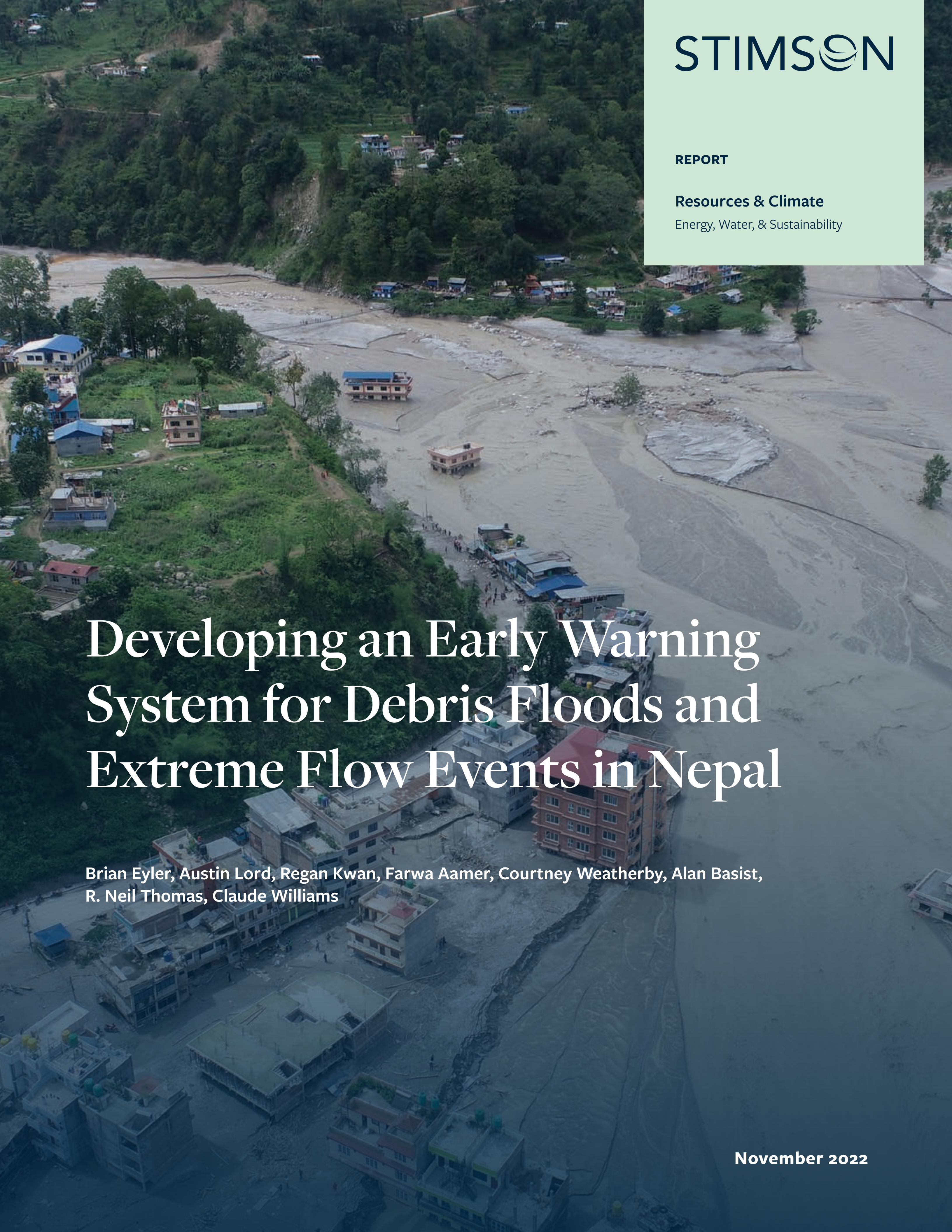

STIMSON

REPORT

Resources & Climate
Energy, Water, & Sustainability

Developing an Early Warning System for Debris Floods and Extreme Flow Events in Nepal

Brian Eyler, Austin Lord, Regan Kwan, Farwa Aamer, Courtney Weatherby, Alan Basist, R. Neil Thomas, Claude Williams

November 2022

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Brian Eyler, Austin Lord, Regan Kwan, Farwa Aamer, Courtney Weatherby, Alan Basist, R. Neil Thomas, Claude Williams, 2022, *Developing an Early Warning System for Debris Floods and Extreme Flow Events in Nepal*. The Stimson Center, Washington D.C., USA.

Cover image: Melamchi Bazaar after 2021 debris flow.
Photo taken by Pravin Lamsal, Geovation/Nepal Flying Labs.

November 2022

Developing an Early Warning System for Debris Floods and Extreme Flow Events in Nepal

> **This report explores a pathway to a real-time risk monitoring and early warning system (EWS) for debris floods and extreme flow events in Nepal.**

By Brian Eyler, Austin Lord, Regan Kwan, Farwa Aamer, Courtney Weatherby, Alan Basist, R. Neil Thomas, and Claude Williams

Debris floods and extreme flow events have long posed serious risk to communities and infrastructure in Nepal. These disasters are unique because they can be triggered by a range of geohazards and have the potential to run-out over long distances, causing extensive damage downstream. This report outlines a rationale and process to assessing risk and implementing an early warning system (EWS) for debris floods and extreme flow events. We build on a robust reservoir of scientific knowledge and the efforts of government agencies, communities, and NGOs in Nepal to reduce risk to debris floods and other geohazards. The report demonstrates how remote sensing methods, hydrometeorological data, and information collected by communities can be integrated into an innovative system which monitors and communicates risk in real time. We emphasize the importance of a community-oriented approach throughout and outline co-creation process with partners at multiple scales including the Government of Nepal and other like minded NGOs and institutions to develop the EWS.

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Executive Summary

This report proposes an integrated approach to the development of a nationwide, real-time risk monitoring and early warning system (EWS) for debris floods and other extreme flow events in Nepal. Advances in remote sensing and earth observation techniques make it possible for such a system to be designed and implemented in a timely manner and at a relatively low cost. Importantly, existing efforts of government agencies, communities, and non-governmental organizations—which include field-based methods and investment in EWS infrastructure—also demonstrate a base capacity upon which this early warning system can be built. Further, the reservoir of scientific knowledge published by regional experts and members of the global scientific community focused on Nepal and the Hindu Kush-Himalaya region is reaching a level of robustness that is already pointing the way toward advances in risk monitoring and early warning for a range of natural hazards. What is currently missing from this array of advances and opportunities is a systematic and coordinated effort to integrate these elements together within an inclusive and collaborative program focused on the development of early warning systems for a broad spectrum of mountain hazards.

Nepal is one of the most disaster-prone countries in South Asia, owing to its turbulent geological and meteorological position. The peoples of Nepal have long been subject to recurring earthquakes, flooding, landslides, and a broad array of other hazard regimes, and many of these hazard regimes are growing more volatile due to the impacts of climate change. In the Himalayas, under certain conditions, these hazards combine to produce complex, cascading disasters that cause intense patterns of damage and losses within downstream communities and disrupt critical infrastructure. Human interventions, often in the form of new infrastructure projects also can introduce new risk factors and patterns of vulnerability which may amplify the impacts of cascading disasters. Risk monitoring and EWS for specific kinds of disasters do exist throughout Nepal, but they are often limited in scope or focused on one region or a single hazard type. Other programs utilize approaches that are either too top-down or too bottom-up in orientation to achieve or sustain desired outcomes. As hazard regimes shift, new tools, modes of coordination, and interdisciplinary collaborations are needed to formulate scalable and sustainable EWS approaches. We aim to develop new systems that can augment and elaborate on existing systems while linking efforts across diverse sites and scales.

After a careful review of the state of the art for risk monitoring across a range of natural hazards, we have selected debris floods and extreme flow events as an initial lens for nationwide EWS in Nepal. Debris floods, like the 2021 Melamchi Disaster, are the result of cascading hazards with a high water content that tend to run-out across long distances causing extensive downstream damages. Predicting the likelihood and severity of debris floods and extreme flow events requires complex monitoring and assessment methods. Yet the complexity of contributing factors to debris floods offers the widest lens of features and conditions to observe, thus providing numerous opportunities for risk assessment and monitoring that might help to anticipate other kinds of potential hazards. Overall, our goal is to develop systems that can issue an effective prior warning, to empower individuals at the state and community level to make the most informed and appropriate response to latent and emergent disaster risks.

With this scoping study, we seek to gather our resources and sketch out the process by which we could collaborate with partners to create a useful toolkit for a nationwide EWS for debris floods and extreme flow events in Nepal. At all levels, we assert that it is critical to undertake a community-oriented approach: to consider the socialization of EWS tools and procedures, to engage the diverse communities they serve, and wherever possible to co-create the approach with local stakeholders. With these principles in mind, this report also outlines how we plan to build that toolkit in future phases of this project through a process of co-creation: working with partners at multiple scales including the Government of Nepal, other like-minded NGOs operating in Nepal with common interests and complementary skill sets, and communities and local institutions in disaster areas.

List of Acronyms and Abbreviations

API	Application Programming Interface
AWS	Automatic Weather Station
BIPAD	Building Information Platform Against Disaster
CFGORRP	Community-Based Flood and Glacial Lake Risk Reduction Project
DEM	Digital Elevation Map
DHM	Department of Hydrology and Meteorology (Nepal)
DRR	Disaster Risk Reduction
EWS	Early Warning System(s)
GAPHAZ	Glacier and Permafrost Hazards in Mountains (working group)
GDP	Gross Domestic Product
GIS	Geographic information system
GLOF	Glacial lake outburst flood
GPS	Global Positioning System
HKH	Hindu-Kush Himalaya (a common term for the broader Himalayan region)
ICIMOD	International Centre for Integrated Mountain Development
IMS	Interactive Multisensory Snow and Ice Mapping system
INGO	International non-governmental organization
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
KLL	Kathmandu Living Labs
LEWS	Landslide early warning system
MODIS	Moderate Resolution Imaging Spectroradiometer
MSMRMF	Mountain-specific multi-hazard risk management framework (India)
NASA	National Aeronautics and Space Administration (USA)
NDRRMA	National Disaster Risk Reduction Management Authority (Nepal)
NEOC	National Emergency Operation Center (Nepal)
NGO	Non-government organization
NSET	National Society for Earthquake Technology-Nepal
PDNA	Post Disaster Needs Assessment (after the 2015 Gorkha Earthquake)
PIN	People in Need (International NGO working in Nepal)
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
SSMI	Special Sensor Microwave Imagery
TE28	Tempest Express 28
UNDP	United National Development Programme
UNISDR	United Nations Office for Disaster Risk Reduction
UNOPS	United Nations Office for Project Services
USGS	United States Geological Survey

Namche Bazaar. View on the Mount Everest range on the way to Thyangboche. Photo taken by Flickr user Guillaume Baviere in 2018 and used courtesy of a Creative Commons license.

Introduction

Nepal is one of the most disaster-prone countries in South Asia, owing to its turbulent geological and meteorological position. The people of Nepal are subject to recurring earthquakes, flooding, landslides, and a broad array of other hazard regimes - many of which are growing more volatile due to the impacts of climate change. Nepal is considered among the top 10 countries most impacted by climate change, with some rankings placing it 4th.[1] These patterns of climatic vulnerability are driven by increasing climatic volatility, an increasing number of extreme precipitation events which cause catastrophic flooding, shifting landslide regimes, and climate impacts in the mountain cryosphere. Chronic problems of poverty and underdevelopment, coupled with the intersectional impacts of social exclusion, place many Nepalis in an extremely precarious position.

Nepal is considered a "hotspot" for mountain hazards and is prone to Glacial Lake Outburst Floods (GLOFs) and landslide-induced floods, which can snowball into complex cascading events that pose significant economic and humanitarian risks to communities and infrastructure projects.[2] [3] [4] Experts use a variety of different terms to categorize these unwieldy and hybrid events, to account for the cascading processes that generate them. Scientists have used the term "extreme flow events" to refer to a class of cascading events similar to the Chamoli Disaster of February 2021,[5] while other scientific working groups might characterize such an event within the category of catastrophic mass flows.[6] In this report, we focus on what we call "debris floods" and extreme flow events, understood as a particular genre of cascading hazards. The June 2021 Melamchi Disaster, a complex and unforeseen event that displaced over 100 families and severely damaged the Melamchi Water Supply Project, critical infrastructure for Kathmandu, serves as an example of this type of cascading disaster and a case in point.

These events served as important catalysts for conversations around early warning systems (EWS) in Nepal. Climate change and the emerging patterns of urbanization further highlight the need for an EWS to prepare for and build resilience in the face of natural calamities. The EWS which currently exist in Nepal rely mostly on the collection and analysis of limited streams of physical data and are not sophisticated enough to detect the precise location and time of floods, nor are they capable of real-time or near-real-time monitoring of dynamic cascading events. Lines of communication around disaster awareness and early warning are also inchoate and often do not reach vulnerable people in a timely or effective way – which makes a multi-scalar analysis of social and political factors an essential part of EWS design.

The reservoir of scientific knowledge, mostly published in the form of academic studies of past disasters, is reaching a level of robustness that could soon make possible new forms of monitoring and risk evaluation. Much of the existing work in Nepal has focused on the 2021 Melamchi disaster, severe debris flows resulting from GLOF in the upper Bhotekoshi river basin over the last decades, and efforts for landslide risk assessment and monitoring after the 2015 Ghorka earthquake. Cases outside of Nepal such as the 2021 Chamoli disaster and the 2020 Uttarakhand floods, both of which occurred in the Indian Himalaya (within mountain environments similar to Nepal), demonstrate common hazards across the Himalayan region.

When taken as a whole, existing studies map out a comprehensive range of geophysical hazards and methods which can be used to monitor and assess risks related to these hazards. Recommended methods for risk assessment and monitoring typically comprise a mix of on-ground monitoring infrastructure, as well as remote sensing techniques and GIS analysis which have become more readily available and applicable in the last decade at increasingly lower costs. Many of these techniques and analytical processes are available on free and open-source software and data archives suitable for low-income countries like Nepal. Reading these studies chronologically provides a clear view of the rapid evolution in risk assessment processes which narrows past gaps in understanding and the aperture of uncertainty. While many of these studies focus on singular trigger factors of hazards, a few academic efforts have begun to examine and explain interrelated processes that can turn individual hazards into complex, cascading disasters that deliver the greatest loss of life and the highest severity of damage to communities and infrastructure. Using a blend of remote-sensing and field-based analysis, we seek in this study to map out the steps one can take to transition from a retroactive study of a past disaster to anticipatory action in Nepal's disaster risk reduction sector.

For a variety of reasons, the conclusions of scientific studies often do not reach key actors in the disaster risk reduction or policy planning sectors who can translate those findings into action. This science-action or science-policy gap is a problem not unique to Nepal. This report demonstrates that a comprehensive set of actors in Nepal are actively working or well poised to engage in disaster risk reduction and early warning for geophysical hazards in Nepal. Yet despite an urgent need to implement EWS, proper mobilization of these actors is challenged by uneven capacities in human and physical capital between government and non-government stakeholders and between national-local levels of government. Importantly, donor support within this sector can also be mercurial. This leads to a sub-optimal deployment of initiatives that could respond to this urgency.

Historically, both scientific studies and state-supported initiatives for assessing risk in Nepal have tended to be top-down in orientation and lacked meaningful engagement with at-risk communities that recognizes and incorporates localized knowledge and locally situated modes of assessing and responding to risk. The top-down approach can result in miscommunication and misunderstanding, or even erroneous messaging and 'study fatigue', which can undermine the effectiveness of any resulting early warning system. Further, a more inclusive, bottom-up approach can harness the energies of citizen scientists and crowd-sourced data from social media or other platforms which already have community use and buy-in can result in more effective risk assessment and timely issuance of early warning.

Ultimately this report outlines a preliminary model for nationwide risk assessment, monitoring, and EWS focused on debris floods and other extreme flow events created by the failure of natural dams and triggered by climatic or other extreme events. The model combines existing methods with unique remote sensing and GIS analysis methods derived by the project team. We hypothesize that while predicting the likelihood and severity of this kind of disaster requires complex monitoring and assessment methods, the complexity of contributing factors to debris floods offers the widest lens of features and conditions to observe. With appropriate investment in physical and human capital, these features can be prioritized and focused on days to weeks prior to failure. The benefit of time provided by this particular lens of debris flood assessment and monitoring would also provide more opportunity to forecast impacts, issue effective prior warning, and empower individuals at the state and community levels to make the most appropriate response decision.

At all levels, it is critical to undertake a community-oriented approach: to consider the socialization of EWS tools and procedures, to engage the diverse communities they serve, and wherever possible to co-create the approach with local stakeholders. It is critical to recognize the knowledge and agencies of communities potentially exposed to geohazards. This means recognizing that no person or community is inherently vulnerable, but rather that conditions of vulnerability are socially and historically produced. Working toward disaster risk reduction by improving EWS and other hazard-focused forms of anticipatory action can help reduce exposure, but it cannot by itself resolve all issues related to social vulnerability. Our goal is to view the project of designing an EWS system as a social *process* and to try to create spaces within that process for community empowerment.

This report, which focuses largely on the geophysical and technical issues that could shape the process of designing an EWS for cascading hazards and flows, is the first step in that process - but we are always thinking ahead to future phases where community engagement will be critical. In doing so, we draw from recent scholarship which considers the ways in which differently situated communities relate to EWS programs in Nepal,[7] [8] [9] [10] as well as ongoing studies of the ways people relate to shifting Himalayan hazards over time.[11] [12] [13] We are acutely aware of the politics inherent in framing disaster risks and uncertainties which are differently conceptualized and experienced "from above and below".[14] While our treatment of community concerns may seem thin at this scoping and pre-fieldwork phase of our study, that is partly because we are waiting to hear what communities facing these issues think: how they conceptualize these issues and what they think is necessary, helpful, or possible. With this scoping study, we seek to gather our resources and sketch out the process by which we might create a useful toolkit. In future phases of this project, we plan to build that toolkit, through a process of co-creation: working with partners at multiple scales including the Government of Nepal, other like-minded NGOs operating in Nepal with common interests and complementary skill sets, and communities and local institutions in disaster areas. This report marks a critical waypoint in the broader process of developing and applying these EWS tools, but this process has only just begun.

A Map of this Report

Section 1 unpacks a comprehensive array of background conditions and geophysical hazards which contribute to natural disasters in both a global and Nepalese context. Understanding these broader processes and typologies of mountain hazards is critical to understanding the complex multi-hazard interactions that shape cascading hazards. Illustrations drawn from the deep reservoir of existing scientific research as well as the project team's own efforts visualize these background conditions and geophysical hazards. Further, the current status of global and local mapping and monitoring of these conditions and hazards is discussed.

The remaining sections build into a step-by-step progression of a preliminary model for a nationwide EWS for debris floods and extreme flow events. **Section 2** provides a rationale for why the mapping and assessment of risk around natural dams and debris deposits in river valleys serves as a viable opportunity for a debris flood-focused EWS in Nepal, looking at the 2021 Melamchi Disaster as a case study. We outline an integrated system of how to map and assess risks of individual natural dams as well as risks related to the entrainment/recruitment of debris and other material found in segments between natural dams. By linking these segments and natural dams together and incorporating socioeconomic data from downstream communities, risk scores for corridors and systems of river valleys can be developed. Corridor and system scores can inform decision makers on where to place investment in physical infrastructure for EWS monitoring and develop human capital required to make an EWS system effective and reliable.

Section 3 discusses methods and modalities for real-time monitoring of background conditions. This section also discusses how to build upon existing datasets to create a nationwide inventory of natural dams and at-risk debris deposits as well as the assessment frequencies necessary for updating those inventories so that risk scores can be updated in real-time. Here we demonstrate how our designed EWS would have been put to use to provide early warning ahead of the 2021 Melamchi Disaster.

Section 4 overviews of the organizations already active in Nepal in collecting, analyzing, and/or sharing data on water flow, weather forecasting, and early warning for disaster risk. This section acts as a useful resource in tracking what types of data are already available and where there could be opportunities to coordinate or collaborate on a proposed early warning system. Section 4 also discusses knowledge and awareness gaps and analyzes obstacles to coordination and information sharing as well as capacity challenges among key organizations.

Section 5 outlines the steps needed to co-develop this EWS with local partners across three phases. This section includes a suggestive list of activities and partners needed to prepare and implement the EWS. This section emphasizes the benefits of local consultative processes for incorporating an effective cultural milieu into the implementation of an early warning system. It also explores the technical and on-ground partnerships necessary to achieve success and briefly discusses aspects of ownership of the EWS.

SECTION I:

Overview of Background Conditions and Geophysical Hazards in Nepal

Developing an EWS that focuses on cascading hazards requires understanding the broader field of hazard types and processes: a diverse gamut of possible combinations and pathways along which a hazard can unfold and evolve, eventually becoming an extreme flow event. Natural disasters in Nepal can be singular and localized events, such as a landslide that falls a few hundred meters downslope engulfing a settlement, or complex and cascading events, such as when a landslide dams a river valley and creating an outburst flood hazard, which in turn can trigger other slope failures along the flood path. In the Himalaya, the scale of the topography is such that cascading processes are common. These are the scenarios that we seek to understand and anticipate with this study, focusing on the multiplicity of cascading events that involve multiple geohazards which could culminate in an extreme flow event, like a debris flood.

Debris floods occur under a variety of conditions and a variety of triggers can initiate a cascading hazard chain that eventually becomes a debris flood. For example, a small avalanche or landslide falling into a glacial lake can cause a glacial lake outburst flood (GLOF), which then cascades through downstream reaches collecting previously deposited materials along the river course, swelling with energy and gathering force until it becomes a devastating debris flood. The largest of such events, with volumes over tens of millions of cubic meters, can destroy communities and infrastructure along the flow path, and the impacts of such events can be felt over 100 kilometers downstream (the “run-out distance” increases with the volume and fluid content of the flow). This kind of cascading event can itself destabilize the landscape, changing landforms and increasing the risk of future slope failures. Several such events have occurred in the Himalayan region in recent years—such as the Chamoli Disaster[15] and the Melamchi Disaster of 2021[16]—and many scientists are worried that increasing climatic volatility will only increase the potential for such cascading flow events in the future.

When analyzing mountain hazards or monitoring hazard potential, it is critical to recognize that a variety of different tipping points are possible and that a cascading event is really a chain of tipping points. All scales of slope failures occur when gravity overwhelms the friction in the slope system. The conditions within a slope system are constantly in flux, often hovering around the tipping point for slope failure. Any given Himalayan slope is constantly seeking equilibrium as it emerges and erodes, and this is an ongoing process punctuated

Dig Tsho moraine and outburst fan. Photo taken by Flickr user -MattW- and used courtesy of a Creative Commons license.

by disequilibrium and recurring slope failures. There are several ways this can occur, but basically either the mass which gravity acts on changes (i.e. through the accumulation of snowpack or icy masses, or water saturation of the slope) or the level of integrity or friction changes (i.e. soil conditions, melting permafrost, fractures in rock). Similarly, the total mass or volume that can be mobilized by a triggering event such as seismic activity, precipitation, or human-animal activity is also in flux. The key is to monitor background conditions as they change and to model scenarios for potential tipping points, in anticipation of a potential triggering event.

In this report, we adopt the conceptualization of hazard that the GAPHAZ group has used, itself aligned with the definitional principles of the IPCC and UNISDR: "Hazard is defined herein as the potential occurrence of a natural physical process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. This definition aligns with that of climate adaptation (IPCC, 2014) and disaster risk reduction communities (UNISDR, 2009). Technically, hazard is assessed as a function of the probability that an event will occur and the expected intensity (magnitude) of the event".[17]

Our assessment seeks to assess the potentiality of a given cascading event and to frame a handful of different scenarios of varying intensity. This is a matter of evaluating certain thresholds and potentialities of failure under particular geomorphological conditions – which are in turn affected by seismic and climatological or meteorological or anthropogenic conditions. As we discuss below, large flows have more mass and thus generate more energy and capacity (the ability to mobilize, recruit, or entrain more materials). The larger the flow, the greater the potential for cascading hazards.

In the Himalayan region, many of the largest mass movements are triggered by seismic activity or by upslope geomorphological activity (when a small landslide or avalanche begets a larger one, for example). Yet studies have also revealed that climatic conditions contribute to slope destabilization over time and hydrometeorological events such as intense precipitation and rapid snowpack melt events can also serve as triggers. On one hand, geohazards have always been a part of the geomorphologic processes by which Himalayan landforms evolve; on the other, hazard regimes seem to be changing more rapidly in the context of anthropogenic climate change.

To understand the possibility of disaster, we need to understand the ways in which any given disaster emerges from slowly-unfolding earth processes. Often, a disaster emerges from a conjuncture of different processes—unfolding independently and in parallel, or evolving together over time–which intersect with one another at a specific moment in time, creating tipping points that trigger cataclysmic processes, which we experience as disasters. To understand the potential risk of geohazards like landslides and debris floods in Nepal, one also needs to examine seismic and climatic regimes. For example, earthquakes are a necessary outcome of ongoing seismic processes still creating the Himalayan mountains. Periodic earthquakes destabilize large regions of the landscape, triggering a swarm of slope failures in the immediate future as well as increasing landslide susceptibility over a longer period of time by destabilizing already precarious slopes. Seismic periodicity remains relatively consistent, if uncertain. At the same time, climatic forces are always acting on the mountains and broader landscape through erosion and weathering. The geographic complexity of the Himalayan region, due in large part to the scale of topographic relief, and the monsoonal climate regime which interacts with and helps shape these geographies creates famous levels of meteorological and hydrological complexity.[18] [19] Climatic volatility has always been a factor in the Himalayan region, but in recent years anthropogenic climate change is creating additional volatility and uncertainty.[20] Climatic volatility means shifting hazard regimes. For example, the increasing occurrence of extreme precipitation events throughout the so-called "Himalayan landslide hotspot" is a cause of major concern.[21] And this is to say nothing of new patterns of human intervention and terraforming (i.e. infrastructure development) which add other anthropogenic layers and trigger potentials to these systems.

Seismic activity is endemic, chronically destabilizing slopes in waves across the Himalayas; and climatic changes and extreme meteorological events act on these unevenly destabilized slopes. Research is needed to understand the interactions here to disentangle the complex web of related causal factors.

This section provides a brief and illustrated overview of the background conditions, potential triggers, and mountain geohazards that are most prevalent in Nepal before diving into a discussion of our specific area of focus: cascading hazards. Each background condition or hazard is discussed from a global perspective and within a Nepal-specific context citing specific cases where these background conditions or hazards led to natural disasters. Where appropriate, interconnections between hazards are discussed (i.e. co-seismic avalanches or persistent slope destabilization following an earthquake). Finally, monitoring and risk assessment techniques deployed in both Nepal and the Hindu-Kush Himalayan (HKH) Region are discussed.

Background Conditions

TEMPERATURE

Nepal's climate ranges from the cryosphere - the area where water is frozen for most or all of the year - in the high Himalayas with a maximum elevation of 8,848 meters at the peak of Mt. Everest to warm tropical regions with elevations below 100 meters above sea level along its southern border with India. As elevation from the lowlands of the Ganges valley increases into the Himalayan mountains, temperatures generally cool at a rate of about 6.5 degrees Celsius to each 1000-meter ascent in elevation. Generally speaking the cryosphere in Nepal falls above in elevations above 3000 to 4000 meters, which is on average at least 19.5 degrees cooler than the lowlands. In the cryosphere, winter temperatures are usually below freezing; therefore, much of the Himalayan mountains rarely warm above freezing in months when the sun is low in the sky. Precipitation falls as snow and accumulates into glaciers and snowfields that flow into the high valleys. Farther down in the mountain valleys, temperatures do rise above freezing in the warmer months of the year. Therefore, snowfields and glaciers melt when the sun is high in the sky. During these warming periods, sudden or gradual melting events can contribute to or trigger a range of natural hazards such as avalanches, landslides, debris floods, or flash floods.

A natural phenomenon called snowpack ripening can also contribute to gradual or sudden melting events. At latitudes near 30 degrees north, the sun is nearly overhead in the heart of the summer, and the intense sunlight heats the surface and melts the snowpack. However, due to the high altitude and thin air, the surface of the earth radiates heat away from the surface as soon as the sun goes low in the sky. Therefore, temperatures frequently drop below freezing at night and the snowpack tends to recrystallize, only to melt again the next day. **This is known as the ripening of the snowpack** and occurs in the spring, depending on the altitude. The higher the altitude, the later in the year ripening occurs. In the 2021 Melamchi disaster, a prolonged period of snowpack ripening preceded a simultaneously occurring temperature spike and intense rain event. This contributed to the intensity of the catastrophic debris flood in the Melamchi valley.

Related to temperature conditions are changes to permafrost. Permafrost forms below the surface of the earth when the mean annual surface temperature is below freezing for two consecutive years, meaning the ice content in the soil never has a chance to thaw. This forms a solid, hard layer, growing into the soil over the years to a depth of several meters. Changing permafrost leads to changes in cryospheric hazard regimes, particularly in the context of climate change. As the mean temperature rises in a warming environment, the upper reaches of the permafrost layer begin to melt, while the soil remains frozen deep below. Snow melt and water cannot penetrate the deep frozen layer and therefore saturates the soil above, introducing potential hazards. Where the surface is steep, this heavy, wet soil could slip off the frozen soil below it. Under mild conditions, this slipping can cause a gradual shifting in the surface, called mass creep. However, in an extreme event, the sliding soil could promote an avalanche or landslide. **All slope failures occur when gravity overwhelms the friction in the slope system - and when permafrost melts it reduces the friction in the upper soil layers, creating volumes that can be mobilized by other triggers such as an earthquake or precipitation.**[22]

Collecting data on temperature changes at the highest available temporal frequencies (hourly and sub-hourly) is a fundamental component of risk monitoring for natural disasters because tracking temperature change can identify the rate of snow melt and monitor conditions related to snowpack ripening. In Nepal, temperature and other general hydro-meteorological conditions are observed hourly by 16 synoptic weather stations collecting meteorological information every 3 or 6 hours and 93 automatic weather stations (AWS) owned and operated by the Department of Hydrology and Meteorology (DHM). Indicators from these stations are publicly available on the DHM website. Additionally, in Nepal ICIMOD owns and operates 3 AWS as well as a number of precipitation gauges that monitor precipitation, snow depth, and temperature.[23] Several remote sensing methods are available to measure temperature at varying rates of temporal frequency. The advantage of remote sensing methods is global coverage and the ability to pinpoint specific temperature changes within the area of the method's highest spatial resolution. For example, Eyes on Earth's twice-daily surface temperature product can identify the degree to which currently observed temperatures change within a 144 km2 area. This process uses remote sensing data from the Special Sensor Microwave Imagery (SSMI) which observes the surface under most sky conditions almost every day. It can also detect the diurnal cycle of temperature fluctuations each day, which can be used to identify times when the snowpack is ripe and likely to contribute to flooding downstream. The image below visualizes SSMI data to show anomalous conditions in surface temperature during the weeks of extreme flooding in Pakistan and severe drought in much of China. It shows the extreme cold conditions in Pakistan, which is associated with cloud cover and wet ground, and the anomalous hot conditions in southern China which conversely are associated with the drought in the Yangtze River valley.

