CDRI
Coalition for Disaster Resilient Infrastructure

Shaping Resilience in Mountains

The Case for Disaster Resilient Infrastructure

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Foreword

This publication, *Shaping Resilience in Mountains: The Case for DRI*, is timely and necessary. It consolidates evidence from across mountain geographies, captures grounded practices and innovations, and offers actionable recommendations. Climate risks are intensifying, and the need for infrastructure systems that can withstand, adapt, and recover quickly is critical.

This is a call to action. Governments, multilateral development banks, policymakers, and practitioners must take these lessons forward: turning knowledge into policies, and policies into investments. Building resilient infrastructure in mountain regions is not just about protecting mountain communities; it is about safeguarding shared security, prosperity, and nature itself.

Mountains are home to over 1.2 billion people, host a quarter of terrestrial biodiversity, and act as the world's water towers, supplying freshwater to half of humanity. Yet these regions are also among the most fragile. Their rugged terrain, remoteness, and environmental fragility make mountain communities highly vulnerable. Climate change is accelerating glacial lake outburst floods, landslides, and extreme precipitation events. Infrastructure and services here are often sparse, lack redundancy, and when disrupted, can cascade into crises. For mountain communities impacted severely by climate-induced extreme events and disasters, reliable and inclusive infrastructure is a matter of survival. A bridge or road often serves as the only connection to markets, schools, and health facilities. When lifelines fail, the impacts ripple far beyond the mountains, disrupting lives, livelihoods, and economies downstream.

This publication showcases that resilience is possible and already being built. From Indigenous and ecosystem-based solutions to advanced early warning systems, local ingenuity, traditional knowledge, and technological innovation can converge to deliver resilience. By bringing these examples together, it strengthens the case for scaling such solutions, influencing investment decisions, and embedding resilience in policy and planning frameworks, and overall infrastructure lifecycles.

I acknowledge the lead authors from Global Mountain Safeguard Research (GLOMOS), the contributors who provided rich case studies, and all reviewers whose insights have sharpened the analysis presented in this publication. Their collective effort has produced a resource that not only informs but presents a way forward.

Amit Prothi
Director General, CDRI

Foreword

Mountains play a vital role in maintaining the planet's ecological balance and supporting the well-being of communities worldwide. They sustain diverse ecosystems, safeguard rich biodiversity, and uphold vibrant cultures shaped by centuries of Indigenous and local knowledge. Mountains are also places of remarkable resilience and innovation, yet their remoteness, fragile environments, and challenging terrain present unique pressures. For the people who inhabit these areas, resilient infrastructure forms the backbone of safe and thriving communities. Reliable access to roads, bridges, energy, and communication networks sustains livelihoods, connects communities, and supports well-being. However, this critical infrastructure—essential for linking people to basic services and ensuring safety—is also among the most exposed to natural hazards and the impacts of climate change. Damage, loss, or disruption of infrastructure can rapidly lead to isolation, triggering a chain of impacts on livelihoods, safety, and resilience.

Recognizing these challenges, it is my pleasure to provide this opening foreword for a publication that underscores the critical importance of resilient infrastructure in mountain regions. This report on *Shaping Resilience in Mountains: The Case for DRI* led by the Coalition for Disaster Resilient Infrastructure (CDRI) in collaboration with the Global Mountain Safeguard Research (GLOMOS) programme (a partnership between the United Nations University – Institute for Environment and Human Security [UNU-EHS] and Eurac Research) as the knowledge partner—brings together evidence, experience, and key lessons to inform recommendations and actions for stakeholders across sectors on the design, implementation, and monitoring of infrastructure that reflects mountain-specific challenges and opportunities.

Climate change is magnifying impacts in mountain regions, making these landscapes increasingly vulnerable. The latest IPCC Assessment Report (Adler et al., 2022) highlights that rising temperatures, shifting seasonal weather patterns, glacial retreat, and thawing high-altitude permafrost are adding unprecedented uncertainty to planning and development. Addressing this reality requires approaches that are not only adaptive and inclusive but also grounded in both rigorous scientific research and the rich insights of Indigenous and local knowledge systems.

UNU advances the safeguarding of mountains and their sustainable development through GLOMOS, which acts as a bridge between the global mountain research community and the United Nations frameworks and conventions. GLOMOS works to raise awareness of and inform actions on mountain issues in frameworks such as the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), the United Nations Sustainable Development Goals (SDGs, UNGA, 2015), and the Paris Agreement

(UNFCCC, 2016). Through applied and transdisciplinary research, GLOMOS aims to strengthen the resilience of mountain communities, protect their rich biological and cultural heritage, and support sustainable transformation.

This publication presents practical examples, key recommendations, and replicable solutions, demonstrating that resilient infrastructure in mountain regions is not only possible but essential to safeguarding the future of these environments and the communities who call them home.

I extend my sincere appreciation to all who contributed their knowledge and experience to this work. May the insights gathered here inspire collaboration, innovation, and concrete action to ensure that mountain infrastructure can withstand the challenges ahead and continue to serve as a lifeline for generations to come.

Prof. Xiaomeng Shen
UNU Vice-Rector in Europe & Director of UNU-EHS

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Abbreviations

CDRI	Coalition for Disaster Resilient Infrastructure
COP	Conference of the Parties (to the UNFCCC)
CoW	Cell on Wheels
DRI	Disaster Resilient Infrastructure
DRR	Disaster Risk Reduction
EbA	Ecosystem-based Adaptation
EW4All	Early Warnings for All (UN initiative)
GDP	Gross Domestic Product
GLOF	Glacial Lake Outburst Flood
GLOMOS	Global Mountain Safeguard Research programme
HPC	High-performance concrete
ICIMOD	International Centre for Integrated Mountain Development
ILK	Indigenous and Local Knowledge
MH	Multi-Hazard
NAP	National Adaptation Plans
NbS	Nature-based Solutions
NDC	Nationally Determined Contributions
NGO	Non-Governmental Organization
O&M	Operation and Maintenance
SOP	Standard Operating Procedure
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNU-EHS	United Nations University – Institute for Environment and Human Security

Image by Timo Volz, Unsplash

1. Introduction

Mountains are vital to our planet's ecological balance and the socioeconomic and cultural well-being of millions of people worldwide.

Covering 27 percent of the Earth's land surface, they are home to approximately 1.2 billion people, representing 15 percent of the global population and sustaining about 25 percent of terrestrial biodiversity (Parisi et al., 2025). These regions are also repositories of rich cultural heritage and linguistic diversity, with Indigenous and local knowledge systems shaped over generations by mountain landscapes and traditional livelihoods.

Climate-related hazards such as floods, debris flows, landslides, and avalanches have increased the incidence of disasters, affecting growing numbers of people and disrupting economies both locally and further downstream. Despite their global significance, mountain regions face complex challenges stemming from rugged terrain, remoteness, extreme climatic conditions, hazard exposure, and fragile ecosystems. Climate change is intensifying these challenges, posing serious risks to lives, livelihoods, and infrastructure.

When infrastructure fails in mountain systems, the consequences cascade far beyond the highlands, impacting water supplies, health services, food security, and transport downstream. While this report focuses on mountains, global data reveal the broader pressing need for infrastructure resilience: between 2015 and 2023, over 92,000 critical infrastructure units were damaged or destroyed annually, while more than 1.6 million basic services—including schools and health facilities—were disrupted each year (UNDRR, 2025).

Recognizing this critical issue, the Coalition for Disaster Resilient Infrastructure (CDRI), in collaboration with the Global Mountain Safeguard Research (GLOMOS) programme (a partnership between the United Nations University – Institute for Environment and Human Security [UNU-EHS] and Eurac Research) developed this report to consolidate the needs and opportunities for Disaster Resilient Infrastructure (DRI) in mountain regions. This publication showcases practical examples, key lessons, and recommendations that underscore the critical importance of infrastructure resilience in mountainous environments and aims to catalyze action at global, regional, and national levels to embed resilience within the broader sustainable mountain development and climate adaptation agendas.


Image by Jorgen Hendriksen, Unsplash

2. Disaster Risks in Mountain Areas

Mountains are recognized for their rich cultural heritage, exceptional biodiversity, and vital role as water sources for billions. However, the same geological and climatic forces that create these spectacular landscapes also generate significant natural hazards, including landslides, avalanches, and flash floods. Geographic isolation, characteristic of mountain regions, creates distinct challenges for local communities. Distance from urban centres and essential services often limits economic opportunities, forcing many residents to depend primarily on agriculture, livestock, and forest resources for their livelihoods (Bhatta et al., 2019). This economic constraint drives ongoing out-migration as people seek employment opportunities in urban and coastal areas (Chen et al., 2021). Beyond economic pressures, disasters triggered by avalanches, floods, landslides, and mudflows often result in population displacements in mountain regions. Between 2008 and 2021, earthquakes, landslides, and floods led to 15,100 displacements in Kyrgyzstan and 41,000 in Tajikistan[1]. Geographic constraints also influence settlement patterns in mountain regions. Limited space forces communities to build in hazard-exposed areas, increasing vulnerability of both people and infrastructure when safer locations may simply not be available or economically feasible (Papathoma-Köhle, Schlögl & Fuchs, 2019; Shu et al., 2024). Climate change adds an additional layer of complexity to mountain risk management. Rising temperatures and changing precipitation patterns are increasing both the frequency and intensity of extreme weather events, compounding existing challenges and creating new risks that mountain communities must navigate, often with limited resources and institutional support (Zoï Environment Network, 2018; IPCC, 2022).

Mountain infrastructure faces vulnerabilities that amplify natural hazard impacts. Transportation networks are often limited and fragile, with single roads or bridges serving as lifelines for entire communities (Singh & Pandey, 2023). In many cases, this scarcity of infrastructure exacerbates negative consequences, disrupting essential services, and isolating communities. The failure of a single component in interconnected communication networks can trigger cascading and compounding effects throughout entire systems, causing prolonged isolation. Limited accessibility, constrained financial resources, and inadequate disaster preparedness combine to impede mountain communities' ability to implement effective risk management measures (Flanagan et al., 2011).

Together, these interconnected challenges underscore the importance of integrated approaches that strengthen resilience to the climatic, physical, and socioeconomic dimensions of risk in mountain areas.

1 FAO and IOM, *Policy Brief on Human Mobility in Mountain Areas in a Changing Climate*. https://openknowledge.fao.org/server/api/core/bitstreams/b4d99d0d-c138-48fe-a159-06b8bf4730a7/content

2.1. Key Hazards in Mountain Areas

Hazards significantly impact mountainous infrastructure due to complex terrain, climate-sensitive ecosystems, and exposure to various natural, climate-induced and human-induced risks. These hazards often unfold through cascading or compound processes, where one event triggers or amplifies another.

Geophysical hazards: Mountain slopes are inherently unstable. Landslides and debris flows occur when intense rainfall, snowmelt, or seismic activity trigger the sudden movement of rock, soil, and debris down steep terrain, rapidly causing significant damage to roads, bridges, telecommunication towers, optical fibre cables, and settlements. Their unpredictable nature challenges preparation and response efforts. Avalanches can block critical transportation routes for extended periods, isolating remote communities from essential services and emergency assistance—particularly problematic during winter months, when alternative access routes are often unavailable, leaving communities vulnerable to medical emergencies and supply shortages.

The 2015 Nepal earthquake demonstrates how seismic activity can trigger widespread secondary hazards (Kargel et al., 2016). The earthquake not only caused direct structural damage, it initiated thousands of landslides, severely damaging water supply systems, communication networks, and transportation infrastructure, leaving many communities without basic services for extended periods. The interconnected nature of these failures illustrates how a single geological event can have far-reaching consequences for mountain infrastructure. Volcanic mountain regions face additional challenges from lahars—fast-moving flows of volcanic debris mixed with water that can travel considerable distances, affecting valleys and communities far from the volcanic activity itself.

Hydrometeorological hazards: Mountain topography can transform ordinary rainfall into dangerous flash floods within minutes, leaving little time for warnings or evacuations. Intense precipitation, rapid snowmelt, and seasonal storms can trigger floods and debris flows, overwhelming drainage systems, washing out roads and bridges, and disrupting settlements. Cloudbursts—sudden, highly localized rainfall events—pose an additional risk, often triggering flash floods downstream. Major flood disasters in Asia and the United States of America have caused heavy casualties and economic losses in July and August 2025. China, India, Nepal, Pakistan, the Republic of Korea were among the countries affected in Asia, with hundreds of lives lost, whilst flash flooding in the US states of Texas and New Mexico resulted in more than 100 casualties[2].

Cryospheric hazards: As global temperatures rise and glaciers retreat, meltwater collects behind unstable natural dams formed by glacial debris. When these moraine dams fail, they release Glacial Lake Outburst Floods (GLOFs)—sudden, high-volume water releases that can cause extensive

2 WMO. *Devastating floods highlight need and challenges for warnings.* https://wmo.int/media/news/devastating-floods-highlight-need-and-challenges-warnings

downstream damage. These events threaten transportation networks, hydropower facilities, and residential communities in valleys below glacial lakes (Harrison et al., 2018). The 2021 Chamoli disaster in India illustrated the destructive potential of high-altitude hazards, demonstrating how cryospheric processes can trigger cascading risks across entire watersheds, including the destruction of two hydropower plants and the loss of over 200 lives (Shugar et al., 2021). The October 2023 Sikkim flood caused widespread devastation, inundating, damaging, or destroying over 25,900 buildings, destroying 31 major bridges, and affecting approximately 270 km^2 of agricultural land (Sattar et al., 2025).

Anthropogenic hazards: Human activities have significantly altered natural hazard dynamics in mountain regions. Urbanization and infrastructure construction in previously undeveloped areas have modified natural drainage systems and slope stability, often increasing landslide and flooding likelihood (Li et al., 2022). Tourism development exemplifies how human activities can inadvertently increase hazard exposure: the expansion of tourism facilities in mountain regions such as the Andes has substantially altered natural water drainage patterns, intensifying rainfall impacts, and creating new flood risks (Barros et al., 2015). Deforestation and slope modifications destabilize mountain terrain, increasing landslide frequency and severity of other geological hazards. Global mountain green cover declined from 83 percent in 2000 to 82.2 percent in 2021, with roughly 3.5 percent of mountain areas experiencing detrimental land cover changes. The annual rate of mountain degradation increased between 2015 and 2021 compared to the 2000–2015 baseline, largely driven by land cover changes in Eastern Asia and sub-Saharan Africa[3]. These human-induced changes often compound natural hazard processes, creating more complex and unpredictable risk scenarios for mountain communities.

> *Climate change is an important driver in mountain regions and can push infrastructure to—or even beyond—its limits, resulting in greater damages or impacts. Changes may also stem from social or economic development. For instance, a mountain site that becomes a tourism hotspot may experience visitor numbers far exceeding the infrastructure's design capacity. Such social and environmental changes pose significant challenges to mountain regions and their infrastructure, especially since mountainous topography often limits spatial development.*
>
> *- Prof. Dr. Christian Huggel, Professor, Environment and Climate, University of Zurich*

3 Food and Agriculture Organization of the United Nations (FAO). *SDG Indicator 15.4.2: Mountain Green Cover and Proportion of Degraded Mountain Area.* https://www.fao.org/sustainable-development-goals-data-portal/data/indicators/1542-mountain-green-cover-and-proportion-of-degraded-mountain-area/en

2.2. Unique Vulnerabilities of Mountain Infrastructure

Topographic and geophysical constraints, environmental fragility, and remoteness make critical infrastructure[4] and essential services highly susceptible to disruption and damage, posing significant challenges to infrastructure construction, maintenance, and emergency response operations.

Infrastructure isolation and connectivity challenges: Mountainous areas typically have much lower road and railway network density compared to lowland areas, reflecting challenging terrain and construction costs. This limited connectivity means that individual roads, bridges, and power lines often serve as the sole connection points for entire communities. Accessibility is further reduced during winter months, when heavy snowfall and icy conditions frequently block mountain passes and roads, delaying maintenance and the transportation of goods and people (Davies, 2015; Hao et al., 2023). Roads and bridges built on steep, unstable slopes face constant exposure to landslides, floods, and avalanches (UNDRR, 2019). When critical connections are damaged or destroyed, mountain communities can be isolated for extended periods, creating both immediate safety concerns and longer-term economic hardships.

