), and regulatory planning tools like river corridor zoning and setback enforcement. Public awareness and integrated watershed management are also essential to ensure long-term stability and safety of river-adjacent communities.

On 15 June 2021, Melamchi Municipality in Sindhupalchok District experienced a devastating flood, followed by a second major event on 31 July 2021. These floods caused extensive damage to 255 households, destroyed two concrete and two suspension bridges, and inundated thousands of hectares of agricultural land, isolating the municipality and its surrounding areas for several weeks. Although the scale of destruction was immense, early warning from upstream communities played a critical role in preventing human casualties. Scientific investigations suggest that the main trigger

of the flood was the outburst of Pemdan Glacial Lake (Figure 5), which led to the breaching of an old natural dam near Bhemathan. This initiated rapid riverbed erosion, sediment mobilization, and a cascading series of landslides along the Melamchi River (Figure 5). The downstream impacts extended up to the Sipaghat area of the Indrawati River, with severe debris deposition particularly around low-clearance bridges. Based on flood hazard modelling, settlements from Talarang to Sipaghat are vulnerable to high-magnitude floods with 100-year return periods and should be avoided for permanent habitation. The 2021 event revealed the inadequacy of the earlier 20-meter river setback, prompting the development of new setback standards, risk-sensitive land use plans, and structural as well as bioengineering mitigation measures. The total estimated cost for implementing a comprehensive rehabilitation and disaster mitigation plan in the Melamchi area is over NPR 3.38 billion.



Figure 5, Pemdan Glacial Lake in 4750 m and status of erosion in Pemdan creek and burst of the lake.

4 Monitoring and Early Warning Systems

Suitable monitoring and early warning systems (EWS) are major components of disaster risk reduction in the geohazard-prone regions of the Himalayas. Given the frequent occurrence of landslides, floods, earthquakes, and glacial lake outburst floods (GLOFs), timely detection and communication of potential threats can save lives, minimize economic losses, and protect ongoing development efforts. Monitoring involves the continuous observation of environmental and geological conditions using tools such as automated rainfall gauges, ground motion sensors, GPS, satellite imagery, and remote sensing technologies. These tools help detect changes in slope stability, precipitation, snow cover, seismic activity, and glacial lake dynamics, critical indicators of impending geo-disasters. Early warning systems translate this data into actionable information, which must be effectively communicated to at-risk communities before a disaster hits.

In Nepal, early warning systems have been developed at both local and regional scales. Local systems focus on specific slopes or communities and rely on real-time monitoring and alerts when conditions change. Regional systems, which cover broader geographic areas, utilize rainfall forecasts and other environmental data to provide advance warnings to a larger population. Both systems face specific challenges: local systems require accurate, low-cost, and sustainable monitoring technologies, while regional systems demand improved forecasting capabilities, access to free and high-resolution data, and the development of geographically specific and impact-based forecasts that consider vulnerability and exposure. Community-based early warning systems (CBEWS), piloted in river basins like the Koshi and Karnali, offer valuable models for localized preparedness but face limitations in scale, infrastructure, and public response.

To build a more robust EWS network in Nepal, several key actions can be recommended: improving the use of existing knowledge and data products, localizing hazard and susceptibility assessments, developing impact-based forecasting, enhancing forecast accuracy, strengthening governance and coordination, increasing data collection, and promoting slope-scale, community-managed warning systems. Various projects have already produced national and local hazard, vulnerability, and susceptibility maps, but their uptake by national, municipal, and local stakeholders remains inconsistent. Assessing awareness and use of these products, identifying gaps, and addressing barriers to access and implementation will be crucial.

5 Risk Reduction Strategies

Action oriented disaster risk reduction requires a comprehensive approach that integrates engineering solutions, strong policy frameworks, community involvement, and international collaboration. Engineering interventions such as bioengineering, slope stabilization, and seismic-resistant design help for mitigating physical risks, particularly in hazard-prone regions of the Himalaya. These measures enhance the resilience of infrastructure and reduce the likelihood of catastrophic failure during extreme events like landslides, earthquakes, and floods. Equally important are refined and evidence-based policy frameworks and the enforcement of building codes, which ensure that development is aligned with safety standards and hazard assessments. Institutionalizing risk-sensitive land use planning and regulating construction in vulnerable areas are essential components of long-term risk management. This was well practiced in Melamchi and local government is now implementing such land use planning. Similarly, international cooperation and funding support are vital for capacity building, technology transfer, and the implementation of large-scale resilience programs, especially in the Himalaya. These collaborative efforts help bridge resource gaps and promote shared learning, ultimately contributing to more sustainable and inclusive disaster risk reduction outcomes.