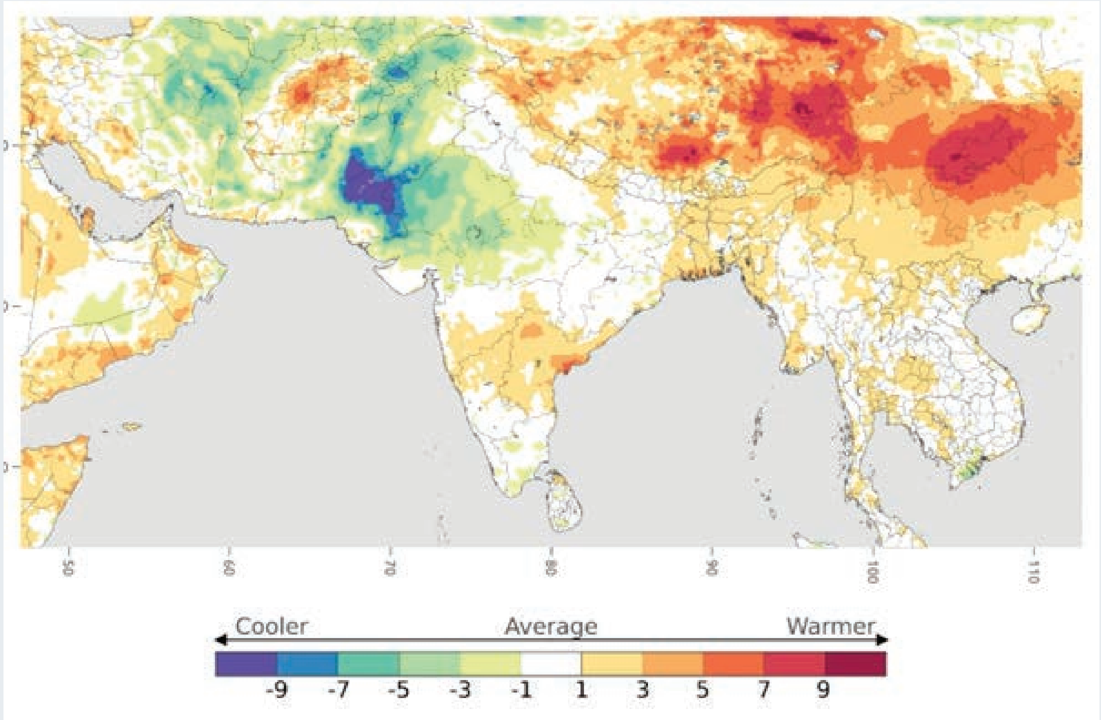


Fig. I.1: South Asia Surface Temperature Anomalies (August 21, 2022-August 27, 2022). [24]

PRECIPITATION

Nepal's climate is dominated by the southwest monsoon which brings high levels of precipitation from May to October of each year with the remaining months of the year relatively dry. From November to April the sun is low in the sky, and winds typically come from the Tibetan plateau to the north. These cold winds cross high elevations and then warm as they descend southward towards the Ganges lowlands of India at a rate of about 6.50° Celsius per 1000 meters. Thus air starting at extremely cold temperatures at 5000 meters can become warm or even hot as it descends into the lowlands. This continental air is usually dry and does not produce much precipitation.

Into the late spring, the sun rises higher in the sky causing a warming effect on the Tibetan Plateau. This warming air over the plateau starts to rise much like a hot air balloon rises. This promotes a flow of air from the Indian Ocean, causing a springtime shift in wind patterns in Nepal which allows warm, moist air to flow toward the Tibetan plateau from late May through early October. The warm air brings a sustained period of rainfall commonly known as the monsoon season. About 80% of Nepal's mean annual precipitation of 1263 mm[25] falls during the monsoon season. Precipitation levels vary significantly across the country with some central and northern parts receiving an average of 3000 mm per year.

Both the intensity of precipitation events and overall precipitation patterns are changing, likely due to climate change. Studies have demonstrated that more intense rains in the cryosphere of the western United States and Europe during warmer months are increasing the likelihood of rapid snowmelt and flood events,[26] yet more study is required to confirm whether this is happening in the HKH. May, which is traditionally the first month of the monsoon season, is also getting wetter as demonstrated by Eyes on Earth's wetness anomaly comparison over the last 30 years.

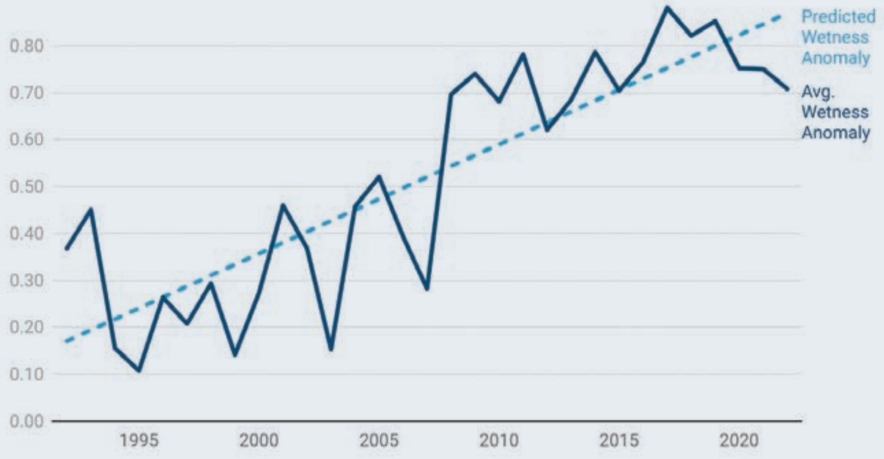


Fig. I.2: Monthly Mean Wetness Anomaly Values for May 1992-2022, Melamchi Basin.[27]

Monitoring precipitation in near real-time is essential to assessing rapidly changing surface conditions. Unfortunately, high-resolution precipitation data is limited, both in terms of *in situ* and remotely sensed observations. *In situ* surface measurements are usually limited to more populated areas of the world, and interpolating from one location to a larger area is complicated since the magnitude of rainfall is frequently a localized event. The AWS owned and operated by DHM and ICIMOD all monitor precipitation conditions at 60-minute and 10-minute intervals respectively. Remote sensing methods for measuring precipitation are improving, but this data is often only available one day after it is observed which makes real-time monitoring of specific short-term events difficult. However, remote-sensing precipitation products can detect short to long-term trends developing in real-time which can be put to use for early warning and risk monitoring.

A number of remote sensing data inputs for precipitation are available publicly including Global Precipitation Measurement data provided by NASA and JAXA (sub-daily estimates at a resolution of .01km2). Eyes on Earth has also developed a wetness product derived from an algorithm applied to daily/sub-daily data from the SSMI which measures levels of wetness of the surface of the earth, including precipitation and snowmelt, at a spatial resolution of 144km2). The figure below (Figure I.3) uses anomalies from average wetness to show the late August 2022 extreme flooding in Pakistan and the drought in the Ganges Basin. The dark blue color represents that the observed high amount of water near the surface in August is present less than 5% of the time. Conversely, the dark red represents that less than 5% of the time in August is there so little water near the surface.

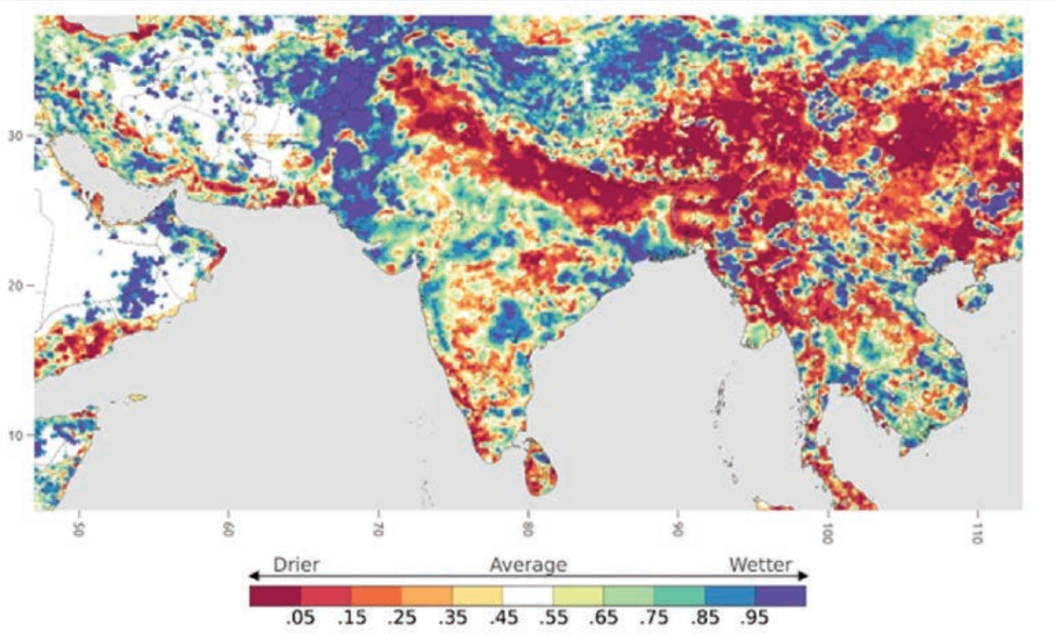


Fig. I.3: South Asia Surface Wetness Index Anomaly (August 21, 2022 - August 27, 2022)[28]

SNOW COVER AND SNOWPACK DYNAMICS

Although most of the precipitation in Nepal occurs during the wet monsoon months, the high elevations can receive precipitation throughout the year. This is largely attributed to the inability of air to hold moisture as it cools. The warmer the air, the more moisture it can contain–and therefore as the air cools while rising in altitude, it must release excess moisture. This causes clouds to form, and as they get thicker they release moisture in the form of precipitation. The moisture falls as snow if temperatures are below freezing. Generally, the greatest snowfall at the highest elevations occurs in the latter half of the wet season when moist air flows up from the south and then cools. Snow cover continues to accumulate during the dry season bringing additional precipitation at high elevations. The snow cover starts to melt in the springtime, first at the lower elevations and then melting moves northward to the higher altitudes as the high sun season advances.

While many stations across Nepal monitor snow conditions daily, only a few in the entire HKH region publish real-time data and are openly accessed. Sentinel-1 and ERA5 remote sensing data can provide estimates of snow depths. However real-time snow depth monitoring is limited given that data is collected in 6-10 day intervals. Remote sensing methods can be used to measure snow cover and changes to areas of snow coverage over time, and snowpack retreat and melting rates can be inferred from this data for use in risk monitoring and early warning systems. One publicly available method can estimate daily snow cover change at a 144 square kilometer resolution by integrating observations from the MODIS instrument, *in situ* surface measurements, and microwave observations from the SSMI. This data is updated daily, and it is derived from the Interactive Multisensory Snow and Ice Mapping system (IMS).

Hazard Types

EARTHQUAKES & SEISMIC TRIGGERS

In the Himalayan region, earthquakes are both a constant source of uncertainty and an inevitability. The Hindu Kush Himalayan Range lies on the Himalaya plate boundary, an area that faces both small earthquakes ($M_w < 3$) daily and large earthquakes ($M_w > 6$) intermittently, followed by periods of further accumulation of energy caused by friction from the convergence of the Indian and Eurasian Plates (Bilham, 2019). Earthquakes occur mostly around faults that make up the boundary areas between tectonic plates. Most of the earthquakes in this area happen at shallow depths, which is the zone where earthquakes are generally more destructive. Earthquake-related damages originate from larger earthquakes with magnitudes greater than 6.0 that are longer in duration and have a greater intensity of ground movement. **Critically, as disaster risk reduction specialists often say: earthquakes don't kill people, but collapsing buildings and secondary hazards like landslides and avalanches, tsunamis, fires, and infrastructural failures do.** The devastation wrought by earthquakes is further exacerbated by ensuing aftershocks and other recurring hazards (such as debris floods) over a prolonged period.[29]

Historical accounts outline how central earthquakes have been, as disasters and as a source of uncertainty, to Nepalese history and society. The earliest Himalayan earthquake in the historical record of Nepal dates to 1255 CE and reportedly claimed the lives of one-third of the population in the Kathmandu valley, including the king.[30] In the year 1505 CE, a massive earthquake sometimes referred to as the Lo Mustang Earthquake, estimated to be between 8.4 M_w and 8.9 M_w, struck the Western Himalaya—killing perhaps one-third of the entire population of what is now the nation-state of Nepal and causing widespread devastation across Tibet and what is now the Indian state of Uttarakhand.[31] Another devastating 8.0 M_w earthquake struck Kathmandu, the eastern region of Nepal, and Bihar in 1833. Other large earthquakes of around or just below 8.0M_w occurred in 1344, 1681, 1767, and 1916 respectively.

Himalayan earthquakes typically release stress along faults in only part of the range, leading to "seismic gaps" where stress remained unreleased. In some places of the Himalayas where earthquakes have not recently occurred, including Far-Western Nepal, a large earthquake estimated to be greater than 8.0 magnitude with more destructive potential than the 7.8 M_w Gorkha Earthquake of April 2015 is now several hundred years overdue.

The two largest and most notable earthquakes include the 1934 Bihar-Nepal Earthquake (8.4 M_w) and the 2015 Gorkha Earthquake 7.8 M_w. The Bihar-Nepal earthquake often referred to in Nepal as the *Mahabhukampa* (or "Great Earthquake") in Nepal was the most devastating in Nepal's history [32] The epicenter of the quake was in the eastern plains of Nepal, less than 10 miles south of Mount Everest (N: Sagarmatha) and it killed over 8,500 people in Nepal alone, with roughly half of these casualties occurring within the built environment of the Kathmandu Valley. The rupture propagated over 1200 miles along the main Himalayan fault and triggered an array of co-seismic landslides, flows, and other secondary geohazards: it was "accompanied by spectacular effects of slumping, subsidence of the ground, fissures in alluvium and sand, and water fountains" .[33] While detailed records of this event from non-urban parts of Nepal are limited (reflecting a broader historiographic trend), oral histories and anthropological research indicate that it had significant impacts throughout Nepal—owing in part to the wave of associated slope failures and other secondary geohazards.

The more recent Gorkha earthquake (7.8 M_w) on April 25, 2015, caused over 9,000 fatalities and 22,300 injuries. In the wake of the Gorkha Earthquake, Nepal experienced more than 300 aftershocks over 4.0 in a period of three years–creating lingering instabilities that created a new risk environment by shaping hazard regimes across Nepal .[34] Research has shown that earthquakes leave a signature in the landscape by creating lingering instabilities, serving as a contributing factor to landslides and other slope failures for years after the main tremor subsides.[35] [36] [37]

In general, earthquake prediction is still largely impossible. Experts can anticipate the rough magnitude of an earthquake that may occur within a "seismic gap" based on analyses of historical seismic activity and assumptions about the recurrence interval of such events, but earthquake models are not able to accurately predict incidents. In large part, earthquake early warning systems rely on seismic detection networks - effectively accelerometers distributed across the territory which automatically register and analyze seismic motion and then broadcast warnings.[38] These alerts can be distributed via text message -though the lead time is typically not much. Domestic "earthquake alarms" are the last line of defense, but most are only triggered once ground motion starts. A team from Duke University and Nepal's Tribhuvan University is currently working on creating a more sophisticated and culturally sensitive early warning system for earthquakes in the Kathmandu Valley—which seems like a promising interdisciplinary collaboration.

All that said, some new opportunities for using remote-sensing technologies for mapping and monitoring earthquakes are emerging. High-resolution optical imagery can be used to create building inventories and map potentially affected urban areas to model pre-event loss estimates for emergency response planning.[39] Synthetic Aperture Radar (SAR) imagery can track and assess changes to surface roughness and displacements.[40] SAR can also monitor earthquake-prone areas regardless of weather and time of day as radar imagery uses radio waves and the measurement of reflections of transmissions rather than sun reflectance. High spatial and temporal resolution images of both types are publicly available for purchase, or for free through governmental space agencies like the European Space Agency (Sentinel-1). Finally, studies have looked at using measurements of gravitational anomalies on Earth to monitor temporal variations due to larger earthquakes.[41]

Crowdsourced humanitarian mapping of disaster impacts and infrastructures is also a promising tool for disaster response and disaster management—as the team from a Nepali organization called Kathmandu Living Labs showed. The team at Kathmandu Living Labs set up their systems in anticipation of an event like the Gorkha Earthquake, and then "once the quake hit, they launched the site quakemaps.org, onto which [they] added layers allowing people to report earthquake data and response information in real-time. Thousands of volunteer mappers in Europe and the US then worked to create precise maps of Nepal's rugged terrain, which is otherwise extraordinarily difficult to navigate without local knowledge." [42] In the professional and academic worlds of disaster preparedness, people work to anticipate and model future disasters as potential events, using a variety of different tools to build forecasts, scenarios, and disaster plans. Typically this is a process where different aspects of past events are reassembled into fictive events, scenarios, and simulations which are used to formulate disaster plans. [43] [44] These plans function as speculative blueprints for action in response to potential disasters, and they are meant to evolve over time as new layers emerge and the shape of unknowns shifts.

Such projections and plans existed before the Gorkha Earthquake—most substantively in formalized disaster plans that the Government of Nepal designed at multiple scales, the disaster management protocols of Nepalese security forces, and the projections of the National Society for Earthquake Technology-Nepal (NSET).[45]

In the wake of the Gorkha Earthquake, new rounds of disaster planning began almost immediately when disaster planners from around the world gathered in Kathmandu in 2015 to plot out response scenarios in response to future seismic disasters. This gathering was called "Tempest Express 28" or TE28, as the twenty-eighth such mass planning exercise conducted in the Asia-Pacific region, but the first in Nepal since 2007.[46] Such disaster games pivot around a "reference event" designed to provide participants with an elaborate and representative scenario that helps responders rehearse in anticipation. The potential "reference event" for TE28 was a magnitude 8.6 earthquake in western Nepal—where such an event is now considered an eventuality and roughly 500 years overdue.[47] From this seismic trigger, disaster experts from Durham University and NSET modeled out a broader scenario of primary and secondary impacts, based on geological data about the impacts of a similar earthquake that struck western Nepal in 1505 and a still-evolving cache of data about the 2015 Gorkha Earthquake and its impacts.[48] Apparently, this was the first Tempest Express simulation to use landslide modeling data, which was an adaptation based on the intensive impacts of co-seismic landslides during the Gorkha Earthquake and based on generalizations drawn from data on landslide patterns collected by the team from Durham University. While it is truly surprising that prior planning exercises did not account more fully for loss and damage caused by landslides, this is precisely how disaster games and "event technologies" evolve. But layering in landslides within exercises like Tempest Express 28 is just the tip of the iceberg.

Disaster planners in Nepal know very well that further large earthquakes are an inevitability in Nepal - particularly in zones where significant "seismic gaps" exist, where tectonic stress is building up, and soon to be released (such as Western Nepal). Going forward, disaster planners and planning exercises like this will also need to recalibrate all models of disaster and disaster response to account for hazard regimes transformed by climate change. They will need to reckon with co-seismic hazards such as massive debris floods that could also be partially climate-change-induced events—with the growing possibility of new kinds of cascading hazards and extreme events.

LANDSLIDES

The term landslide is used to refer to several different types of slope failures, and it is a category of mass movements that can include soil, rock, and/or other earthen debris.[49] Landslides can entrain other artificial materials as well, depending on the intensity of flows. The ubiquity of landslides has led to a destructive toll on communities and people worldwide, affecting an estimated 4.8 million people, and causing over 18,000 fatalities and approximately $8 billion in recorded economic losses between 1998-2017.[50] Landslides are often triggered by naturally occurring events like heavy rainfall, snowmelt, or shallow earthquakes.[51] But as the USGS states: "Almost every landslide has multiple causes. Slope movement occurs when forces acting down-slope (mainly due to gravity) exceed the strength of the earth materials that compose the slope. Causes include factors that increase the effects of down-slope forces and factors that contribute to low or reduced strength."[52] In the Himalayan region, landslides are also increasingly triggered by human activity like infrastructure development, which can undermine slope stability and elevate latent landslide risk.[53] [54]

Additionally, landslides can cause drastic changes to the surrounding natural environment. Landslides flowing into rivers and streams can block the main channel creating flood risks (see below) or affect the potability of water and reduce the environment's ability to support ecosystems for fish and aquatic plants. Landslide swarms following earthquakes can cause widespread denudation of forest cover in tropical areas.[55]

Like all hazards, landslides only become disasters when they cause human suffering and/or disrupt human systems. In this sense "they arise from the interaction of both geophysical/meteorological processes and social vulnerability."[56] Understanding landslide risk and working to anticipate or mitigate the harmful impacts of landslides, therefore, requires understanding uneven physical and human geographies.

Nepal is situated in one of the most active regions for landslides. The country, and the surrounding HKH Range in general, experiences frequent seismotectonic activities as the entire country is situated in the convergent boundary where the Indian Plate continuously slides beneath the Eurasian Plate.[57] Large-scale landslides have occurred and will continue to occur across the Himalayan region throughout geologic time, often seismically triggered. Each seismic event is inevitably accompanied by a wave of secondary hazards.

In the wake of the Gorkha earthquake, a team from Durham University empirically analyzed new and evolving landslide activity in the earthquake-affected zone. For example, geoscientists estimate that the Gorkha Earthquake triggered approximately 13,000 new landslides across Nepal - adding to over 6,400 previously identified active landslide zones within the earthquake-affected areas of central and mid-western Nepal alone (Oven et al 2021: 160).[58] Critically, they found that the monsoon after the earthquake led to a 35% increase in the total number of landslides within this area. A little less than five years later after the monsoon season of 2019, the total number of landslides in the area had increased by 51% since those enumerated in the immediate wake of the Gorkha Earthquake. All this activity was far above the typical background rate in the region—though it is hard to disentangle this trend from increased precipitation trends and determine what portion of this activity can be attributed to seismic legacies and what can be attributed to abnormal/anomalous climatic conditions and extreme weather events linked to climate change. This confusion is entirely the point: we know that these factors are compounding, but they are inextricably entangled and it is impossible to apportion attribution among various factors.

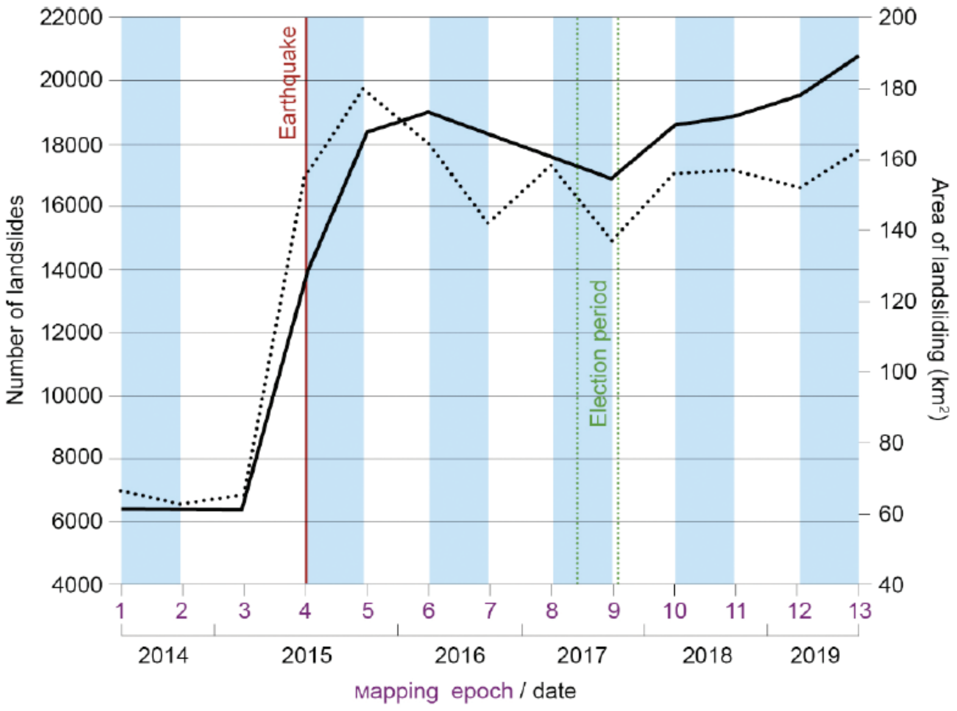


Figure I.4: Changes in mapped landslide numbers and area of landsliding in Nepal (Rosser et al, 2021)

Importantly, seismically induced hazards do not occur at a single point in time but rather are distributed over longer periods of time. Perhaps one-third of the total landslides partially-triggered by the 2015 Gorkha Earthquake occurred over an extended five-year period.

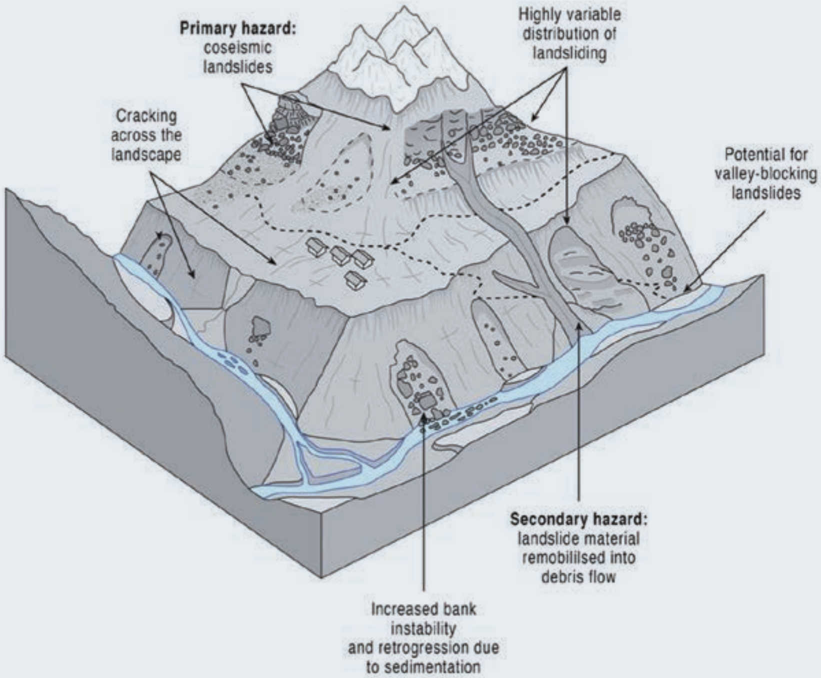


Fig. I.5: a schematic of different kinds of landslide hazards and slope failures in a landscape destabilized by an earthquake[59]

Critically, the signature of this burst of seismic activity lingered in the landscape, because it left slopes across the earthquake-affected area *destabilized* and thus more easily mobilized by other triggering events. Emergent patterns of "extreme precipitation in the Himalayan landslide zone" which appear to be linked to climate change are cause for considerable concern.[60]

At a basic level, Nepal is a high-risk zone for landslides with or without earthquakes or climate change - simply because the young and friable geology of the Himalayas is repeatedly exposed to the weathering and erosional onslaught of the monsoons. Prior to the 7.8Mw Gorkha earthquake in 2015, landslide frequency was highly dependent on the monsoon season and monsoonal landslides accounted for 92% of landslide fatalities and 90% of fatal landslides.[61] Recently, landslide risk has been further exacerbated by infrastructure development in more rural areas of Nepal. In pursuit of gaining more economic benefits from access to existing road networks, localities (towns and villages) construct informal and non-engineered roads. However, these roads significantly alter its surrounding physical landscape, and they regularly fail during the monsoon season.[62]

Nearly all districts in Nepal are at risk of landslides but the highest instances of landslides are mainly centered in districts within the Mahabharat Range (Lower Himalayan Range), Chure Range, and central Nepal. From 1971-2016, Nepal experienced over 3,400 landslides that affected over 200,000 lives and caused over 5,000 fatalities, and in 2017 alone landslides caused an estimated $70 million in damages and 276 casualties.[63] Notable examples in modern Nepalese history include the 1962 Darbang landslide in Myagdi District that buried a bazaar and killed 500 people, the 1976 Bhagawatitar landslide in Kaski District that killed approximately 75 people, a second landslide in Darbang in 1988 that killed over 100 people, the 1993 Phedi Gau landslides and debris floods in Makwanpur District that destroyed over 50 homes and caused 52 deaths. More recently, the 2014 Jure landslide in Sindhupalchowk District destroyed a 1-kilometer stretch of the Araniko Highway, Nepal's only road connection to China, and killed 156 people, among many other damages.

Under these circumstances, multiple efforts have been made to monitor and map landslides in Nepal. At the time of writing, the most comprehensive assessments and inventories of landslide hazards come from work done in the wake of the 2015 Gorkha Earthquake. Several institutions conducted complementary assessments of landslides and geohazards across the earthquake-affected area (the hill and mountain zones of Central and Near-Western Nepal). First, a suite of assessments conducted by the Government of Nepal (Department of Mines and Geology) with technical support from UNOPS and the INGO People in Need were coordinated under the name "the Geohazard Assessment." This assessment focused on human settlements, conducting site-based analyses of over 130 settlements identified as at-risk by the National Reconstruction Authority, and classified these households into three categories, for the purposes of post-disaster hazard zoning and resettlement programs. A team from NSET and Durham University also conducted an extensive satellite-based survey that identified a broader gamut of landslide hazards and monitored evolving patterns of landslide activity.[64]

Earliest modern records show the first landslide monitoring system was installed by the Nepalese government in 1993 to monitor the Kathmandu-Trishuli Road.[65] In the following years, the government in partnership with various NGOs deployed regional and local landslide early warning systems (LEWS) throughout the country. These early warning systems focused on weather-induced landslides and looked for triggers by monitoring rainfall or displacement measurement of slopes. Community-led warning systems often include rain gauges and rely on focal members of the community who would warn the community after being alerted by the system by sirens or megaphones.[66] However, these systems are too small-scale or, in the case of regional LEWS, lack the ability to predict exact locations of failure, making targeted early warning systems at a national level immensely difficult.[67] Recent studies have demonstrated the potential of remote sensing to create inventory datasets that could feed into dynamic assessments of landslide risk. Kargel et al. (2015) and Martha et al. (2016) created point and polygon datasets respectively using high-resolution optical satellite imagery and manpower from many researchers to locate and, in the case of Martha, draw the landslide extent.[68] [69] Marc et al. (2019) built on these efforts by applying an automated mapping algorithm using similar remote-sensing data and the temporal and spatial changes to vegetation cover because of landslides.[70]

LANDSLIDES AND CLIMATE CHANGE

Climate change will undoubtedly have an impact on slope stability across the world, particularly in places facing intense climatic volatility like the Himalayan region.

"Warming of the Earth climate system is unequivocal. That climate changes affect the stability of natural and engineered slopes and have consequences on landslides, is also indisputable. Less clear is the type, extent, magnitude, and direction of the changes in the stability conditions, and on the location, abundance, activity, and frequency of landslides in response to the projected climate changes." [71]

Most landslide modeling efforts that attempt to account for climate change use some variation of downscaled global circulation models.[72] This technique is largely useless in the Himalayan region, however, where the topography famously creates meteorological and geomorphological "uncertainty on a Himalayan scale." [73] Therefore, anticipatory models should be driven off a combination of region-specific (Himalayan) and even watershed-specific data wherever possible. Given the intensity of climatic volatility and the unevenness of precipitation patterns between watersheds, such models should be based on real-time monitoring to the extent possible - which is where we come in. The takeaway is that conditions can change extremely quickly, radically reshaping the hazard regime by changing the potential energy stored in the mountains. Abstract projections of future climate regimes based on general circulation models are perhaps useful for policy, but they cannot be realistically downscaled to fit the situated complexities of the Himalayan region or used as the basis for any kind of near-term disaster risk reduction plan. Forecasting Himalayan hazards and shifts in hazard regimes requires situated, empirical data and models or systems capable of responding quickly.

In India, scientists working with the government have created a "mountain-specific multi-hazard risk management framework" (MSMRMF) which government institutions use to assess the overlapping risk of seven different kinds of mountain hazards across twelve Indian states.[74] But as Rusk et al (2022) point out, the scale of this analysis is the district, which is not truly fine-grained enough, and it is limited to the boundaries of the Indian nation-state which misses some transboundary hazards.[75] For pragmatic purposes, the most useful scale of analysis when it comes to geohazard assessment is that of the watershed— and this is most obviously the case when one considers cascading hazards. In Section 2 we demonstrate that our analysis begins at the watershed scale, and moves up the hazard chain into sub-watersheds and particular corridors of cascading hazard risk. While our work is currently limited to Nepal, we acknowledge that, in some watersheds, understanding the risks and uncertainties of cascading hazards in Nepal requires considering potential hazards located upstream, across borders.

AVALANCHES: SNOW, GLACIER, AND ROCK

The term avalanche is used to describe a particular category of cascading cryosphere hazard which can begin with a single trigger and rapidly escalates to an often overwhelming scale. There are many kinds of avalanches, ranging from small-scale snow or "powder" avalanches (the kind most people are familiar with) to rock and ice avalanches that resembled landslides, but begin with snow/ice. Avalanches, like landslides, are part of broader geomorphological and climatological processes and hydrological cycles- they speak to the ways that the mountains shape and receive weather.