Communities often rely on air transport for the timely delivery of critical medicines and perishables (Aggarwal et al., 2024). However, weather conditions can also disrupt air services, creating additional supply chain vulnerabilities. Challenging terrain and unpredictable weather patterns complicate both initial construction and ongoing maintenance, often limiting accessibility precisely when emergency response is most needed (Shahzad et al., 2024).

> *The current state of multi-hazards in the Hindu Kush Himalaya (HKH) means that disasters are occurring with increasing frequency and intensity and continue to pose significant challenges to vulnerable communities. What is evident from recent events, including the multiple glacial and flood related disasters, is that more attention needs to be given when determining future investment in our infrastructure. Many of these, including the construction of important road networks and power plants, are also linked to the well-being of millions that live downstream of the Himalayas. Thus, there is a need for a paradigm shift in our approach to infrastructure development by incorporating climate models and other risk assessments from site selection to planning and execution. Furthermore, given the transboundary nature of hazards in this region, all countries across the HKH would benefit greatly from having infrastructure that are not just safe and resilient locally but also helps reduce cross-border hazards.*

- Pema Gyamtsho, Director General, ICIMOD

4 Critical Infrastructure - The physical structures, facilities, networks, and other assets, which provide services that are indispensable to the social and economic functioning of society, and which are necessary for managing disaster risk. *DRI Lexicon.* https://lexicon.cdri.world/topic/4

Cascading infrastructure failures: In mountain environments, a single hazard event triggers secondary failures that can transform localized incidents into regional crises. The interconnected nature of mountain infrastructure systems, combined with their limited redundancy, creates conditions where failures rapidly spread across multiple sectors (Purwar et al., 2024).

A landslide illustrates these cascading effects. Beyond blocking a mountain road, the event might damage fibre-optic cables running alongside the transportation corridor, creating communication blackouts when emergency coordination is most critical (Ravet et al., 2024). Power lines may also be affected, disrupting electricity to communities and emergency response facilities. In the case of rural mountain population, only 29 percent have reliable access to water and sanitation, technology and communication, and electricity. The majority—around 442 million people—reside in areas with limited services, and about 17 million individuals (nearly 3 percent) have little to no access to basic town facilities and essential services (Romeo et al., 2020). Given these pre-existing service gaps, infrastructure failures can quickly escalate from manageable local incidents to complex humanitarian emergencies (Kadri et al., 2014).

Vulnerability to cascading risks underscores the importance of comprehensive planning that considers interdependencies between different infrastructure systems. Effective risk management requires understanding not just individual hazards, but how failures in one system trigger problems across entire infrastructure networks. This complexity highlights the need for strategic investments in infrastructure resilience that can better protect mountain communities from compounding effects of cascading disasters.

> *The key opportunity for DRI in mountain regions lies in adopting a systems thinking approach that recognizes human and ecological interdependence. By designing infrastructure that works with, rather than against, the natural environment, mountain communities can enhance not only safety and continuity of services but also ecosystem health, cultural resilience, and long-term sustainability.*
>
> *- Julia Watson, Co-director of the Lo–TEK Institute*

2.3. Climate Change and Extreme Events: A Risk Multiplier

Mountains are experiencing temperature increases that exceed global warming rates—a phenomenon called elevation-dependent warming. This accelerated warming is making mountains climate hotspots, resulting in an increase of extreme precipitation events that intensify existing hazards such as floods and landslides (MRI, 2015). Glacial retreat and high-altitude permafrost thawing accelerate under climate change pressures (IPCC, 2022). As glaciers melt, they leave behind unstable lakes contained by natural debris dams, significantly increasing GLOF risk. Simultaneously, thawing permafrost weakens rock slopes, leading to more frequent and larger rockfall events (Haeberli et al., 2017).

Mountains are known as "water towers" because their vegetation stabilizes headwaters, regulates floods, and sustains year-round water flows for downstream populations (Xu et al., 2019). They face a critical transition point called "Peak Water"—when glacier meltwater runoff begins to decline steadily and eventually ceases. Research indicates many glacier-fed rivers, particularly in major mountain ranges including the Alps, Andes, and Himalayas are expected to reach this tipping point by 2050 (Huss & Hock, 2018). This transition presents serious challenges for hydropower production and threatens energy security for communities and nations that depend on glacier-fed rivers for electricity generation.

The rapid pace of environmental change means that historical hazard patterns are becoming unreliable guides for future planning. Areas previously considered safe may now face new risks, while traditional hazard zones may experience different types or intensities of threats. Understanding these climate-driven changes is essential for developing adaptive strategies that can address the growing complexity of disaster risk in mountain regions (Xu et al., 2020).

2.4. Socioeconomic Challenges: The Human Dimension of Mountain Risk

Physical hazards threatening mountains intersect with complex social and economic conditions that often determine whether natural events become disasters. These socioeconomic factors can either increase resilience or amplify vulnerability, making them critical considerations in mountain risk management.

> *In the Andes, most local authorities prioritize visible road works over risk management measures. Few municipalities and regional governments incorporate climate and risk information into their investment plans, and preparedness is often limited to occasional drills.*
>
> *- Karen Price, Head of the Technical Secretariat of the Andean Mountain Initiative, CONDESAN*

Many mountain communities face economic vulnerability, with residents depending on livelihoods particularly vulnerable to natural hazards and climate variability. Small-scale agriculture, livestock herding, and tourism form the economic backbone of many mountain areas—activities that can be severely disrupted or entirely halted by disasters triggered by natural and climate-related processes (Romeo et al., 2020). The seasonal nature of many economic activities, combined with limited economic diversification options, creates situations where a single disaster event can undermine entire community economies.

Political and economic marginalization often limit mountain communities' ability to advocate for necessary resources and infrastructure investments. While these communities possess valuable knowledge about local environmental conditions and risk management practices, institutions typically lack adequate funding and technical resources to implement comprehensive disaster risk reduction measures (Adler et al., 2022).

This institutional weakness is compounded by development pressures and land-use constraints in mountain environments, often resulting in settlements and infrastructure being built in high-risk areas. The rural mountain population is slowly decreasing, from 40 percent in 2000 to 33 percent in 2030. Cities, though representing the smallest share of the mountain population, are growing fastest: from 26 percent (230 million) in 2000 to 30 percent in 2025, and projected to reach 31 percent (387 million) in 2030, reflecting the ongoing trend towards urbanization in mountain regions (Parisi et al., 2025).

Image by Vincent Yuan @USA, Unsplash

3. Disaster Resilient Infrastructure in the Context of Mountains

CDRI defines disaster resilient infrastructure as "infrastructure systems and networks, the components, and assets thereof, and the services they provide, that are able to resist and absorb disaster impacts, maintain adequate levels of service continuity during crises, and swiftly recover in such a manner that future risks are reduced or prevented" (CDRI, 2023). This definition brings together two essential and complementary perspectives, often summarized as "resilience of infrastructure and infrastructure for resilience."

More specifically, the first dimension refers to the resilience of infrastructure itself—its ability to resist, absorb, and recover from hazard events and shocks, reflecting the traditional engineering focus on robustness and functionality. The second dimension highlights that broader social and economic resilience to climate change depends on infrastructure's ability to adapt to and absorb climate impacts (OECD, 2024). Together, these dimensions underscore the dual role of resilience: infrastructure must be able to withstand specific hazards, while at the same time ensuring continuity of essential services that underpin broader social and economic systems.

The need for resilient infrastructure is clear when we look at global trends. Between 2015 and 2023, more than 92,000 units of critical infrastructure were damaged or destroyed annually worldwide, disrupting not only physical assets but the daily lives of entire communities (UNDRR, 2025). This figure reveals the serious human and developmental consequences when infrastructure fails during disasters. Importantly, it is not hazards alone that cause disasters, but the exposure of people and infrastructure that turn hazard events into crises. This is especially true in mountain regions, where infrastructure systems face unique challenges and their failure can have particularly severe impacts (Muñoz-Torrero Manchado et al., 2021).

There are many documented cases of single events that demonstrate how hazard processes unfold and what damage they cause. For instance, the 2023 monsoon season in Himachal Pradesh, India, triggered landslides and floods that killed over 500 people and caused approximately INR 12,000 crores ($1.45 billion) in damages, affecting hydropower projects, roads, and buildings (Kumar et al., 2024). Similarly, the October 2023 GLOF in Sikkim (India) destroyed the Chungthang Dam and major transport links, affecting many residents (Nath & Choudhury, 2024). While such individual events might be well documented, comprehensive and systematic data for mountain regions remain limited. Data gaps stem from various challenges, including the difficulty of systematically documenting disaster impacts in remote mountainous terrain and the practical constraints of gathering information during emergencies, when conditions are unstable and evolving (UNDRR, 2023). These data limitations obscure the true scale of loss and damage, restricting the ability to design and implement sound, evidence-based policies and adaptive measures[5]. Strengthening collaborative observation

5 United Nations Office for Disaster Risk Reduction (2025). Policy brief: loss and damage. https://www.undrr.org/publication/policy-brief-loss-and-damage#editors-recommendations

and monitoring systems has been increasingly recognized as a way to bridge these data gaps, improve knowledge exchange, and enable more coordinated adaptation efforts in mountain regions (Adler et al., 2022).

Climate change—particularly warming that increases with elevation—has become a powerful risk multiplier. Systems designed based on historical climate patterns are now under unprecedented stress as hazard zones shift and extreme events become more frequent and severe. Remoteness, harsh environmental conditions, and fragile infrastructure of many mountainous areas make regular maintenance significantly difficult and economically challenging, which can contribute to higher mortality rates (UNDRR, 2025).

Despite considerable challenges, mountain regions offer unique opportunities for innovative infrastructure solutions that could serve as models for resilient development worldwide.

> *Nature-based solutions are a good example, e.g., dykes complemented with the restoration of wetlands or high-Andean peatlands (bofedales) that buffer floods, regulate water flows, and reduce sediment loads. These systems are considered "infrastructure" because they provide functional services of protection, regulation, and provision; and they are "resilient" because, when restored and managed, they reduce exposure and vulnerability to hazards.*
>
> *- Karen Price, Head of the Technical Secretariat of the Andean Mountain Initiative, CONDESAN*

3.1. Technological and Engineering Innovations

Innovative technologies and engineering solutions are critical to enhancing the resilience of infrastructure in mountain regions. Respective technologies can strengthen the autonomy and resilience of mountain systems by reducing their reliance on large scale, centralized infrastructure systems. Examples of key innovative engineering solutions with particular significance for mountain regions include:

- Centralized infrastructure systems that ensure continued access to essential services—such as energy and clean water—during and after disasters. Micro-hydropower systems, solar mini-grids, and off-grid water purification units, which provide decentralized, reliable, and climate-resilient infrastructure alternatives (Katsoulakos & Kaliampakos, 2016; IRENA, 2023; ESCAP, 2021). A practical demonstration of this approach can be seen in Nepal's 2015 earthquake response, when modular, solar-powered emergency shelters were deployed to remote mountainous areas. Their compact, transportable design enabled delivery by helicopters to inaccessible regions, providing immediate shelter for medical teams and displaced villagers[6].

- Targeted interventions to improve slope stability and resilience, such as geosynthetics like geogrids and geotextiles, help reinforce soil structure and reduce surface degradation. Slope protection and stabilization techniques, such as soil nailing and rock bolting, provide mechanical anchoring to unstable terrain. Bioengineering approaches that combine vegetation with structural elements, further enhance slope resilience by utilizing natural materials and physical reinforcement. For instance, in the embankments along the Ranganadi river in the Indian region of Assam, geotubular mattresses were installed to stabilize slope and reduce erosion, delivering effective protection (Indian Geosynthetics Society, 2022).

> *In Noto, Japan, people have built terraced paddy fields on gentle slopes formed after repeated landslides and have utilized the valuable geological features that have risen due to historical tectonic movements as materials for crafts. These resources are also used for environmental education in the region.*
>
> *- Dr Yuta Hara, Assistant Professor, International Research Institute of Disaster Science (IRIDeS), Tohoku University*

- Resilient techniques to mitigate the risk of cascading hazards, such as elevated or cantilevered roads, can reduce direct exposure to flooding and landslides. In mountainous terrain, landslides alone contribute to an estimated average annual economic loss of $26 billion globally (UNDRR, 2025).

- Advanced materials capable of withstanding extreme weather conditions, such as high-performance concrete (HPC), fibre-reinforced composites, and corrosion-resistant steel, are used to ensure infrastructure can resist conditions such as extreme temperatures and freeze-thaw cycles (Liao et al., 2024; Xie et al., 2025; Grandón-Soliz, Sandoli, & Fabbrocino, 2025). In the Swiss Alps, the construction of the Gotthard Base Tunnel employed HPC to meet the structural demands posed by high rock pressure, aggressive groundwater, and severe thermal variation[7].

- Early warning and monitoring systems using remote-sensing data, the Internet of Things (IoT), radars, and artificial intelligence provide real-time information

6 EU Solar. Resilience and Emergency Preparedness. *Solar-powered emergency shelters: Life-saving power when disaster strikes.*

7 Sika. *Moving mountains – The tunnel that conquered the Alps.* https://www.sika.com/en/media/insights/sikanews/moving-mountains--the-tunnel-that-conquered-the-alps.html

on infrastructure conditions and system performance (Kyriou et al., 2023). By addressing remoteness and limited accessibility, these technologies enable early identification of potential failures, reducing the likelihood of catastrophic infrastructure collapse. Digital communication systems ensure continuity during crises, supporting emergency response and recovery efforts[8]. Solutions such as Cell on Wheels (CoWs) for temporary network deployment (Shakhatreh et al., 2021), as well as emerging concepts like Cell on Balloon, can provide critical backup when conventional networks are disrupted. The *Inform@Risk* project in Medellin, Colombia, is an example where IoT-enabled landslide monitoring systems have been installed in informal settlements on steep, hazard-prone slopes (Gamperl, Singer & Thuro, 2021).

3.2. Indigenous Approaches and Ecosystem-Based Adaptation

Indigenous approaches and ecosystem-based adaptation (EbA) are increasingly recognized as vital strategies for enhancing disaster resilient infrastructure. Both rely on a place-based understanding of the local socio-environmental challenges, developed and refined through continuous observation, adaptation, and practice across generations. Indigenous and local knowledge (ILK) encompasses sustainable land management techniques, such as terracing, agroforestry, and traditional water conservation methods, that effectively mitigate hazardous processes in mountains, including landslides, floods, and soil erosion (Jiao, Yang & Li, 2024; Frogley et al., 2025). A compelling example comes from the Andean ancestral terraces in Peru, where Indigenous communities have engineered intricate stone terraces that stabilize steep slopes, reduce erosion, and improve water management[9]. Bioengineering measures, which can incorporate ILK principles, are used to enhance slope stability and mitigate landslide risks. These include the use of native plant species, such as bamboo, shrubs, and trees, that bind the soil and prevent erosion. Techniques like brush layering, fiberschine, and bamboo fencing are utilized to reinforce slopes and reduce the impact of heavy rainfall and landslides (ICIMOD, 2012). Combining Indigenous and local knowledge with engineering techniques requires ethical and respectful engagement. This can be supported by providing dedicated training for technical teams working with Indigenous partners, involving Indigenous scholars in research ethics committees reviewing such projects, and encouraging reporting on the methods used to ensure respectful and reciprocal engagement (Dimayuga et al., 2023).