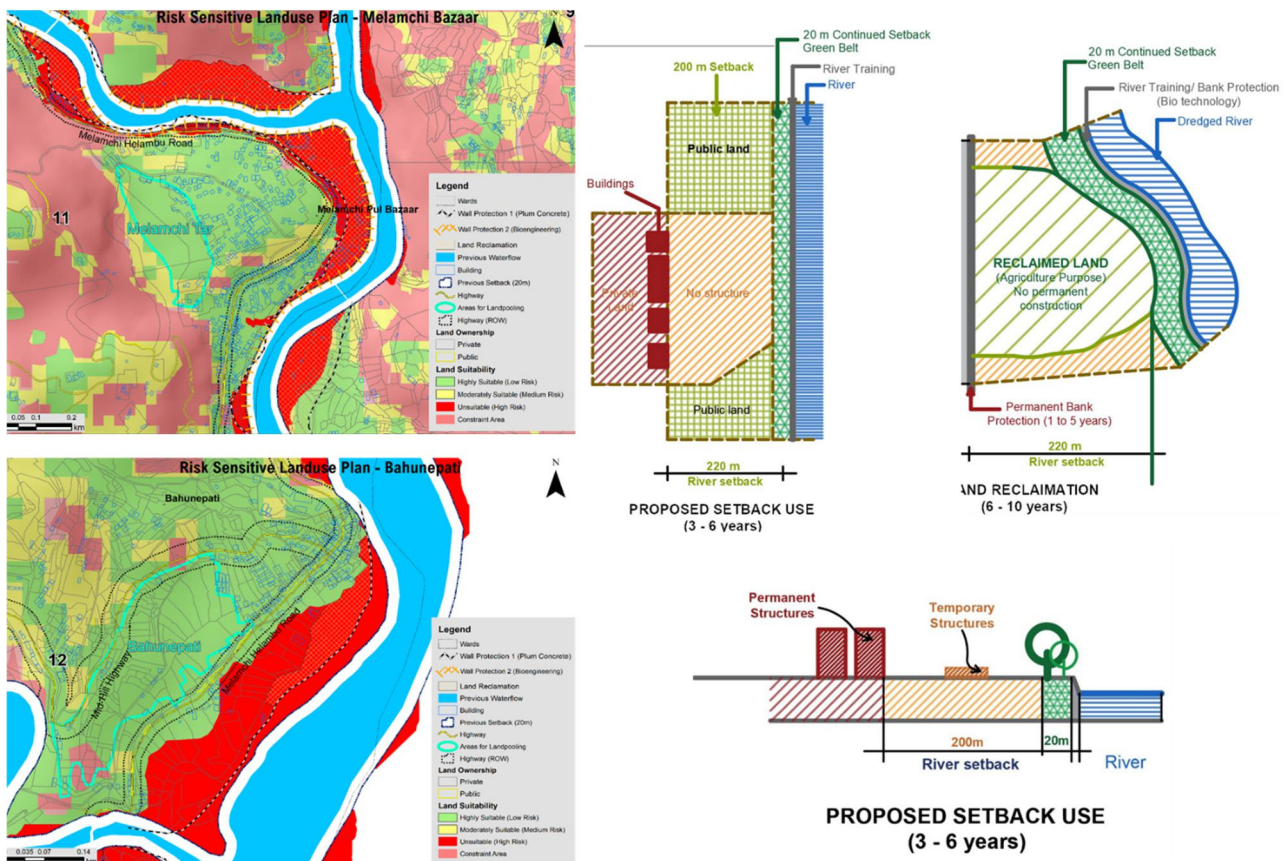


Figure 6, Risk-Sensitive Land Use Planning and Setback Implementation following the Melamchi Flood Event in the Melamchi River Valley, Nepal

6 Conclusion

The Himalayas represent not only a remarkable geological formation but also one of the most hazardous regions on Earth. As this study has shown, the combination of active tectonics, intense monsoon systems, steep topography, and increasing human intervention for development activities has created a complex risk environment, one where infrastructure and communities are persistently vulnerable to geohazards. From recurrent landslides and catastrophic floods to seismic

events and glacial lake outburst floods, the impacts on roads, hydropower, settlements, and lifeline systems are widespread and intensifying.

The Melamchi disaster and the instability at Pakyong Airport of Sikkim, India exemplify the exclusive consequences of overlooking engineering geological assessments and the pervasive threat of Deep-Seated Gravitational Slope Deformations. Meanwhile, repeated earthquake and landslide events underscore the urgent need for science-based approaches to development planning and disaster mitigation.

In fact, a paradigm shift is needed, from reactive disaster response to proactive, risk-informed infrastructure development. This includes thorough engineering geological site investigations, detailed hazard mapping, monitoring systems, resilient design practices, and the integration of engineering geology into every phase of infrastructure planning and policy. With climate change adding further uncertainty, there is little room for complacency. The safety, sustainability, and resilience of Himalayan infrastructure and the wellbeing of millions who depend on it hinge on scientific ability to understand, anticipate, and adapt to the evolving geohazard landscape of the Himalaya.

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