Most avalanches occur beyond the edges of society, in remote regions of the mountain cryosphere: they do not impact human settlements and cause relatively few casualties compared to other disasters. But for people living and working in places where avalanches are a fact of life—from the Andes to the Alps to the Himalayan region —avalanches are a recurring and terrifying concern.[76] [77] [78]

Ice is a process, and in the high mountains, avalanches are a part of that process. On one hand, avalanches begin when ice and/or snow loses its integrity, as when a hanging glacier fractures. On the other hand, avalanches can also help create and feed glaciers by adding and compacting ice and snow in their upper portions. As one science writer recently suggested: "Another way of looking at avalanches is to think of them as frozen packets of energy from different parts of the climate system that are all being intensified by global warming—tropical heat, moist atmospheric rivers, and the Arctic winds all stored in the form of snow on a mountainside."[79]

Large ice and rock avalanches can be extremely destructive on their own (i.e. Langtang in 2015 or Yungay in 1970) or they can generate a cascading series of hazards that results in a different kind of extreme debris flow further downstream (i.e. Chamoli in 2021). As Gnyawali et al stated in their analysis of the Langtang Disaster: "large ice–rock debris avalanches can be extremely hazardous owing to their high mobility, long runout, and entrainment capacity." [80] [81] [82] [83] Large avalanches can mobilize and carry millions of cubic meters of debris. They can also create temporary dams by impounding rivers. The turbulent motion of the largest avalanches can create air cushions beneath the snow, ice, and debris that decrease friction and thus increase their run-out distances and cause pressure waves at the avalanche front that cause destruction before the avalanche itself even arrives.

The Langtang Avalanche that occurred during the Gorkha Earthquake is a terrifying and telling example of what an avalanche can be—it was the deadliest in the recorded history of the Himalayan region, and one of the deadliest in human history. The Langtang Avalanche started with a collapsed ice block at around 7,000 meters elevation on the face of the Himalayan massif called Langtang Lirung. The avalanche gathered force and materials as it plummeted, falling over 4,000 meters, and it came over the cliff above the village of Langtang like a wave, suspended in free fall for the last 500 meters. It created a pressure wave, referred to in the technical literature as an "airblast", equivalent to a Category 5 hurricane that flattened houses and trees for more than a kilometer beyond the edge of the avalanche itself.[84] The total volume of turbulent mass was estimated to be around 15 million cubic meters, about 15 times the size of the Empire State Building.[85] When the front of the avalanche hit Langtang village, it was traveling at an estimated 200 miles per hour. When it hit the valley floor, it released a force estimated to be equivalent to that of the Hiroshima atomic bomb.[86] [87]

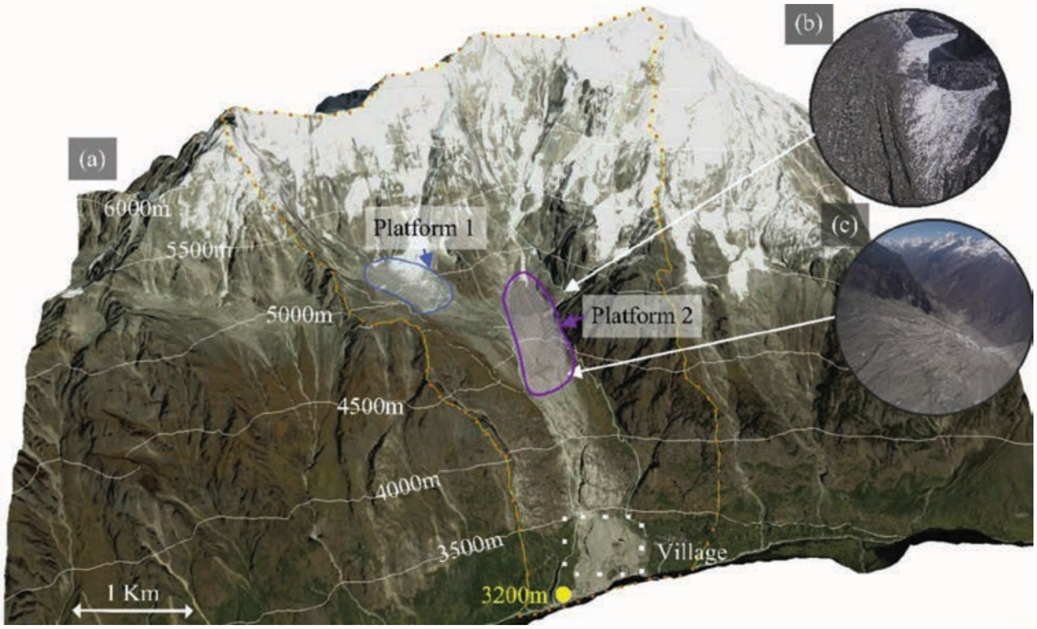


Fig. I.6: Multi-stage analysis of the Langtang Avalanche from Gnyawali et al (2020)

The avalanche that destroyed Langtang Village was actually a concentrated multi-stage event, where multiple avalanches and landslides were funneled into a single chute, becoming a massive mixed-debris avalanche of rock, ice, soil, but mostly snow and melted snow.[88] [89] The Langtang avalanche was just one of the hundreds of avalanches that occurred throughout the Langtang Valley that day, and thousands across Nepal—due to anomalous snowpack estimated to recur on 100-500 year intervals.[90] It was the most intense cascading process within a broader avalanche swarm, which was–and this is critical–generated by climatic conditions and not just an earthquake. This event was triggered by an earthquake, but an avalanche of this scale, volume, and capacity required the weakened ice block and the anomalous snowpack to supply enough potential energy to generate multiple avalanches that could become confluent, something greater than the sum of their parts. In this way, it was also a climatic event.[91]

The Langtang Avalanche was an outlier and a kind of perfect storm. But it also showcases the potential for cascading hazards: what is possible when mountains filled with unstable hanging glaciers and unseasonal snow shake. The Yungay Avalanche, which occurred on the slopes of Mt. Huascaran in Peru during the 1970 Ancash Earthquake, killing several thousand people as the deadliest single avalanche or landslide in human history is another example. These events index similar entanglements of seismic, geomorphological, and climatological processes.[92]

Importantly, such extreme avalanche events don't always require a seismic trigger—they can be meteorologically or geomorphologically triggered. For instance, the Chamoli Disaster began with a massive rock and ice avalanche that was not seismically triggered, but nonetheless initiated a cascading hazard sequence. Here, the initial avalanche fell onto the glacier at the floor of the high valley, entraining accumulated snowpack and glacier materials (much like the Langtang Avalanche). Then, swollen with new materials, the capacity of the flow increased as it surged down the river course, gaining more fluid volume and becoming a massive debris flow.[93] Media and scientists initially reported this as a flood or a glacial lake outburst flood because it behaved like a flood-triggered debris flow. But in fact, there was no lake; rather, the force of the avalanche melted the compacted snow and ice in the glacier areas, creating a lake's worth of melted water on the move.[94]

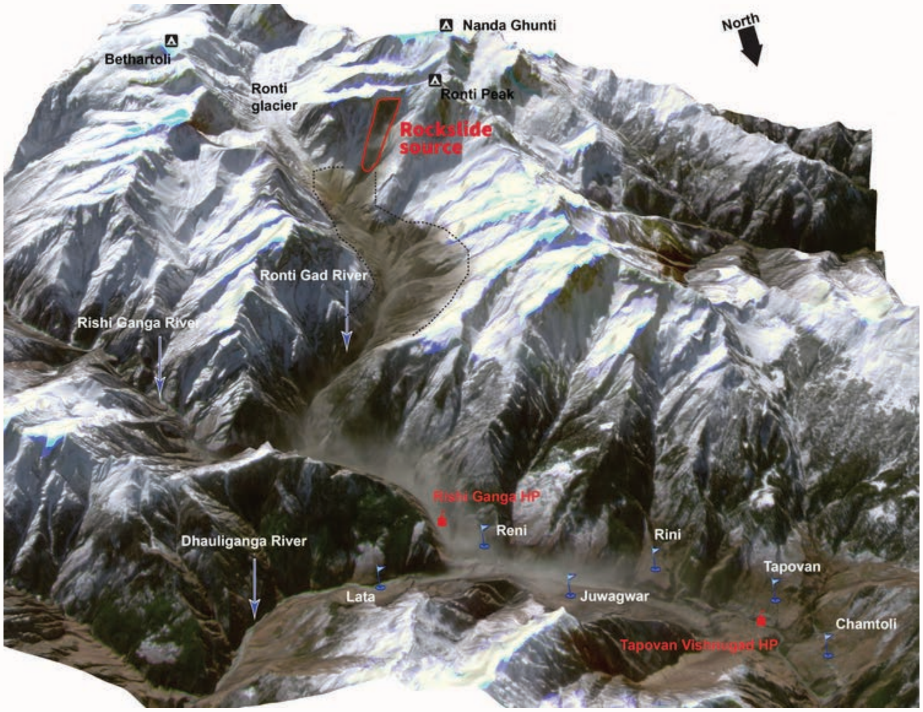


Fig.I.7: Chamoli debris flood just before it reached the Tapovan Hydropower Project site. Origin of the rock avalanche is marked in red. The dotted black line shows the sediment deposited on the adjacent slopes of the river valley.

Scientists continue to debate the extent to which the Chamoli Disaster might have been shaped by climate change. While this gets into the complexities of attribution science, this event speaks to the scale of what might be possible under climate change, and that it is causing people to reevaluate and recalibrate their models of geohazards and disaster risk reduction. In general, however, extreme avalanches that become cascading events like the Langtang Avalanche and the Chamoli Disaster are expected to become more common as the impacts of climate change accumulate in the mountain cryosphere.[95] [96] The factors are interwoven: from weakened glaciers and melting permafrost to changes in snowpack and ice accumulation at high elevations, to the immediate or accumulated impacts of volatile unseasonal storms which store climatic energy in the mountains or cause the mountains to release that potential energy.

To monitor for avalanches, most technologies use meteorological data or point-source sampling to monitor snow conditions such as snow accumulation or the structure of snow layers. Laser-based systems such as LIDAR can be used in locations where these assets are available. Snow science is in fact its own subdiscipline, which speaks to the complexity of monitoring and modeling constantly shifting snow conditions. Remote-sensing technologies offer some new tools, but accurately modeling snowpacks in remote high-mountain regions is a fundamental challenge.

When the precise location of a potential avalanche is known, the toolkit expands further. Radar devices can monitor pre-defined areas of interest, for instance, a potential avalanche path or the face overlooking a railway line. Geophonic sensors can be installed in known avalanche chutes to monitor for and pick up on sound waves triggered by an avalanche above, providing several minutes of alert time below. Repeat photography (land-based) techniques with algorithm recognition are being used in select sites in Switzerland, Italy, and Norway. In areas where critical infrastructure is at risk, or at ski resorts, people even use remote triggering methods (controlled blasts, sound) to trigger and release avalanches preemptively. Building such monitoring and avalanche control systems requires a major investment, which has led to private sector firms entering the market. Ultimately, the calculus all depends on how people value this knowledge and what is at stake.

For a variety of technical and economic reasons, the majority of these methods are not used in the Himalayan region - because of the scale of the terrain that would need to be monitored, as well as the prohibitive cost of doing so. As snowpack is extremely hard to model accurately, it is near impossible to get the fine-grained data necessary to evaluate avalanche conditions in the high Himalayas in real-time. Where instrumentation networks exist, such as in the Langtang Valley or the Everest region, it is possible to collect and relay snow data. But conditions can change rapidly—hence the need to keep an eye on meteorological conditions and watch for conditions of “ripening” as described above. In the Himalayan region, localized reporting of snow conditions by local residents familiar with situated avalanche risks or Nepali travelers, tourists, guides, and mountaineers remains the best source of grounded information on snowpack. [97]

GLACIAL LAKE OUTBURST FLOODS (GLOF)

Glacial lakes are common features of the cryosphere, but a variety of factors can cause the glacial moraines that contain these lakes to fail, triggering glacial lake outburst floods (GLOFs) which can contribute to the creation of cascading downstream disasters such as debris floods and extreme flow events. Scholars suggest that communities living in the high Himalayas are aware of these hazards, and the Sherpa people refer to GLOFs as *tshoscrup*. [98] [99]

Most glacial lakes are formed by changes in glacial composition and can be found on top of glaciers, by glacial ice dams, by moraine dams left after glacial retreat, or by bedrock dams. Some glacial lakes are fed by glacial melt but are not dammed as a result of the glacial process.[100] The water volume of glacial lakes can change seasonally with the normal seasonal melting of snowpack, increasing suddenly as a result of a precipitation or rapid snowmelt event or gradually as the cryosphere warms. Expansion of the glacial lake's footprint adds pressure to the natural dam which forms at the toe of the lake and can cause the natural dam to crack or breach, sending some or all of the glacial lake's contents into river valleys below. When this natural dam fails or is overtopped by an increase in volume, this is called a GLOF. Natural dams can also fail as a result of changes to the material which forms them. Natural dams formed entirely or partially of ice can fail if that ice melts. Earthquakes, avalanches, and landslides can also cause the natural dam to lose its integrity or can send debris into the lake, creating a wave of water that overtops the dam. Glacial lake dams without an outlet are more susceptible to failure than those with an outlet.

The 1985 Dig Tsho glacial lake disaster—which destroyed homes, trails and bridges, farmlands, and a hydropower station in the western Khumbu Valley near Thame–triggered greater interest in surveying glacial lakes and other glaciological hazards in the Himalayan region.[101] [102] To date, various glacial lake inventory processes have identified 30,000 glacial lakes across the Himalaya. A 2020 ICIMOD study identified 3,624 glacial lakes in the middle to upper portions of Nepal's major river systems: the Karnali, Gandaki, and Koshi. Importantly the headwaters of these rivers rise in China and the Tibetan autonomous region, introducing the risk of a GLOF in China which then forms a transboundary debris flood that could impact Nepali communities downstream. The largest number of glacial lakes were identified in the Koshi Basin (2,064), followed by the Karnali Basin (1,128), and the Gandaki Basin (432). The average mean area of glacial lakes in the Koshi basin is significantly higher than those in the Karnali and Gandaki Basin. Most of the glacial lakes in all three basins are formed by moraine dams (2,003), followed by bedrock dams (1,255) ice dams (339), and others (27).

Instances of GLOF are perceived to be increasing due to increasing intensity of rainfall, increasing warming of the cryosphere, quickened retreat of glaciers, and increasing instances of landslides. Likely due to its high quantity and larger size of glacial lakes, GLOF occurrence is increasing most in the Koshi Basin. The most recent transboundary GLOF in the Koshi Basin occurred in in 2016 after a landslide on the upper banks of the Gongbatongsha glacial lake in the Tibetan Autonomous Region of China caused the lake to fail, sending its contents and considerably more debris recruited along its path into the Sun Koshi River. This caused an estimated $70mn in damage in Nepal inclusive of damage to the Arniko Highway and the Sun Koshi hydropower plant more than 40 kilometers away from the point of origin (Sattar). The 2021 Melamchi debris flood– which carried debris 60 kilometers and resulted in 5 deaths, 20 mission persons, and damaged infrastructure and the construction site of the Melamchi Water Supply project–was also exacerbated by a GLOF.[103]

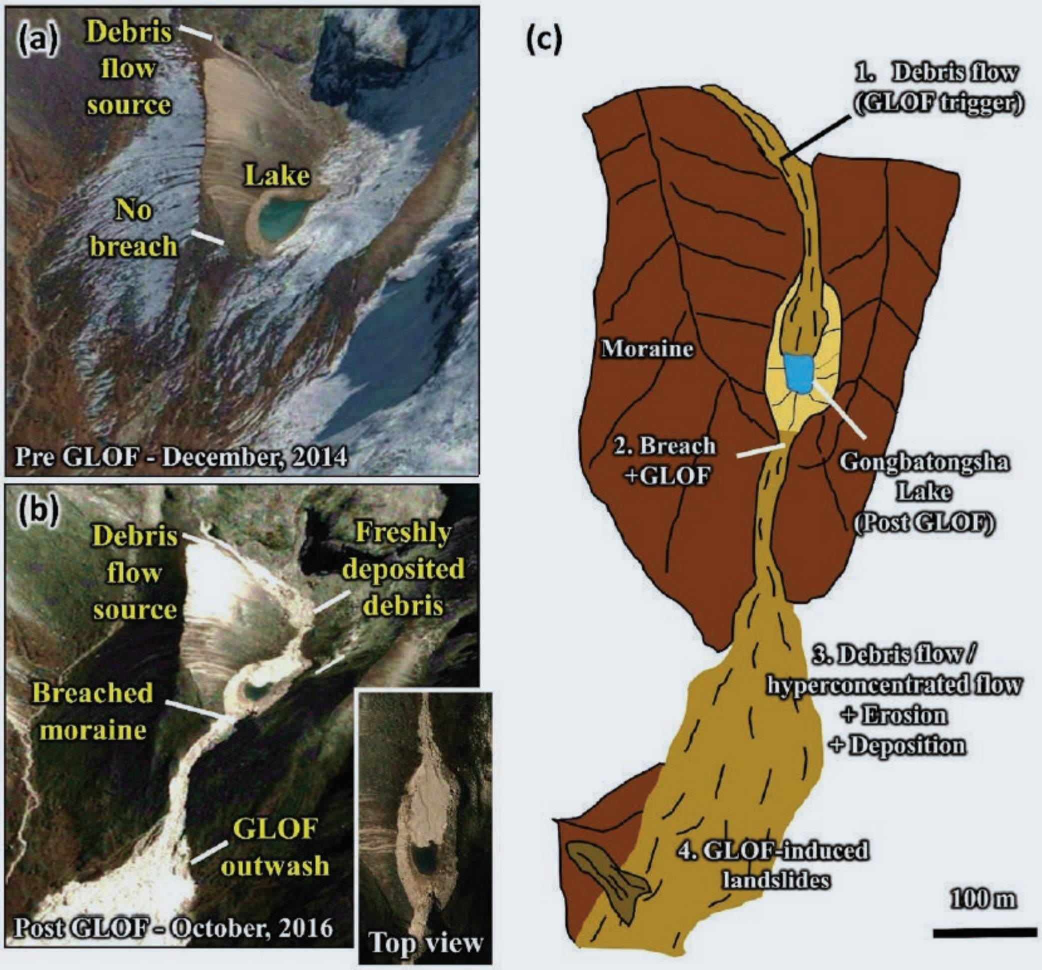


Fig.I.8: Transition of a Small Himalayan Glacier Lake Outburst Flood to a Giant Transborder Flood and Debris Flow. From A.Sattar et al (2022) a) pre-GLOF conditions of the Gongbatongsha Lake b) post-GLOF imagery showing freshly deposited debris originating from the headwall entering the lake, breached moraine, and GLOF outwash; background imageries in panels a and b are from Google Earth (@CNES/Airbus Maxar Technologies); c) schematic showing the different processes of the Gongbatongsha GLOF (Coral Draw Software)[104]

The global and local Nepali scientific and disaster risk reduction sectors have focused much effort on glacial lake analysis and GLOF risk assessment over the last two decades. Remote sensing techniques using high-resolution optical imagery from sources such as Google Earth, Sentinel-2, Landsat, Planet Labs, Maxar, and Airbus, synthetic aperture radar (SAR) imagery from publicly available such as Sentinel-1, and proprietary inputs such as ICEYE, and various digital elevation maps (SRTM, ALOS, Copernicus) have made it possible to produce inventories of glacial lakes. In response to rising GLOF risk due to climate change, a handful of different disaster risk reduction and mitigation projects have been proposed and implemented.

In Nepal, the most famous of these projects focused on Tsho Rolpa, a high-risk glacial lake in the upper watershed of the Tamakoshi River, in the central-eastern district of Dolakha. This lake is commonly identified as one of the most hazardous in the Himalayan region, and the total volume is estimated to be over 85 million cubic meters. Scientists have been monitoring its expansion periodically since the 1950s, but concern increased after a smaller GLOF occurred from nearby Tso Chubung and damaged a few houses in the village of Beding, immediately downstream.[105] Prior to recent interventions, the level of the lake was rising at the rate of 0.43 meters per year, threatening to overtop or break the end moraine that holds it in.[106] Given the volume of water and the steep gradient of the Rolwaling River below, it is estimated that a GLOF from Tsho Rolpa could have impacts as far as 100km downstream.[107] [108]

Because this was a major concern for downstream settlements and infrastructure, several different iterations of EWS systems have been installed over the years: from siren relay systems in the early 2000s to automatic mass text-message alerts more recently. In 2000, the level of Tsho Rolpa Lake was successfully lowered by 3 meters via the construction of a dam built into the end moraine and a canal that could release water from the lake in a controlled fashion.[109] These "lake-lowering" efforts were part of a broader "Community-Based Flood and Glacial Lake Risk Reduction Project (CFGORRP)" funded by the United Nations Development Programme (UNDP) in Nepal—a risk mitigation system initiated to complement the (still-evolving) early warning system.[110] [111]

Imja Lake (or Imja Tsho) is another major GLOF risk. A large glacial lake in the Khumbu region, near Mount Everest (*Sagarmatha*) that is 75 million cubic meters in volume and about 500 ft deep, Imja Tsho has an end moraine that is considered unstable because it contains glacial ice deposits which have been slowly melting within, referred to as "dead ice".[112] This lake has attracted a great deal of attention from scientists, NGOs, and engineers over the years, but these efforts have also drawn criticism from local Sherpa communities, who feel they have not been meaningfully engaged and that all these efforts create undue anxiety.[113] Reflecting a broader (and welcome trend) more recent research acknowledges the need to meaningfully engage community members and local knowledge.[114] [115] [116] Watanabe and his team (2016) who have been working on this issue for several decades now "argue for the need of a "science-based, community-driven" approach to glacial lake and other climate change research in the interests of finding meaningful and effective solutions to contemporary problems.[117]

Jeffrey Kargel, one of the lead geomorphologists on the Imja Tso evaluation project describes the risks and the range of potential scenarios as follows:

> ***"It's not that all possible Imja GLOF scenarios would result in utter destruction. 'Slow GLOFs' generated somewhat gradually by partial moraine melt-through might last as long as several hours to a full day, limiting peak flows and downstream damage. The major villages downstream from Imja Lake***

> ***are situated just outside of and above a deep, broad outwash and debris-flow channel system. Imja and other glaciers in the area have built a large fan, now deeply trenched, which could accommodate the peak discharges of any potential slow GLOFs, sparing the villages. However, 'fast GLOFs' are another story. A fast GLOF could be caused by a tsunami, initiated by a large mass movement of ice, dirt, and rocks into Imja Lake. Resulting waves could override and damage the end moraine in less than a couple of minutes. Villages downstream would be very vulnerable to such a "fast GLOF."***[118]

This quote usefully highlights the need to monitor and prepare for a range of different GLOF risks - and makes the broader point that potential hazards and tipping points can come in all shapes, sizes, and speeds.

Remote sensing techniques make it possible to define features of glacial lakes and rank their hazard risk. The 2020 ICIMOD study assessed the size, type, expansion rate, physical characteristics and conditions of dams, and features of surrounding areas. Then a reductive approach was used to classify risk across four categories of intensity, ultimately labeling 47 of 3,624 lakes identified as potentially dangerous.

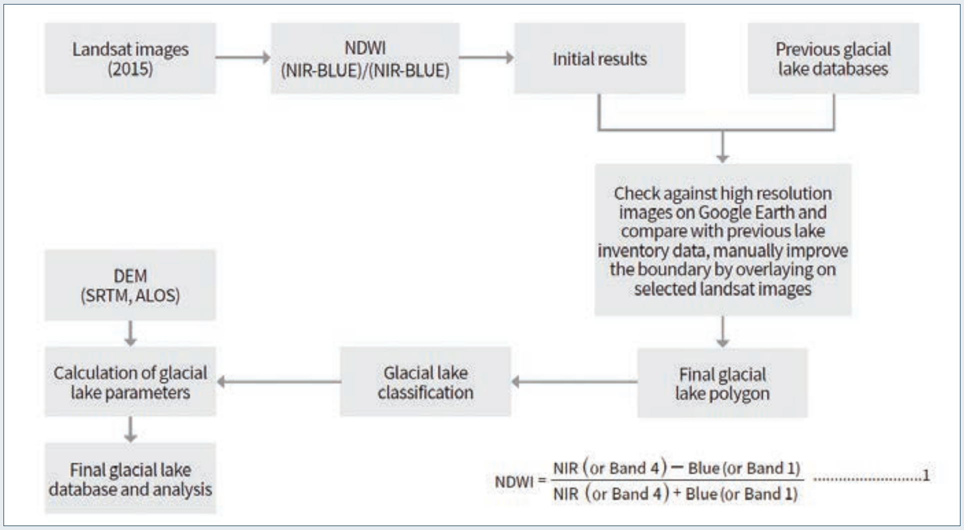


Fig.I.9: Remote sensing-based glacial lake inventory process used in the 2020 ICIMOD effort to develop, categorize, and analyze risk of potentially dangerous glacial lakes[119]

Liu et al suggested a similar set of criteria for identification and assessment and adds a lake volume calculation and defined GLOF hazard across four categories (very high, high, medium, and low) with consideration to the drainage gradient, the mass of potentially recruited debris in valleys below glacial lakes, and distance to nearest settlements.[120] Outside of Nepal, Allen et al (2015) updated an existing inventory of glacial lakes in the Indian states of Uttarakhand and Himachal Pradesh and developed a risk ranking system using topographical features of lakes and their surrounding watersheds.[121] This was part of an effort to retroactively examine the 2013 Uttarakhand floods, which killed more than 6,000 and were to a degree triggered by the Chorabori Lake failure above the village of Kedarnath. The study considered features such as the stream size of waterways running into the lake (wider streams promote the transport of more water), average daily precipitation, and the abundance of steep sediment around the lake in its risk assessment. This study found the Chorabori Lake to rank second in "unfavorable topographic disposition" among 169 dams in the inventory.[122] The table below (Figure I.8) lists five watershed parameters used in Allen's rank assessment of glacial lake risk. Each of these parameters can be collected by remote sensing methods or by field observations.

Assessed watershed (WS) parameters	Relevance	Median all lakes [range]	Chorabari value	Chorabari rank
Lake elevation	Lower elevation increases likelihood of rainfall and snowmelt within the lake watershed.	4830 m [3750-5670]	3850 m	2
Nonglacial watershed component (WS_{ng}) $(Ws_{ice\text{-}free}\ Ws_{dir})$	Glaciers provide a buffering effect during high and low run-off events. More immediate response to rain and snowmelt is expected in an ice-free watershed where fluvial drainage dominates.	0.24 [0.00-10.73]	2.27	13
Mean stream size[a] *(Strahler number)*	Large waterways increase the capacity of the watershed to transport run-off from snowmelt and rainfall to the lake.	1.21 [0.00-1.91]	1.76	7
Drainage density[a] (Stream length/$WS_{ice\text{-}free}$)	High drainage density increases the capacity of a watershed to transport run-off from snowmelt and rainfall to the lake.	1.57 km km^{-2} [0.00-6.27]	2.3 km km^{-2}	36
Mean slope[a]	High relief and steep-sided watersheds favour faste run-off and flow concentration within streams.	26° [6-42]	35°	9

Fig.I.10: Topographical parameters calculated for 169 glacial lakes across Uttarakhand and Himachal Pradesh[123]

Sherry et al (2018) highlight this in their study of local risk perceptions and cultural response to GLOF risk in the Rolwaling Valley of Nepal, immediately beneath Tso Rolpa—which in turn builds from the social science literature about glacial hazards from other contexts, such as Carey (2010) in the Andes. Sherry and her colleagues they argue that: "Technological and engineering-based solutions to glacial hazards cannot stand alone in preventing disasters from GLOF's, because *GLOF responses will always be enmeshed with social and cultural factors...*

If any future mitigative response to GLOF risk is to take place in Nepal, *the social and cultural capacities of communities like the Rolwaling Sherpa could be incorporated to engage local people and co-manage non-structural measures for risk reduction*, such as land use planning, building management codes, seeking insurance protection, perception and awareness building, and emergency warning systems" (emphasis ours).[124] We agree entirely.

Cascading Hazards & Flow Events

LANDSLIDES IN THE CONTEXT OF CASCADING HAZARDS

Landslides pose a great risk as secondary hazards that can often trigger additional hazards downstream or downslope of the event. Earthquake-triggered landslides are the most important secondary hazard associated with large continental earthquakes, accounting for approximately 70% of all earthquake-related casualties.[125] Extensive coseismic landslides across a region following large earthquakes have resulted in significantly higher death tolls than earthquakes without landslides, as well as wider infrastructural disturbances and the transportation of large volumes of sediment into downstream river systems.[126] Instability continues following an earthquake and may persist for several years, with activities eventually subsiding either through land stabilization or exhaustion.[127] Earthquake-triggered landslides occur in the months and years following earthquakes as a direct result of earthquake damage in the region, but can also be triggered by intense rainfall.

Oven et al (2021) suggest that landslide hazard regimes changed after the earthquakes of 2015, shifting toward a "hazard context increasingly dominated by debris flows–which are highly sensitive to intense rainfall when saturated."[128] They argue that "living with landslide risk after the earthquakes was therefore not simply a case of more of the same, but rather of living with a very different hazard landscape."[129]

Landslides can be both the triggering, or primary, hazard in a cascade or a secondary hazard. In the context of cascading hazards, landslides in Nepal are susceptible to both large earthquakes and heavy rainfall during the monsoon season. Since the Gorkha earthquake, Nepal has continued to experience a sharp increase in both the number and area of landslides, an indication that coseismic landslide hazards remain relevant years after the event.[130] Rosser et al. (2019) note that earthquake-triggered landslides following the 2015 earthquake tend to occur along certain segments of the landscape where the ground's material strength was weakened due to shaking. This reduction in material strength lowers the threshold at which monsoon season rainfall can trigger landslides. As triggering hazards, landslides surging into river valleys have the potential to form landslide dams, blocking river flow with its material composition. These landslide dams can exact a devastating toll downstream when they inevitably break and are an additional component of cascading hazards.

Several examples frame the danger of landslides as it relates to cascading hazards in Nepal. The previously mentioned Jure landslide that occurred in 2014 struck a densely populated area after two days of heavy rainfall. It destroyed everything in its path until its material stopped at the Sunkoshi River where it formed a 55 m high landslide dam, effectively blocking the river and creating a lake that inundated riparian communities.[131] [132] The effects of the Gorkha earthquake destabilized the landscape of the region and led to the widespread distribution of landslides even in areas that were previously thought safe from landslides or showed no signs of historic landslides.[133] In 2020, two separate landslide events were triggered in Lidhi village and Jambu settlement in Sindhupalchok District, resulting in 37 and 23 fatalities respectively.[134] Both events have been associated with the Gorkha earthquake. Although the relationship between seasonal monsoons and the rate of landslides in Nepal is well established, there is more to learn about how earthquakes affect this relationship.

Efforts to create detailed inventories of coseismic landslides are integral to understanding their spatial and temporal distribution, assessing potential failure mechanisms, and generating hazard maps. Rosser et al. (2021) explored the changes to landslide hazards following the 2015 Gorkha earthquake by mapping landslides between 2014 to 2019.[135] Using Landsat satellite imagery, the team identified and traced landslide events for each year before and after the monsoon season as well as immediately after the earthquake. By creating a time-series inventory, they were able to assess the evolution of coseismic landslides months and years after the event and discover how the earthquake affected areas that previously were not known to be susceptible to landslides.

RIVER BLOCKAGES: LANDSLIDE DAMS AND SLUMPS

The formation of natural dams that block rivers can be induced through landslides surging into river valleys, the slumping of large slopes into river valleys, the movement of glaciers or ice sheets, and along fault ruptures.[136] While the initial hazard itself presents a localized danger, natural dams can pose a greater risk to downstream populations and assets along the river or stream channel, as they can create a risk of sudden outburst floods. Most landslide dam failures occur through overtopping, where dams gradually erode or collapse which leads to a catastrophic break and the devastating release of impounded lake water.[137] The sudden and rapid release of water forces massive amounts of material from previous avalanches, landslides, and debris to flow downstream, which can alter river channels through erosion and/or deposition, thus destroying communities and infrastructure.[138] The larger the landslide event and the dam created, the more likely it is to persist, and the larger the sediment reservoir that it creates upstream—but it can fail catastrophically again later under extreme flow conditions. By impounding water and other materials, they thus create an additional layer of potential energy - literally creating another stage in a cascade of hazards, through which hazards evolve in a chain of events.