8 TechRadar Pro. *Keeping emergency services connected when it matters most through link bonding.* https://www.techradar.com/pro/keeping-emergency-services-connected-when-it-matters-most-through-link-bonding

9 For Tomorrow. *Andean ancestral terraces in Peru.* https://fortomorrow.org/explore-solutions/andean-ancestral-terraces-in-peru

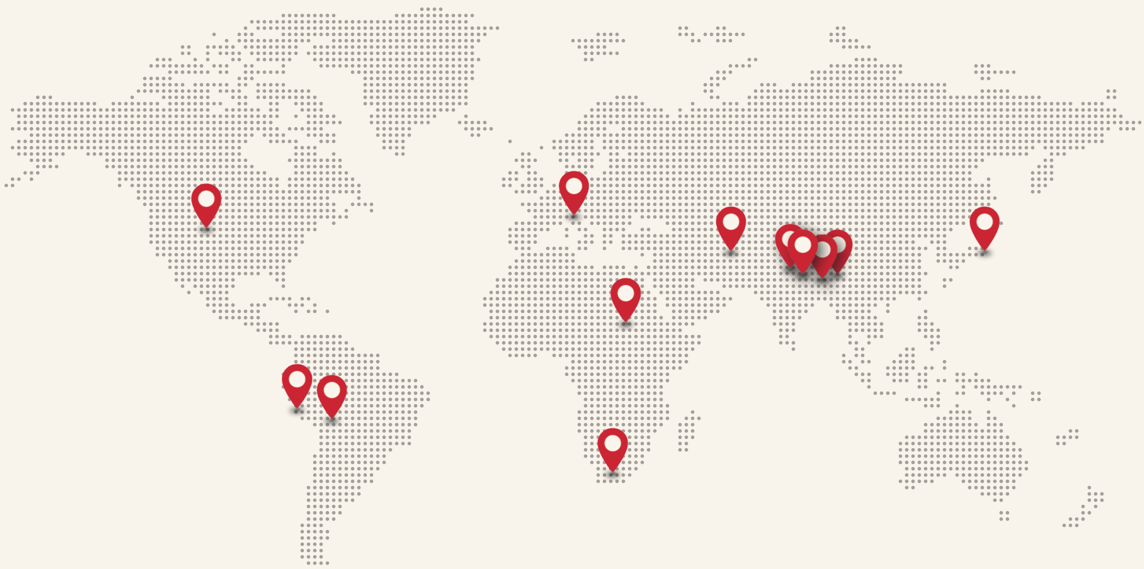
EbA represents a nature-centred alternative to engineered or technology-driven solutions. Delivering accessible and affordable options, EbA generates multiple co-benefits, including improved food security, livelihood enhancement, and the preservation of biodiversity (Monty et al., 2017; Marggraf, Chumacero de Schawe & Reichel, 2024). The project 'Scaling-up Mountain EbA: building evidence, replicating success, and informing policy' worked in Kenya with an Indigenous community to conduct community-based vulnerability assessments, spatial mapping, and feasibility analyses for the construction of infrastructure to safeguard a spring and ensure local water security[10].

> *DRI in mountain regions must be understood as more than the physical robustness of infrastructure—it is about designing with the flows of ecosystems, seasonal variability, and cultural landscapes in mind.*
>
> *- Julia Watson, Co-director of the Lo–TEK Institute*

10 International Union for Conservation of Nature (IUCN). *Scaling-up Mountain Ecosystem-based Adaptation: building evidence, replicating success, and informing policy.* https://iucn.org/sites/default/files/2022-11/oct_30_2022_introduction-information-brief.pdf

4. Lessons from the Mountains: Disaster Resilient Infrastructure in Practice

This section features 12 case studies that highlight the remarkable diversity of DRI across mountain regions worldwide. Organized by continent, these cases invite readers to explore the unique challenges and solutions emerging in different mountainous contexts. Read on to discover inspiring stories of resilience and innovation.



South Africa	Nepal
South Sudan	Italy
Afghanistan	Bolivia
India	Peru
Japan	USA

Categories used across case studies

Infrastructure sector(s) and service(s)
- Transport (roads, tunnels, bridges, ropeways, airports, helipad, etc.)
- Energy (power generation, hydropower, transmission, distribution)
- Water and wastewater management
- Telecommunications
- Health and social infrastructure (e.g., educational, public safety, community service, housing)

Scale of the case study
- Local (within a specific community/region)
- Regional (covers one or multiple regions within a country)
- National (implemented across the country)
- Transboundary (collaboration across borders between two or more countries)
- Global (international programme or initiative)

Specific communities/actors involved in design and implementation
- Local communities
- NGOs
- Academia
- Private sector
- Government/authorities

Key hazard(s)
- Landslides and rockfalls
- Slow-onset events (e.g., drought, glacial retreat and related impacts)
- Floods
- Earthquakes
- GLOFs
- Avalanches
- Soil erosion
- Wildfires
- Extreme weather (cloudburst, heavy snowfall, cold wave, extreme heat)
- Multi-hazard events

Focus area(s) that best describes the case study
- Integrated watershed approaches for infrastructure planning
- Early Warning System for critical infrastructure
- Risk-informed planning of resilient infrastructure
- Region specific policies, standards, and guidelines
- Climate and risk data
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)
- Other

Image by Kirsten Oliver

South Africa

Nature-Based Solutions Supporting Green and Grey Infrastructure for Improved Water Security in the Upper uThukela Catchment

Upper uThukela Water Fund

Upper uThukela region,
KwaZulu Natal Province, South Africa

Maloti-Drakensberg mountain range

Scale
Local, Transboundary

Implementation
Ongoing

Intended Beneficiaries

Local communities of AmaZizi and AmaNgwane, private landowners and downstream water users

Local Population

Indigenous

Key Livelihoods

Subsistence agriculture (rangelands (cattle, sheep and goats), tourism, commercial agriculture

Infrastructure sector(s) and services

- Water and wastewater management
- Health and social infrastructure (e.g., educational, public safety, community service, housing)

The uThukela River supplies water to both local and downstream communities through local water infrastructure of pipelines and dams, and also supports multiple inter-basin transfers to other parts of the country, including the Tugela-Vaal Transfer Scheme (T-VTS) to the Integrated Vaal River System (IVRS) and the Eskom Drakensburg Hydropower Pumped Storage Scheme, the uThukela-Mhlatuze Transfer Scheme and the Lower uThukela Bulk Water Supply Scheme

Prominent geographical features

High-altitude mountain grasslands leading up to the basalt escarpment with exposed rock-faced cliffs. The area boasts the Tugela Falls.

Key environmental features

High altitude grasslands interspersed with indigenous forest patches in river valleys. High altitude wetlands, pans and springs.

Typical climate conditions

High rainfall summers with violent thunderstorms, dry and cold winters, with occasional snow in the upper reaches.

Name of implementing actor(s)/organization(s)

WILDTRUST (Wildlands Conservation Trust)

Funding sources

Multiple donors and partners

Actors involved in design and implementation

Local communities, NGOs, Academia

Key hazard(s)

- Landslides and rockfalls
- Floods
- Soil erosion
- Wildfires
- Extreme weather (cloudburst, heavy snowfall, coldwave, extreme heat)

Focus area(s)

- Integrated watershed approaches for infrastructure planning
- Risk-informed planning of resilient infrastructure
- Region specific policies, standards, and guidelines
- Climate and risk data
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)
- Other: Nature-based Solutions for water security

***Case study contributed by:** Kirsten Oliver (Wildtrust)*

Key achievements, co-benefits, and lessons learned

Water security in South Africa is reliant on the implementation of NbS to maintain healthy catchments that effectively support built or grey infrastructure for water supply and storage. Traditionally water management has invested and prioritized grey infrastructure through hard engineering solutions that do not accommodate catchment management, with the result that ecological deterioration continues unchecked and ultimately leads to the costly compromise of both ecosystems and grey infrastructure. This project addresses the challenge of deteriorating grey and green infrastructure for water security through the implementation of three priority NbS, specifically:

1. Invasive Alien Plant (IAP) control,
2. Improved rangeland management and
3. The establishment of a community owned protected area, in the Upper uThukela catchment, upstream of Woodstock Dam and the Tugela-Vaal Transfer Scheme.

Over the past three years the project has simultaneously continued to implement the NbS on the ground, while also conducting a feasibility and Cost Benefit Analysis for upscaling to a Water Fund where NbS may provide a viable and cost-effective alternative. Overall, the study found a positive benefit cost ratio (BCR) of 2.3:1, and net present value (NPV) of R216 million, with additional co-benefits to livelihoods through job creation and improved local water and food security, and biodiversity through habitat protection and landscape rehabilitation.

Some of the main lessons learned from the project include:

1. The value of collaboration with stakeholders at various levels;
2. Long-term investment, both financial and human, is critical to building sound projects with greatest impact; and
3. NbS is a cost effective and biodiversity beneficial alternative to building resilient communities and reducing risk to built and green infrastructure in mountainous regions.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

The primary limitation to the project progress is the availability of funds for implementation, including the employment of field teams for alien clearing, the development of a suitable management plan and tools and infrastructure for monitoring and evaluation. To this end, the feasibility study has been summarized down into a business case document that may be used to present the outcomes of the study to prospective funders.

Previous projects on IAP removal in the area have resulted in distrust from the communities, who are unwilling to see all woody alien plants removed as they are used for domestic livelihood purposes. The WILDTRUST team work consistently alongside the community leadership to negotiate where and how much may be cleared – this positive collaboration is vital to the success of the project.

The establishment of a protected area (PA) that is owned by the community is a challenge unlike that experienced in the declaration of PAs in privately owned properties, understanding the process, nuances and complications around working with PA management in community owned areas is currently the subject of a parallel project being run by the WILDTRUST to develop an improved understanding and develop guidelines for best practice.

Scalability

The project was developed and continues to work alongside similar initiatives across South Africa and around the world – specifically with respect to Water Funds and Integrated Catchment Management using NbS. The result is that this is a highly replicable project, almost anywhere in the world, while taking into consideration local circumstances, resources and challenges. The methods for planning, implementation, reporting and monitoring provide a sound basis for replication. The project is also expandable into adjacent areas and communities and further afield both downstream and into other catchments.

There are already discussions to expand into adjacent catchments and communities that fall within the Strategic Water Source area.

Image by Kirsten Oliver

Image by Ole Stockholm

South Sudan

Integrated Water Resources Management with Resilient Pilot Interventions for Possible Replication Across South Sudan

Water for Eastern Equatoria (W4EE) project

Eastern Equatoria State, South Sudan

Imatong Mountain range

Scale
Local, Regional, National

Implementation
2013 - 2019

Intended Beneficiaries

Targeted communities, private sector, local and national authorities.

Local Population

906,176 inhabitants, 81 percent in rural areas and 19 percent in urban areas

Key Livelihoods

Agriculture, pastoralism, agroforestry/forestry

Infrastructure sector(s) and services

- Water and wastewater management
- Health and social infrastructure (e.g., educational, public safety, community service, housing)

Prominent geographical features

Elevation ranges from Mount Kinyeti (3,187 m) to Lafon's floodplains and wetlands (490 m)

Key environmental features

Torit in Eastern Equatoria features mountain rivers, forests, farmland, wetlands, and an annual flooding lowland, while Greater Kapoeta is semi-arid and arid with pastoral lands, dry rivers, and yearly flash floods.

Typical climate conditions

Rainy and dry seasons, but in recent years flooding, droughts, and unpredictable weather, including intense rainfall, have become more frequent.

Altitude of infrastructure assets addressed

Peak of Mount Kinyeti 3,187 m.a.s.l.

Name of implementing actor(s)/organization(s)

NIRAS International Consulting, communities, local and national authorities

Funding sources

Embassy of the Kingdom of the Netherlands (EKN) in South Sudan

Actors involved in design and implementation

Local communities, NGOs, Academia, Private sector, Government/authorities

Key hazard(s)

- Slow onset events (e.g., drought, glacial retreat and related impacts)
- Floods
- Soil erosion
- Wildfires
- Extreme weather (cloudburst, heavy snowfall, coldwave, extreme heat)

Focus area(s)

- Integrated watershed approaches for infrastructure planning
- Early Warning System for critical infrastructure
- Risk-informed planning of resilient infrastructure
- Region specific policies, standards, and guidelines
- Climate and risk data
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)
- Other: Private sector development, hands-on training

Case study contributed by: *Ole Stokholm Jepsen and Yunda Andrew Stephen (NIRAS Consulting)*

Key achievements, co-benefits, and lessons learned

The project focused on improving water resource management for communities, agriculture, livestock, and fisheries. Key achievements included:

- The provision of water supply for 332,000 people and 67,000 people received sanitation services which majorly concentrated on rehabilitation of existing infrastructures, improvement of high yielding boreholes to motorized solar system powered water schemes, with the establishment of Water Management Committees—50 percent of whom were women—taking ownership of operations and maintenance. Compost toilets suitable for rocky terrain were introduced, contributing to the eradication of cholera in several villages.

- Rainwater harvesting systems—including one haffirs, four charco and pan dams, three subsurface dams in sand rivers, and gravity-fed systems in the highlands—serve both as water solutions and climate change adaptation measures.

- The project also strengthened local services through Water and Farm Service Centers and trained pump mechanics and community members on management, operation and maintenance (O&M). Gender and equity were central to all interventions.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

South Sudan has endured prolonged conflict, severely hampered development and causing immense suffering for its people. During this time, most international support came in the form of emergency and humanitarian aid from NGOs, UN agencies, and other international actors. While lifesaving, this extended reliance on free handouts fostered dependency, making it difficult to promote sustainable development and undermining private sector growth. Community-led ownership and responsibility are key to lasting impact, but dependency-oriented approaches can restrict these opportunities.

In conflict settings, it is essential to continuously assess: What is the reality on the ground, and what is realistically achievable? Project terms and resources (T&R) must be flexible to adapt to changing conditions. In some areas, the team was unable to travel due to security risks. Rather than suspend operations, we engaged local professionals to lead interventions while maintaining coordination with the core project team. This model enabled continuity and local ownership, even in insecure areas.

Conflict erodes trust and leaves people feeling powerless. Quick-impact interventions that improve livelihoods can play a critical role in rebuilding trust—but they must be strategically linked to long-term development goals.

Realistic ambitions are crucial. Communities need to experience early success to build confidence, and technologies must be appropriate—easy to operate, maintain, and fully owned by the users.

Despite limited resources, the dedication and trust between all stakeholders allowed the project to succeed. The support from the NIRAS head office, the flexibility of the client (EKN), the commitment of local authorities and the National Ministry of Water Resources and Irrigation (MWRI), and—most importantly—the determination of the communities themselves ensured that change took root.

Scalability

Many components, implementation approaches, and interventions of the project are replicable and scalable, and replication began immediately after the project's launch. New initiatives in South Sudan have adopted some of the principles and approaches applied in other provinces.

It is crucial that scaling up is done correctly, remains affordable, and is led by the recipients. Donor support should increasingly establish development funds that facilitate matching grants, ensuring that recipients' own investments result in a stronger sense of ownership and long-term sustainability.

Unique features

To create trust between the implementing facilitators and recipients, it was crucial to implement some quick impact interventions that improved the livelihoods of certain groups and communities. This paved the way for the recipients' taking ownership and responsibility also for long-term development interventions, which were defined through participatory dialogue processes.

Instead of always opting for the development of new water supply facilities, this project showed the importance and effectiveness of rehabilitating non-functional facilities, creating thus a win-win situation for the communities and the donors (value for money).

Frequent consultation with key people at the local level, national authorities and the donor (EKN) was critical for sharing information and seeking guidance. Engagement at the state level strengthened the overall process and ensured implementation.

Related links:
https://www.niras.com/projects/clean-drinking-water-for-330-000-people-in-south-sudan/

Afghanistan

Scaling Up Hydro-Meteorological Hazard Mitigation in Afghanistan's Remote Mountains through Nature-based Solutions

Food-security and Agricultural Sustainability for Livelihood improvement (FASL)
Subcategory: Disaster Risk Reduction (DRR)

Parwan, Surkhparsa, Beghamak

Hindu Kush Himalaya

Scale
Local

Implementation
2022-2025

Intended Beneficiaries
Local community

Local Population
Rural

Key Livelihoods
Agriculture, livestock

Infrastructure sector(s) and services

- Water and wastewater management
- Health and social infrastructure (e.g., educational, public safety, community service, housing)

Prominent geographical features

High-altitude

Key environmental features

Mountainous terrain and waterways

Typical climate conditions

The climate in Surkhparsa is classified as warm, dry-summer continental, featuring hot summers and cold, snowy winters

Name of implementing actor(s)/organization(s)

Aga Khan Agency for Habitat (AKAH)

Funding sources

Swiss Agency for Development and Cooperation (SDC)

Actors involved in design and implementation

Local communities,
NGOs,
Government/authorities

Key hazard(s)

- Avalanches

Focus area(s)

- Risk-informed planning of resilient infrastructure
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)

Case study contributed by: *Amit Kumar and Noorudin Akbari (Aga Khan Development Network)*

Key achievements, co-benefits, and lessons learned

The Beghamak watershed mitigation project successfully transformed a disaster-prone landscape into a safer and more resilient environment. By addressing hazards like avalanches through watershed trench excavations and nature-based solutions, the project protected households and vital agricultural land. It will restore the natural ecosystem balance, improve water retention, reduce erosion, and safeguard social infrastructure, especially housing and livelihoods. Community participation was integral, with residents contributing local seeds and labour. This initiative strengthens disaster resilience of rural infrastructure and promotes sustainable, inclusive approaches to hazard mitigation in vulnerable mountainous regions of Afghanistan.