Such events, particularly landslide-blocked rivers, are relatively common in the Himalayan region, when a large landslide occurs. Nepal's frequent exposure to landslide-triggering events like seasonal monsoons and intermittent large earthquakes makes landslide dams a common occurrence. Landslide dams in Nepal are generally unstable due to lithology, weathering, and high water saturation in sediment which often leads to failure within a short period of time. For example, in the wake of the 2015 Gorkha Earthquake, a 7.3 M_w aftershock triggered a landslide that formed the Baisari landslide dam across the Kali Gandaki River.[139] The landslide dam filled a lake for 16 hours until overtopping occurred. Water levels downstream of the breach rose up to 2 m above normal monsoon flood levels. Fortunately, loss of life was avoided due to the timely evacuation of riparian communities downstream.

The lifespan of such landslide dams can vary greatly, between several hours to thousands of years. Some of the most enduring dams can eventually become home to human settlements—many villages in the high Himalayas are located on deposits from old landslides, slumps, or other slope failures.[140] When these natural deposits dam rivers they can change the river morphology and backfill sediment, creating relatively flat alluvial floodplains and braided channels that provide agricultural and pastoral opportunities—examples in Nepal include Ringmo village in Dolpa and Lamabagar in Dolakha.[141] In the Himalayan region, the scale of these events is sometimes so large that outsiders, or even trained scientists, don't initially recognize that the whole village is located on a landmass created by a mass movement.[142]

Slumps are another major cause of river blockages. Slumps are a different type of mass movement distinct from landslides because they refer to a process whereby large blocks of earth or rock move suddenly downslope, sliding en masse rather than in a cascading landslide/avalanche pattern—as if the whole mountain just broke off in a large chunk and slid into a river.[143] Because the materials fall as a cohesive mass, they are far more likely to create a significant and enduring dam, but that doesn't mean they will not overtop and produce a sudden flood later. Himalayan slumps can be massive.

More recently, the aforementioned Jure Landslide of 2014, properly identified as a slump, in Sindhupalchowk District fell into the Sunkoshi River valley, forming a lake that expanded up to 3 km upstream from the dam, inundating parts of the Arniko Highway and riparian farmland and communities. The resulting destruction of the highway that linked Nepal and China disrupted cross-border commercial activity and cost nearly $400,000 daily for nearly 2 months.[144] Downstream of the base of the landslide, the dam effectively stopped all water flow to five hydropower plants downstream, causing a major disruption in power generation.[145] The Nepal Army mobilized rapidly to manage flood risk and sought to channel the impounded water downstream. Heavy rainfall eventually caused the dam to breach 37 days after it formed, damaging homes downstream of the site, yet the scale of impacts was lessened by the Army's efforts and fatalities were avoided.[146]

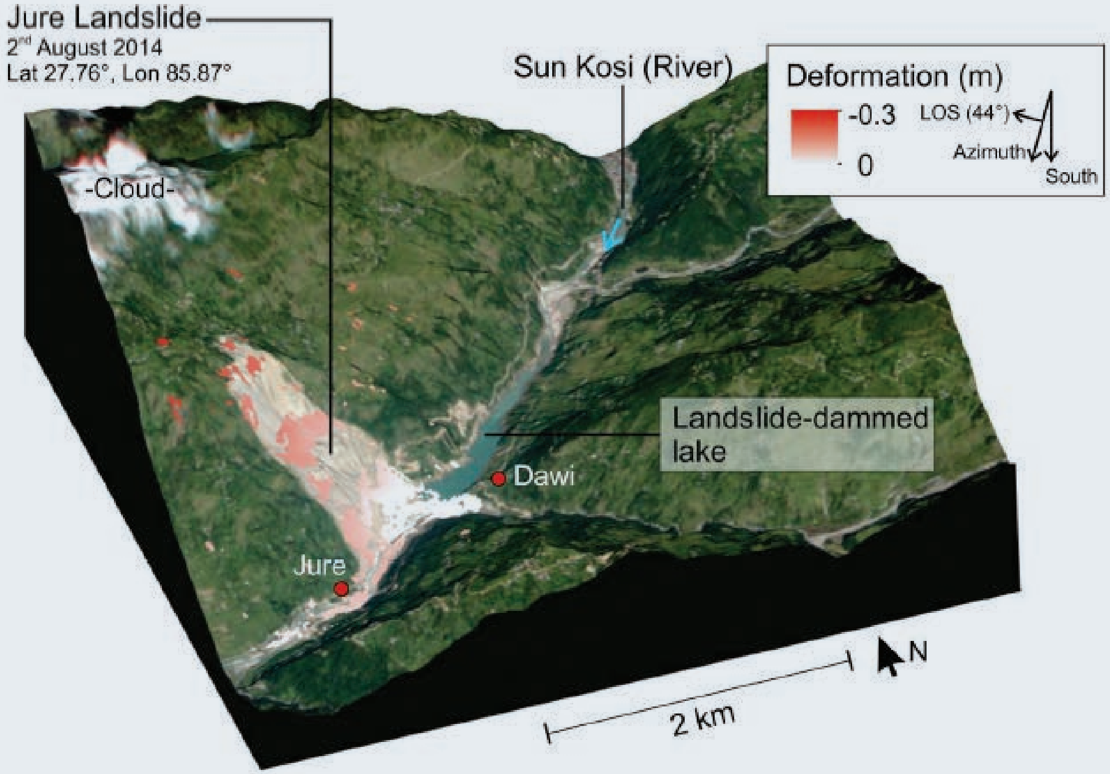


Fig. I.11: Earthquake triggered Jure landslide deformation in the Sun Kosi River measured from COSMO-SkyMed SAR for May 5-29, 2015[147]

In both of the cases mentioned herein, the natural dams created by landslides and slumps were detected, risks were thereafter mitigated as the water levels rose or were managed, and downstream communities had time to adapt. But this is not always the case. In these cases, the natural dams are not singular sites of risk, but another stage in a chain of cascading hazards—as the following section and our detailed analysis of the 2021 Melamchi Event shows below.

Inventories and datasets of landslide dams have been created from a global to subnational scale.[148] However, despite the number of studies and research teams mapping and monitoring landslides in Nepal, mapping landslide dams is uncommon. Existing work is mostly descriptive in nature, presenting landslide dams as case studies or inventories. Dhital et al. (2016) present a general analytical approach to creating hazard maps of landslide dams by incorporating seismic, geological, hydrological, meteorological, and anthropogenic factors into a criteria-based model to identify susceptible hazard regions.[149] Critically, landslides and slumps can also be re-mobilized by extreme flow conditions. The deposition of new materials in and around existing natural dam areas effectively creates a new risk profile for each natural dam feature, shifting the patterns of pressure and erosive processes that act on them.

At the simplest level, a comprehensive hazard monitoring system needs to account for both a) emergent extreme events linked to flood risks arising from dams created by slumps and landslides and b) background conditions and potential cascading hazards created by past events (i.e. an inventory) which can help inform and focus monitoring efforts.

DEBRIS FLOWS CUM DEBRIS FLOODS, AND OTHER EXTREME FLOW EVENTS

Mass movements like landslides and high-altitude floods from the failure or breach of natural moraine or landslide dams can also trigger massive cascading hazards in the form of debris flows and more severe debris floods. These hazards occur when debris and sediment become saturated and agitated with water, causing it to flow rapidly down steep tributary channels until it fans out into the mainstream channel.[150] Along the path, these flows may grow by entraining (gathering and transporting) sediment and other materials picked up by the rapid flow. The largest flows have the force or capacity to re-mobilize debris from past landslides, which have long been static.

The term debris flow is generally used to characterize a high velocity type of mass movement with a high fluid content, akin to a landslide but with longer run-out distances. The USGS provides a basic overview of these processes:

> ***"Debris flows generally occur during periods of intense rainfall or rapid snowmelt and usually start on hillsides or mountains. Debris flows can travel at speeds up to and exceeding 35 mph and can carry large items such as boulders, trees, and cars. If a debris flow enters a steep stream channel, it can travel for several miles, impacting areas unaware of the hazard. Areas recently burned by a forest fire are especially susceptible to debris flows, including the areas downslope and outside of the burned area. Debris flows are a type of landslide and are sometimes referred to as mudslides, mudflows, lahars, or debris avalanche."***[151] [152]

This statement shows that debris flows and debris floods can be triggered by a variety of different factors and that they are also known by a variety of other names, including countless vernacular terms and localized categories used by people living with these hazards.[153] Debris flows are often characterized as a sub-type of landslide, but we use the term as a separate category of its own since Himalayan debris flows are generated by and evolve in relation to a variety of different hazards, growing to an unimaginable scale.

Although debris and sediment flows may originate from various sources, the most common form of mobilization is from landslides.[154] Nepal is incredibly vulnerable to debris flow due to active tectonics, its mountainous and hilly terrain, and its concentrated monsoon season. Sediment and debris are often agitated and mobilized during the monsoon season, and then redeposited in other downstream valleys due to variations in the river channels and water flow, only to be agitated again by future triggering hazards.[155] These rapid flows can be devastating once they reach densely populated areas, destroying infrastructure and homes as well as killing or injuring those caught in the flow.

Most debris flows are small and relatively localized events, though they can also be deadly. For example, in July 1993, the Kulekhani watershed about 30 km south of the Kathmandu Valley experienced an unprecedented 24 hours of rainfall that subsequently triggered landslides and debris flows.[156] A debris flow of large boulders destroyed over 50 houses in the village of Phedigaun and resulted in the deaths of 62 people. The flow itself subsequently fanned out and covered more than 30 hectares of land, disrupting local agriculture. The Kiteni River was also affected by a debris flow composed of boulders and sand. which spilled over the river channel, burying the Kiteni village, destroying farmland and several houses, and killing 11 people. In this case, these debris flows occurred in a typical group or swarm pattern, during extreme precipitation events.

In 1996, Larcha village in the upper Bhotekoshi Valley experienced a devastating debris flow after high precipitation triggered upstream landslides dams which eventually breached.[157] As with other debris flows, like the Chamoli Disaster, this event was initially mistaken as the result of a glacial lake outburst flood. The mass movement of debris swept away over 70% of the homes in Larcha and killed 54 people in a matter of minutes. As of September 2022, the Araniko Highway which was historically the main road between Nepal and China remains closed due to landslides during and following the Gorkha Earthquake (see below). Interestingly, the main dry port for customs is now being built in LarchaIn, a highly unstable corridor. This area is considered relatively safe, and Nepal and Chinese authorities are investing heavily in disaster mitigation infrastructure along the river channel, with the hopes of re-opening and protecting this major trade corridor.

Most debris flows do not travel over long run-out distances, though this depends on a variety of factors: such as fluid content, to gradient, to surface roughness. The most decisive factor in the destructive power of debris flows is the water content - the more water content, or the higher the fluid ratio, the more powerful and more sustained a debris flow can be. In the Himalayan region, monsoonal bursts, unstable slopes, and steep river channels create a perfect situation for large debris flows which can become something else: what we might call *a debris flood.*

These debris floods are a particular genre of cascading mountain hazards—in some ways they are the sum total or endgame of several other cascading factors. In the end, a GLOF, landslide, avalanche, or debris flow can trigger a chain reaction that eventually leads (given enough water) to a debris flood. Debris floods are essentially highly fluid and liquid debris flows, and they will eventually slow down and settle out, *unless* they are fueled by further water and new cascades in the system - as occurred in the Melamchi case, where the hazard evolved over a series of cascading flows.

Debris floods carry a particular risk of re-mobilizing other materials as these floods grow in scale and more water enters the system. In addition to all the identified landslides triggered by the 2015 Gorkha earthquake and aftershocks, many masses were only partially mobilized. When these masses become saturated again during subsequent monsoons, they could potentially remobilize and form debris flows.[158] The natural processes of erosion and transport by rivers lead to the creation of sediment reservoirs in places where the river channel has been impounded by natural dams—or what, in the context of these high-capacity debris floods like the Melamchi Disaster have recently been referred to as "Himalayan sediment bombs". [159]

In recent years, several of the most destructive mountain hazards in the Himalayan region debris flow events are immediately thought to be floods (like the Chamoli Disaster of 2021) and they are in a way, but they are not always due to GLOFs or dam failures upstream. The end of the hazard chain, however, resembles a flood. Many different triggers can create cascading hazards, but many of these diverse chain reactions can lead to what we are calling a debris flood event.

The Himalayan landscape is filled with massive debris flood events that seem to defy all categories. Perhaps most notable is the fact the entire city of Pokhara, Nepal's 2nd largest and fast-growing metropole, is located on a massive alluvial fan created by repeated catastrophic debris flows.[160] This unique feature is nearly 150 sq km in size and the deposits are nearly 50m thick.[161] The exact events which created this geological anomaly are not yet apparent—but recent research, namely (Stolle et al 2017) outlines the main processes. Dave Petley (2017) world-renowned landslide expert, summarizes their findings and the enduring mysteries as follows:

> ***"Stolle et al. (2017) interpret these deposits as being the geomorphic legacy of earthquake-driven sedimentation....They have found that the deposits represent three pulses of sediment delivery from the mountains, dated at around 1100 AD, 1255 AD, and 1344 AD. They consider that each of these three deposits was the result of a large earthquake, each of which generated huge debris flows that, as they put it, invaded and plugged the tributary valleys, allowing lake deposits to form. There is evidence from archive sources of two of these large earthquake events.[162]***

While the source of these huge debris flows is not clear and these huge deposits are essentially unique,[163] it presents the disturbing possibility that future events of this scale are possible in the Himalayan—particularly in the context of a megaquake, which technically could occur at any moment within one of the "seismic gaps" along the Himalayan range. While extreme events of this scale are beyond the scope of our study or warning systems, they show how active and how dangerous this landscape is and encourage us to anticipate other extreme flow events (like the Melamchi Disaster or the Chamoli Disaster) which occur regularly, do not require a megaquake to trigger, and are becoming more common due to climate change.

Importantly, data suggest river valleys that have experienced debris flow in the past are more likely to experience debris flow again (Sattar). Remote sensing has demonstrated the potential to map changes to landscape after debris flows and monitor changes to river banks and channels. Bandhari and Dhakal (2019) have attempted to create debris flow inventories for the Siwalak Hills in Nepal using satellite imagery, as has been done with landslides.[164] Shapes of scars and fans were drawn using high-resolution imagery from Google Earth by following the river channel. Inventories of landslides and debris flow contribute to the model development and analysis of landslide and avalanche run-out. The United States Geological Survey developed Laharz, a computer program originally designed to generate debris flow and hazard maps by calculating hazard zones around volcanoes, that has shown use-capability for debris flows.[165]

In Section III we discuss the scale of the debris flow at the core of the 2021 Melamchi Disaster, which is a telling example of the potential for future large debris flows intensified by "Himalayan sediment bombs"--and our methodology focuses on these issues.

Hazards In The Built Environment

INFRASTRUCTURE & HAZARDS

According to a 2019 World Bank assessment, Nepal requires investment of about 10-15% of its annual GDP in infrastructure development for the following decade.[166] Among the various sectors analyzed, energy and transport remain integral to Nepal's economic growth. Despite recent progress in solving chronic energy security problems, inadequate access to electricity still hinders the country's potential economic growth. Nepal's hydropower potential presents an economic opportunity to export power to neighbors in Southeast Asia, becoming a "hydropower nation"—similar to how Laos presents itself as the "battery of Southeast Asia". Continued development in the transport sector aims to broaden domestic and international market access and the tourism sector.[167]

Although improvements in both sectors are necessary for the economic development of Nepal, more consideration is needed of how natural disasters and particularly cascading hazards can affect infrastructure and the communities and industries that rely on it. Nepal's susceptibility to hazards like landslides, earthquakes, and debris floods poses an obstacle to the construction of roads and hydropower plants. Road building is critical for connectivity and well-being in rural areas, but is often unregulated and can further destabilize slopes.[168] Since 2014, Nepal has continuously expanded its road system with an aim to strengthen the country's international trade network and connect its rural-majority population to domestic markets for their agricultural products.[169] As of 2022, Nepal has 178 operational hydropower plants, 138 under construction, and an additional 91 projects planned for development.[170] The increase in infrastructure has brought and will continue to bring economic benefits to Nepal and its people, but it may also be affected by or even unintentionally induce natural disasters and cascading hazards.

The 2015 Gorkha earthquake clearly demonstrated both the precarity of Nepal's infrastructure and the ways in which infrastructure development plays a role in creating landslide risks. According to the Government of Nepal's formal Post Disaster Needs Assessment (PDNA), several hydropower plants which collectively generated about 175MW were severely or partially damaged, and 1,000MW of hydropower plants under construction were partially damaged.[171] Approximately 800 km of transmission and distribution lines were also damaged, which led to over 600,000 households without access to electricity either due to house collapse or damage to electricity supply facilities. The same report noted significant damage to the road system: while a relatively small percentage of major roads was damaged by the earthquake or landslides, a much greater percentage of rural roads were destroyed.[172] This effectively cut off access to rural communities from essential services and economic hubs which rural populations relied on. The relationship between rural road building and hazards is more complex than simple cause-and-effect. Multiple studies have looked into the relationship between transportation development and mass movements. The development of roads and railroads destabilizes upper slopes by changing their hydrological and morphological patterns as loose materials are left along the roadsides and water accumulates, which may eventually lead to landslides.[173] McAdoo et al. (2018) similarly conclude that informal, non-engineered rural roads meant to connect rural populations to greater economic opportunities have led to a higher concentration of landslides during the monsoon season occurring within 100 m of a road than landslides induced by earthquakes.[174]

Hydropower infrastructures are also vulnerable to earthquakes and other geohazards—perhaps more than most hydropower developers or government officials working in Nepal or the broader Himalayan region prefer to admit .[175] The process of constructing dams and hydropower facilities can destabilize slopes along the river corridors, especially the practice of tunneling and blasting for run-of-the-river projects. Tellingly, many Himalayan hydropower projects are designed so that the powerhouses are located underground precisely *because* of chronic exposure to geohazards along the river channels.[176] Recent reviews of hazard exposure in the Himalayan hydropower sector suggest that over 25% of all projects experience landslides and other hazards during the construction phase alone.[177] And yet, in the wake of the Gorkha Earthquake, key stakeholders active in Nepal's hydropower sector gathered to discuss disaster risk reduction, but ultimately most plans for hydropower development have remained mostly unchanged and the cumulative impacts on landscapes remain largely unaccounted for.[178]

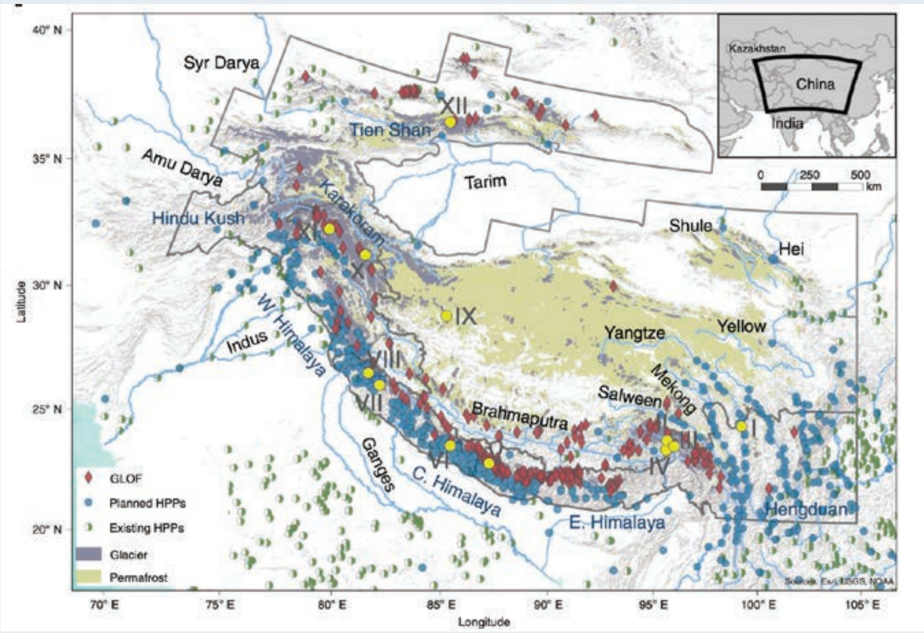


Fig.I.12: A map of the Himalayan region highlighting the density of hydropower projects and potential GLOF risks upstream.[179]

Looking at the Bhotekoshi corridor through Sindhupalchowk district–the district where the Melamchi Disaster occurred–provides an excellent example of the ways in which Nepal's critical infrastructure faces chronic risk exposure. The Jure Landslide along the Bhotekoshi River in 2014 damaged two hydropower projects and cut off the main Nepal-China trade corridor. The Gorkha Earthquake of 2015 triggered dozens of co-seismic landslides throughout the corridor, damaging roads, hydropower facilities, and the main customs facilities at the Nepal-China border (which led to the indefinite closure of the trade corridor altogether). In 2016, a series of floods linked to the Gongbatongsha GLOF in an upstream tributary on the Chinese side of the watershed damaged the roads and the single hydropower project that had remained largely unscathed to date.

While this is a particularly rapid sequence of successive hazards, this is indicative of a larger pattern of interwoven infrastructural risks which plays out in *many* watersheds across Nepal. Climate change is both increasing the risks and the frequency (or the likely recurrence interval) of such risks at the same time that infrastructure networks are rapidly propagating across Nepal. A recent study highlights this emerging issue: underscoring some of the ways in which hydropower infrastructures are "threatened by climate-driven landscape instability across the Himalayan region and "High Mountain Asia."[180] One of the most significant risks to in-stream infrastructure is the possibility of large cascading debris floods, such as the Chamoli and Melamchi Disasters of 2021, which both caused significant damage to dams and water infrastructure. This is another reason our project and the broader work of disaster forecasting becomes meaningful: to understand the ways in which infrastructure is exposed to shifting hazards *and* to understand the ways in which infrastructure development affects vulnerability for people living in project-affected areas.

Disaster events like the cascading debris floods that destroyed two hydropower facilities during the Chamoli Disaster of February 2021 and the cascading debris floods which damaged the Melamchi Drinking Water Project during the Melamchi Disaster of June 2021 are a major wake-up call for planners and developers alike. These events discussed above have begun to shift the discourse, leading to greater recognition of potential and evolving risks which may be magnified due to climate change. Our conversations and long-term research indicate that the authorities in the public and private wings of Nepal's hydropower sector are increasingly ready to engage in disaster risk reduction efforts and that they are interested in developing and applying risk assessment and monitoring tools, as well as EWS systems.[181]

While the boundary between calculable risks and possible uncertainties is difficult to identify, we can say with certainty that Nepal's critical infrastructure is more exposed now than at any other point in history - and will be even more exposed in the years to come. As the Government of Nepal and donor institutions are increasingly recognizing, "anticipatory action" is critically needed to mitigate evolving risks to infrastructure in Nepal. As emergent geohazards and new scientific studies create greater awareness of disaster risk, the political conditions and discourse are changing. This creates a timely and strategic window of opportunity for better coordination and better decision making - which we hope to foster through the creation of an improved EWS toolkit(s) aimed at the leading edge of contemporary geohazard-infrastructure problems.

SOCIALLY-CONSTRUCTED VULNERABILITIES

Hazards like landslides or debris occur with or without human impacts, but *disasters* are a uniquely human experience, and human experiences of disaster are shaped by uneven and socio-historically produced conditions of vulnerability. Disaster scholars use the concept of vulnerability to highlight the social and political-ecological aspects of vulnerability, which is separate from the generalized patterns of exposure, potential or realized.[182] While undertaking this study and laying a development pathway for proposed toolkits, we are aware of the socially-constructed aspects of vulnerability and the hidden political work done by naming things as "natural" disasters and risks when they are modulated by human interventions and uneven patterns of risk exposure. We are aware of the critique of normative thinking about hazards which reproduces vulnerabilities by "locat[ing] risk in the hazard itself" rather than the social dimensions of risk and vulnerability.[183] Risks do not exist out there in the world, without us. Exposure to hazards is always shaped by human patterns of vulnerability, which are uneven and socially produced by infrastructural interventions, the politics of land use zoning, and chronic patterns of social exclusion or discrimination, for example.

While this preliminary report focuses mainly on analyzing and monitoring mountain hazards, we are acutely aware that such mountain hazards are also deeply *social* and *political* and that patterns of exposure to hazards and downstream risks are highly uneven. Simply put, some people are at much greater risk than others to natural hazards - particularly impoverished people struggling to eke out a living from marginal lands and those who are marginalized from or within a given society. In her study of flood-oriented EWS programs in the Lower Karnali Basin of Nepal implemented by Practical Action, Sierra Gladfelter clearly articulates the need to account for social and historical factors in disaster risk reduction: “If the goal of humanitarian and development organizations is to build “people-centered EWS”, then they will have to not only look forward and toward the skies, anticipating and mitigating the next disaster, but also backwards and to the ground where historical patterns of marginalization continue to structure people’s uneven experience with and capacity to resist disasters.”[184]

As hazard regimes shift and debris floods become more common, Nepal needs better models to help people assess, anticipate, and manage disaster risks and to understand the factors which shape uneven patterns of potential *exposure*. Ensuring that planners and local stakeholders have the best possible access to these tools is a justice issue. But understanding the full complexity of disaster risk reduction also requires studies of the intersectional factors which shape situated patterns of vulnerability in society and in place. For an example of such an intersectional approach that foregrounds the ways persons with disabilities experience disaster risk and vulnerability in Nepal, see the study titled “Disaster, Disability, and Difference” (Lord et al 2016) prepared for UNDP Nepal.[185] In this vein, as our own work proceeds and we attempt to apply the tools and systems we have created, we will also work to examine and unpack socially-produced patterns of uneven hazard *vulnerability*, using an intersectional approach that recognizes critical factors of gender, ethnicity, caste, class, age, and ability.

In short, vulnerability is a socially-constructed state of affairs, not a quality of a person. For this reason, our approach seeks to account for and explore the ways in which differently positioned Nepalis are *made* vulnerable to cascading hazards under certain conditions in Nepal, but we do not seek to identify or pathologize vulnerable communities. To provide a more tangible example: communities living in informal settlements who have ‘encroached’ into the riparian zone or floodplains of any given river in Nepal are not residing there because they are unaware of the risks, but because their choices are constrained by broader structural patterns of exclusion and power—and sometimes by other disasters or hazards regimes, as was and still is the case with some communities displaced after the 2015 Gorkha Earthquake.

At the same time, we also want to highlight that people living with hazards are not inherently vulnerable, though their situation may at times exaggerate conditions of vulnerability. As critical disaster scholars have repeatedly emphasized in recent years: “There is a growing discomfort that categorizing the “vulnerable” acts to flatten and simplify diverse communities, as well as discursively nullify the everywhere-visible “resilience,” toughness, and genius that exists in communities, and subsets of communities, that are habitually exposed to risk” (Marino & Faas 2020: 1). Other scholars within disability studies have also repeatedly emphasized that persons living with disabilities are not inherently vulnerable, though intersecting social factors may render them vulnerable to specific disaster impacts and harms.[186] [187]

Understanding and reckoning with socially-constructed vulnerabilities can and should inform the design of EWS platforms. Not only when accounting for potential patterns of harm, loss, and damage, but when organizing community engagement and designing EWS communication protocols. For example, a variety of different outreach efforts may be needed to engage and/or alert differently positioned populations, particularly marginal communities or people that lack access to real-time information or unevenly distributed technologies. For example, as Lord et al (2016) have shown, early warning systems must be made accessible to people with sensory disabilities, and evacuation protocols need to account for people facing mobility-related challenges.[188] Staff from the NGO People in Need have also found when working in Nepal: "Observation on the ground show that redundant channels are needed to ensure that the information reaches everyone be it SMS alerts or sirens. It is especially imperative to mobilize a community task force to reach the elderly, people with disabilities, single women-led households, among others."[189] As Lord et al (2016) have argued[190], ensuring that principles of accessibility and "universal design" intended to benefit persons with disability are incorporated into DRR protocols can benefit *everyone* - because such intentioned design makes alerts more effective and evacuation easier for all. In short, EWS design needs to reflect the diversity and diverse vulnerabilities within a given population, accounting for these differences and building some productive redundancy and principles of accessibility into EWS protocols can help counteract socially-constructed patterns of marginalization and vulnerability. These systems can inform more equitable and just disaster risk reduction protocols: providing more inclusive patterns of early warning and anticipatory action protocols, helping to limit harm and displacement, and hopefully helping to save lives.

All this said, this preliminary report is merely a scoping study, rather than a field-based one. Because vulnerabilities are highly situated, we would then wait until later stages in this project to unpack the specific configurations of power and social processes that configure vulnerability in a given watershed or community.[191] This analysis will be conducted mostly through field-based interactions and community engagement. Further, to make these tools and systems effective, we will need to assess and understand the social, political, and cultural layers in a given context. When the time comes, we can and will also consult with experts and NGO colleagues working on issues of social inclusion and vulnerability in Nepal to ensure our tools are inclusive and accessible in the specific contexts they are deployed. For now, we simply want to state that we know that a better model or an improved configuration of EWS technologies will not answer these questions (though it will certainly help). In sum, even the most precise remote-sensing tools need to be ground-truthed, and EWS systems in particular need to account for social factors such as governance issues, communication challenges, and uneven vulnerabilities produced by social exclusion.

SECTION II:

Focusing on Debris Floods and Extreme Flow Events

Monitoring Natural Dam Risk: A critical component of early warning for debris floods and extreme flow events

Of the multiple hazards discussed in the previous section, we conclude that debris floods and other extreme flow events are the category of hazard most in-need of investment and capacity building for monitoring and early warning in Nepal. Debris floods tend to rank high in the level of severity and number of people, assets, and infrastructure affected. Partially this is due to their runout distances. Since debris floods tend to have long runout distances (due to the higher relative volume of water within flows) and are typical to stream and river valleys (as opposed to singular landslides which can occur in a broader variety of terrain), it is possible to model the intensity of runout under different scenarios and identify probable affected areas. Further, patterns in the spatial distribution of debris floods and spatial occurrence in stream and river valleys create a more delimited and mappable landscape for assessment and monitoring upon which, we can focus our efforts.

Debris floods tend to involve sets (or webs) of numerous, inter-related background conditions and hazards discussed in depth in Section I. Debris floods can be triggered directly by intense rain, landslides, avalanches, or by a GLOF, all of which have the potential of creating a cascading hazard chain. The effects of debris floods can be amplified by the mobilization or entrainment of other materials in its flow path, including secondary cascades such as when a debris flood leads to the breaching of natural dams or when the flow triggers new landslides. A minor slope failure can thus create a chain reaction of increasingly large events that contribute to the flow. With massive cascading-style debris floods like the Melamchi Disaster of 2021, causality can be linked to both a specific hazard chain and a shift in background conditions.

Evaluating the conditions that shape debris floods requires attention to the broader geomorphological conditions, climatic context, close observation of evolving meteorological conditions, and monitoring for extreme weather events that deviate from those trends. The range of possible triggering background conditions and contributing hazards provides a wide selection of indicators to monitor. When areas are identified as nearing or reaching possible trigger thresholds, deeper and rapid monitoring and assessment methods could lead

Chukhung Glacier moraine and GLOF breach. Photo courtesy of Flickr user -MattW- and used under a Creative Commons license.

to appropriate levels of early warning and action. A final opportunity for the assessment and monitoring of debris floods is that risk thresholds could appear weeks to days prior to the final set of events that initiate a debris flood. For example, a gradual expansion of a glacial lake previously determined to be risky could be observed weeks prior to its bursting. Also, snowpack ripening can be tracked long before conditions emerge which causes a rapid snowmelt event. And as will be demonstrated below in the case of the Melamchi disaster, a debris flood could initiate and move in trackable phases down a river valley, providing time for devastating debris flood to be observed, assessed, and then provision of early warning days to hours before it hits downstream communities with the densest populations.

The 2021 Melamchi Disaster as Case Study

Based on our review of evolving hazards, we decided to take a deep dive into analyzing the Melamchi Disaster which occurred in central Nepal in June 2021. We chose this event as our principal case study for several reasons. First, this event was generated by a cascading series of hazards: a chain reaction that included many different kinds of geohazards leading to a massive debris flood. Second, while debate continues over the attribution of the Melamchi Disaster to climate change, it speaks to contemporary concerns with extreme precipitation and climatic volatility. Third, it was a very recent event in Nepal, which we could compare with past disasters in Nepal and other events across the Himalayan region (i.e. the Chamoli Disaster). Fourth, because this event is currently being studied, but only a handful of preliminary reports are available to date,[192] providing an opportunity to apply our models and approach to a real-time problem to see at what points in time and with what methods a monitoring system could have helped increase preparation for this event.

This cascading debris flood that became known as the Melamchi Disaster unfolded over the course of four days from June 15-18, 2021.[193] The debris flood cascaded along the Melamchi-Indrawati watershed and triggered a number of other subsequent hazards along its course. This cascading event began at an elevation of around 5,000 meters, but flows finally subsided near the village of Dolaghat more than 70 kilometers downstream at an elevation of only 630 meters. The disaster fully damaged 337 houses and displaced 1,700 people, and debris floods took out 20 bridges and destroyed more than 300 local enterprises. It caused severe damage in and around the market town of Melamchi Bazaar, inundating the entire community in a thick layer of debris and sediment. The debris flow also severely damaged the intake area of the multi-billion dollar Melamchi Drinking Water Project, aimed at augmenting water supply to the Kathmandu urban area.

Our analysis, like other reconstructions of this event, suggests that the initial triggering event was likely driven by extreme precipitation and its impacts on snowpack and/or glacial features. In the days prior to the event, heavy rainfall across the Himalayan region had triggered other hazards and lesser debris floods in regions like the Kali Gandaki corridor of lower Mustang–a familiar pattern triggered by slope saturation during the pulses of the monsoon. This was preceded by heavy rains in the pre-monsoon period as reported by Nepal's Department of Hydrology and Meteorology and, prior to that, two cyclone-driven storm sequences. These weather patterns led to heavy snow accumulation in the Central Himalayas, which was rapidly eroded due to mixed precipitation in this warmer monsoon period. This pattern is typically referred to as a "rain-on-snow event" which leads to significant snowmelt and destabilization of the snowpack. According to a 2021 ICIMOD study, this rapid melting and erosion of deposited snow led to a moraine failure at a glacial lake in the upper reaches of the Pemdang Khola, a tributary to the Melamchi river system.[194] This is one plausible theory of how and where this cascading event began.

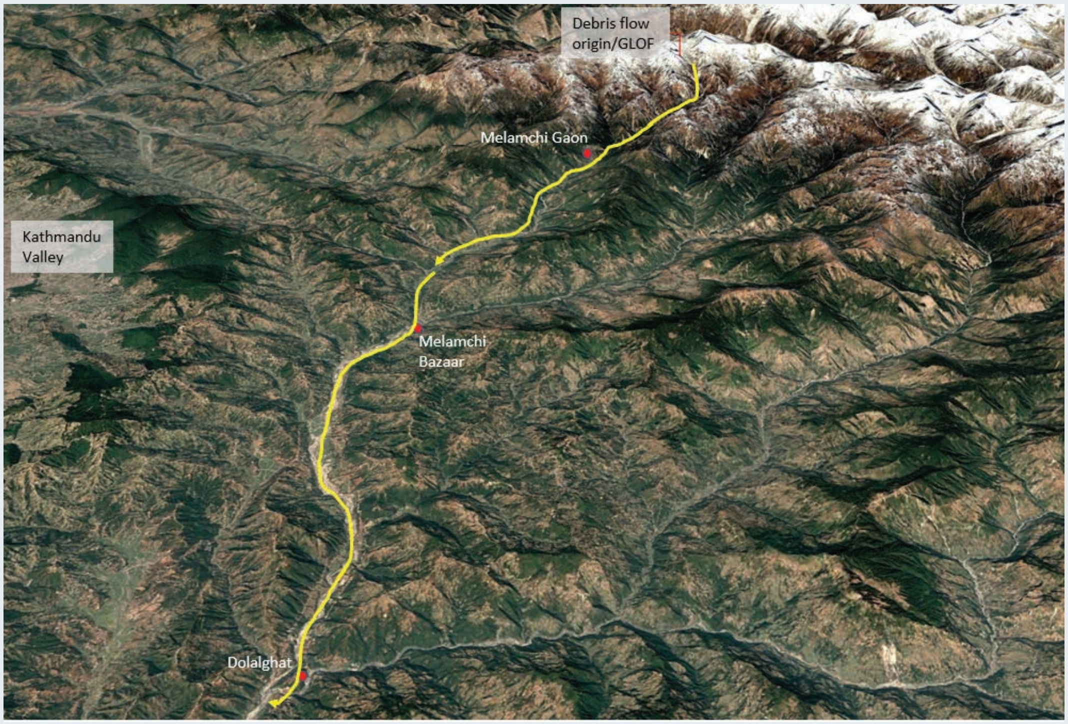


Fig.II.1: Upper Indrawati Basin. The yellow line marks the path of the debris flow from the headwaters of the Melamchi river to Dolalghat 70 kilometers away. (*Google Earth*)

The ICIMOD study places particular focus on the failure of a small glacial lake in the headwaters of the Pemdang Khola likely caused by a rapid lake expansion from upstream snowmelt and runoff from intense rains which sent its contents down into the valley below. The GLOF entrained debris previously deposited by landslides and then caused a large, old landslide dam (Bremthang Old Landslide Dam) 5.5 km away from the GLOF location to burst. As it moved down the Melamchi river valley, the debris flow picked up more debris from old landslides and undercut river banks causing new landslides. The largest of these new landslides happened below the community of Melamchi Gaon. This landslide was about 550 meters wide at its bottom and fell a total 400 meters from its highest point. The Melamchi Gaon landslide prevented the major debris flow from hitting downstream communities for an unknown period of time (likely several hours) before eventually breaching, sending its added contents downstream to the Melamchi Bazaar and communities downstream.

The ICIMOD study offers an excellent two-dimensional cross-section of the cascading disaster (Figure II.2 below) showing the total elevation loss (4500m), run-out distance (70+km), and key hazards which contributed to the compounding debris flow. Below in Figure II.3, we include a 3D map from Google Earth that provides spatial perspective and the actual location of key hazards.

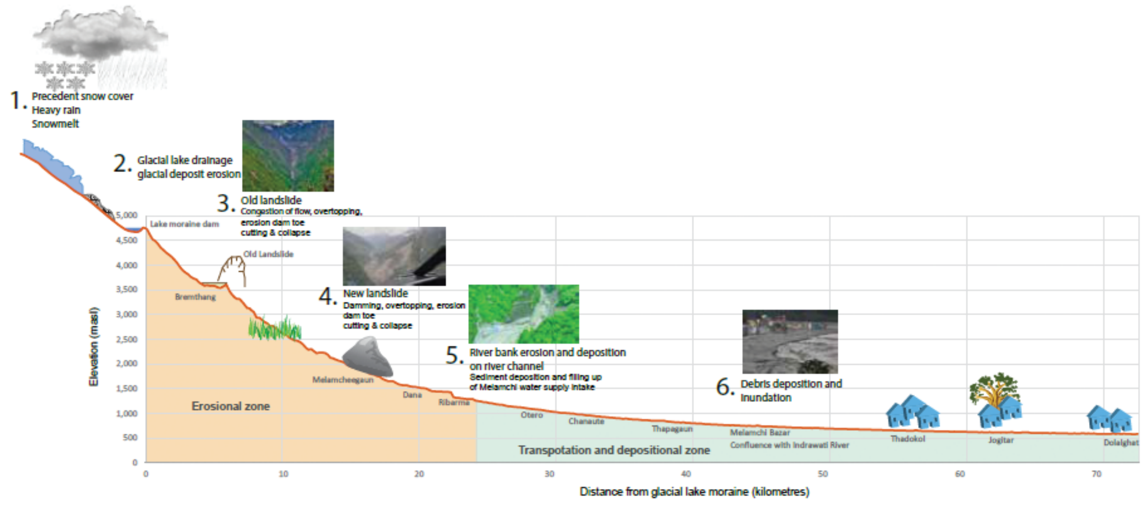


Fig. II.2: Longitudinal profile of the Melamchi-Indrawati River showing various processes leading to the disaster[195]

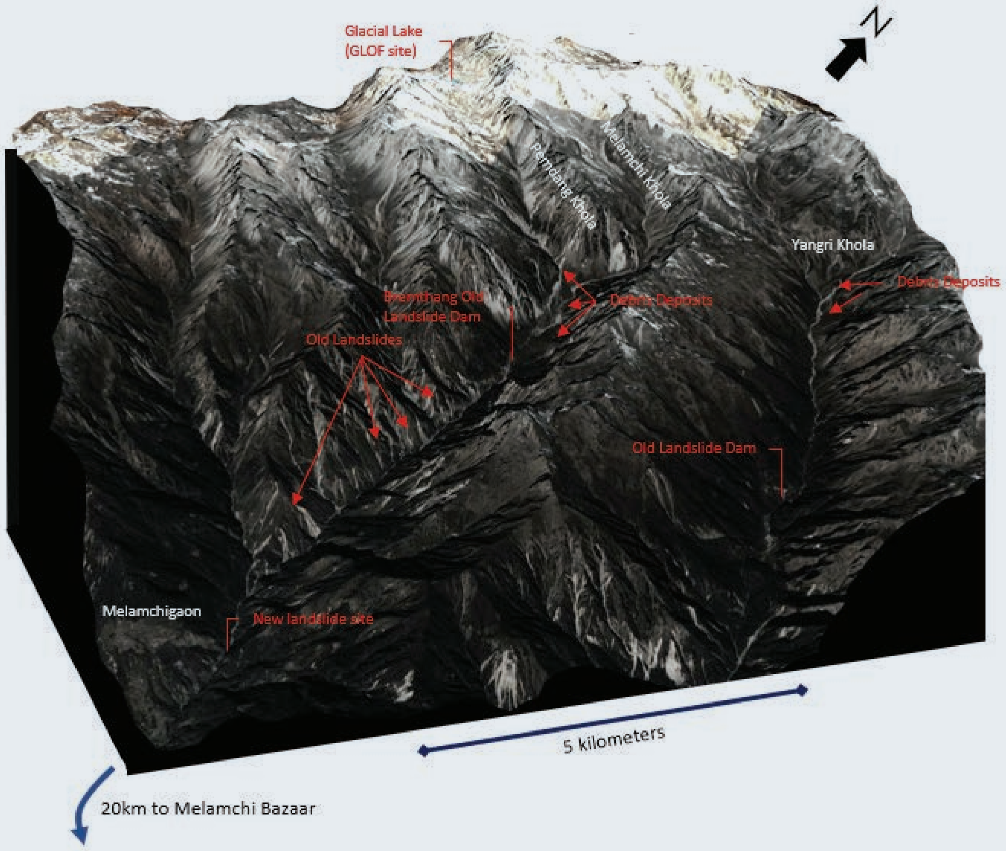


Fig.II.3: 3D Map of conditions prior to the Melamchi Disaster for Spatial Perspective

Additionally, we found the ICIMOD study's presentation of background conditions very useful in explaining the climate triggers of this event (see Figure II. 4 below). The ICIMOD report points to a prolonged period of rainfall and snowfall happening from late May into mid-June, with a severe rainfall event occurring on June 14-15 which likely triggered the glacial lake breach. Our own analysis of climate data sheds more light on how conditions in the cryosphere in late May led up to the disaster. As temperatures rise into the spring, a typical diurnal cycle appears where temperatures are just above freezing during the day and then return to below-freezing temperatures overnight. The snowpack responds to this cycle by warming during the day and then refreezing at night, a process referred to as a ripening of the snowpack. During this period of time, the snowpack releases limited water which fills the space between the snow grains and recrystallizes into larger ice grains at night, becoming increasingly compact as the days progress. Between May 30 and June 9, this snow-ripening pattern is observable in the temperature data.

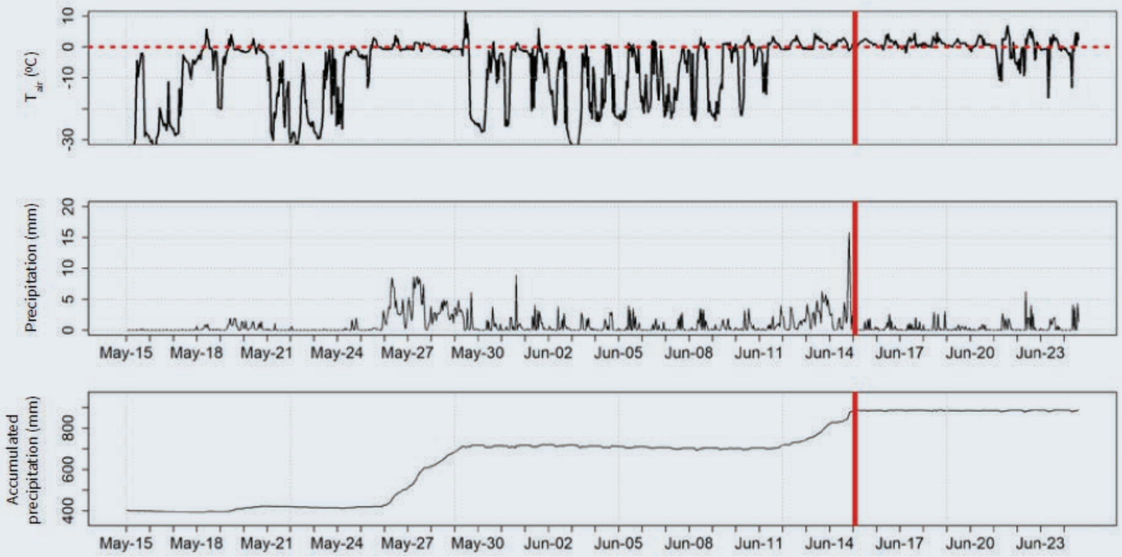


Fig. II.4: Climate data from the automatic weather station (AWS) in the Upper Melamchi Watershed. The red line denotes when most known mass movements occurred. (Maharajan et al 2021)

On June 10, the diurnal cycle shifted and temperatures no longer dropped below freezing. Instead, they hovered around freezing throughout the day and night. This is an indicator that the snowpack was ripe, composed of wet snow saturated with liquid water. Ripe snowpack coupled with the intense rains around June 14-15 released large quantities of water into the basin, likely causing a flush of rain and snow melt to flow towards the glacial lake. The lake was partially covered by a layer of ripe snow, adding additional water to the flash flood. This flush of water likely overtopped the dam and eroded the dam's integrity to impound water.

To form a debris flow, a significant flow of water must entrain a significant amount of material mass. While the ICIMOD study focused most of its analysis on material movement in the Melamchi River watershed, we also examined whether the Yangri River watershed–which runs parallel to the Melamchi and joins the Melamchi river at the Melamchi Bazaar–contributed to the debris flow. We assume the climate data above likely also applied to the cryosphere conditions in the high-mountain headwaters of the Yangri, meaning similar snowpack conditions and flow could have been released from the Yangri. Yet, a pre-post comparison (see Figure II.5) shows the scarring effects of the debris flow in the Melamchi valley were much more extensive and severe than in the Yangri basin.

Fig. II.5: Pre- and post- Melamchi Disaster Comparision

Importantly, more scarring points to a higher volume of entrained debris flow and likely a more severe intensity of the event. In the Melamchi watershed, scarring in the October 2021 image helps to identify the location where two natural dams failed: the first which formed the small glacier lake and a second at the old Bremthang landslide dam. A third natural dam not shown in the image and formed by a landslide at Melamchi Gaon during the cascading event also failed. However, the scarring in the Yangri watershed was minimal compared to the Melamchi watershed and mostly observed in the higher reaches. In the Yangri watershed, the natural dam remained intact through the event whereas the Bremthang landslide dam in the Melamchi watershed did not, possibly serving as a buffer to slow or stop debris flow from continuing downstream. This observation led us to consider whether the topographic and geological qualities of these natural dams introduced or reduced the risk of severe debris flow running out farther downstream. We began to consider whether the vegetation covering the Yangri natural dam, the age of the natural dam, or the side outlet of the natural dam contributed to a lower level of risk in the Yangri watershed given similar climate and background conditions. The Melamchi natural dam was covered with less vegetation and had a central outlet which can cause a natural dam to erode more quickly and lose its integrity. Importantly, in the Melamchi watershed, the mass of material released from the upstream GLOF and the likely entrainment of debris deposits behind the natural dam also were key hazards causing the Bremthang Dam to fail.

From this assessment, it is logical to conclude that underlying geohazard conditions in the Melamchi watershed were riskier than the Yangri watershed, particularly in consideration of the impact on communities from the confluence of the two rivers at the Melamchi

Bazaar and downstream. Building an inventory of hazards in these watersheds, with a focus on natural dams and settled debris deposits, and developing indicators that assess risks around these two features can lead toward a quantifiable system capable of producing a risk score for each watershed. Further, modeling how climate-related triggers–such as the rapid introduction of water into the upstream reaches due to sudden warming of the ripened snowpack and intense rains–can initiate a debris flow or other cascading hazard can test the viability of natural dams to withstand or fail during a debris flow event. Additionally, debris deposits sitting in the watersheds can be assessed to estimate under what conditions their material could be uplifted and entrained in a debris flow. Other contributory factors such as the severity of wildfire burn which can substantially contribute sediment and increase runoff velocity in watersheds[196] can be included in this assessment These inventories, assessments, and models can support the setting of background condition thresholds that can be monitored in real-time to provide a form of anticipatory action and early warning before estimated breaking points are reached.

As the Melamchi Disaster unfolded, informal communication via social media and cellular phone, particularly from upstream hill communities of Helambu and Melamchi Gaon to downstream communities, provided a kind of informal early warning. This demonstrates the importance and effectiveness of engaging local individuals, social media, and crowdsourcing platforms in disaster response mechanisms. Local municipal and district governments also responded to communication from upstream communities with action to evacuate people from communities downstream. This early warning is credited with saving an unknown number of lives in downstream communities affected by the debris flow when it eventually entered their communities.[197]

Evidence and analysis from the 2021 ICIMOD study point toward the potential for the design and implementation of an early warning system for debris flow, but that study is missing a few key elements we can bring to the ongoing discourse of hazard mapping and monitoring in Nepal and the greater HKH via our team's experience with remote sensing and communicating findings to key stakeholder groups.

Building Baseline Inventories of Natural Dams and Debris Flows

In order to develop a comparative assessment of river valleys based on potential risk and vulnerability to downstream communities, the various hazard features of these river valleys need to be mapped and then assessed. Based on our study, we believe natural dams (ice dams, moraine dams, and landslide dams) mark an important starting point for assessing risks of catastrophic debris floods in Nepal's river valleys.

Natural dams either hold back the potential flow which initiates a debris flow and eventually a debris flood (in the case of ice dams and moraine dams in glacial lakes) or the valleys behind landslide dams form areas where older debris from landslides and other earth movement has come to temporary rest. During a debris flood event, sediment and material entrained by the debris flood can build up behind a natural dam over time eventually causing the dam to break or the compounding debris flood to accumulate such a force that the natural dam breaches, as in the case of the old Bremthang landslide dam and the newly formed Melamchi Gaon landslide dam.

Developing an inventory of natural dams for all of Nepal's streams and river systems can be done using remote sensing techniques and GIS analysis via medium to high-resolution satellite imagery and digital elevation maps (DEM). Once an inventory is developed, it should be updated on a semi-frequent basis if it is to be used for real-time risk assessment and early warning system implementation. A suggested frequency for updating the inventory is bi-weekly during the monsoon season through the utilization of SAR imagery which can see through clouds and once a quarter or once a month outside of the monsoon season, as well as following significant geohazard events such as a major earthquake or debris flood. A portion of this inventory is already completed via ongoing efforts to map glacial lakes in Nepal. The most updated inventory is the ICIMOD 2020 inventory of glacial lakes, and ICIMOD plans to publish a new inventory in November 2022. To bring this inventory up to date, inventory managers can employ a combination of remote sensing inputs such as Sentinel-1 SAR imagery, Google Earth imagery, high-resolution optical imagery from providers such as Planet Labs, Maxar, or Airbus, and digital elevation maps (DEM). Additionally, the Land Surface Change model described below (see Figure II.6)–which uses Sentinel-1 SAR imagery and Google Earth Engine for processing–can be used.

After the dams which form glacial lakes are inventoried, the task of detecting landslide dams and other natural dams which do not impound water remains. Landslide dams are relatively easy to find because they cause the streams which flow into them to become braided behind the dam, are located beneath scars of landslides or appear as hills in the middle of a valley with flat land behind them that would otherwise follow the natural slope of the valley stream.

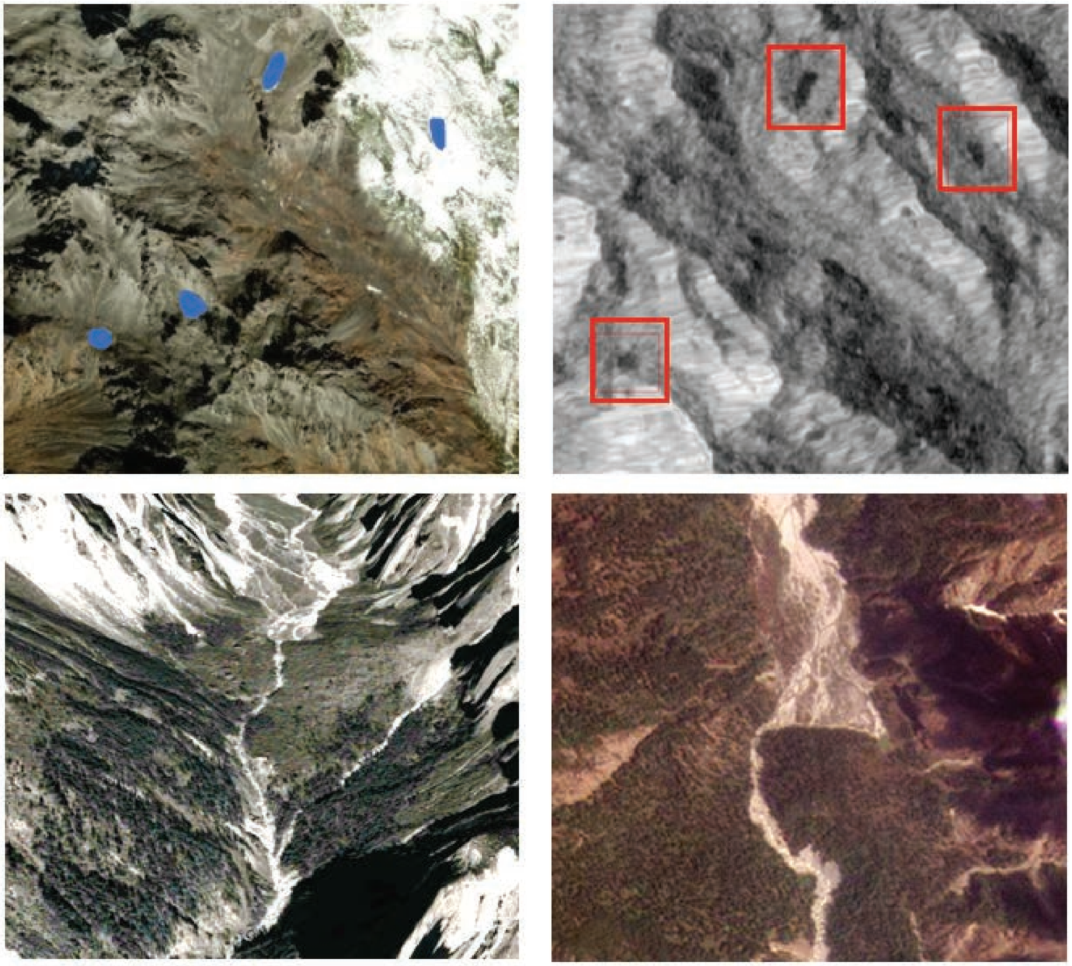


Fig. II.6: Glacial lakes and natural dams in the Upper Indrawati watershed identified by earth observation and remote sensing methods. Clockwise from the top left: Image 1 shows a selection of glacial lakes from the ICIMOD glacial lake inventory in blue displayed on an optical imagery basemap in ArcGIS Pro. Image 2 uses Sentinel-1 SAR imagery to show the same selection of glacial lakes. Note a 4th lake is not shown due to angles and distortions in the imagery. Image 3 is a Planetscope high-resolution image of the Yangri watershed landslide dam. Image 4 is a Google Earth (Maxar) high-resolution image of the Bremthang Landslide Dam.

This task can be completed at high levels of confidence and accuracy using Google Earth imagery, high-resolution optical imagery from providers such as Planet Labs, Maxar, or Airbus, and digital elevation maps (DEM). A research team can likely identify and draw the extent of all natural dams in Nepal's streams and rivers in a relatively short period of time (approximately three months for initial work and three months for expert validation), and a few key topographical features of natural dams (such as geolocation, elevation, dam width, dam height, surface area, and material composition) can be collected during this process which could later be incorporated into risk assessments.

Below (see Figure II.7) are the results of a rapid mapping assessment of natural dams located above the Melamchi Bazaar in the Melamchi Valley and Yangri Valley prior to the 2021 disaster. A pre-disaster inventory is demonstrated here to identify various hazards which could have or did contribute to the disaster.

Valley	Geolocation	Elevation (masl)	Natural Dam Type	Height (m)	Width (m)	Surface Area (m^2)	Composition	Post-Disaster Status
Melamchi	85.4582835°E, 28.0885067°N	4787	Glacial Lake Dam	1	93	2362.699	Bedrock/ Moraine	Intact
Melamchi	85.5164328°E, 28.1308916°N	4767	Glacial Lake Dam	8	74	2480.513	Moraine	Fully Destroyed
Melamchi	85.4579419°E, 28.0861580°N	4751	Glacial Lake Dam	1	54	1228.729	Bedrock/ Moraine	Intact
Melamchi	85.4598104°E, 28.0863545°N	4739	Glacial Lake Dam	2	76	1179.294	Bedrock/ Moraine	Intact
Melamchi	85.4622429°E, 28.0867837°N	4715	Glacial Lake Dam	3	73	1344.422	Bedrock/ Moraine	Intact
Melamchi	85.5073445°E, 28.0829563°N	4457	Glacial Lake Dam	3	63	841.4869	Bedrock	Intact
Melamchi	85.5365749°E, 28.1056999°N	4315	Glacial Lake Dam	6	52	1165.745	Bedrock	Intact
Melamchi	85.5476483°E, 28.0907593°N	3580	Landslide Dam	292	949	472627.7	Landslide	Fully Destroyed
Yangri	85.5611593°E, 28.1579458°N	5010	Glacial Lake Dam	1	28	162.7081	Bedrock/ Moraine	Intact
Yangri	85.5607137°E, 28.1553717°N	4976	Glacial Lake Dam	1	54	432.8869	Bedrock/ Moraine	Intact
Yangri	85.6192244°E, 28.1045977°N	4805	Glacial Lake Dam	5	134	3911.182	Moraine/ Landslide	Intact
Yangri	85.6134827°E, 28.1026650°N	4589	Glacial Lake Dam	4	100	3814.88	Moraine/ Landslide	Intact
Yangri	85.5988883°E, 28.0606383°N	3142	Landslide Dam	434	625	625151.9	Landslide	Intact

Fig.II.7: Natural Dams in Melamchi and Yangri Valleys

Similar processes can be used to develop inventories of major debris deposits situated within the stream and valley systems of Nepal's rivers. Like landslide dams, these debris deposits can be located beneath scarred slopes, identified by their fan-shaped deposit pattern, or identified by their material composition (fine material in contrast to vegetation around them or boulder deposits, etc). Key topographical features of these debris deposits can be collected during the inventory process (geolocation, altimetry, surface area, gradient, and preliminary assessment of material composition).

Below (Figure II.8) are the results of a rapid mapping assessment of debris deposits above the Melamchi Bazaar in the Melamchi Valley and Yangri Valley.

Debris Deposits	**Number**	**Surface Area** (m^2)
Above Bremthang Landslide Dam (Melamchi Valley)	8	1,606,756.93
Below Bremthang Landslide Dam (Melamchi Valley)	9	379,621.48
Total Melamchi Valley	**17**	**1986378.41**
Above Landslide Dam (Yangri Valley)	3	29,426.87
Below Landslide Dam (Yangri Valley)	4	161,085.86
Total Yangri Valley	**7**	**190512.73**

Fig. II.8: Debris Deposits in Melamchi and Yangri Valleys

Updating Natural Dam and Debris Deposit Inventories in Real-Time

Once baseline inventories of natural dams and debris deposits are established, they need to be updated on a frequent basis. This section introduces a model which uses remote sensing imagery to detect land surface change. This low-cost model was developed by the authors of this study and can be used to provide frequent updates to landslide, natural dam, and debris deposit inventories. The model can also provide a partial assessment of changes affecting risk around already inventoried natural dams, debris flows, and landslides.

The proposed land surface change model uses satellite imagery to monitor distortions based on detectable changes to the land surface. The model uses the European Space Agency's Copernicus Sentinel-1 (S1), a constellation of radar imaging satellites that can provide imagery regardless of weather and daylight. The radar technology, also known as Synthetic Aperture Radar (SAR), uses the echo from radio waves transmitted towards the Earth's surface to generate images of land surface roughness. Its many applications include monitoring flooding or water, land use change, and changes to geology or glaciers. With a 12-day revisit cycle, S1 makes possible near-real-time tracking for emergency management, land monitoring, and maritime monitoring. Notably, S1 imagery is available for public use at no cost. Higher temporal and higher spatial resolution SAR imagery is available by service providers such as ICEYE and Umbra at competitive prices, and this is likely to become increasingly affordable as the costs of satellite technology drop.

The echo that the radar antenna on the satellite picks up forms the basis of how SAR satellite imagery is created. The echo, also known as backscatter, is processed and its resulting value corresponds to surface roughness. In general, backscatter redirected from land, trees, or buildings has a higher value than backscatter from surfaces that are smoother, like water. If there are two images of the same area of interest across two different time periods, changes to the surface and its surroundings can be detected by simply tracking the differences in backscatter values. The land surface change model aims to leverage this relationship between backscatter and land surface to track changes to the land surface. The model is further strengthened by the satellite's relatively short 12-day revisit cycle, or the time it takes the satellite to revisit the same location, as this allows for consistent tracking of a region both before and after individual hazard events as well as gradual changes to existing hazards that could affect river systems or nearby communities. S1 imagery can be accessed via Google Earth Engine, and the differencing analysis can also be calculated using Google Earth Engine.

Changes at three areas of interest from the Melamchi disaster demonstrate the effectiveness of this land surface change model: the Bremthang natural dam, the new landslide at Melamchi Gaon, and the debris flood that hit the Melamchi Bazaar. Below, we discuss how the model visualizes and tracks these changes.

The Bremthang landslide dam broke when water from the upstream GLOF and its entrained debris flood came downstream, thereby entraining the material composition accumulated at the natural dam and transporting it further downstream. Using SAR imagery, our model can show how the dam breaking affected the land surface and track the future formations of other natural dams and their subsequent breaking.

The SAR imagery in Figure II.10 shows the area around the Bremthang natural dam before and after the Melamchi event. Visual inspection shows the relative change of the surface roughness at the confluence of the two rivers is more noticeable than the relative change of the surrounding hillslopes. These two images can be overlaid to demonstrate surface change, as shown in the third image in figure II.10 which visualizes the difference in the backscatter values between the before and after SAR imagery of Bremthang. The most noticeable differences will display as either red or blue, with variations of green and yellow as minor backscatter distortions or noise. In the case of the natural dam, blue is the most prominent feature, representing a negative change in backscatter value which can be interpreted as a reduction in the land surface where a relatively rough surface flattens or smooths. This aligns with our understanding of the Melamchi disaster impacts at Bremthang and we can interpret this change as the impact of the debris flood from the upstream GLOF breaking the natural dam and taking with it nearly all of the accumulated debris, soil, and rocks from old landslides.