Beyond direct community members, the project benefits include improved ecosystem services, reduced risks to downstream settlements, and strengthened local governance capacity. It also supports regional disaster resilience efforts and enhances socio-economic stability by protecting essential rural infrastructure such as homes, irrigation systems, and agricultural lands.

Community-driven approaches significantly enhance project ownership, sustainability, and impact. Early integration of local and indigenes knowledge, such as choosing native plant species for reforestation, ensures ecological compatibility and long-term success. Collaboration between local authorities, technical teams, and residents fosters mutual trust and efficient implementation. Furthermore, combining engineering measures with nature-based solutions yields effective, cost-efficient, and environmentally friendly outcomes. Strong community engagement, as seen in Beghamak, demonstrates that resilience-building is most effective when solutions are locally adapted, socially inclusive, and technically sound.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

One key limitation of the Beghamak project was the shortage of financial and technical resources needed to scale interventions across all at-risk areas of Surkhparsa district, Parwan province. The rugged topography and remoteness of the site posed significant logistical challenges for equipment mobilization. While the emphasis on natural infrastructure strengthened local resilience, the absence of robust structural measures (e.g., reinforced retaining walls or protective barriers) left certain high-risk zones partially exposed to extreme events. Expanding coverage and adopting hybrid mitigation approaches—combining structural and non-structural measures with nature-based solutions—could further enhance resilience and substantially reduce overall disaster risk.

The project also faced several operational challenges, including difficult terrain and limited community technical capacity at the onset. Ensuring timely coordination among stakeholders in a resource-constrained and politically complex environment required continuous effort. Furthermore, balancing the need for environmental preservation with immediate disaster mitigation involved trade-offs that demanded careful planning. Despite these hurdles, the strong commitment of the community, coupled with AKAH's technical guidance, was instrumental in achieving the project's core objectives.

A key knowledge gap remains due to the scarcity of localized data on soil behaviour and long-term climatic trends in Beghamak, which constrains the accuracy of hazard prediction and simulation models. Integrating scientific research with community-based monitoring helped bridge this gap, informing infrastructure design and advancing resilience-building efforts.

Scalability

- The model is highly replicable in other mountainous, hazard-prone rural communities with similar geographic.
- Strong community participation, technical expertise from AKAH, and funding support from SDC were critical enablers. The integration of Hazard Vulnerability Risk Assessment (HVRA) assessments and use of Nature-based Solutions (NbS) ensured context-specific interventions.
- Limited financial resources in remote areas can hinder replication. Inconsistent political or institutional support may delay or undermine project outcomes.
- The approach is adaptable and scalable across Afghanistan and similar high-risk regions globally, particularly where communities are vulnerable to climate-induced hazards and where ecosystem-based mitigation strategies are feasible.

Unique features

1. Integration of NbS with engineering interventions.
2. Data-driven hazard identification via HVRA.
3. Deep immersion and community engagement.
4. Focus on social infrastructure protection.
5. Climate adaptation through local commercial species plantation.
6. Multi-stakeholder coordination.


Image by Aga Khan Agency for Habitat

Image by Utkarsh B, Unsplash

India

Jingkieng Dieng Jri Living Root Bridges of the Khasis

Jingkieng Dieng Jri Living Root Bridges & Living Root Ladders

Cherrapunji, Meghalaya, India

Shillong Plateau

Scale
Local

Intended Beneficiaries

Khasi communities and their future generations and the surrounding environment

Local Population

Indigenous communities

Key Livelihoods

Agriculture, tourism

Infrastructure sector(s) and services

Transport (roads, tunnels, bridges, ropeways, airports, helipad, etc.)

Prominent geographical features

Jaintia Hills, remote Khasi villages situated between the Brahmaputra and Barak River Valleys, forested plateaus above the plains of Bangladesh

Key environmental features

Highest levels of rainfall, monsoonal climate, seasonal flooding during monsoon, presence of Ficus elastica (rubber fig tree)

Typical climate conditions

Monsoonal

Altitude of infrastructure assets addressed

1,200 - 1,500 m.a.s.l.

Name of implementing actor(s)/organization(s)

Khasi communities

Actors involved in design and implementation

Local communities

Period of implementation

Planning: ~10 years ahead of when the bridge is needed

Training & growth: ~30 years until functional

Full maturity: ~50 years

Lifespan: potentially centuries, with some bridges over 250 years old

Key hazard(s)

- Floods
- Soil erosion

Focus area(s)

- Integrated watershed approaches for infrastructure planning
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)

Case study contributed by: Julia Watson (Lo–TEK Institute)

Key achievements, co-benefits, and lessons learned

The living root bridges and ladders of the Khasi tribe in Meghalaya, India, are extraordinary examples of indigenous, nature-based infrastructure. Crafted from the aerial roots of the Ficus elastica tree, these structures are living systems that grow stronger over time and have lasted for centuries. The Khasi people developed this method to adapt to one of the wettest climates on Earth, turning seasonal monsoon floods into an opportunity for resilient, regenerative design.

Key achievements include the creation of hundreds of low-maintenance, self-sustaining bridges and ladders that enable safe passage between remote villages and farmland during the monsoon. These structures are ecologically harmonious, relying on local biodiversity, and cost virtually nothing to maintain. Co-benefits include enhanced biodiversity, flood resilience, cultural preservation, and climate adaptation. The bridges also serve as micro-habitats, stabilize soil, reduce erosion, and remain functional even under intense rainfall, where conventional infrastructure fails.

Rooted in spiritual and cultural traditions, the project demonstrates how mythology, ecological knowledge, and community stewardship can produce long-lasting, adaptive infrastructure. Sacred forest practices (law kyntang) protect the trees used in bridge-making, reinforcing conservation through cultural taboo.

The living bridges show that infrastructure can be grown, not built—offering a sustainable model for flood-prone regions globally. As urban areas grapple with climate-induced disasters, the Khasi tradition provides a compelling blueprint for how people and nature can co-create infrastructure that heals and adapts with time.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

One of the most pressing issues is over-tourism, which threatens the structural integrity of these delicate, living systems. Many of the bridges are not equipped to handle the high foot traffic brought by increasing visitor numbers, leading to stress and potential degradation. Without regulation, unmanaged tourism could jeopardize both the physical structures and the surrounding ecosystems.

Another major challenge is the gradual erosion of traditional knowledge. The skills required to grow and maintain living root bridges are passed down orally and through practice within Khasi communities. As younger generations migrate to urban areas and lifestyles shift, this knowledge risks being lost. Currently, there are limited formal mechanisms in place to document, preserve, and teach these techniques beyond local communities.

Additionally, the process of growing a new bridge can take 30 to 50 years, requiring long-term community planning, commitment, and uninterrupted stewardship. This long timescale poses challenges for scalability and integration into mainstream infrastructure models.

There are also gaps in scientific research on the biomechanics and ecological dynamics of the bridges. While community knowledge is rich, further interdisciplinary collaboration could enhance understanding of the structural performance and potential applications of this living technology.

Efforts to address these issues include cultural preservation programmes, tourism management initiatives, and growing interest from architects, conservationists, and researchers seeking to document and support this unique heritage through respectful partnership and sustainable development models.

Scalability

The living root bridges and ladders of the Khasi tribe demonstrate a rare example of scalable, regenerative infrastructure that can be adapted to both rural and urban contexts. The potential for replicating this model lies in the principles rather than exact replication. There have not yet been any realized urban pilot projects using Ficus elastica for elevated pedestrian walkways. The idea has been explored in design research, like in the paper *Growing Living Bridges in Mumbai*, which outlines a conceptual proposal for the city. In urban contexts like Mumbai, where monsoon flooding and environmental degradation are pressing concerns, the concept of inosculation—growing and grafting tree roots into usable infrastructure—offers a compelling, nature-based solution. A pilot project in Mumbai could use rubber fig trees to grow elevated pedestrian walkways that not only protect against flooding but also clean the air, sequester carbon, and enhance biodiversity. These structures are inherently low-cost, self-sustaining, and community-built, making them ideal for cities with limited access to resources but high social engagement.

Key enabling factors include:

- Time and patience for growth, suitable tree species (Ficus elastica), community stewardship and cultural integration, protection of sacred zones (law kyntang), and favourable climate (humid, tropical, with seasonal rain).

Barriers to scalability include:

- Lack of long-term policy support for slow-growing systems, mismatch with rapid urban development timelines, and loss of traditional ecological knowledge.

Despite these challenges, early research in cities like Mumbai suggests a clear opportunity to adapt the system as a hybrid of ecological design and civil infrastructure. Community involvement is essential—just as the Khasi guide root growth over decades, urban communities must embrace a long-term, participatory model. Living root infrastructures represent a paradigm shift: from building against nature to growing with it, inspiring the next generation of cities to root resilience and adaptability in living systems.

Unique features

This project reimagines infrastructure—not as something to be built, but grown. Inspired by the living root bridges and ladders of the Khasi people, it introduces a system that is ecological, cultural, spiritual, and technological.

Several distinctive features make this approach truly unique:

1. Living architecture: Made from Ficus elastica, a sacred tree in Khasi mythology, these self-repairing, resilient bridges and ladders strengthen over decades.

2. Inosculation-based Design: Roots graft and fuse together naturally, blending botany with architecture in a new typology of arboreal engineering.

3. Cultural intelligence: Embedded in Khasi myths, rituals, and ecological knowledge, ensuring generational stewardship.

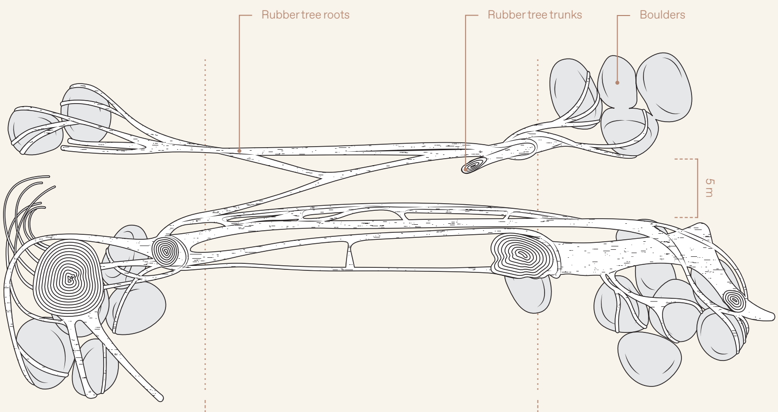
4. Climate resilience: Thrives in monsoonal climates, turning heavy rainfall into a growth catalyst, suitable for cities like Mumbai, where flooding, heat, and pollution are interlinked urban challenges.

5. Scalable co-design: Community-driven, participatory growth of infrastructure that integrates local practices and social rituals.

6. Multifunctionality: Provides transport routes and ecosystem services—carbon sequestration, air purification, biodiversity support, and canopy cooling.

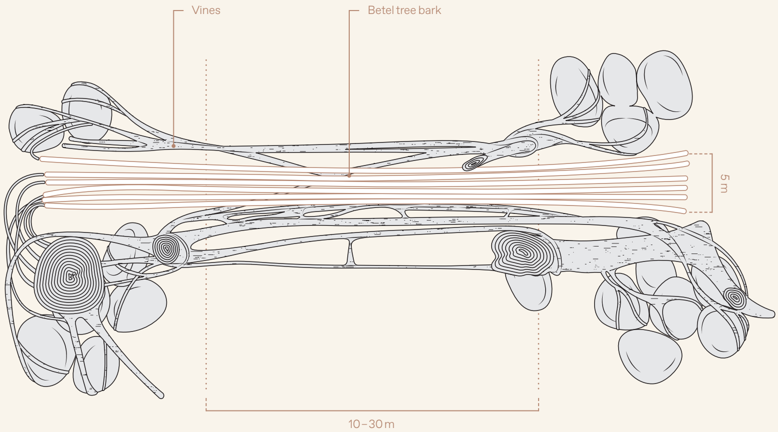
This project is more than a proposal—it's a provocation to reimagine urban infrastructure that is slow, sacred, and alive.

Plans of the Four Stages of Growth of the Bridge Structural System



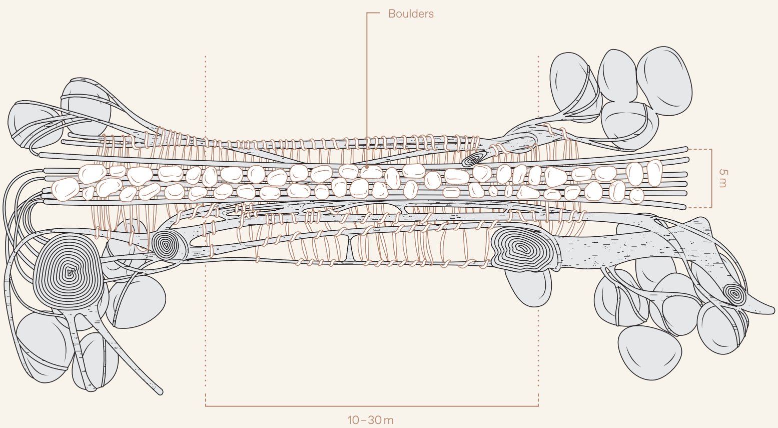
1. Main Roots

Plans of the bridge structural system (Taken from the Lo–TEK book)

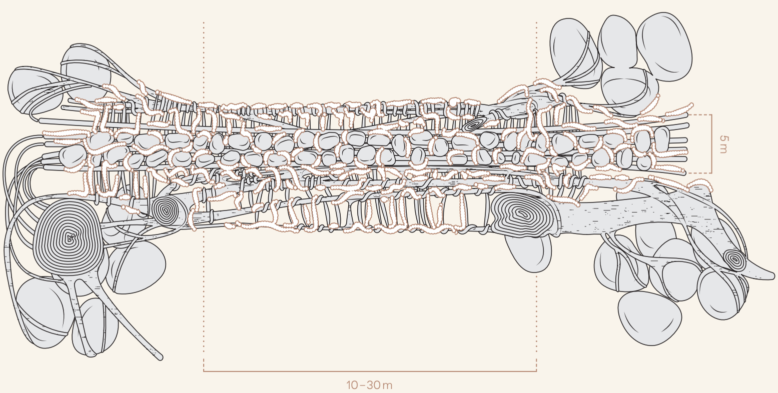


2. Root-Guidance System

Betel nut trunks are cut down their center and hollowed out to form a root-guidance system that crosses a stream



3. Secondary Root System



4. Root Flowering

A networked system of roots and bridging structures that function as an integrated infrastructure

Plans of the bridge structural system (Taken from the Lo—TEK book)

India

Benefits of the Early Warning System (EWS) at the Subansiri Lower Project in Assam

Subansiri Lower H.E. Project

Subansiri Lower Project, Assam, India

Foothills of Eastern Himalayas

Scale
Regional

Implementation
2022 – present

Intended Beneficiaries

Downstream population and Subansiri Lower Project of NHPC

Local Population

Rural population

Key Livelihoods

Agriculture, fisheries

Infrastructure sector(s) and services

Energy (power generation, hydropower, transmission, distribution)

Prominent geographical features

The Subansiri River, a major Brahmaputra tributary, flows through steep gradients with fast currents. Its Himalayan-fed glacial lakes and snow streams cause high seasonal discharge variability during monsoon and snowmelt.

Key environmental features

Dense sub-tropical and temperate forests with endemic and endangered species; the snow-fed Subansiri River, originating from the Tibet Plateau, has glacial sources that drive perennial flow and seasonal variations

Typical climate conditions

Heavy rainfall area with snow-covered catchment. The monsoon season lasts from May 1 to October 31, with average temperatures ranging from 7.85°C to 34.15°C.

Altitude of infrastructure assets addressed

205 m.a.s.l.

Name of implementing actor(s)/organization(s)

Subansiri Lower H.E. Project, National Hydroelectric Power Corporation (NHPC) Ltd

Funding sources

NHPC (Self-funded)

Actors involved in design and implementation

Government/authorities

Key hazard(s)

- Landslides and rockfalls
- Floods
- Soil erosion

Focus area(s)

- Early Warning System for critical infrastructure

Case study contributed by: *Manjusha Mishra (NHPC Limited)*

Key achievements, co-benefits, and lessons learned

The EWS of Subansiri lower HEP consist of two EWS sites on two prominent limbs of the River, one at Daporizo (70 km u/s of dam) on Subansiri River and another at Tamen (70 km u/s of dam) on Kamla River a tributary of Subansiri.