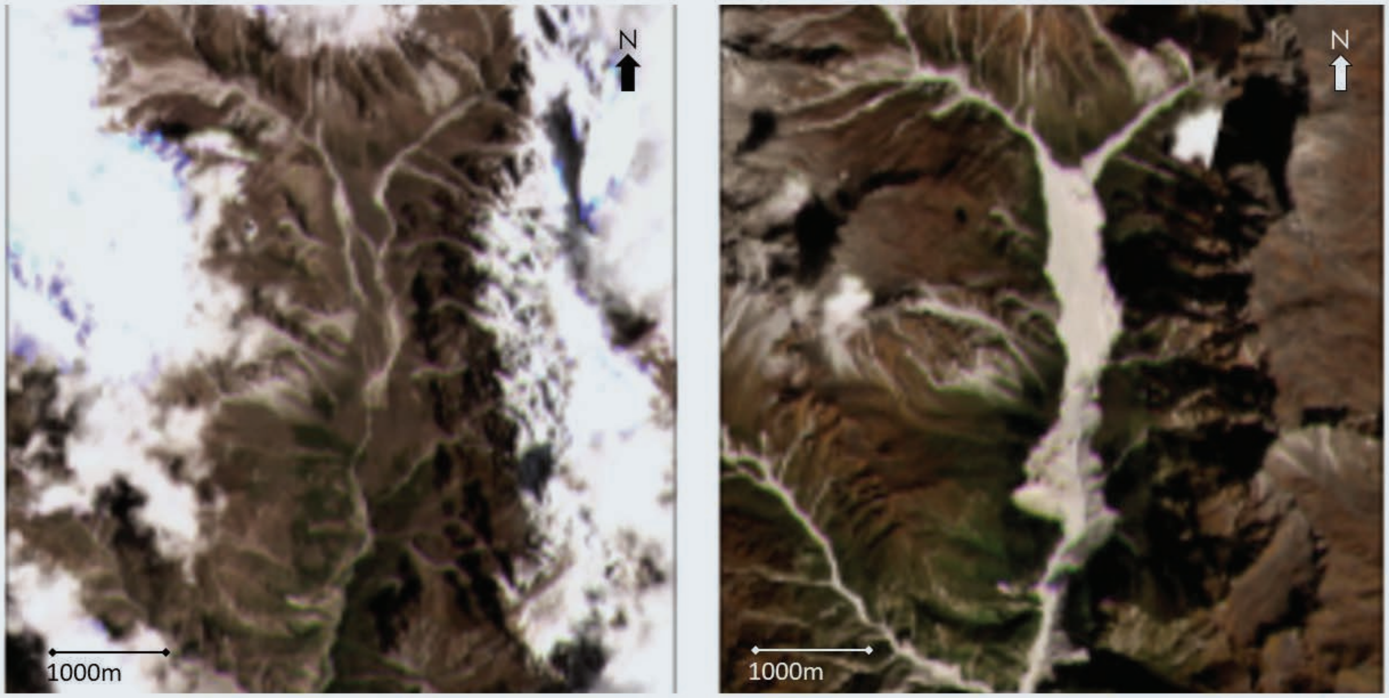


Fig. II.9: Planetscope 3-meter resolution optical imagery of the Bremthang landslide dam area before the disaster (left) and after the disaster (right). Planetscope imagery is not publicly available, but its archive houses one image per day from 2016 to the present of any location on the planet under semi-cloudy and non-cloudy conditions.

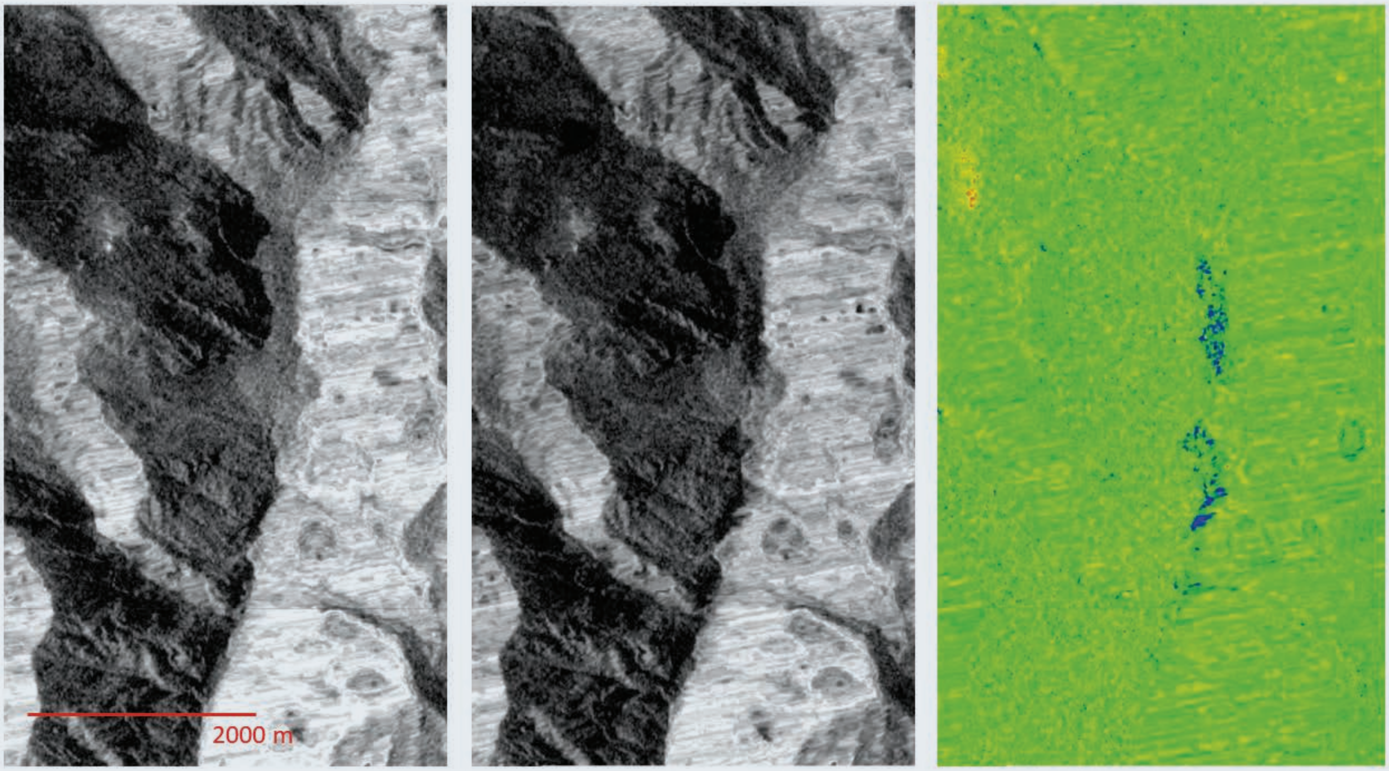


Fig. II.10: Sentinel 1 imagery of the Bremthang natural dam on June 12 (left) and June 24 (middle), and the difference of the two images.

The community of Melamchi Gaon is located on a hill on the right bank of the Melamchi river about 8 kilometers downstream from the Bremthang natural dam. After the debris flood destroyed the Bremthang natural dam, it triggered a large landslide immediately to the east of Melamchi Gaon. Using SAR imagery, our model can detect the new landslide and how the surface of the hillside has changed as a result of the landslide.

The first and second images in figure II.12 show SAR images of Melamchi Gaon before and after the landslide. The visual changes here are harder to discern than in the Bremthang example above but are still visible. By overlaying these images and calculating the difference, two distinct changes at the location of the site of the landslide are identified in the last image of Figure II.12 in blue and red. Blue represents a smoother, flatter, or reduced surface compared to the time period before the event, whereas red is the positive change in backscatter value from before and after the event which can be interpreted as the surface becoming rougher or higher. Looking back at the optical imagery, we can interpret this change as showing the loss of vegetation from the highest point of the landslide (blue) and the accumulation of some portion of the mass movement (debris, rock, and/or soil) in the middle of the hillside (red) as it slid downhill to the river valley.

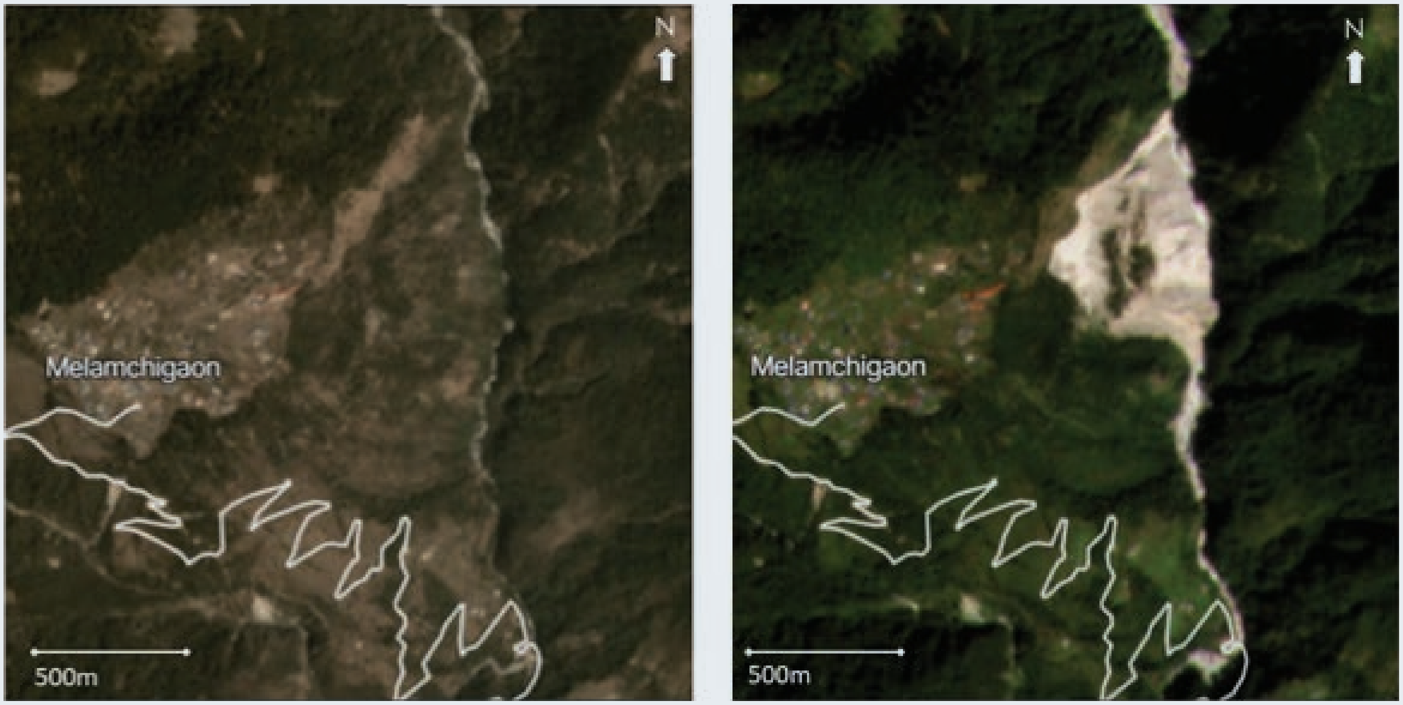


Fig. II.11: Planetscope 3-meter resolution optical imagery of Melamchi. Gaon village on April 2021 (right) and October 2021 (left).

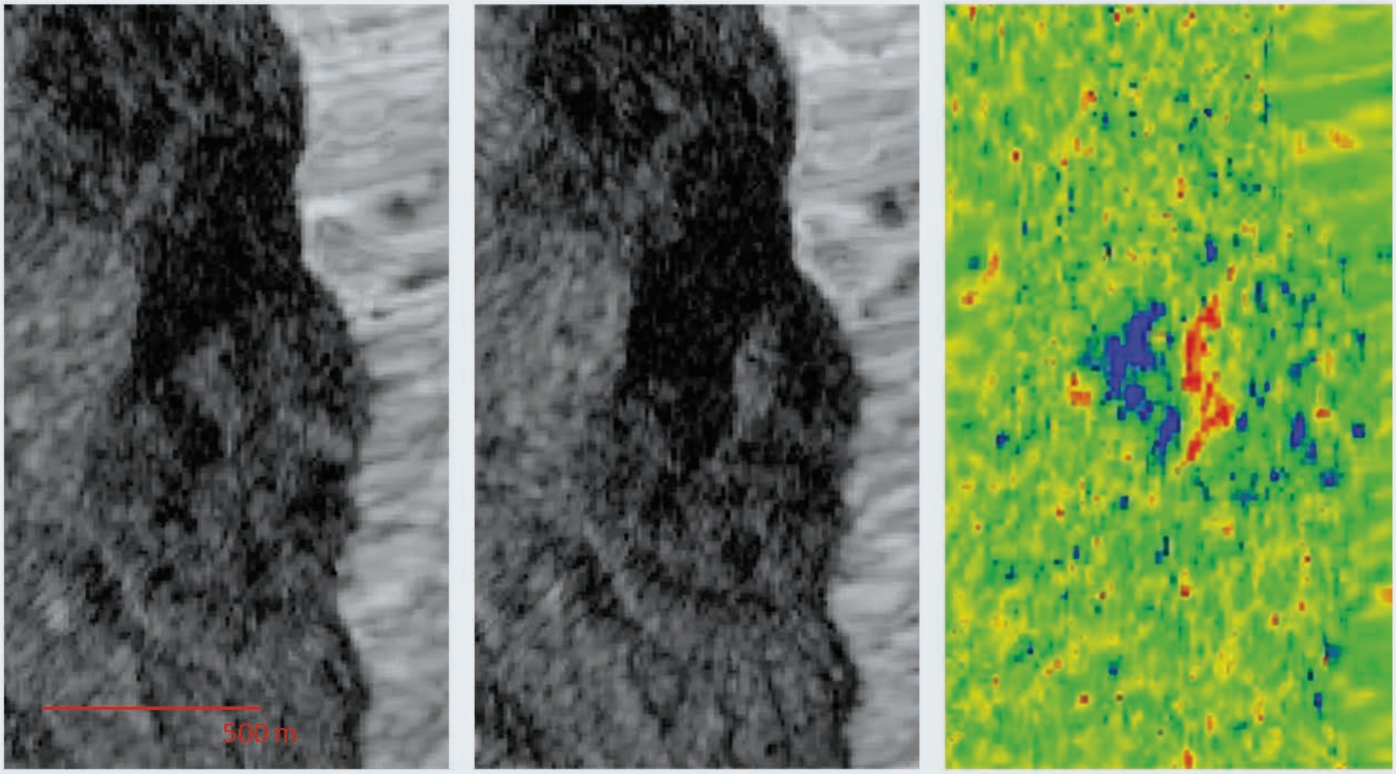


Figure II.12: Sentinel 1 imagery of landslide east of Melamchi Gaon, June 12 (left) and June 24 (middle), and difference of the two images. The most notable change of these two backscatter images is the drastic change of the upper portion of the hillside on the western slope of the river valley and some distortion of the lower portion of the hillside.

The debris flood that devastated the Melamchi Bazaar can be visibly seen on the optical satellite imagery (Figure II.13), eroding the banks and laying the area bare of any vegetation and development. Using SAR imagery, our model can trace the length of the destruction of the debris flood and show how it fans out further downstream until it eventually stopped.

The SAR imagery shown in Figure II.14 shows the Melamchi Bazaar at the confluence of the Melamchi River (left) and the Yangri River (right) where the major debris flow originated. Similar to the analysis of the Bremthang natural dam, a more pronounced change in land surface roughness is visible in the river valley below the confluence as noticeably darker pixels in the lower half of the second image. In the third image, the smoothing or flattening of the land surface from before the event is represented in blue and can be understood to show how the debris flood that hit the Melamchi Bazaar eroded the riverbanks and cleared it of all vegetation before it continued further downstream.

SAR imagery has many advantages over optical imagery to detect changes in land surfaces. Figure II.15 shows differences detected at all three areas of interest and can shed light on the cascading effects of the Melamchi disaster and the relationship between the three individual events. S1 data availability makes it possible to generate a land surface change image for the entirety of Nepal or the HKH in a matter of minutes. Time-efficient processes are important because inventories need to be updated on bi-weekly frequencies during the wet season. Similar approaches to calculating land surface differences using optical imagery are not currently feasible at the low cost or the wide geographic scale that SAR provides.

Yet the SAR-derived land surface change model has its limits: it is useful for detecting negative and positive change and relative intensity of change, but cannot directly assess specific changes in physical attributes of features. The process is useful for detecting the areas of greatest change, which can help pinpoint areas to watch and target the dedication of resources to follow-up efforts. Once a change is detected by SAR analysis, publicly available optical imagery from Landsat or Sentinel 2 or proprietary imagery from optical imagery providers can be analyzed to measure specific changes such as the width of natural dams, the mass of debris deposit removed, etc. Or the detection can guide field scientists or local data collectors to visit the area of interest and conduct in situ assessments. In summary, SAR imagery is currently the best starting point to rapidly and affordably detect land surface change over a large geographic scope.

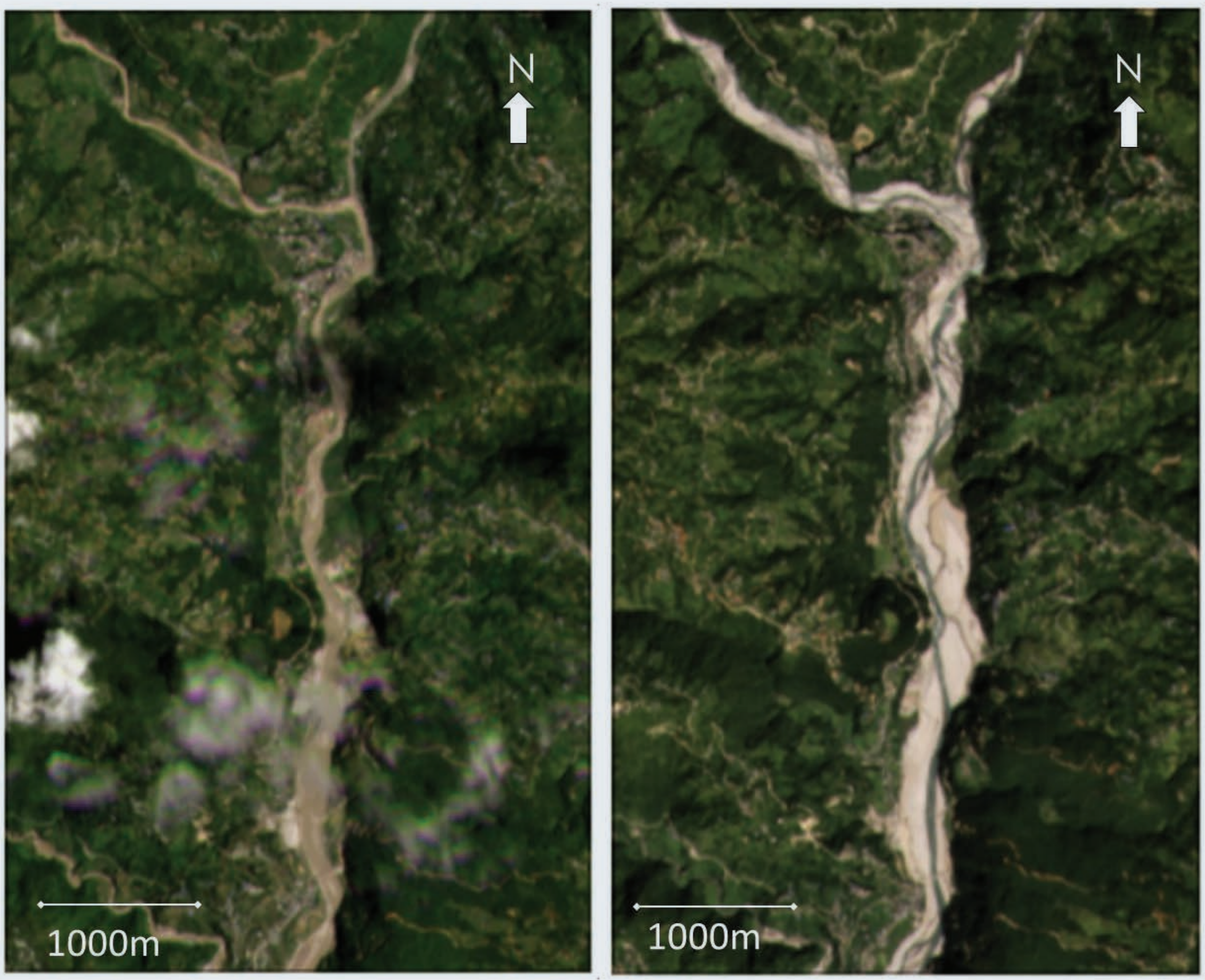


Fig II.13: Planetscope 3-meter resolution optical imagery on Melamchi Bazaar on August 2020 (left) October 2021 (right).

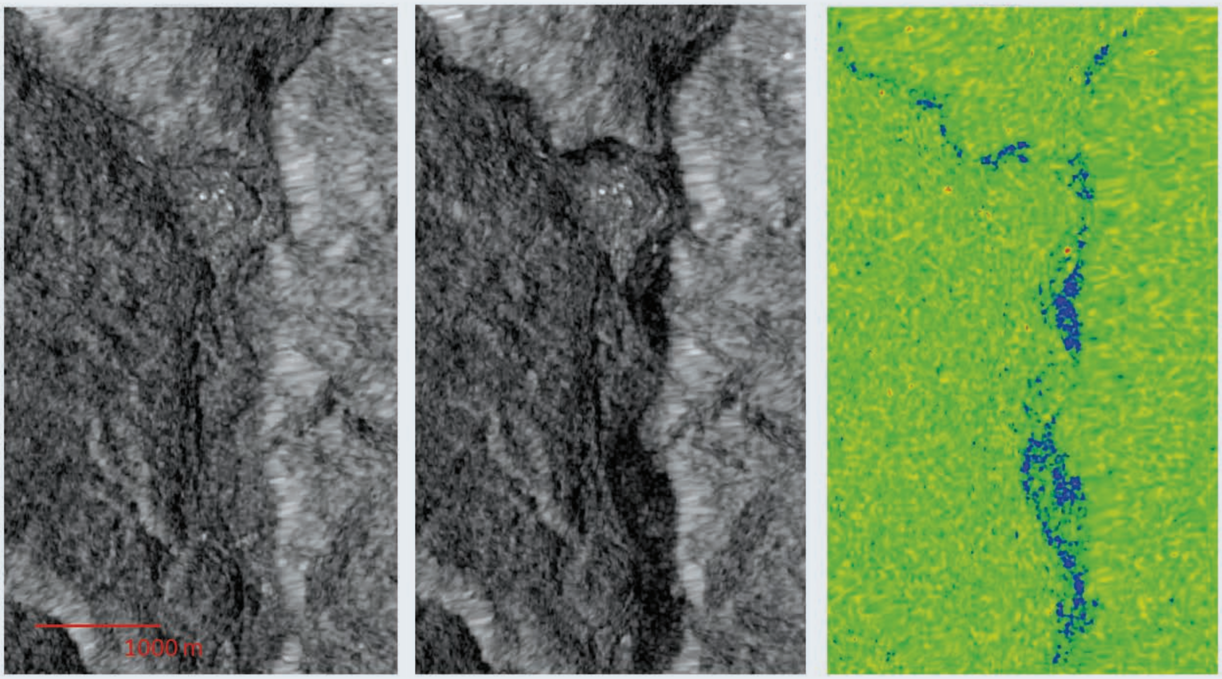


Figure II.14: Sentinel 1 imagery of Melamchi June 12 (left) and June 24 (middle), and the difference of the two images.

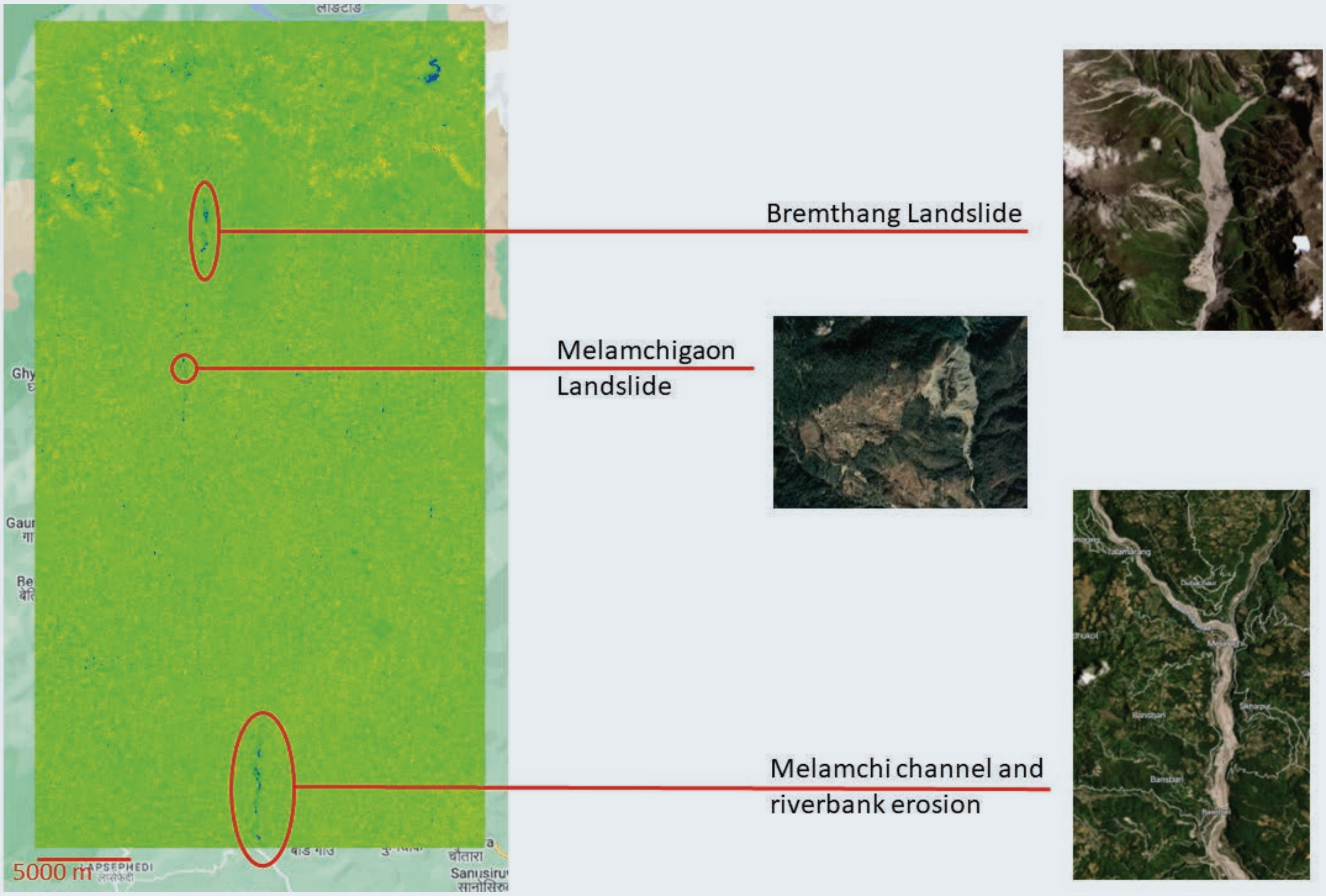


Figure II.15: Land surface difference between Sentinel-1 SAR imagery before and after the Melamchi disaster for major cascading hazards. (Sentinel-1 & Planetscope)

Assessing Risk and Vulnerability of Natural Dams

Once natural dams and debris flows are mapped into inventory databases, these features can be analyzed across common sets of topographical indicators, assessed, and ranked by comprehensive scores of inherent risk and vulnerability. These assessments can be put to use to determine levels of vulnerability and exposure of downstream communities, socio-economic activities, and physical infrastructure. Past efforts to assess and rank risk related to glacial lakes (which are formed by ice and moraine dams) and GLOF can be extended to develop a risk assessment methodology that covers all natural dams identified in a nationwide inventory. A comprehensive ranking system can be developed to score the risk related to each natural dam in the inventory.

Allen et al made a first attempt at ranking risk related to glacial lakes by assessing the topographical features and watershed features of glacial lakes in India in a retroactive study of the 2013 Kedarnath disaster. The team found that the lake which failed and triggered a debris flood that contributed to the deaths of more than 6,000 people ranked 2nd in an inventory of glacial lakes with "unfavorable topographic conditions" (Allen). Further, the ICIMOD 2020 study of glacial lakes ranked 47 of 3,624 glacial lakes identified in Nepal's river basins as "potentially dangerous" using an approach that ranked categories of topographical features, changes to those topographical features over time (through referencing at a back-library of remotely sensed imagery), and consideration of the geophysical features around those glacial lakes. Liu et al (2020) developed a similar ranking system for glacial lake risk on a four-tier scale ranging from "Very High-High-Medium-Low" and included additional indicators such as volume of water in the glacial lake, volume and mass of debris found in proximity to the glacial lake in question, and distance from human settlements. The Liu et al model for risk ranking is demonstrated in the diagram below. Liu et al's more integrated approach which looks at the relationship of natural dams to other features - geophysical and human-built - around them is explored further in later sections.

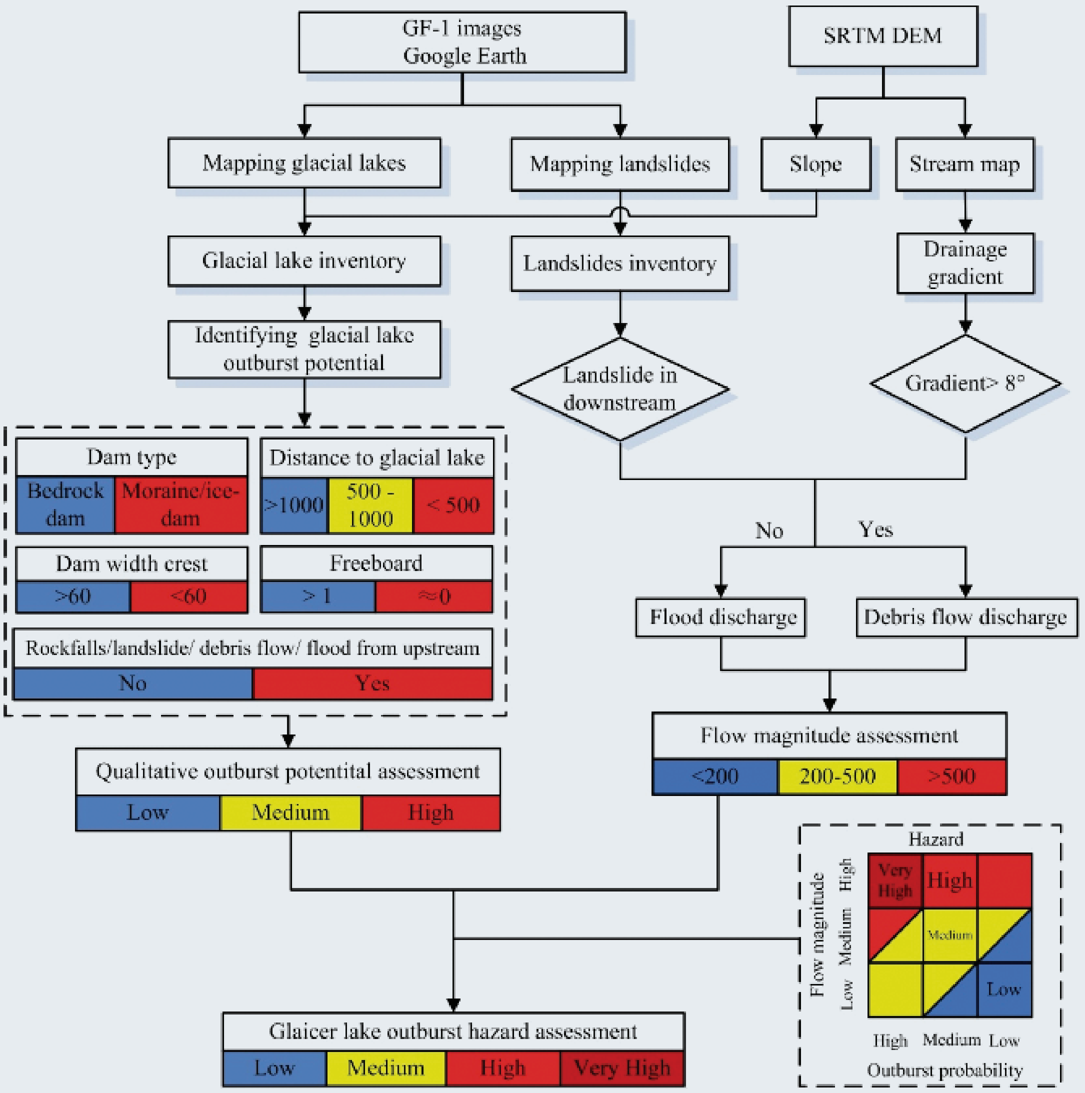


Figure II.16: Flow chart for the process of creating glacial lake inventory and hazard assessment for Bhote Koshi Basin[198]

With effort and fine-tuning, an assessment technique similar to the ones applied to glacial lake risk in the studies above can be applied to landslide dams or to all dams in a national inventory of natural dams in Nepal. While indicators and ranking systems are best determined by a joint effort of qualified geophysical scientists and relevant disaster risk reduction stakeholders in Nepal, we recommend adding the following indicators techniques for landslide dams: location of water outlet, age of natural dam, percent vegetation coverage, etc.