The implementation of project demonstrated significant success in mitigating disaster risks during multiple high-flow events, including those triggered by Cyclone Sitrang in 2022. EWS alerts, issued with a lead time of up to 6 hours from upstream Automatic Water Level Recorder (AWLR) sites at Tamen and Daporijo, enabled timely and organized evacuation of over 5000 workers from the dam and downstream construction sites at least 4 times in 2022.

Key Achievements:

- Zero casualties during extreme floods; complete evacuation of personnel.
- Protection of critical infrastructure and equipment worth crores of rupees.

Co-benefits:

- Improvedhydro-meteorological coordination and on-site preparedness.
- Reduced project delays, financial losses, and insurance risks.

Lessons Learned:

- Real-time hydrological monitoring and forecasting are essential.
- Robust communication and regular drills ensure EWS effectiveness.
- Investment in upstream sensing and local capacity-building enhances outcomes.

This case underscores the role of EWS in enhancing the safety, sustainability, and resilience of large infrastructure projects in flood-prone regions.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

While the EWS at Subansiri Lower Project proved crucial in safeguarding lives and assets during extreme events, several challenges and limitations emerged during its implementation:

- Limited upstream data coverage: Sparse monitoring infrastructure in remote upstream areas.
- Communication disruptions during severe weather can hinder real-time information flow.
- False alarms due to instrument error and associated uncertainty in discharge forecasts sometimes led to over-preparedness, affecting construction schedules and stakeholder confidence.

Knowledge gaps:

- Limited understanding of catchment specific hydrometeorological behaviour under compound extreme events.
- Inadequate local modelling capacity for flood forecasting and impact-based assessment.
- Challenges in accurately representing large and complex catchments due to localized precipitation variability, necessitating frequent field validation and real-time adjustments.

Efforts to address challenges:

- Deployment of additional upstream Automatic Water Level Recorder (AWLR) stations/Automatic Weather Stations (AWS).
- Introduction of automated alert systems and redundant communication channels.
- Training and capacity-building exercises for on-ground staff to improve response protocols. These insights highlight the need for integrated, adaptive, and locally tailored EWS frameworks to ensure continued resilience in complex hydropower projects

Scalability

EWS have been installed at almost all the under-construction project and power stations of NHPC.

Unique features

The EWS implemented by NHPC is designed to be simple, practical, and cost-effective, making it easy to understand, implement, and operate. Its structure ensures high operational efficiency while delivering significant safety and economic benefits, making it a highly viable solution for flood risk mitigation in hydropower projects.

Japan

Tadami Biosphere Reserve's *suigen no mori*

Fukushima Prefecture,
Tadami Municipality, Japan

Echigo Mountains, Northern Japan

Scale
Local

Implementation
Ongoing

Intended Beneficiaries

Local Municipality, local communities

Local Population

4,044 inhabitants (2020)

Key Livelihoods

Agriculture, farming. In the past, the economy was based on forestry

Infrastructure sector(s) and services

Water and wastewater management

Prominent geographical features

Two main mountain valley catchments, the Ina River and the Tadami River, along with smaller valleys shaped by rivers like the Kurotani, Shionomata, and Nunozawa. Peaks up to 1,819.9 m.a.s.l and floodplains.

Key environmental features

Steep slopes, exposed bedrock, and nivation landforms. Notable peaks and diverse vegetation: evergreen conifers, avalanche shrubs, beech forests on lower slopes, and riparian forests. Fauna includes golden eagles, mountain hawk-eagles, and Asiatic black bears. Host of rare alpine lilies like the *Lilium rubellum*.

Typical climate conditions

Humid-subtropical influenced by the Japan Sea's currents. Temperatures range between -3°C in winter and a maximum of 31°C in summer. Heavy snowfalls influenced by the winter monsoon.

Altitude of infrastructure assets addressed

c.a. 500m.a.s.l.

Name of implementing actor(s)/organization(s)

Tadami Municipality and local community

Actors involved in design and implementation

Local communities, NGOs, Academia, Government/ authorities

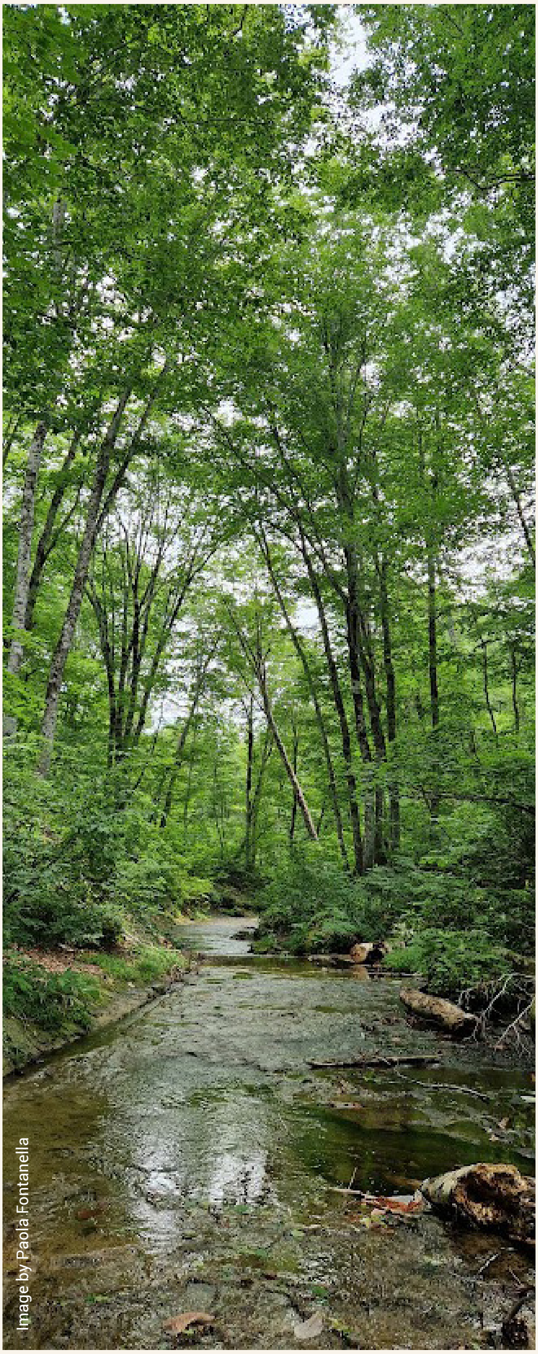
Key hazard(s)

- Landslides and rockfalls
- Floods
- Avalanches
- Soil erosion
- Extreme weather (cloudburst, heavy snowfall, coldwave, extreme heat)

Focus area(s)

- Region specific policies, standards, and guidelines
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)

Case study contributed by: *Paola Fontanella Pisa (UNU-EHS)*



Key achievements, co-benefits, and lessons learned

The protection of beech forests has been directly associated with disaster risk reduction measures by most of the people interviewed and consulted about it, as it is of common knowledge that beech tree roots have the capacity of retaining and absorbing a lot of water, and the soil under which they grow is more stable and less susceptible to landslides or floods. Hence, many people confirm that landslides and flood events have since decreased, and mountain roads are safer from such events.

Key limitations, challenges, and knowledge gaps

Lack of maintenance of beech forests due to the lack of revenue coming from it and the limitations imposed on logging, have also led to new emerging risks, such as the risk of debris flow in case of heavy rainfall (as it happened in 2011).

Scalability

The project could be replicated or expanded. Nevertheless, the project's function is extremely context-specific, and both expansion and replicability could be undertaken only through a thorough assessment of the need for such a measure, its applicability, and its functioning in a different context.

Image by Nippon Koei Co., Ltd.

Nepal

Construction of the Sindhuli Road & Nagdhunga Tunnel in Nepal through Japan's Development Cooperation

Sindhuli Road Construction Project | Nagdhunga Tunnel Construction Project

Sindhuli Road: Kavrepalanchok, Sindhuli and Ramechhap district, Nepal
Nagdhunga Tunnel: Kathmandu and Dhading District, Nepal

Hindu Kush Himalaya

Scale
Regional

Implementation
Sindhuli Road: 1995–2015
Nagdhunga Tunnel: 2020–2025

Intended Beneficiaries

Local Communities

Local Population

Sindhuli Road: Approximately 2.6 million vehicles per year (serving 3 million people in the Kathmandu Valley and 1.3 million in the Terai)
Nagdhunga Tunnel: Over 3 million vehicles per year

Key Livelihoods

Sindhuli Road: Supports agriculture, mining (such as quarrying and gravel extraction), manufacturing, and domestic logistics toward the southeast
Nagdhunga Tunnel: Supports tourism, domestic logistics toward the west, and trade with India

Infrastructure sector(s) and services

Transport (roads, tunnels, bridges, ropeways, airports, helipad, etc.)

Prominent geographical features

Steep mountainous terrain, active geological formations along the Himalayan orogenic belt.

Key environmental features

Sindhuli Road: Steep slopes along the Sunkoshi River with severe erosion
Nagdhunga Tunnel: Valuable groundwater sources and mountainous watershed areas

Typical climate conditions

Dry season with minimal rainfall and a rainy season of heavy precipitation driven by the monsoon.

Altitude of infrastructure assets addressed

Sindhuli Road: 200–1,600 m.a.s.l.
Nagdhunga Tunnel: 1,300 m.a.s.l. approximately

Name of implementing actor(s)/organization(s)

Department of Road, Ministry of Public Infrastructure and Transportation of Nepal, Hazama Ando Corporation, Nippon Koei

Funding sources

Japan International Cooperation Agency (JICA)

Actors involved in design and implementation

Private sector, Government/authorities

Key hazard(s)

- Landslides and rockfalls
- Floods
- Earthquakes
- Soil erosion
- Multi-hazard events (Foundation degradation after the earthquake)

Focus area(s)

- Risk-informed planning of resilient infrastructure
- Region specific policies, standards, and guidelines
- Indigenous and ecosystem-based approaches for DRI (incl. community focused approaches)

Case study contributed by: *Kozo Nagami (Tohoku University), Tetsuo Igari (JICA), Motoki Iwamaru (Nippon Koei Co. Ltd.)*


Image by Nippon Koei Co., Ltd.

Key achievements, co-benefits, and lessons learned

The Sindhuli Road serves as a vital piece of infrastructure supporting the sustainable prosperity of the entire mountainous nation of Nepal, connecting the capital city of Kathmandu with the Terai plains that lead to India. The road has produced diverse outcomes, including stabilizing logistics, promoting industrial development, and revitalizing regional economies.

The Sindhuli Road, constructed with Japan's support, was fully opened in 2015. However, just before the scheduled opening ceremony in May, Nepal was struck by a devastating M7.8 earthquake on April 25, which caused widespread destruction. The Sindhuli Road sustained damage at more than 24 locations. In response, emergency restoration was promptly initiated at the 12 most severely affected sites through collaboration between Nepal's Department of Roads and JICA. Thanks to swift action, traffic functionality in the main sections was restored within just five months. This rapid recovery was made possible by on-site assessments and design support from Japanese engineers, combined with construction carried out by Nepalese companies, all while minimizing road closures. Further support came in 2018, when Japan provided grant aid for full-scale restoration, and by 2021, all sections had been restored by Japanese contractors. Guided by the principle of "Build Back Better," the restoration incorporated advanced technologies such as slope stabilization, which were transferred to local engineers. Reborn as disaster-resilient infrastructure, the Sindhuli Road has since become a symbol of Nepal's resilience.

Through more than 30 years of cooperation, Japan's support—grounded in excellent engineering expertise—helped foster a highly resilient road infrastructure in Nepal, capable of recovering quickly from natural hazard impacts. This was achieved by integrating local construction techniques, strengthening the capacity of human resources, organizations, and enterprises, and enhancing governance systems. The goal was not simply to complete and hand over a road, but to nurture people and institutions through construction and maintenance processes, encourage positive behavioral and societal changes, and ultimately transform the project into a symbol of trust and friendship between Japan and Nepal. Recognizing that the overwhelming and uncertain power of nature, especially in harsh mountainous environments, cannot be fully anticipated or prevented, the approach emphasized building spontaneous, agile, and sustainable capacities within Nepal. The success of these initiatives laid the foundation for Nepal's first-ever road tunnel development—the Nagdhunga Tunnel.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

The construction of the Sindhuli Road took place during a tumultuous period in Nepal's history, marked by the fall of the monarchy, the rise of a democratic government, and the transition to communist rule in the 2000s. This project was carried out amidst significant political instability. The area surrounding the Sindhuli Road is characterized by steep mountainous terrain formed by the Himalayan orogeny and is covered by fragile geological formations. These natural features, combined with the region's susceptibility to monsoon rains and earthquakes, made the project scientifically challenging and unpredictable. The road was also prone to damage from landslides and collapses, which are common in such complex natural environments.

In planning the construction, it was deemed more appropriate to adopt flexible construction methods that harmonize with nature and are easy to maintain, rather than aiming for an unyielding structure that could resist all natural forces. The project also incorporated Japan's advanced safety management expertise, which helped to gradually improve the construction practices and processes that Nepali engineers and companies found challenging. This approach significantly enhanced their awareness of safety management, minimizing construction accidents. Despite the challenging natural conditions, the project maintained a strong safety record, with minimal incidents over the multi-year construction period, thanks to the introduction of Japanese safety management practices.

Scalability

In Nepal, where 90 percent of transportation relies on roads and 80 percent of the country's roads are located in mountainous areas, the knowledge and experience gained from projects like the Sindhuli Road and the Nagdhunga Tunnel can be widely applied.

Unique features

The on-site construction work was carried out by Nepali companies, with Nepali engineers playing a central role. Japanese companies served as supervisors and were responsible for quality control, risk management, project scheduling, and safety management as the main contractors. Over more than 20 years, they nurtured and developed Nepali companies and engineers, leading them toward independence and growth. Today, these companies and professionals have become some of the leading general contractors in Nepal and are now active in the global market.

Image by Nippon Koei Co., Ltd.

Image by Sundar Rai, ICIMOD

Nepal & India

Community-owned Sustainability Mechanism for Long-term Flood Early Warning

Community Based Flood Early Warning System (CBFEWS)

Different locations along the Ratu, Lal Bakaiya, and Khando rivers in Nepal and India.

Hindu Kush Himalaya

Scale
Local, Transboundary

Implementation
2015 - ongoing

Intended Beneficiaries

Flood-prone communities living along the tributaries of the Ratu, Khando, and Lal Bakaiya rivers

Local Population

Primarily rural populations

Key Livelihoods

Agriculture, small industries, agroforestry

Infrastructure sector(s) and services

Health and social infrastructure (e.g., educational, public safety, community service, housing)

Prominent geographical features

Floodplains downstream of the Chure Range, with active erosion and sedimentation shaping the watershed.

Key environmental features

Floodplains with a number of tributaries of the Koshi river.

Typical climate conditions

Monsoonal with a distinct wet season followed by a prolonged dry season. This extreme variation creates a paradoxical situation of 'too much and too little water'.

Name of implementing actor(s)/organization(s)

International Centre for Integrated Mountain Development (ICIMOD), Sabal Nepal, Community Development & Advocacy Forum Nepal, Mandwi Nepal, Sustainable Eco Engineering Pvt. Ltd, CARE Nepal, Oxfam Nepal

Funding sources

Australian Aid, Tilathi Koiladi Rural Municipality, three municipalities in Khando watershed, eight in Ratu and thirteen in Lal Bakaiya

Actors involved in design and implementation

Local communities, NGOs, Private sector, Government/authorities

Key hazard(s)

- Floods

Focus area(s)

- Other: Community-based flood early warning system

***Case study contributed by:** Debabrat Sukla (ICIMOD)*

Key limitations, challenges, and knowledge gaps

The Community-Based Flood Early Warning System (CBFEWS) has evolved from a pilot to a scalable model of risk reduction across the many flash-flood prone tributaries of the Hindu Kush Himalaya. The initiative gained initial international recognition through the United Nations Framework Convention on Climate Change (UNFCCC) Momentum for Change: 2014 Lighthouse Activity award, having been piloted in the districts of Lakhimpur and Dhemaji in Assam. Following its scaling in other regions, including Afghanistan, India, Nepal and Pakistan, the system has fostered strong local ownership where the community has been involved in co-designing alerts, roles, and maintenance with residents and local governments.