After concluding their study of the 2013 Kedarnath disaster triggered by the failure of the Chorabori Lake in Uttarakhand, India, Allen et al offered the following statement:

> ***"The assessment of topographic disposition is simple and easily established over large datasets but clearly identified the unique susceptibility of Chorabari Lake within a sample of 169 glacial lakes. Successful application of this concept to other known snowmelt and rainfall-triggered GLOFs, and particularly across other high mountain regions, will enable refinement and potentially weighting of the most important topographic parameters. Where topographically predisposed glacial lakes are located in areas of high precipitation, further local-scale investigations of dam structure and recognition of downstream threats are recommended."***

This last sentence points to an important next step where the limits of remote sensing techniques are exposed. A ranking system will reveal the natural dams at the highest risk, yet *in situ* research is likely required to determine a more refined understanding of the risk to those features and possible mitigation techniques to reduce risk. Such an approach to risk mitigation was applied at the Tsho Rolpa, a high-risk glacial lake in the upper watershed of the Tamakoshi River in the central-eastern district of Dolakha where glacial lake levels are drawn down through human-built infrastructure. Further, those natural dams which are determined to have the highest levels of risk can receive dedicated investments for high-resolution remote sensing monitoring (such as tasked satellites or frequent drone observations), the construction of monitoring equipment (optical or radar cameras or water gauges), or motion detectors for landslides.

Once an initial assessment begins, update frequencies for these assessments must be determined and adhered to since conditions around natural dams change frequently. We recommend assessments occur concurrently with updates to natural dam inventories such as bi-monthly updates during the monsoon seasons, monthly or quarterly updates outside of the monsoon season, and after significant events such as earthquakes or major debris floods. Depending on the resources available to support this effort, update frequencies do not need to be the same for all natural dams. Those with low risk could be revisited less frequently, and those with higher risk should receive more attention.

Moving From Natural Dams Inventories to a Scored System of Vulnerability and Exposure Assessments to Downstream Communities and Infrastructure

To determine vulnerability and exposure to downstream communities and physical infrastructure, a widened scope of risk assessment should be developed which combines not only the cumulative risk posed by the potential failure of natural dams in a river or stream system but also debris and other materials which could be entrained within a debris flow above and below natural dams. This kind of assessment requires additional risk assessment of debris deposits and old landslides described in previous sections and modeling of the force of flow required to uplift that material. Revisiting the 2021 Melamchi Disaster, a rapid assessment and comparison of the Melamchi river system to the Yangri River system just east would have revealed the Melamchi river system had 17 noticeable debris deposits where the Yangri River had 7 noticeable debris deposits, leading to a conclusion that the Melamchi system posed more cumulative risks in terms of potential entrained debris than the Yangri system. Another simple way of assessing this kind of risk is by calculating the total surface area and estimated volume of debris materials located in a segment above or below a natural dam to provide insight into threats to that natural dam within an entire segment of streams and rivers. From here, it is possible to assign scores to segments of streams and rivers based on total cumulative risk to debris flow. When scores are compiled, a risk-oriented heat map of Nepal's streams and river systems can be developed where the riskiest stream segments glow red and the least risky segments glow green. An illustrative example of this map for the upper Indrawati watershed, of which the Melamchi river is a tributary, is demonstrated below in Figure II.17. This map is purely an illustrative example and uses one indicator, the number of glacial lakes per sub-basin, which is not a direct indicator of risk.

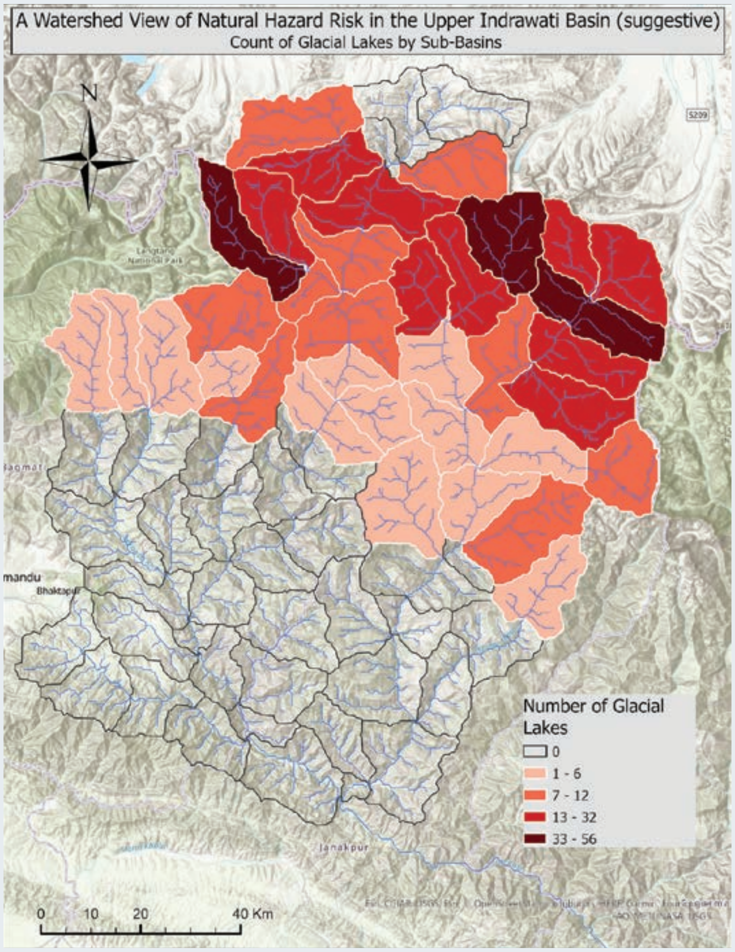


Fig.II.17: Count of glacial lakes by sub-basin. A suggestive example of how to visualize watershed view of natural hazard Risk in Upper Indrawati Basin[199]

From here, various layers of demographic, socioeconomic, and infrastructure data can be included in the analysis to demonstrate levels of vulnerability and exposure to low-lying communities and infrastructure built in river valleys. This approach integrates the risk of natural features and debris flood with vulnerability and exposure data and can support decision-making for investment by communities or governments in risk monitoring and mitigation measures, as well as an early warning system and/or disaster risk response system established in the communities with the highest level of exposure.

Importantly, despite the fact that population density in Nepal's river valleys is rising and infrastructure is increasingly built in river valleys, the low-lying areas of some river valleys in Nepal are not populated at all. Therefore, a cumulative scoring of natural dams and debris deposits within a river valley might identify individual valleys at high risk to debris flood, but with zero risk to communities downstream due to a lack of population or a low potential for run-out across long distances into populated areas. If resources are limited in carrying out a nationwide assessment, then these risky yet unpopulated valleys could be removed from ongoing updates and ongoing risk assessments related to early warning. However, efforts should not ignore these valleys if they are commonly used for socio-economic activities such as pastoral practices or trekking/tourism. Implementers should not rule out the possibility of reincorporating these valleys into updates and early warning systems if new communities or new infrastructure are formed in these valleys. This cumulative risk ranking system can be used as a critical component of risk assessments for future infrastructure such as reservoirs or roads which could be affected by debris floods.

Evaluating segments of river systems that consider and rank cumulative scores of natural dams and potentially entrained debris facilitates an integrated approach to risk assessment and can help point decision-makers toward a kind of early warning system and monitoring and mitigation efforts that could be effectively applied in various localities throughout Nepal. This integrated approach also graduates away from previous efforts at assessing single geohazards on a case-by-case basis and moves toward more anticipatory action by identifying and categorizing the most vulnerable and exposed areas. Run-out models for debris floods, such as those employed by Sattar, could also be employed to determine the probability of risk to communities farther downstream and better inform local planning and disaster risk prevention and mitigation efforts in farther downstream communities.

Aftermath of the Melamchi incident. Photo courtesy of Jakob Steiner.

SECTION III:

Design and Build of a Risk Monitoring and Early Warning System for Debris Floods and other Extreme Flow Events

This section discusses how to design and build a real-time risk monitoring and early warning system for debris floods and other extreme flow events in Nepal. This system incorporates relevant meteorological data inputs provided by both physical monitoring and remote sensing tools with natural dam inventories assessed for risk and integrated into the approach mentioned above. Some aspects of meteorological real-time monitoring for debris flood triggers can be employed via automatic computing processes, but ultimately individuals must manage and update the system, check processes to verify information, and determine the kind of early warning to be communicated. Further, to develop trust and confidence in the overall system, local stakeholders at the community level must be consulted and participate in the co-design, build-out, and real-time implementation of the system alongside key institutional actors.

The diagram on page 78 (Figure III.1) is a modification of the cross-section of the key features of the Melamchi disaster developed by ICIMOD. Key features are assigned color codes to categorize them with consideration to monitoring techniques and risk assessment.

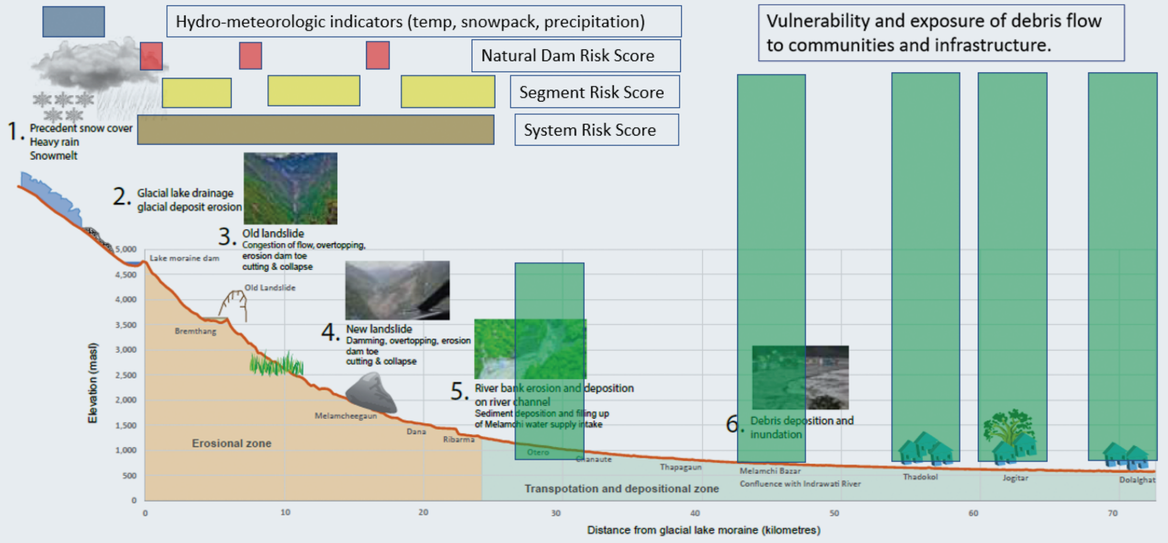


Fig. III.1: Modification of cross-section of key features of Melamchi disaster from ICIMOD.

In Figure III.1 above, hydro-meteorological indicators are identified in blue, natural dams in red (the glacial lake dam, old landslide dam, and new landslide dam), segments between the dams in yellow, and finally at-risk communities (Melamchi Bazaar, Thadokol, Jogitar, and Dolalghat) and infrastructure (Melamchi water supply project) are identified in green. These color-coded categories are transferred to the table below (Figure III.2) to demonstrate monitoring and assessment methods, outputs, and ideal frequencies for monitoring and updating indicators and underlying inventories. Processes outlined in the table below can inform a real-time risk monitoring and early warning system for debris floods in Nepal.

Category	What is assessed?	Inputs and Methods	Output	Frequency on monitoring
Hydro-meteorologic Indicators	Trigger monitoring of snowpack, rain, temperature	**Snowpack:** MODIS, SSMI derived snow-cover anomaly; SAR via automatic computing processes with thresholds set to identify triggers **Rain:** Hydro-meteorologic gauges, AWS data, SSMI derived wetness product **Temperature:** Hydro-meteorologic gauges, AWS data, SSMI derived surface temperature product	Assessed indicators; time series and trigger thresholds	Constant/hourly
Natural Dams	Topographic and watershed indicators and risk assessment of individual dams	Manual compulation and assessment via high-res optical imagery and DEM; updated through Google Earth Engine landslide identification model and refined analysis using high-res optical imagery and on-ground observation.	GIS mapped inventory and Risk score or ranked inventory based on risk score	Initial assessment Bi-weekly in monsoon season; Quarterly/monthly during dry season; post event (earthquake, etc.)
Segments	Landslide debris (mass and mobility of deposited debris), bank undercutting, infrastructure	Manual compulation and assessment via high-res optical imagery and DEM; updated through Google Earth Engine landslide identification model and refined analysis using high-res optical imagery and on-ground observation.	GIS mapped inventory and Risk score or ranked inventory based on risk score	Initial assessment Bi-weekly in monsoon season; Quarterly/monthly during dry season; post event (earthquake, etc.)
System	Composite of above outputs	Quantitative method and GIS processing to develop heat-map and scores for systems.	Composite scores of above outputs; heatmap or other visualization	Initial assessment, updated as above are updated
Community/ Infrastructure	Distance from above, population size, household location, etc.	Integrate abd overlay socioeconomic, demographic, and infrastructure layers with system processes above via GIS processing; calculate debris flow run-out models at varying levels of intensity	Vulnerability and Exposure Score/ assessment	Initial assessment, updated as above are updated

Fig.III.2: Monitoring and Assessment methods, outputs, and ideal frequencies for monitoring and updating indicators and underlying inventories

Approaches and methods for developing inventories and risk assessments for natural dams, segments, systems, communities, and infrastructure were discussed in the previous section. To set up a system for monitoring hydrometeorological indicators, a team or agency coordinating the risk assessment and early warning system project should collaborate with relevant government agencies and remote sensing inputs to establish application programming interfaces (APIs) that communicate a constant stream of information to a centralized digital platform that is designed to identify when triggers for debris floods are approaching. These triggers could include thresholds to determine intense rain and snow events, cumulative precipitation levels, sudden temperature spikes, and long periods of snowpack ripening among other indicators. Similar applications can be implemented for earthquake monitoring. In river systems where debris flood run-out models have been developed, trigger thresholds can be determined or suggested by those models. In river systems without such models, general triggers can be determined or trigger regimes can be determined by overall risk scores or risk to specific geohazards such as a glacial lake identified to have a high risk of GLOF. It is important to utilize a combination of physical gauge and remote sensing inputs to both corroborate data and findings as they are generated and also to develop redundancies in the event that a physical gauge malfunctions or is fully or partially damaged during an extreme event. Additionally, APIs which communicate data from physical river gauges can be set up to also monitor for extreme flow events or at-risk flow levels. If implementation resources are limited, then those river systems determined to hold the highest level of risk and greatest levels of vulnerability and exposure to communities and infrastructure can receive more dedicated attention from the monitoring processes.

An early warning and analysis assessment process will be triggered when data approaches or passes predetermined thresholds or warning levels. This process will focus efforts toward risk analysis on specific geohazards through remote sensing processes and/or on-ground observation. For instance, if a signal suggests a gradual or rapid expansion of a glacial lake, then data analysts can review high temporal resolution radar imagery available through Sentinel-1 or from a proprietary satellite company to monitor the lake for a period of time to detect and determine the level of change. If the lake is physically accessible by a nearby community, local community members or other individuals could be tasked to observe and assess conditions at the lake (if their personal safety can be reasonably guaranteed).

Such an approach could have been applied prior to the Kedarnath disaster, as the Chorabori Lake which ultimately failed and caused the outburst was located fewer than 2 kilometers from the Kedarnath community. Snowmelt had been pouring into the lake for about one month prior to the disaster and two days of intense rain ultimately caused the lake's natural dam to fail (Allen et al). This could have been identified by the above-mentioned satellite monitoring process and could have triggered local review ahead of the disaster. In the Melamchi case, the nearest community to the failed glacial lake was 15 kilometers away at an elevation of more than 2000 meters below the lake. In this instance, a more viable option for observing the lake could have been to fly drones that could have been permanently or temporarily located in a nearby downstream community to observe the geohazard in question and the conditions around that geohazard.

Communities or DRR agencies in Nepal could invest in the purchase, maintenance, and training capacity for drones with optical imagery capabilities as well as synthetic aperture radar capabilities which will enable the drones to see through precipitation and cloudy conditions. Drones can also be used to drop off or pick up monitoring equipment that can provide greater focus on risk around the geohazard. Drones can also interact with the risk area by dropping explosives to create landslides or breach a natural dam in order to reduce the impact of future potential debris floods. Localities at either the provincial or district level could invest in mobile drone systems that could be tasked to observe risk in a matter of hours after a trigger signal is approached or surpassed. Through community-level consultations and the process of building partnerships to implement the early warning system, it is likely that other forms of verification will be identified–such as the development of local data collection teams–and designed in a fashion fit for the local socio-economic context and ability to invest in technology hardware and training.

It is also possible to build capacity for community-level participants to participate in ongoing data collection either through voluntary or paid efforts. Regular or periodic data collection activities would allow community-level data collectors to refine their collection techniques and provide a continuous data record for a site that can be uploaded or submitted to a central management system. Mapping an inventory of established data collection sites would provide a distribution map identifying areas of coverage and confirm whether high-priority risk areas are appropriately monitored. Data collected from this system may not be as reliable as hydrometeorological or gauge readings from established data services, but the information would help establish the existing conditions on the ground in a particular location at a particular time which are otherwise unavailable while also building community-level buy-in for disaster risk reduction.

Extreme signals given via hydrometeorological monitoring processes or from a major event such as an earthquake could be sufficient to issue an early warning or a disaster watch notification without a secondary verification process. However, going through steps related to secondary verification will help reduce instances of false positives and establish trust in early warning messaging by the beneficiaries of the early warning system. Secondary verification processes should also be seen as opportunities to build capacity within communities for participatory approaches to disaster risk reduction and early warning systems.

Implementing strong secondary verification processes can also provide a pathway to verifying trigger signals that are identified not through hydrometeorological monitoring or other systemic risk monitoring mechanisms but rather through social media or crowd-sourced methods. For instance, if a pastoralist herder or foreign tourist takes a photo of a crack in the ground beneath a natural dam at a high altitude and shares this image on a social media platform, it could initiate a community-level discussion that eventually communicates information to local authorities, who would then be able to call on a secondary verification process to further diagnose conditions around the natural dam. A more sophisticated but expensive and possibly less socially acceptable process could employ data scrubbing techniques and artificial intelligence to constantly monitor public social media accounts for such imagery or trigger word-related text and automatically submit this information to a centralized EWS platform for secondary verification. Further, social media platform scrubbing techniques could also be used as part of a secondary verification process to rapidly assess if an image of the geohazard in question had been taken within a recent period, to string together photos of the geohazard to observe change or interview the individual who took the image for further information which could verify the level of concern around early warning or disaster watch.

Applying Our Methods to the Melamchi Disaster

The following section briefly describes how the risk assessment and early warning system outlined in this section could have provided a more rapid assessment and early warning in the June 15, 2021 Melamchi Disaster. We fully acknowledge that forms of early warning communications were indeed put to use via social media and the involvement of local government authorities, but with this analysis, we sought to explore how our proposed toolkit could have provided additional indicators of concern or even warning for nearby communities.

To begin, a natural dam inventory and risk assessment process would have identified the small glacial lake in the high reaches of the Pemdang Khola as well as the natural dam created by the old landslide at Bremthang. These natural dams as well as all natural dams in the streams and river systems above Melamchi Bazaar would have been identified and categorized in a natural dam inventory. It is likely that the glacial lake in the Pemdang Khola and the Bremthang natural dam would both have ranked among higher quartiles or groupings than other natural dams above Melamchi or all natural dams in a nationwide inventory. As such, the combined Pemdang-Melamchi system would have been ranked comparatively higher in terms of risk than the other rivers above Melamchi and in Nepal. Adding to the risk ranking of the Pemdang-Melamchi system would have been the debris deposit inventory, which identified 17 debris deposits estimated at 1.98 million square meters of surface area composed of various sizes of material when compared to adjacent river systems. This risk assessment likely could have informed communities in the Melamchi valley to target risk assessment resources on this system and supported capacity-building efforts for crowdsourced or local participation in risk assessment and monitoring. It is possible that monthly observations via drone or other methods to the two natural dams in question could have revealed topographical changes or accumulating conditions that would have brought even more attention to these geohazards These would have been the underlying conditions present prior to the onset of the cascading disaster which culminated on June 15, 2021.

With a central data system in place that monitored hydrometeorological indicators via API with national and local monitoring stations as well as remote sensing stations, a snowpack assessment for the cryosphere portions above Melamchi Bazaar could have revealed details on snow cover status. For example, the SSMI-derived snow cover product would have identified higher-than-usual snow cover conditions leading up to the week before the disaster (see Figure III.3). Then during the week of June 7, hydrometeorological signals would have sparked an alert that snow cover percentage maps indicated a rapid decrease in the percentage of snow cover compared to the previous week, indicating snowpack ripening.

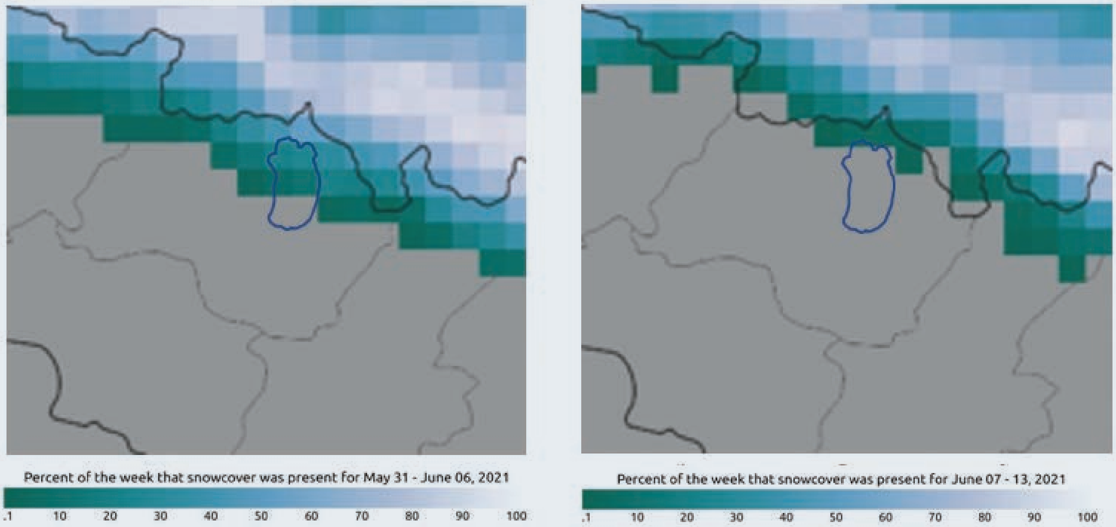


Fig. III.3: Visualization of SSMI-derived snow cover presence data (% of week snow cover present) for 5/31-6/6 2021 and 6/7-6/13 2021. The Melamchi-Yangri watershed is outlined in blue. The data show a rapid retreat of snow cover from the first week to the second.

Returning to data provided by the ICIMOD 2021 report via the automatic weather station in the Melamchi valley, the late May rains could have initiated processes at the local level to check on water levels or conditions around the Pemdang glacial lake or the old Brethang landslide dam. The snow retreat pattern demonstrated in the above images, coupled with the observations of temperature change between June 1 and June 10 when temperatures hovered around freezing during the day and returned to below-freezing temperatures at night, signal a ripening of the snowpack and would likely have kicked off an assessment. A sudden change in temperature patterns on June 11, when temperatures did not return to below freezing during the nighttime hours, could have additionally signaled that a major melt-off event was forming even prior to the increased precipitation starting on June 13.

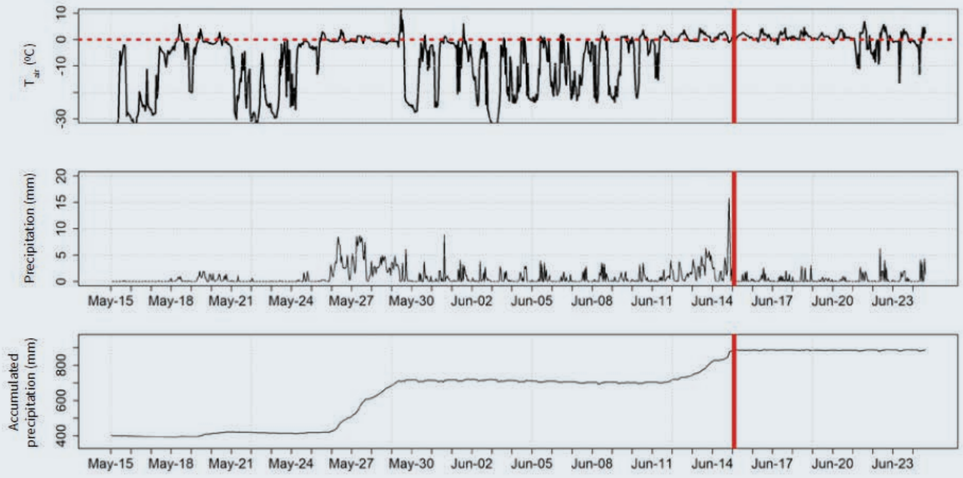


Fig.III.4: Climate data from AWS on Upper Melamchi Watershed. The red line denotes when most known mass movements occurred. (*Maharajan et al 2021*)

This data would have been compelling enough to inspire local participants to take action. Even if no local risk assessment methods were available, data analysts could have reviewed a high-resolution image of the lake from June 10 via the Planet Labs online platform on June 11, which would have revealed the glacial lake to be completely free of snow cover where only 5 days prior it was covered in snow and ice.

Fig. III.5: June 5 to June 10 comparison of snow retreat using Planetscope Image archive. The glacial lake is identified by the black marker.

At this point, a calculation of changes to topographical and watershed indicators could have elevated the risk score of this natural dam, and a possible early warning message could have been communicated to communities downstream. At the least, the sudden precipitation event which started on June 12 and dumped 200mm of rain into the Melamchi Valley over the next three days would have brought increased attention to risk assessment throughout the Melamchi valley. We know the Pemdang glacial lake was intact on June 10 and breached prior to June 15 when the debris flood hit the Melamchi Bazaar. If the proposed early warning system was in place, it would have triggered attention to the valley area above the Bremthang landslide well before any incident, and it is possible that preliminary risk assessment could have determined a need for a flow gauge above the Bremthang dam instead of at Nakote below Melamchi Gaon.

The ICIMOD report noted that the Nakote gauge observed a severe flow decrease for 45 minutes prior to a massive increase in flow, likely capturing 45 minutes of the rapid buildup of material behind the Bremthang Landslide Dam before it burst. A gauge above the Bremthang Dam would have provided corroboration evidence that debris entrainment was indeed happening and this could have been measured somewhat prior to the 45-minute period at Nakote. Importantly, the data from that gauge would have needed to be provided in real-time to be included in a real-time assessment. If monitoring efforts were closely watching river gauge data at Nakote, there would have been time to fly a drone from Melamchi Gaon or Melamchi Bazaar to observe the mass of debris collecting and brewing behind the Bremthang Dam. It is at this point when all evidence would have been present to issue full early warning guidance to downstream communities. In coming decades, advancements in real-time monitoring and assessment provided by drones or other methods will likely be able to provide rapid analysis of flow volume and speed to estimate the run-out distance and path of destruction a debris flood will create in a real-time fashion.

Crowdsourcing: Applications for Multi-Hazard Data Collection and Mitigation

Crowdsourcing is "the practice of obtaining needed services, ideas, or content by soliciting contributions from a large group of people and especially from the online community rather than from traditional employees or suppliers (Meriam Webster)."

Crowdsource networks can take many forms but networking is typically done via the internet and social media platforms. Network interactions are conducted through a computer and/or cell phone apps or call-in or login options. Depending on the process, data collection efforts are either organized or opportunistic; some processes pay data submitters while others are unpaid.

- For hazard data collection, monitoring, and response, crowdsourcing may help authorities better identify, track, manage, prioritize and respond to hazards. When regional or local hazard identification and response systems are not well developed, are compromised because of some catastrophe, or are overwhelmed because of mass casualties or the overwhelming need for responses, crowdsourcing may be useful.

- Crowdsourcing provides "on the ground" observers who can view and relay conditions from a specific location. Geo-referenced photographs can provide near real-time observations and standardizing photographic methods may be able to provide comparable data both temporally and spatially. At any rate, photos can provide very useful information whether it captures the standardized variables or not.

- Crowdsourced data can also be collected via "data form" applications with standardized questions. A variety of cell phone sensors such as geolocation, light, movement, audio, and visual sensors can all provide reliable data for a small selection of metrics. There are a number of smartphone apps available to crowdsource information that may be useful in the context of Nepal.

- Time of reporting can be helpful in determining the progression of an event. Knowing the location, the time, and the actual conditions at a specific location may help predict or assess the risk levels at the site and other sites downstream as an event unfolds. If a bridge or dam has just been overtopped or blown out, an analyst should begin to look downstream for hazard risks as the event evolves. "Pre" and "post" event reporting may help with change analysis or damage estimations.

- During an event it is entirely possible that the internet and/or cell phone infrastructure will be damaged. Data collectors could still collect their data and submit it when the system is again operational. The data may still be useful in understanding the event and its development and help inform future responses to similar events. Cell phone photography and GPS positional data should be available whether the cell towers are active or not.

- Predetermined data collection sites may also be unavailable to the collectors in some situations. In such cases, it still may be useful for data collectors to document the conditions contributing to the access constraints unless collections cannot be done safely.

- Data analysts could work with data collectors to inform local residents of pertinent event information. The data collectors then become data distributors. Alerts and other safety info can be distributed from a central data platform to the individual data collectors and then out into the community. This type of system would depend entirely on the resources available for information dissemination for a specific location.[200]

Crowdsourcing via the internet and smartphones is entirely dependent on telecommunications coverage and the ability of project managers to organize a meaningful crowdsourcing response group. The initial assessment process can determine whether involved communities already participate in existing crowdsourcing efforts and determine whether participants will volunteer or need to be remunerated for their efforts. Further assessment is required to determine the feasibility of training programs and the most optimal language and methods used to conduct training programs in local communities. When a crowdsourcing group is ready for operation, assessments should determine how to activate and maintain the group and how to test their readiness. Finally, assessment is required to determine how crowdsourced data is integrated and used in assessment and decision-making processes for regular reporting, during events, and post events.

Finally, when data supports the issuance of an early warning message to a group of affected people, the language, wording, and visualizations should be pre-determined by consultation processes that engage the beneficiaries of early warning systems in order to achieve optimal levels of response. Our own consultations with local stakeholders in Nepal note that existing early warning regimes are prone to communicating unclear information and instructions, likely due to a top-down and scientific focus on the early warning messaging process. Also, some respondents noted that during the monsoon seasons, flood notifications are issued so frequently that the value of their information is ignored. Focus groups can help identify which forms of communication and content will produce the most optimal behavioral response from individuals at risk. It is important to note that different groups will have different preferences based on ethnolinguistic needs, socioeconomic status and livelihood practices, and gender needs among others. Focus groups will also help determine the most optimal methods of early warning message delivery such as push notifications on smartphones, cellular text notifications, notifications via commonly used social media platforms such as Facebook or Instagram, or something else entirely.

EXISTING EWS-CROWDSOURCING EFFORTS IN NEPAL

- The National Disaster Risk Reduction Management Authority (NDRRMA) utilizes a "Text Warning System—effectively a policy of messaging mobile phones for citizens in areas along the floodplains near major rivers to provide a warning about potential flooding. Citizens can then get further information by calling the toll-free number 1155."

- GLOF EWS systems, such as the UNDP system with Tso Rolpa, also used these kinds of auto-generated mass text message systems

- In the wake of the Gorkha Earthquake, Facebook's "mark safe function" popularized social media as a way to share this kind of information.

- Organizations like Kathmandu Living Labs (KLL) that use open source mapping technologies were also critical in generating disaster response and damage/hazard maps in the wake of the Gorkha Earthquake in 2015 - effectively articulated in collaboration with the broader Humanitarian Open Street Map community. In many cases, these efforts to accurately map damage utilized a phone-based reporting system that required Nepalis in rural areas to call in the report conditions, which a team of KLL volunteers would render on a map.