The initiative has contributed to the global *Early Warnings for All* agenda by incorporating a unique sustainability mechanism that complements its four core elements—risk knowledge, monitoring and forecasting, warning dissemination and communication, and preparedness to respond. This approach enables communities to move beyond being passive recipients of warnings, allowing them to actively participate in response and resilience planning, including developing clearer response protocols. The sustainability mechanism also strengthens local risk governance by establishing community-owned basket funds for the maintenance and upkeep of the CBFEWS, giving communities greater control and ownership over early warning systems.

Key lessons include: early engagement of communities and local governments, which strongly predicts long-term ownership; integration of CBFEWS into local disaster risk-reduction plans and budgets to anchor responsibilities and financing; and partnerships with hydrometeorological agencies, telecom providers, media, civil protection authorities, and NGOs, which are essential for smooth implementation, reliable operations, and long-term functionality.

Scalability

A key enabler of scalability is the relatively low-cost of the system installed in a target tributary.

Additionally, engaging volunteer members with first-hand experience of flood impacts helps ensure the system continues to function long after project leads have left a watershed. Equally important, the model's effectiveness is amplified through word-of-mouth and local media coverage, factors that have contributed significantly to scaling the CBFEWS across multiple watersheds in Nepal.

At the same time, making this a truly transboundary measure that achieves success and recognition across countries also requires some form of cross-border collaboration. In the Hindu Kush Himalaya context, geopolitical sensitivities can often hamper cooperation on critical fronts, including knowledge and data sharing. While the CBFEWS has succeeded through informal communication channels, effective scalability will require countries to recognize its transboundary potential and collaborate accordingly.

Unique features

Technology enhancement and fifth pillar on sustainability mechanism innovated by ICIMOD

Image by Sundar Rai, ICIMOD

Italy

Passiria Valley Integrated Monitoring Approach for infrastructure resilience

Moso in Passiria,
Bolzano Autonomous Province, Italy

Alps

Scale
Local, Transboundary

Implementation
2021 - ongoing

Intended Beneficiaries

Local communities, tourists, transboundary commercial freights

Local Population

Rural and urban, mountain dwelling community

Key Livelihoods

Agriculture, tourism

Infrastructure sector(s) and services

- Transport (roads, tunnels, bridges, ropeways, airports, helipad, etc.)
- Water and wastewater management

Prominent geographical features

V-shaped alpine valley

Key environmental features

River Passirio, steep valley flanks with forest cover

Typical climate conditions

Alpine climate

Altitude of infrastructure assets addressed

~1400 m.a.s.l.

Name of implementing actor(s)/organization(s)

Research Institute for Geo-Hydrological Protection of the Italian National Research Council (CNR-IRPI);
Bolzano Autonomous Province, Torrent Control Functional Area, Civil Protection Agency;
University of Innsbruck, Unit of Geotechnical Engineering

Actors involved in design and implementation

Academia, Government/authorities

Key hazard(s)

- Landslides and rockfalls
- Avalanches
- Multi-hazard events: In case of river blockage (and lake formation) by landslide deposit, the dam can suddenly collapse and cause flooding of the downstream area)
- Floods
- Soil erosion
- Extreme weather (cloudburst, heavy snowfall, coldwave, extreme heat)

Focus area(s)

- Integrated watershed approaches for infrastructure planning
- Early Warning System for critical infrastructure
- Region specific policies, standards, and guidelines
- Other: Geohazard monitoring

Case study contributed by: *Danilo Godone (National Research Council)*

Key achievements, co-benefits, and lessons learned

The Hahnebaum landslide, located in the upper Val Passiria (Bolzano Province, Italy), can be defined as a complex phenomenon with secondary processes. Its main risks include potential valley damming in the event of slope collapse and the interruption of the SS44B interstate road, which connects Italy with Austria. A historical precedent occurred in the early 15th century, when a partial slope collapse caused valley occlusion, lake formation, and dam failure, resulting in ~400 fatalities. To monitor the state of landslide activity, a complex monitoring network was established to track surface, deep and infrastructure (river barrier) deformations. Geotechnical measurements at torrent barriers focus on creep pressures induced by landslide movements, supported by sensors measuring strain, pressure, and displacement. These data, combined with robotized inclinometer results, inform assessments of landslide behaviour and kinematics, forming the basis for the Early Warning System and safety management of the upstream interstate road.

To deepen the analyses, an indirect approach was also adopted. Snow height data from a nearby automatic weather station was downloaded and used to feed a model able to calculate the snow water equivalent. Peaks of water input were compared with landslide accelerations, showing strong correlations and offering an additional interpretive key for the phenomenon. Altogether, the data provides essential information to secure road functionality and safeguard neighbouring settlements.

Key limitations, challenges, and knowledge gaps

Installing a monitoring station in a mountainous environment can be a demanding task. In this case, ensuring sufficient power was difficult since the system is solar-powered and the valley is narrow, limiting sunlight exposure. The choice of station location and installation strategy therefore required balancing scientific objectives with technical and logistical constraints. To optimize performance, inclinometric measurements can be remotely scheduled, supported by full-charge backup batteries. Since freezing winter temperatures risk probe jamming, heaters were added both in the instrumentation and within the inclinometer tube, where water has been present since the beginning of the campaign.

For data validation, a Global Navigation Satellite System (GNSS) benchmark was installed near the inclinometer to provide independent cross-checks. Other remote sources, such as satellite-based interferometry, were not feasible due to dense forest cover, which prevents reliable detection of displacements.

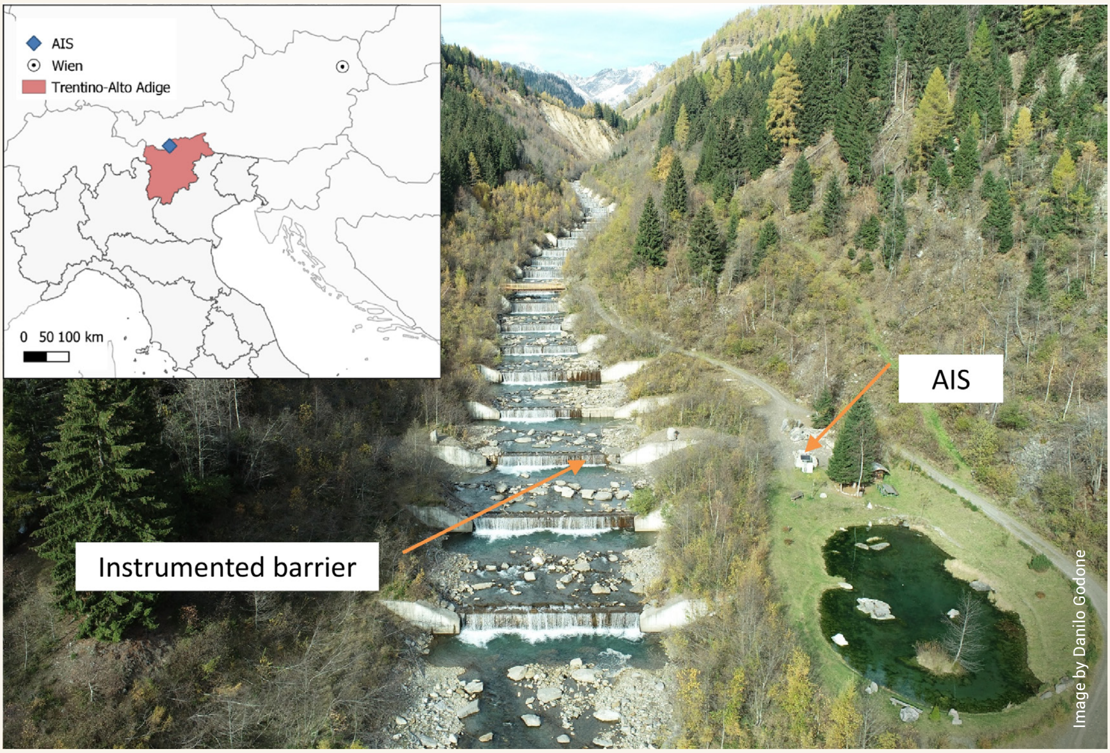
Integrating monitoring and meteorological data has improved interpretation of phenomena such as landslide acceleration and secondary triggers. The inclinometer's ability to detect displacements along the whole tube length, revealed sudden, shallow accelerations in spring, which correspond to peaks in precipitation. Additionally, the contribution of snowmelt can be used as a proxy of landslide kinematics.

Scalability

The approach can be applied to any slope and/or strategic infrastructure endangered by a low-kinematic phenomenon. In case of particularly large ones, the monitoring station can be doubled or repeated in significant spots.

Unique features

The monitoring station is equipped with a unique instrumentation setup. The robotized or Automated Inclinometric System (AIS), which performs high frequency in clinometric measurements, provides daily updates of the landslide behaviour. Additional info on the instrument can be retrieved from https://doi.org/10.3390/s20133769



Bolivia

El Alto International Airport: High Altitude Challenges

Global Study on Disaster Resilience of Airports (GSDRA)

El Alto, Bolivia

Cordillera Real Mountain range, Andes

Scale
Local

Intended Beneficiaries

Local population, infrastructure operators

Local Population

Urban

Key Livelihoods

Tourism, commercial activities

Infrastructure sector(s) and services

Transport (roads, tunnels, bridges, ropeways, airports, helipad, etc.)

Prominent geographical features

High-altitude plateau or "Altiplano", characterized by its impressive elevation, steep valleys, and proximity to the Cordillera Real Mountain range. Glacial regions and dramatic landscapes, snow-capped peaks and deep, winding valleys.

Altitude of infrastructure assets addressed

4,061.5 m.a.s.l.

Name of implementing actor(s)/organization(s)

NACO, a company of Haskoning Nederland B.V.; El Alto International Airport

Funding sources

NACO, a company of Haskoning Nederland B.V.

Actors involved in design and implementation

Private sector
Government/authorities

Typical climate conditions

Alto International Airport, situated at a remarkable altitude of 4,061 metres (13,325 feet above sea level), experiences a cool and predominantly cloudy climate throughout the year. Temperatures typically range from -2°C to 16°C, rarely dipping below -5°C or exceeding 18°C. The region receives an annual precipitation of approximately 782 mm, with January being the wettest month and June the driest. Humidity levels peak in February, while sunshine hours vary between 6 to 9 hours daily, depending on the season. This unique climate, characterized by cool temperatures and significant seasonal variations in rainfall, is influenced by the airport's high-altitude location and surrounding mountainous terrain.

Key hazard(s)

- Floods
- Extreme weather (cloudburst, heavy snowfall, coldwave, extreme heat)
- Multi-hazard events: Reduced air density, high winds, turbulence, sudden temperature fluctuations, low visibility.

Focus area(s)

- Early Warning System for critical infrastructure
- Risk-informed planning of resilient infrastructure
- Climate and risk data

__Case study contributed by:__ Asmeeta Das Sharma (NACO, Netherlands Airport Consultants)

Key achievements, co-benefits, and lessons learned

El Alto Airport (LPB) has implemented several measures to address natural and climate-related challenges, ensuring safe and efficient operations despite demanding climate conditions. Key achievements include climate resilience planning, which involves assessing risks and adapting infrastructure to withstand extreme weather conditions, and extending runways to accommodate longer take-off and landing distances required at high altitudes. The airport's buildings and runways are designed to endure heavy rainfall and temperature fluctuations, utilizing reinforced structures and materials. Enhanced drainage systems have been installed to manage significant rainfall during the wet season, preventing flooding and ensuring continuous operations.

The airport also monitors air quality to ensure safe operations during periods of increased pollution or dust storms and collaborates with local emergency services to manage natural hazards efficiently.

To handle low visibility conditions, LPB employs the Surface Movement Guidance and Control System (SMGCS) and Wide Area Multi-Lateration (WAM) system, which enhance safety and efficiency by providing real-time position and movement data to air traffic controllers and pilots. These systems, along with standard low visibility procedures like Instrument Landing Systems (ILS) and Runway Visual Range (RVR) systems, help maintain operational efficiency and safety. Additionally, LPB incorporates energy-efficient technologies to reduce its environmental footprint through the use of renewable energy sources and energy-saving lighting and heating systems.

The airport has developed comprehensive emergency response plans, including an Aerodrome Emergency Plan (AEP), regular drills and training sessions for staff, as well as coordination with airlines, government agencies, and local communities. The high-altitude environment necessitates rigorous control procedures and infrastructure adaptations, highlighting the importance of real-time data and collaboration with local emergency services for effective disaster management. These measures collectively ensure that El Alto International Airport operates safely and efficiently, even under challenging weather conditions.

Key limitations, challenges, and knowledge gaps

Some key limitations and challenges that the airport faces include being considered one of the worst airports regarding aeronautical infrastructure and connectivity to other airports. Moreover, due to the state of the infrastructure, high altitude and low visibility, airlines operate with a lower number of passengers.

Scalability

Airports located at high altitudes or facing challenges on low visibility may be able to replicate elements of this project.

Unique features

The El Alto International Airport is located at a high altitude, which is not generally common for other airports.


Image by The Mountain Institute

Peru

Restoring Ancient Water Management Systems in the High Andes as an Adaptation to Climate Change-Miraflores, Peru

Mountain Ecosystem based Adaptation Project

Community of Miraflores, Lima, Peru
Nor Yauyos Cochas Landscape Reserve

Andes

Scale
Local

Implementation
2012-2015

Intended Beneficiaries

- Direct: 80 families (approximately 400 people) in the community of Miraflores.
- Indirect: Populations living in the middle and lower part of the watershed.

Local Population

Rural mountain, Indigenous community

Key Livelihoods

Livestock, agriculture

Infrastructure sector(s) and services

Water and wastewater management

Prominent geographical features

High altitude mountain, above 3,000 m.a.s.l.

Key environmental features

Puna ecosystem with mountains, lakes, and high-altitude grasslands.

Typical climate conditions

Drought, erratic rainfall, extreme heat, glacial retreat, increasing temperatures.

Altitude of infrastructure assets addressed

3,149 m.a.s.l.

Name of implementing actor(s)/organization(s)

The Mountain Institute in partnership with the Nor Yauyos Cochas Landscape Reserve and IUCN

Funding sources

Federal Ministry for the Environment, Nature Conservation, Public Works and Nuclear Safety of the German Government (BMUB)

Actors involved in design and implementation

Local communities

Key hazard(s)

- Slow onset events (e.g., drought, glacial retreat and related impacts)
- Soil erosion
- Multi hazard events: Erratic rainfall, increasing temperatures, land and forest degradation, changes in socio-cultural context.

Focus area(s)

- Indigenous and ecosystem-based approaches for DRI (including community focussed approaches)

***Case study contributed by:** Aneli Gomez and Florencia Zapata (The Mountain Institute)*

Key achievements, co-benefits, and lessons learned

Key achievements:

The Ecosystem-based Adaptation (EbA) initiative in Miraflores, Peru, successfully integrated ancestral knowledge with scientific knowledge to enhance water and pasture management. In collaboration with The Mountain Institute, Nor Yauyos Cochas Landscape Reserve, and IUCN, the community restored a 700-year-old water system integrating green and grey infrastructure. A participatory process led to the development of a pasture and water management plan, the restoration of degraded wetlands and pastures, and infrastructure improvements including pipeline repair, wetland fencing, and construction of watering sites. Vegetation cover in key areas improved significantly (from 69 to 90 percent), 160 ha of native pastures were set aside for seasonal conservation and pasture management improved in 6,000 ha of the community.

Co-benefits:

The project boosted livestock productivity, strengthened local governance, and fostered intergenerational knowledge sharing. It increased community cohesion, improved local livelihoods, and enhanced climate resilience. It also supported gender and youth inclusion and created spaces for dialogue among indigenous communities and government agencies.

Lessons learned:

Strong community participation, trust-building, and consistent field presence are essential. Applying participatory tools and combining capacity building with hands-on learning ensures local ownership. Effective communication and collaboration with local authorities increase sustainability. Adaptive management is crucial to respond to emerging challenges. Engaging locals in planning, implementation, and monitoring builds long-term stewardship and aligns conservation with community priorities.

Key limitations, challenges, and knowledge gaps

Key challenges and limitations:

Initial weak community organization, limited technical capacity, and initial distrust of external institutions. Water scarcity, degraded pastures, low livestock productivity, and labour shortages due to migration. Limited experience with participatory planning. The communal workload also caused delays in construction and maintenance activities.

Knowledge gaps:

There was limited baseline data on ecological conditions, water availability, and grazing impacts. A lack of understanding around adaptive management, sustainable grazing, and the long-term maintenance of infrastructure also presented difficulties.

Many community members had little exposure to formal planning or technical concepts related to EbA.

Efforts to address challenges:

The project responded by strengthening local institutions, building technical and organizational capacity, and applying a participatory action-research methodology. Trust was built through sustained field presence, hands-on training, and local researchers serving as liaisons. Communication tools such as participatory videos and artistic events involving youth and elderly people helped improve understanding and engagement. Adaptive management was emphasized, allowing the project to adjust as new challenges arose. The establishment of a pasture and water management plan fostered long-term planning and ownership. Inclusive approaches ensured that women, youth, elders, and diverse community groups contributed to and benefited from the project.

Scalability

The Miraflores EbA initiative demonstrates strong potential for replication and expansion, especially in highland Andean communities facing similar climate and water-related challenges. Its core strengths—combining ancestral knowledge with scientific approaches, using participatory methods, and promoting hybrid green-grey infrastructure—can be adapted to other socio-ecological contexts.

Key enabling factors:

- Active community involvement and local ownership from design to implementation
- Use of participatory tools such as 3D modelling, rural appraisals, and capacity-building workshops
- Strong alliances with local and national institutions (e.g., Nor Yauyos Cochas Landscape Reserve, SERNANP, municipalities)
- Integration with existing conservation and development plans
- Flexibility and adaptive management in project implementation

Challenges to scalability:

- Need for sustained field presence and long-term engagement, which requires time and financial resources
- Variability in governance structures and levels of trust in other communities
- Limited technical and institutional capacity in remote areas
- Dependence on effective facilitation and the availability of trained local facilitators

Replication example:
The EbA and participatory approaches that informed the project in Miraflores have been included in other projects Instituto de Montaña implemented in nearby communities within the Nor Yauyos Cochas Landscape Reserve and other Andean regions, focusing on grassland restoration, community planning, and hybrid infrastructure solutions.

Unique features

The local committee as a community anchor of governance: The local committee was formed through participatory processes and is responsible for leading the implementation of restored water systems and pasture use. It is a sustainability mechanism because it reinforces communal responsibilities and the continuous operation of the EbA infrastructure. Integrates into local structures working in coordination with community authorities and supports communal tasks (e.g., maintenance, planning, mobilization).

'Dialogue of Knowledge' is a bridge of integration between local knowledge and science through participatory planning, community mapping and shared fieldwork. It allows hybrid solutions that combine ancestral water systems with modern engineering (green and gray infrastructure).

United States of America

Climate Resilience through Nature-based Solutions at Road-Stream Crossings

Stream Simulation Design at Road-Stream Crossings

Mountainous regions throughout the United States of America

Rocky Mountains, Central Colorado

Scale
National

Implementation
Ongoing

Intended Beneficiaries

American public that accesses public lands

Local Population

Primarily rural

Key Livelihoods

Tourism and recreation, grazing, timber harvest

Infrastructure sector(s) and services

Transport (roads, tunnels, bridges, ropeways, airports, helipad, etc.)

Prominent geographical features

Moderate to high elevation mountainous regions with narrow, steep valleys. Geology varies, but glacial outwash is common.

Key environmental features

Streams in forested settings, sometimes including meadow systems with wetland margins.

Typical climate conditions

Climate and flow regime is typically snow melt dominated, but can be punctuated by large convective rainfall events.

Altitude of infrastructure assets addressed

1,800 - 3,600 m.a.s.l.

Name of implementing actor(s)/organization(s)

United States Forest Service

Funding sources

Federal funding for work on public lands (National Forests)

Actors involved in design and implementation

Private sector, Government/authorities

Key hazard(s)

- Floods

Focus area(s)

- Integrated watershed approaches for infrastructure planning
- Risk-informed planning of resilient infrastructure

Case study contributed by: *Mark Weinhold (US Forest Service)*

Key achievements, co-benefits, and lessons learned

Stream Simulation is a nature-based solution for designing road-stream crossings for flood/climate resilience and unimpeded aquatic organism migration. The premise is to 'build a stream and put a lid over it' such that natural stream channel dimensions are maintained through the road crossing.

Our research of post-flood road damage suggests that most road failures occur where roads and water interact, which is most often at road-stream crossings. At those locations, over 90 percent of failures are caused by plugging from watershed products like woody debris and sediment. Road crossing structures (i.e. pipes) were historically designed narrower than the stream channel width, causing debris to lodge at the inlet. Small accumulations of debris result in very large changes in hydraulic capacity, which leads to overtopping and road failure. Road failures mean loss of vehicle access and very large quantities of sediment delivered into sensitive aquatic ecosystems.

Designing crossings that maintain the stream channel width and profile, while providing a natural streambed, can safely pass very large floods and debris without damaging the road. Providing a natural streambed (similar to what a bridge does) also accommodates the necessary movements of migratory fish and other animals.

Key limitations, challenges, and knowledge gaps encountered in the initiative or project

Maintaining the stream's width with a larger road-stream crossing structure will increase project costs 10 to 30 percent, depending on several factors. Our challenge has been to communicate with road management agencies that these structures are much cheaper than historic designs when considered with full life cycle economics. Several studies support this, but most transportation agencies are driven by one time installation costs due to annual budget cycles.

Another challenge is that working at the intersection of roads and streams requires two fields of expertise – transportation engineering and river mechanics (fluvial geomorphology). Most transportation agencies only have engineering expertise, so misinterpretation of the river environment is common, which radically increases the risk of road failures.

To address these challenges, we have developed a technical document to describe the design process along with a week-long course to teach the design process.

Another limitation is that large metal culvert structures may not be available in developing countries, so concrete box shapes must be used. Here, the temptation is to use multiple small pipes, which inevitably leads to plugging and failure.

Scalability

The design process applies to any stable stream channel, independent of setting, so it can be easily replicated.

Unique features

In the past decade the US has seen very large flood events that have been categorized at 500-year and 1000-year flood events. Stream Simulation structures, that are simply designed to accommodate the bankfull channel width, have survived these storms and maintain a safe transportation system.

Image by Mark Weinhold

Image by Klaus Birner, Unsplash

5. Strategic Pathways and Recommendations for DRI in Mountains

Building disaster resilient infrastructure in mountain regions requires more than technical solutions. It demands policies and strategies that are inclusive, adaptive, and grounded in local realities. Infrastructure in mountains must be designed with an understanding of what constitutes effective and sustainable infrastructure systems in these unique environments. Resilient mountain infrastructure systems must contend with several interlinked fundamental challenges: remote locations, harsh climatic conditions, geological instability, fragile ecosystems, and the economic vulnerability and livelihood dependence of mountain communities. Given these factors, the planning, design, and execution of infrastructure investments must consider climate-related risks and go hand in hand with interdisciplinary and multi-stakeholder participation from the earliest stages of the project cycle. Ensuring equal and just access to infrastructure services for all community members is essential. Critically, infrastructure systems must also incorporate maintenance needs and associated costs from the very beginning of the planning process.

Strengthening resilience also depends on adaptive governance and policy frameworks that can coordinate diverse actors, align sectoral objectives, and ensure long-term accountability. These non-structural dimensions are vital for developing resilient, risk-informed, and equitable systems capable of supporting sustainable development in mountain regions.

Equally important is the exceptional knowledge held by mountain communities themselves. Integrating Indigenous and local knowledge, as well as ecosystem-based adaptation (EbA), supports the context-appropriate design of infrastructure projects. Likewise, mobilizing capital for disaster resilient infrastructure through comprehensive, multi-faceted financing mechanisms can unlock the full adaptation potential of mountain regions. Combined, these elements can shift responses from fragmented, short-term actions towards holistic strategies that deliver resilient infrastructure while safeguarding lives, livelihoods, and ecosystems in mountain regions.

This chapter highlights key imperatives and offers corresponding recommendations for mountainous regions.

5.1. Recommendations for Strengthening Governance and Decision Making for Resilient Mountain Infrastructure

5.1.1. Strengthening multi-stakeholder collaboration

Collaboration among diverse stakeholders can ensure that infrastructure planning and implementation are both contextually grounded and systemically coherent. By fostering a shared vision, stakeholders can align actions across infrastructure systems, minimizing fragmentation and ensuring more integrated, system-wide resilience (Kannan et al., 2021). This collaboration also facilitates the periodic review and updating of infrastructure policies, frameworks, and regulations to respond to a dynamic, increasingly complex, and uncertain environment. Involving local communities in planning and maintaining infrastructure ensures culturally appropriate solutions that address context-specific needs. NGOs, the private sector, and academia play critical roles in facilitating communication, fostering innovation, providing financial investment, and contributing research on risk assessments and building materials suited to mountain areas. Promoting open data and accountability within these partnerships is equally vital, as it enhances transparency, builds trust, and supports a more coordinated and equitable risk management.

In the Himachal Pradesh State Roads Transformation Project (HPSRTP)[11], local communities and women's self-help groups participate in planning and maintaining roads, while NGOs, research experts, and technical partners contribute guidance on materials and risk assessments. Participatory mechanisms and open data promote transparency, trust, and coordinated, system-wide infrastructure improvements.

5.1.2. Advancing multi-hazard risk-informed decision making

Disaster resilient infrastructure in mountains depends on robust multi-hazard (MH) risk assessments that account for the cascading and interconnected nature of climate-related and geophysical hazards. Conventional single-hazard approaches often overlook these linkages, resulting in fragmented interventions and persistent vulnerabilities. Effective MH risk-informed decision making requires integrating climate projections, socio-economic scenarios, and Indigenous and local knowledge into planning processes, supported by harmonized data systems and participatory approaches.

To operationalize this transition from single-hazard to multi-hazard approaches, the UNDRR (2022b) recommends applying principles for resilient infrastructure to guide risk-informed policy, investment, and sectoral systems across transportation, energy, communications, water, health, and education. Since complex multi-hazard

11 Himachal Pradesh Road & Other Infrastructure Development Corporation Ltd. (HPRIDC). *Stakeholder Engagement Plan – Himachal Pradesh State Roads Transformation Program.* https://himachalservices.nic.in/hpridc/New%20Stakeholder%20Engagement%20Plan_27.09.2021.pdf

risks are frequently underrepresented in existing risk assessments, additional efforts are needed to anticipate cascading impacts and prioritize interventions. For instance, the Aga Khan Agency for Habitat (AKAH)[12] collaborates with communities in Afghanistan, India, Pakistan, Syria, and Tajikistan to ensure that homes, schools, hospitals, and other critical infrastructure are resilient to withstand multiple hazards.

5.1.3. Advancing Cross-Sectoral and Multi-Level Governance to Enhance Adaptability and Coordination

Traditional governance systems are often siloed by sector (e.g., energy, agriculture), time horizon (e.g., short-term vs. long-term) or administrative level (e.g., local, regional, national), which can limit coordination across sectors and levels of governance, leaving infrastructure assets vulnerable to shocks and stresses and amplifying vulnerabilities in mountain areas. Consequently, there is an urgent need for governance and policy systems that are adaptive, coordinated, transformational, and risk-informed.

To address these challenges, risk governance requires horizontal coordination beyond single sectors and seamless vertical alignment of institutions across local, national, and international scales. It must transcend traditional silos and move beyond reactive measures towards an anticipatory approach. This entails building institutional capabilities to foresee plausible future scenarios, plan for rare but severe events, and incorporate insights from past experiences into ongoing governance improvements. Practical steps include revising legal mandates, adjusting budgetary processes, enhancing decision-making procedures, and updating infrastructure codes and standards to reflect evolving climate conditions and multi-hazard risks (Kannan et al., 2021; Alcántara-Ayala, 2025).

For instance, the construction of dams must consider long-term issues such as erosion and sedimentation management to ensure functionality over time. Without coordination and strategic foresight—particularly in addressing climate change and natural hazards—resilience efforts risk being fragmented rather than systemic (Kannan et al., 2021).

5.1.4. Investing in Early Warning Systems and Anticipatory Action

Initiatives such as the Early Warning for All (EW4All) exemplify an anticipatory approach by advocating for inclusive, multi-level, and people-centered early warning systems that strengthen governance and policy dimensions. The EW4All initiative highlights the importance of coordination, accountability, and inclusive decision-making in governance for resilient infrastructure. For mountain regions, early warning systems must be adapted to account for specific hazard profiles, communication challenges in remote areas, and the need to reach all community members effectively. These systems should be integrated with

12 Aga Khan Agency for Habitat, "Safe and Sustainable Construction," Aga Khan Development Network. https://the.akdn/en/how-we-work/our-agencies/aga-khan-agency-habitat/safe-and-sustainable-construction

anticipatory action frameworks that enable proactive measures before disasters strike, considering the particular vulnerabilities and response capacities of mountain communities.

For instance, the UNESCO/Adaptation Fund project on Glacial Lake Outburst Floods in Central Asia (GLOFCA)[13] illustrates how early warning systems in mountain regions must operate on extremely short timescales. Unlike many hydro-meteorological forecasts that provide only several days' advance notice, GLOFCA's alerts can act within minutes. The project combines advanced monitoring technologies with public awareness campaigns, community drills, and institutional coordination. Designed to be cost-effective, scalable, and applicable to other hazards such as landslides, GLOFCA collaborates with communities and national authorities to develop systems tailored to the unique geographical, infrastructural dynamics of remote mountain areas.

5.2. Recommendations for Mobilizing Finance and Investment for Equitable and Resilient Mountain Infrastructure

5.2.1. Strengthening investment through diversified financing mechanisms

Attracting and maintaining investment in mountain regions remains a persistent challenge due to higher costs of delivery of goods and services, difficult terrain, and sparse populations that limit financial returns. These conditions often place mountain communities at a disadvantage when it comes to securing adequate and sustainable infrastructure (Kato et al., 2021). Investing strategically in resilient mountain infrastructure through diversified financing is therefore critical to protect communities, ecosystems, and sustainable socioeconomic development.

Governments and development cooperation partners have introduced mechanisms to finance climate resilience initiatives in mountain areas. These include integrating climate considerations into national and local budgetary processes, ensuring that sectoral investment plans systematically account for climate risks, and establishing incentives that improve the risk–return balance for private actors (Kato et al., 2021). This can be complemented by the allocation of dedicated annual budgets by line departments for infrastructure resilience, guided by historical damage and loss data.

Mobilizing capital for disaster resilient infrastructure in mountains requires a comprehensive, multi-pronged financial strategy. Key options for mobilizing capital include:

- Public and multilateral funding is essential to bridge investment gaps relative to mountain areas. International climate

13 Glacial Lake Outburst Floods in Central Asia (GLOFCA) implements early warning systems for glacial lake floods, integrating monitoring, communication, and community preparedness. https://glofca.org/en/early-warning-systems/

funds such as the Green Climate Fund and Adaptation Fund are particularly relevant for supporting adaptation and resilience projects.

- Public-Private Partnerships (PPPs) enable governments to leverage private capital and expertise while sharing risks, making investment in remote or high-cost mountain areas more feasible.

- Private funding instruments, such as insurance, can shield investors, governments, and communities from the financial impacts of climate-related disasters. In particular, parametric insurance—also known as event- or index-based insurance—covers risks that were previously not insured, bridging gaps left by conventional policies and protecting vulnerable communities and economies (WEF, 2025). Along with greater philanthropic engagement (Adaptation at Altitude, 2024), these instruments offer additional avenues for developing and supporting disaster resilient infrastructure in mountain areas.

- Sustainable finance instruments such as green bonds, blended finance, and other mechanisms can direct investment towards climate-resilient and sustainable infrastructure projects.

5.2.2. Promoting community benefit-sharing mechanisms

Engaging local communities goes hand in hand with sharing project benefits, which is a key approach for ensuring that host communities also receive a fair share of the profits generated (CAN Europe, 2025). Benefit-sharing can take many forms and generally encourages governments and project developers to distribute benefits fairly among stakeholders, with particular attention paid to those most negatively impacted, helping to build local support and legitimacy for projects. Benefit-sharing mechanisms should be adapted to the local context to align with both community needs and project objectives. While each mechanism is unique, the World Bank (2024) identifies common principles that apply across sectors:

- Benefits are often designed to reach not only those directly affected but also the wider area influenced by a project, reflecting the broader impacts.

- The sources of funding and types of benefits can emerge at any stage of the project lifecycle and may take the form of monetary transfers or different forms of in-kind contributions, such as capacity building or local employment. During planning and construction, benefits may come from the project's capital budget or corporate social responsibility programmes. Once the project is operational, they may be drawn from taxes, royalties, or equity participation. In certain cases, dedicated funds are established to prepare for a project's eventual completion.

- The ultimate goal is to improve the well-being of local communities, which requires ongoing engagement and dialogue throughout the life of the project.

Infrastructure Risks and Adaptation Priorities in Mountainous Countries' National Reports

Countries provide information on their climate risks and adaptation needs through various national reports submitted to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat. National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) are two of the most important national reports that countries prepare to support their domestic climate action planning (UNFCCC, 2024). A review of such NDCs and NAPs of 36 developing countries across the six major mountainous regions worldwide , shows that infrastructure consistently appears as one of the most exposed elements to climate hazards. In addition to buildings and human settlements, countries highlight that critical infrastructure—such as transportation networks, hydropower and energy systems, health facilities, and schools—is highly exposed to climate hazards in mountainous countries.

To respond to climate risks in the infrastructure sector, several countries have identified adaptation needs in their NDCs, NAPs, and other domestic policies and plans. Proposed measures emphasize climate-proofing critical infrastructure, greening and retrofitting cities, building resilient water and transport systems, upgrading housing and health facilities, and pursuing institutional and policy reforms. A common thread across these measures is the integration of climate resilience into urban planning and infrastructure development, with emphasis on nature-based solutions (NbS) and community engagement. However, not all countries—particularly in Central Asia, the Andes, and the Western Balkans—have developed NAPs, leading to gaps in adaptation planning.

Infrastructure adaptation finance needs

Given the high exposure and vulnerability of infrastructure in mountainous regions with complex terrain and variable climates, urgent investment in disaster resilient infrastructure and climate-proof housing is required. Financing needs for climate change adaptation and DRR in developing countries are substantial. According to the UNEP (2025) estimates, the total adaptation finance needs of the 36 developing countries in the six mountain ranges amount to approximately $250 billion per year, with a range of $84–792 billion annually (in 2023 prices). This estimate covers all sectors at the national level and includes large economies such as China and India, where absolute financing needs are comparatively high. Overall, these needs account for around 1 percent of GDP, ranging from 0.3 percent to 3 percent. Within the six mountain regions, the infrastructure sector alone requires around 20 percent of total adaptation finance, ranking among the top three sectors alongside agriculture and food, and water supply. In contrast, international adaptation finance flows to developing countries remain 12–14 times lower than actual needs (UNEP, 2025), highlighting a significant adaptation finance gap in the infrastructure and other sectors.

Financing climate change adaptation in developing countries also raises issues of climate justice, where international public finance should play a leading role. The New Collective Quantified Goal (NCQG), agreed at UNFCCC COP29 in 2024, commits to mobilizing at least $300 billion per year by 2035 for climate action in developing countries. This commitment of international climate finance for both mitigation and adaptation falls well short of actual needs and is unlikely to meet the adaptation finance needs. Bridging the gap will require significant contributions from both domestic and private sector finance. In sectors where the return on adaptation investment is low or below market rates—such as health, livelihoods, ecosystems, and biodiversity—public finance should take primary responsibility (OECD, 2023). By contrast, the infrastructure sector shows relatively strong potential for commercially viable returns on adaptation investments, offering greater opportunities for private sector engagement to help close the adaptation finance gap.

5.3. Recommendations for Planning and Designing Resilient Mountain Infrastructure

5.3.1. Integrating Indigenous and Local Knowledge and Ecosystem-based Adaptation in risk-informed planning

Integrating Indigenous and local knowledge (ILK) as well as Ecosystem-based Adaptation (EbA) is vital for designing innovative, resilient, and culturally appropriate infrastructure in fragile mountain ecosystems. This approach moves beyond traditional "grey" engineering by drawing on the deep knowledge of local communities. For instance, such knowledge helps identify areas prone to natural hazards through long-standing observations of local hazard patterns (Hadlos et al., 2022), recognize native species that contribute to soil stabilization and water retention (Allen, 2023), and apply traditional land and water management practices that have proven functional and reliable over centuries (Sharma & Ji, 2024; Garnett et al., 2018). Neglecting this knowledge risks producing infrastructure that is unsuitable to local conditions and less effective in reducing disaster risk (OECD, 2021).

> *During the 2024 Noto Peninsula earthquake in Japan, knowledge of old wells immediately saved lives. Greenhouse also served as a private emergency shelter. Strong social bonds served as mutual aid during this time.*
>
> *— Dr. Yuta Hara, Assistant Professor, International Research Institute of Disaster Science (IRIDeS), Tohoku University*

EbA can leverage biodiversity and ecosystem services to provide cost-effective, flexible, and applicable solutions (Munang et al., 2013). Techniques such as soil bioengineering can enhance natural processes. In Himachal Pradesh, India, communities have applied simple bioengineering techniques combining vegetation with structures like gabion walls, which effectively increase slope stability (Bahri, 2024). Similarly, restoring wetlands and watersheds enhances water retention and regulates flows, while preserving vegetation that serves as a natural buffer against floods, landslides, and other hazards. In the Pozuelos Biosphere Reserve, Argentina, a collaborative initiative has implemented sustainable grazing practices and wetland restoration actions, benefiting local communities and improving water management (Wetlands International, 2024).

> *A concrete example is the Mountain Knowledge Center in Sajama, Bolivia, which integrates climate and glacier monitoring with local water governance and is managed by the community. In water management, projects in Sajhuaya and Sajama have promoted the protection and restoration of high-Andean wetlands (bofedales), which act as natural water storage systems replacing the regulation function of retreating glaciers.*
>
> *— Paula Pacheco, PhD candidate, University of Montpellier*

Risk-informed planning and regulations should integrate both scientific evidence and ILK to capture the dynamic nature of mountain environments. This includes incorporating comprehensive risk assessments, climate projections, and prioritization of EbA or hybrid green-grey solutions, which can generate multiple co-benefits such as biodiversity conservation, improved water regulation, and livelihood opportunities. For instance, the Global Mountain EbA Programme in Nepal has implemented riverbank conservation using engineered structures paired with bamboo plantation, gully- and landslide-control measures, and restoration of degraded lands to improve water regulation and support local communities (UNDP, 2015). Ensuring social equity and justice in the design, governance, and implementation of EbA is critical to prevent creating new risks or unfairly shifting costs and burdens onto vulnerable groups (Boyland et al., 2022).

> *DRI offers various benefits because it significantly reduces negative impacts and losses. And mountain communities directly benefit from this but also need to be involved and integrated in the process of developing or building DRI because this may involve certain trade-offs or conflicts of interest that need to be tackled in a comprehensive way. Ecosystems may benefit when DRI is designed and implemented in a way that considers ecosystem functioning, e.g., through nature-based solutions.*
>
> *— Prof. Dr. Christian Huggel, Professor, Environment and Climate, University of Zurich*

5.3.2. Paving the way for gender-responsive and socially inclusive infrastructure

Gender-responsive and socially inclusive infrastructure is particularly critical for women and other vulnerable groups, including youth, the elderly, and persons with disabilities, as they are often disproportionately affected when infrastructure systems fail and essential services are disrupted. Infrastructure becomes socially inclusive and gender-equitable when it is planned, designed, implemented, and managed with the needs of all users in mind. Gender-responsive infrastructure should ensure implementing respective actions across all stages of projects, such as mainstreaming gender considerations, delivering gender-focused training and capacity building for both project teams and local communities, and involving social inclusion specialists to guide activities (Menon, 2019; Morgan et al., 2020).

For instance, in the framework of the Saving High Andean Wetlands for Nature and People Programme, Wetlands International advanced the project "Empowering Andean Women for Sustainable Water Management in the Wetlands of the Puna Region." [14] The project trains women in the installation and maintenance of clean and renewable technologies, such as solar pumps and automatic drinking fountains, as well as in advocacy and organizational skills. By doing so, it helps reduce the physical workload traditionally carried by women, freeing up time for education, income-generating activities, and community engagement. At the same time, it provides women with new opportunities for personal and collective development, strengthening both social inclusion and local resilience.

5.4. Recommendation for Execution, Operation, and Maintenance of Resilient Mountain Infrastructure

5.4.1. Ensuring robust planning and budgeting for operations and maintenance

A critical yet often overlooked aspect of infrastructure resilience is the establishment of robust operations and maintenance (O&M) systems from the outset of project planning. Many infrastructure projects fail to adequately consider the long-term costs and efforts required for maintenance during the design and construction phases, leading to premature deterioration and functional failures. Effective O&M practices involve regular inspections and repairs to ensure infrastructure continues to function safely over its intended lifespan. This requires the development of Standard Operating Procedures (SOPs) that provide clear, step-by-step instructions for operation and maintenance activities. Additionally, the

14 Wetlands International, *Empowering Andean Women for Sustainable Water Management in the Wetlands of the Puna Region,* Saving High Andean Wetlands for Nature and People Programme, 2024. https://lac.wetlands.org/el-rol-de-las-mujeres-para-la-conservacion-de-los-humedales-de-la-puna/

incorporation of redundancy—such as having backup systems or extra capacity—ensures that critical infrastructure can maintain functionality during extreme events. Crucially, dedicated annual budget allocations by line departments for infrastructure maintenance and resilience strengthening should be established based on historical damage and loss information. By planning for maintenance from the beginning and ensuring adequate financial resources throughout the infrastructure lifecycle, mountain regions can avoid the costly cycle of neglect and emergency repairs while ensuring long-term resilience.

For instance, in Baja California, Mexico, the development of a pavement management model for the Centinela–La Rumorosa Highway demonstrates how systematic planning can enhance infrastructure performance and sustainability. The model integrates georeferenced pavement condition data, structural assessments, and annual maintenance simulations to guide resource allocation and rehabilitation decisions. By providing a structured process for collecting and analyzing road data, the approach enables road agencies—particularly in resource-limited contexts—to optimize maintenance planning, extend the service life of transport infrastructure, and deliver safer, higher-quality road networks [15].

5.5. Recommendations for Advocating for Mountain Priorities in International Frameworks and Climate Policy

The period 2023–2027 has been designated as the "Five Years of Action for the Development of Mountain Regions," building upon the International Year of Sustainable Mountain Development 2022. This initiative, endorsed by the UN General Assembly through resolution A/RES/77/172[16], underscores the need to invest in disaster risk reduction for resilience, address the unique vulnerability of mountain communities, and include mountain-specific policies into national sustainable development strategies.

Aligned with this, the UN Secretary-General's 2025 report (A/80/255)[17] emphasizes the importance of integrating mountain-specific considerations into global climate action and development frameworks. The Expert Dialogue on Mountains and Climate Change [18]convened by the UNFCCC, has further

15 Montoya-Alcaraz, M., Mungaray-Moctezuma, A., & García, L. (2019). Sustainable road maintenance planning in developing countries based on pavement management systems: Case study in Baja California, México. *Sustainability,* 12(1), 36. https://doi.org/10.3390/su12010036

16 Resolution adopted by the General Assembly on 14 December 2022, https://docs.un.org/en/A/RES/77/172

17 United Nations, S*ustainable Mountain Development: Report of the Secretary-Genera*l, A/80/255. https://docs.un.org/en/A/80/255

18 United Nations Framework Convention on Climate Change (UNFCCC), *Informal Summary Report on the Expert Dialogue on Mountains and Climate Change.* https://unfccc.int/sites/default/files/resource/Informal%20Summary%20Report%20on%20the%20Expert%20Dialogue%20on%20Mountains%20and%20Climate%20Change.pdf

highlighted the critical role of mountains in climate resilience, advocating for enhanced scientific collaboration and regional-level cooperation, where countries can synergize their efforts to build resilience together.

Likewise, the UNFCCC's Global Stocktake[19] at COP28 recognized mountains as a priority thematic area, citing them five times in the final document and calling for increased ambition in adaptation actions. Additionally, the Convention on Biological Diversity's Programme of Work on Mountain Biological Diversity[20] provides a framework for conserving mountain ecosystems, highlighting the role of Indigenous and local communities in protecting biological diversity, the fragility of mountain ecosystems—especially in the context of climate change—and the interactions between upland and lowland areas.

Together, these frameworks and dialogues underscore the importance of advocating for the inclusion of mountain-specific considerations in key UN outcome documents, particularly concerning disaster risk reduction. Ensuring such inclusion is crucial for directing attention, resources, and support to enhance the resilience of mountain communities and advance broader sustainable development goals.

19 Food and Agriculture Organization (FAO), *Mountains Cited Five Times in Key COP 28 Final Document.* https://www.fao.org/mountain-partnership/news/newsroom/news-detail/Mountains-cited-five-times-in-key-COP-28-final-document/en

20 Convention on Biological Diversity (CBD), P*rogramme of Work on Mountain Biological Diversity.* https://www.cbd.int/mountain/pow.shtml

Image by Nikola Tasic on Unsplash

6. Call for Collective Action on DRI in Mountains

Mountain communities face disproportionate exposure to climate-related hazards, yet their infrastructure—roads, bridges, energy systems, water networks, and communications—remains fragile, poorly maintained, and underprepared for the cascading and compounding risks of climate change. The complex terrain, harsh climatic conditions, and remoteness of these areas amplify the consequences of infrastructure failure, making resilience not optional, but a necessity. Evidence from recent events in the Himalayas, Andes, and Central Asia underscores a sobering reality: infrastructure failure is not just a technical issue—it is a societal crisis.

Building disaster resilient infrastructure in mountains requires more than engineering solutions. It demands an integrated, coordinated, multi-level approach. This includes technical innovation, ecosystem-based solutions, Indigenous and local knowledge, and governance that is adaptive, transformational, risk-informed, and inclusive. Stakeholders across sectors must collaborate to ensure that the planning, development, operations, and monitoring of infrastructure reflect mountain-specific challenges, account for cascading hazards, and maintain critical services during crises. Multi-hazard risk-informed assessments must be standard practice, capturing the interlinked and cascading nature of geophysical and climate-induced hazards. Roads, highways, bridges, and critical infrastructure require updated, mountain-specific standards and codes that reflect local geographies, environmental conditions, and climate projections. Early warning systems, IoT monitoring, and digital connectivity must be deployed in combination with community-centered response strategies to ensure that people remain connected and protected even when physical infrastructure is compromised.

Indigenous and local knowledge, combined with ecosystem-based approaches, offers vital tools for resilient infrastructure design, implementation, and monitoring. Communities across mountain regions have long used terracing, agroforestry, wetland restoration, and soil bioengineering to stabilize slopes, regulate water, and reduce disaster risks. Integrating these proven approaches with engineering and technological solutions not only strengthens physical infrastructure but also reinforces social cohesion, local governance, and community-led adaptation. Neglecting this knowledge risks creating infrastructure that is inappropriate to the context, costly, or ineffective in reducing disaster impacts. Communities themselves are essential partners in these efforts. Their knowledge is indispensable for understanding hazard dynamics, identifying hazard-prone areas, informing the design of context-appropriate infrastructure, and ensuring maintenance practices are sustainable and culturally relevant.

Financing disaster resilient infrastructure in mountains is urgent. Infrastructure adaptation requires substantial public and private investment, innovative financing mechanisms, and sustained funding for operations and maintenance. The adaptation finance gap is acute in mountain regions, and delays in allocating resources translate directly into vulnerability and loss. Strategic investments in resilient infrastructure deliver multiple dividends: they protect lives, maintain essential services, preserve ecosystems, and enhance the economic viability of mountain communities. Governments, development partners, investors, and philanthropic organizations must prioritize and coordinate funding to ensure these investments are timely, sustained, and equitable.

We cannot afford to wait. Every stakeholder has a role to play, and mountain regions cannot afford inaction. By committing to systemic, multi-hazard risk-informed, and community-centered approaches to disaster resilient infrastructure, we can safeguard lives, livelihoods, and ecosystems—and ensure that mountain communities are not left behind. The choices we make today will determine whether mountain infrastructure is a source of vulnerability or a foundation for resilient, thriving communities for generations.

Image by Yasser Mir, Unsplash

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