Consultative Workshop on Landslide Inventory, Risk Assessment, and Mitigation in Nepal. ***Photo taken by Jitendra Raj Bajracharya/ICIMOD, posted on ICIMOD Kathmandu's Flickr account, and used under a Creative Commons License.***

SECTION IV:

Overview of the Institutional Landscape of Hazard Risk Reduction and Early Warning Systems in Nepal

The following provides a brief overview of existing data initiatives and organizations already active in Nepal on collecting, analyzing, and/or sharing data related to water flow, weather forecasting, and early warning for disaster risk. A more comprehensive list of initiatives and organizations active in this space can be found in the annex of this report. While existing data platforms track near-real-time data on some indicators and provide general risk and vulnerability information, the platforms have relatively limited predictive capability or analytical tools for modeling or simulation.

Notably, there are many overlapping efforts or duplicated efforts within the government of Nepal's online ecosystem. The Ministry of Home Affairs, National Disaster Risk Reduction and Management Authority (NDRRMA), and Department of Hydrology and Meteorology in the Ministry of Energy, Water Resources and Irrigation all host platforms, and there are parallel links to portals from multiple home pages. However, the level of true interconnectivity between these online ecosystems and responsibility chains is not fully clear at a cursory glance. Anecdotal conversations indicate that this is likely tied to limited mandates for individual actors, overlapping obligations among various government departments, pushes for leadership on the disaster risk and response issue set by key individuals in each organization, political interests, and competition over funding from international donors.

Currently, Department of Hydrology and Meteorology (DHM) is mandated for generating forecast data for weather and water level. Integrating the national models with global models, such as Global Flood Awareness System (GLoFAS) are already increasing the lead times of warning. Together, they have contributed to enhance the effectiveness and efficiency of existing community-based systems in some of the pilot areas. However, currently there is no institution or entity that champions on translating the weather forecasts and river level forecasts into specific hazard maps to identify the most at risk. Similarly, there is no government entity championing on landslide early warning and forecasting. NDRRMA, DHM, DMG are all doing different activities on landslides but unless there is one institution mandated and dedicated for landslide EWS, the progress on LEWS will suffer at national level.

Some of these government efforts also parallel non-government initiatives and dataset collection, and these efforts may run into similar challenges. The numerous efforts and relative lack of formal collaboration and coordination do reveal some politicization of data. This appears to be less the case for flood data given the urgency of response, but could have implications in terms of which data sets are integrated into any early warning system. Longer-term data sets related to climatic change and land use could potentially run into challenges of intellectual property and usage rights.

Finally, this survey of available data and relevant organizations does reveal that there is a plethora of online platforms and capacity-building efforts related to hydrology and meteorology, as well as numerous academic papers which include relevant modeling and simulations, but there does appear to be a relative lack of publicly accessible on-ground monitoring. The government–with the support of the World Bank–has improved monitoring stations for weather in recent years, but stations appear to focus primarily on the major rivers and there is limited physical monitoring as you move to smaller tributaries or tributaries of tributaries.

Our conversations with experts in the field indicate also that some hazard types are more institutionally covered than others. For example, as we have shown in this report, floods and GLOFs are a common topic of institutional concern and multi-institutional coordination. In Nepal, however, there are fewer institutions focused on landslides and government responses to landslide-like events (debris flows, slumps, etc.) are more or less reactive. In recent months, PIN Nepal has initiated a new Technical Working Group on Landslides that seeks to connect NGO and academics working on landslides with the government, to promote more effective DRR policies and EWS/response efforts, but this is a brand new initiative—one which we at Stimson are also involved in.

At the level of EWS implementation, generally speaking, EWS programs and DRR protocols remain a patchwork across Nepal. While some level of local articulation and adaptation is of course necessary, it seems that improved coordination and the sharing of information and best practices would be beneficial to all. As the Oxford study by Bhandari et al (2020) has shown, the interactions between scales of disaster governance (federal, provincial, municipal, local) is critical, and roles and responsibilities are still somewhat in flux following the national reconfiguration of provincial and municipal governance in 2017/2018.[201] At the local level, early warning systems remain somewhat of a patchwork, with limited coordination between them. From our perspective, this seems like an opportunity: perhaps to convene EWS practitioners in Kathmandu for an exchange that can lead to knowledge sharing and potentially greater coordination.

Finally, the non-government early warning system and related efforts profiled below largely share one thing in common: they recognize that there is a role for the government in the successful and sustainable implementation of an early warning system. The government's role is particularly relevant for small communities and remote localities where the problem is not just limited to the dissemination of the warnings but also the perception of the risk associated with natural disasters. Going forward, local governments, NGOs, and international agencies will have to empower early warning systems through a framework that also supports educational training, adaptive techniques, and capacity-building.

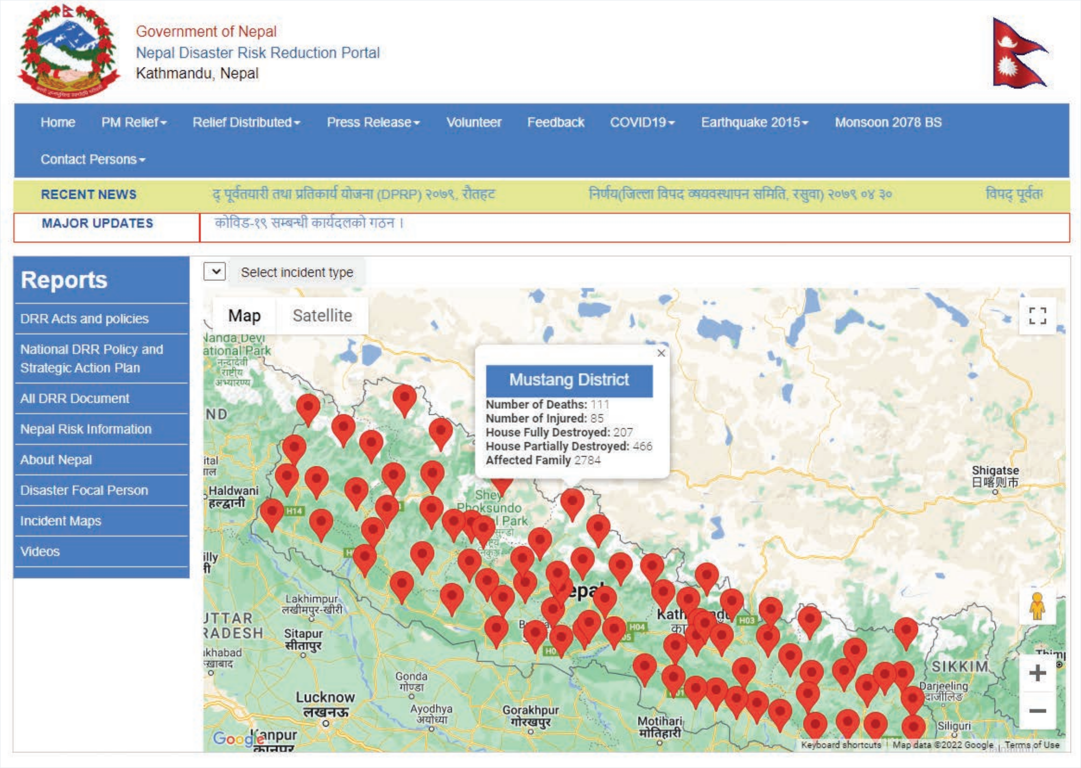
Government Initiatives

There are three major public e-portals managed by government agencies in Nepal to track risks, vulnerabilities, and ongoing disasters. The Nepal Disaster Risk Reduction Portal, the Building Information Platform Against Disaster (BIPAD), and the Hydrology Portal. BIPAD integrates data from the other two portals, but each still exists as a separate entity.

One key government agency involved in integrating these portals together is the **National Disaster Risk Reduction and Management Authority** (**NDRRMA**), which was legally established in 2017 to ensure there is a centralized government body responsible for disaster risk reduction and management and help Nepal meet targets under the Sendai Framework. The NDRRMA is responsible for tracking disasters related to inclement weather (hail, snow, heavy rain), avalanches, drought, flood, landslides, lightning, earthquakes, as well as health emergencies such as snake bites, flu, and industrial accidents. The NDRRMA is guided by the National Council, which is chaired by Nepal's Prime Minister, and regular activities are overseen by the Management Executive Committee chaired by the Home Minister. NDRRMA has a broad mandate to study and investigate natural disaster risks and incidents, and provide financial and technical support at the local level for management plans and disaster management assistance activities and emergency rescue. To fulfill these responsibilities, NDRRMA manages the BIPAD Portal as well as the Disaster Risk Reduction Portal.

Another key government agency is the **National Emergency Operation Center** (NEOC) founded in 2010 under the Ministry of Home Affairs, which acts as a communication hub for disaster information and response coordination in Nepal. The NEOC feeds data into the Nepal Disaster Risk Reduction Portal and BIPAD platform profiled below.

- The **Nepal Disaster Risk Reduction Portal** was established under the Government of Nepal to track various natural disasters and crisis situations including landslides, earthquakes, and pandemics. This portal emerged from the Government of Nepal's vision for establishing a more proactive approach to disaster risk management. The heavy humanitarian and economic losses from the 2015 Gorkha earthquake raised the need for an information system portal along with other concrete DRR efforts. In response, the Ministry of Home Affairs, the Prime Minister's Office, and a range of other key line ministries established a new post-2015 framework for Nepal to address priorities in line with Nepal's commitments under the global Sendai Framework for Disaster Risk Reduction. The two main datasets in this portal are incident maps and a list of recent incidents. See further details in the Annex.



Government of Nepal
Nepal Disaster Risk Reduction Portal
Kathmandu, Nepal

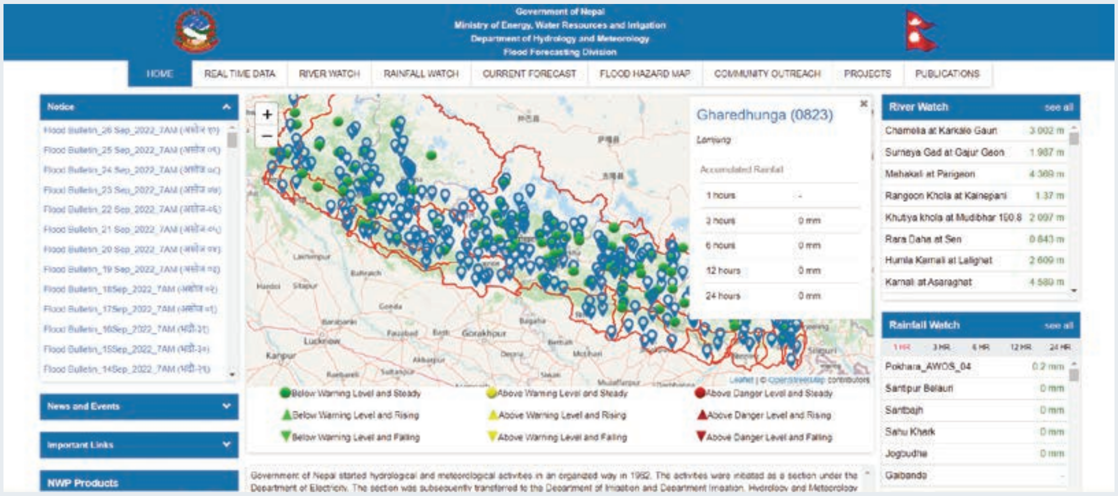
RECENT NEWS द् पूर्वतयारी तथा प्रतिकार्य योजना (DPRP) २०७९, रौतहट निर्णय(जिल्ला विपद व्यवस्थापन समिति, रसुवा) २०७९ ०४ ३० विपद् पूर्वता

MAJOR UPDATES कोविड-१९ सम्बन्धी कार्यदलको गठन ।

Mustang District
Number of Deaths: 111
Number of Injured: 85
House Fully Destroyed: 207
House Partially Destroyed: 466
Affected Family 2784

Fig. IV.1: Screenshot of Nepal Disaster Risk Reduction Portal homepage. This shows overview information at a glance for each district in Nepal, with details on individuals and households impacted by recent disasters.

- **Building Information Platform Against Disaster (BIPAD)** acts as an integrated national platform hosting data from municipal, provincial, and national sources to track disaster incidents and support response. BIPAD integrates information from the Disaster Risk Reduction Portal (Figure IV.2). The portal was developed in consultation with various government agencies, local tech companies, and a range of non-government organizations which collect and manage data. In its current form, BIPAD supports disaster management processes from tracking identified risk to facilitating communication during an ongoing disaster and finally in post-disaster assistance procedures. The platform does not currently support real-time analysis of risk factors or trends, but acts primarily as a notification process for identified disaster incidents. See the Annex for BIPAD's mode of operation.



Gharedhunga (0823)

Lamjung

Accumulated Rainfall

1 hours	-
3 hours	0 mm
6 hours	0 mm
12 hours	0 mm
24 hours	0 mm

River Watch

Chamelia at Karkalo Gaun	3.002 m
Surnaya Gad at Gajur Gaon	1.987 m
Mahakali at Parigaon	4.389 m
Rangoon Khola at Kainepani	1.37 m
Khutiya khola at Mudibhar 150.8	2.097 m
Rara Daha at Sen	0.843 m
Humla Karnali at Lalighat	2.609 m
Karnali at Asaraghat	4.580 m

Rainfall Watch

Pokhara_AWOS_04	0.2 mm
Santpur Belauri	0 mm
Santbajh	0 mm
Sahu Khark	0 mm
Jogbudha	0 mm
Gaibanda	-

Government of Nepal started hydrological and meteorological activities in an organized way in 1962. The activities were initiated as a section under the Department of Electricity. The section was subsequently transferred to the Department of Irrigation and Department Irrigation, Hydrology and Meteorology

Fig. IV.2: BIPAD at a glance[202]

- ▹ **Text Warning System**: The NDRRMA has a policy of messaging mobile phones for citizens in areas along the floodplains near major rivers to provide warning about potential flooding. Citizens can then get further information by calling the toll-free number 1155.[203] There are a few gaps and uncertainties about the system's application, however. Documentation is unclear on how fast the review is for reported incidents in BIPAD and how quickly emergency hotlines report incidents and prompt immediate response. Interviews could provide further clarity on the following questions: How does the alert system work? What determines who receives texts warning about floods? Is this automatic to everyone in a certain vicinity? Which floodplains are covered? How is this information shared with those without mobile phones?

- **Hydrology Portal:** The Department of Hydrology and Meteorology within the Ministry of Energy, Water Resources, and Irrigation is responsible for monitoring all hydrological and meteorological activities in Nepal. To fulfill this key mandate, it tracks and publishes real-time data on rainfall across the country, rainfall watches, and river level warnings during the monsoon season. Most of this is available in an interactive map on the Department homepage, which has been online since 2018 and allows users to check rainfall in many localities around the country and see flood warnings for particular rivers in particular districts. The Department also issues Climate Bulletins and notices for the farming community and industry.

  - ▹ **Pilot Early Warning System:** The Ministry has set up a community-based flood warning system in Devchuli, Divyapuri, and Pragatinagar areas to test the dissemination of flood information from the dataset to local communities, agencies, and authorities.

DATA SHARING OR EARLY WARNING?

The government of Nepal has clearly invested in the creation of analytical platforms and recognizes the value of real-time and near real-time data to inform policymakers and the public about ongoing events and risks. There are numerous references to guidance for how this information should flow through the government network of actors. However, what is not clear is how this detailed analytical information is actionable and how it reaches the average Nepali citizen. Particularly unclear is how data from existing early warning and alert systems reach those who are not in urban communities with cheap and reliable internet access and an understanding of how to use data portals.

While there are some early warning systems in place, they appear to mostly be in pilot phases with some limitations on the scope of areas covered. For instance, the Department of Hydrology and Meteorology has coordinated with communities and can utilize mobile phone systems to warn downstream communities in approximately a dozen river systems when they need to urgently move to emergency flood shelters.[204]

While there are instances of rainfall data and other information being put to use to inform communities along key river systems, there is limited documentation on the early warning process and the geographic scope and limitations. The portal itself appears to have a limited scope to predict rising risk to specific localities for users looking at the data, although it likely has back-end data that is utilized by the government. A desk study doesn’t provide sufficient insight into how information is disseminated or its limitations: Is this information reflected in news or radio broadcasts? Are text alerts automatically issued to everyone in a locality, or do citizens need to sign up to receive them? What are the on-the-ground components of the early warning system? Determining where the gaps in the communications process exist will require on-the-ground field engagement and further dialogue with stakeholders, including groups like People in Need (profiled below) who are actively working on this issue.

Non-Government Initiatives or Government and NGO Partnerships

In addition to official government initiatives in Nepal, there are a range of regionally and nationally active inter-government and non-government organizations which work on data issues. The following section profiles these non-government groups which nonetheless contribute significantly to data sharing and access.

THE INTERNATIONAL CENTRE FOR INTEGRATED MOUNTAIN DEVELOPMENT (ICIMOD)

ICIMOD is an intergovernmental organization operating within the Hindukush Himalayan region. ICIMOD serves as a research and knowledge-sharing platform for key regional challenges ranging from mountain issues to climate change, water scarcity, and disaster risk resilience. With projects across all eight regional countries–Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan–ICIMOD aims to create innovative solutions, provide policy recommendations and facilitate the implementation, bridge data gaps, and enable regional experts from all member countries to come together to advance action and enable more international support for regional challenges.

Existing Early Warning Systems

- **The Community based flood early warning system (CBFEWS)** is led by ICIMOD but is a partnership approach, and is reflected in the following section.

- **Regional Flood Information System in the HKH region (HYCOS-RFIS)**: The project was launched following a series of consultative meetings with representatives from central HKH countries, Bangladesh, Bhutan, China, India, Nepal, and Pakistan between 2001 and 2005. The project aimed at promoting the timely exchange of flood information between member countries through a user-friendly and easy-to-access portal. See the Annex for project details.

- **HI-RISK:** A regional platform set to contribute to the achievement of the Sendai Framework for Disaster Risk Reduction 2015–2030, aims to deliver on data sharing, best practices on DRR, managing river hazards, and building disaster response capacity across the region. The platform engages with a broad range of stakeholders, including relevant governments and community-level stakeholders. The HYCOS User Phase is a project that falls under this broader Hi-RISK Initiative and focuses on water-related hazards. See the Annex for further details.

- **Cryosphere Initiative:** Through the Cryosphere Initiative, ICIMOD also maintains a multi-level remote sensing-based observation system for snow and glacier monitoring which involves the mapping and monitoring of glaciers and glacial lakes through satellite imagery, snow cover through MODIS, and detailed investigation of glaciers in representative basins/sub-basins.

- See Annex for information on other notable data platforms like RDS, HI-AWARE, and KBIS by ICIMOD and further details on some of the above initiatives.

PEOPLE IN NEED (PIN)

PIN is a non-profit international organization established in 1992 by a team of Czech war correspondents and has since grown into an international humanitarian assistance organization working to support human rights, development, and humanitarian aid globally. PIN started operations on disaster response and humanitarian aid in Nepal after the 2015 earthquake. From 2016 to 2017, PIN supported a range of projects supporting recovery for earthquake-affected communities in Nepal. After the 2017 Terai Floods, PIN also worked on the rehabilitation and provision of aid for flood victims. Given the recurring nature of landslide disasters and other hazards in Nepal, PIN also supports efforts to build resilience and response capacity for future disasters.

Projects

- **Pratibaddha: Risk Informed Landslide Management in Nepal's Hill Areas** is an ongoing project which aims to improve local resilience to landslide risks through working with local government actors, communities, and key actors for construction projects to improve understanding of landslide risks. The project has a few aspects: the first is to map landslide risk and hazards, and the second is to raise awareness and local capacity. To date, the team has conducted geo-hazard assessments for 158 sites to determine immediate risks and identify plans for those most at risk in nearby communities.[205] There is a focus within this project to identify new geohazards that have appeared after the 2015 earthquake. This is a collaborative project with consortium partners Community Self-Reliance Centre (CSRC), National Society for Earthquake Technology-Nepal, Scott Wilson Nepal, Durham University, and Northumbria University.

- **Landslide Forecasting (LSF) Technical Working Group:** Building on the hazard-mapping activities mentioned above, PIN has established a technical group to bring together experts working on development, landslide, and other hazard management in Nepal for regular dialogue. The group consists of invited organizations and experts and meets every one to two months to share updates on Nepal-focused initiatives and share case studies and best practices from farther afield.[206]

- **Obstacles to Information Dissemination Study:** Tied to their ongoing work on landslide forecasting and management, PIN is engaging in a survey of existing obstacles to the communication of information and warnings to local communities which will inform future activities. They are currently doing surveys at three locations to explore where the pain points and bottlenecks are in terms of digital access, communications and language used, and additional ways to ensure information effectively reaches marginalized and vulnerable communities.[207]

Photo of relief efforts in a community displaced by a landslide in 2017 at Pahirebesi in Rasuwa district, Nepal. Courtesy of People in Need Nepal.

INTERNATIONAL FEDERATION OF RED CROSS (IFRC) AND RED CRESCENT SOCIETIES

The IFRC Disaster Law program was established to provide technical assistance, capacity-building, tools, and legal guidelines related to disaster risk management and law. The IFRC works closely with the Red Cross and Red Crescent National Societies, which are integrated within domestic disaster risk management and health frameworks. In Nepal, the Nepal Red Cross Society has collaborated with IFRC Disaster Law on a series of studies related to gender equality, disaster risk reduction, and International Disaster Response Law. The IFRC's work is primarily focused on the legal side of things and so it is not directly relevant to the creation of an early warning system, but could help inform best practices on the dissemination of information from such a system and integration of warnings from EWS into government. See the Annex for potential points of project contacts and a list of relevant projects.

FLYING LABS

Flying Labs is a global network of experts who use modern technologies–particularly drones, data, AI, and robotics–to improve social good using decentralized and inclusive approaches. Nepal Flying Labs is a non-profit enterprise which uses drones and AI to support a range of sectors for sustainable development goals. The team has a particular focus on health, development, environmental conservation, agriculture, and disaster risk reduction and management. Activities range from research project support for member organizations to capacity-building and training seminars. Nepal Flying Labs could be a potential partner for exploring the use of drones or modern technology for manual observations to back up satellite data and remote sensing. See the Annex for additional details on projects.

THE INTERNATIONAL WATER MANAGEMENT INSTITUTE (IWMI)

The IWMI is an organization with offices in 13 countries supporting research on water management for social and economic development. IWMI has an office in Nepal and has been active there since 1986 working to produce evidence-based knowledge related to thematic areas of Water, Food and Ecosystems; Water, Climate Change, and Resilience; and Water, Growth and Inclusion. Projects in Nepal focus on integrated water resource management, sustainable agriculture, deployment of solar energy, and community resource management.

Datasets and Platforms

- **The Water Data Portal** (**WDP**) is an online portal that hosts much of IWMI's global data on meteorological, hydrological, socio-economic, and spatial data layers, as well as satellite images and hydrological models. Users are able to download the data for research and other uses. There are a number of smaller tools for detailed analysis on flood risk mapping, climate change vulnerability, global drought patterns, etc. See Figure IV.3.

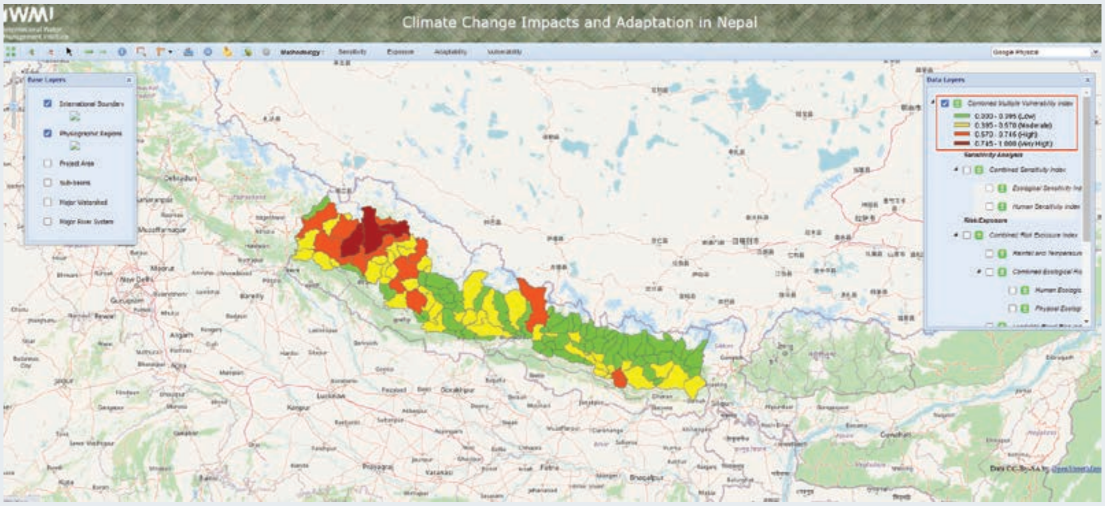


Fig. IV.3: IWMI Portal at a glance

- **Disaster Planning:** IWMI is working with the International Development Research Centre (Canada) on identifying drivers of water disasters and providing guidelines for gender and social inclusion for disaster preparedness and planning. This initiative has multiple partner organizations and could be used to inform early-warning-system design and engagement.

PRACTICAL ACTION

Through its flood resilience program, Practical Action is working with communities to make flood adaptation and planning easier for communities, practitioners, and decision-makers. Incorporating the Zurich Alliance's Flood Resilience Measurement for Communities Framework (FRMC), which uses robust data gathering and analysis to assess a community's existing level of flood resilience, Practical Action works with local communities globally, including Nepal, that are vulnerable to floods and other climate disasters. It also uses the aforementioned Flood Resilience Portals to provide knowledge information required for the designing and implementation of flood resilience policies and practices.

WORLD BANK'S BUILDING RESILIENCE TO CLIMATE-RELATED HAZARDS

This project (2013-2020) was developed to enhance government capacity towards climate mitigation and improve DRR and disaster response. The World Bank has also recently invested in expanding Nepal's network of weather observation stations for forecasting.

USAID

Internationally recognized top development agency which leads efforts on humanitarian challenges, environmental impacts, and strengthening of democratic governance.USAID works to advance US foreign policy through international assistance abroad. In Nepal, USAID works to strengthen the private sector, civil society, and the government's ability to provide locals with better opportunities within a stable political and economic environment.

- **Kamala River Basin End-to-End (E2E) Early Warning System:** The project established a community-centered E-2-E flood EWS in Kamala River Basin to enhance awareness and capacity of vulnerable communities and DRR agencies to understand, monitor, and prepare for effective flood warning and response. The project also worked on supporting flood preparedness and response institutions via Village Development Committees (VDCs), and municipalities. The project collaborated with District Disaster Relief Committee (DDRC) in respective districts and supported Nepal's Department of Hydrology and Meteorology (DHM) to upgrade and manage flood risk monitoring, forecasting, and communication systems. This system proved effective in averting some of the 2016 flood-related casualties and set the tone for multi-stage forecasting and monitoring for DRR in the HKH region.[208]

Academic Research Programs and Partnerships

- **China National Cryosphere Desert Data Center:** A data center and research institute in China which supports seven research laboratories and three research networks focusing on glacier, permafrost, desert, atmosphere, water and soil, ecology, environment, resources, engineering and sustainable development focusing on Qinghai Tibet, Mongolia Xinjiang and loess plateaus. It has partnerships with various institutions under the Chinese Academy of Sciences. The Center publishes a series of datasets that may include relevant baseline information on glaciers, although it does not actively update all of them on a regular basis. The Center is unlikely to be a partner given the irregular updates but may be a good starting data source on glaciers. The Center manages two datasets which are profiled in the Annex.

- **Durham University Institute of Hazard, Risk, and Resilience** is a research institute focusing on working with stakeholders living with hazard and risk, and utilizing research and data to improve resilience and empower those affected. The Institute takes a multi-disciplinary approach and has numerous scholars whose research has focused on Nepal and the complexities of landslides as well as other hazards. General research themes include work on the impacts and effects of natural hazards, improving preparedness, and working on predictive capabilities for disasters.

- **Northumbria University Department of Geography and Environmental Sciences** includes research on five sub-themes: cold and paleo-environments; social and cultural geography; disasters, development, and resilience; environmental geochemistry and ecology. It hosts two major training centers: the Northumbrian Environmental Training and Research Centre, which provides consulting research; and the Centre for International Development, which supports disaster risk reduction work with major international organizations and includes experts on Nepal.

- **China National Cryosphere Desert Data Center:** A data center and research institute in China which supports seven research laboratories and three research networks focusing on glacier, permafrost, desert, atmosphere, water and soil, ecology, environment, resources, engineering and sustainable development focusing on Qinghai Tibet, Mongolia Xinjiang and loess plateaus. It has partnerships with various institutions under the Chinese Academy of Sciences. The Center publishes a series of datasets that may include relevant baseline information on glaciers, although it does not actively update all of them on a regular basis. The Center is unlikely to be a partner given the irregular updates but may be a good starting data source on glaciers. The Center manages two datasets which are profiled in the Annex.

Multi-Stakeholder & Data-Sharing Initiatives

Operating at the intersection of government and non-government actors are a number of platforms and initiatives which act as high-quality examples of coordination. These hybrid initiatives gather the best of both worlds: they can access and draw on government data and plug into official response mechanisms and processes while benefiting from the creativity, technical savvy, and diverse local network that non-government and academic stakeholders cultivate. These efforts are among the most cutting-edge and forward-looking initiatives profiled in this report, and the early warning system as envisioned here would ideally work in a similar manner and in a potential collaboration with many of the efforts profiled below.

SERVIR HINDU KUSH HIMALAYA (SERVIR-HKH)

SERVIR-HKH is a joint initiative of NASA, USAID, and ICIMOD which aims to address critical challenges related to climate change, water, and related disasters through the use of geospatial and satellite data. The SERVIR program is global, but SERVIR HKH covers Afghanistan, Bangladesh, Myanmar, Nepal, and Pakistan and both provide high-quality data and applications and also build technical capacity among key government decision-makers and civil society groups in these countries on how to use them. Most of the SERVIR applications are based on remote monitoring, remote sensing, and modeling. While SERVIR doesn't directly manage on-the-ground gauges, they have partnered with Nepali government institutions to verify measurements where possible from government-controlled gauges. The scientific applications relevant to early warning systems include:

Data Platforms

- **The Flash Flood Prediction Tool—Nepal** provides 54-hour flash flood forecast warnings for 12,428 river segments in Nepal utilizing precipitation forecasts from the High-Impact Weather Assessment Toolkit (HIWAT) and a hydrological model (RAPID) to estimate streamflow.

- **Streamflow Prediction Tool—Nepal:** provides 10-day streamflow forecasts for 519 segments of rivers in Nepal, allowing users to see forecasts for their locality. This uses runoff predictions and the RAPID streamflow model for predictions and verifies forecasts against existing stations that the Department of Hydrology and Meteorology in Nepal manages.

- **High-Impact Weather Assessment Toolkit** uses weather prediction and satellites to identify major weather events including high rainfall rates, hail, etc. It is running actively during the pre-monsoon and monsoon seasons (March-September each year) to help identify extreme weather hazards.

- **Gaps**: Many of the above tools provide data that could be used by the government or other stakeholders to provide early flood warnings. They clearly help to make data widely available and fill gaps. However, it is not clear what the process is for ensuring the appropriate and timely use of the warning tool by key authorities. For instance, ICIMOD is recognized as a data source for the BIPAD portal, but it is not clear which of the above tools or predictions are integrated into the platform.

COMMUNITY-BASED FLOOD EARLY WARNING SYSTEM (CBFEWS)

CBFEWS is a people-centered, timely, simple, and low-cost technology that disseminates information to the vulnerable communities downstream. The system, an effort co-developed and implemented by ICIMOD in collaboration with the Red Cross, DHM, local police, and a range of civil society organizations. This CBFEWS is comprised of three steps: a data acquisition unit system upstream, a data upload unit system at caretaker's house, and a GSM alarm unit downstream. Early warning information comes from individuals or organizations who send it to the concerned authorities and vulnerable communities. The information being sent should be reliable and timely in nature which then gets converted into a trigger message for alarm units. This message–textual (SMS) or verbal/audio, or visual--is sent to nodal persons downstream who are part of the communication network and they instantly communicate it to at-risk households. There can be several recipients of the information depending on location within the downstream area.

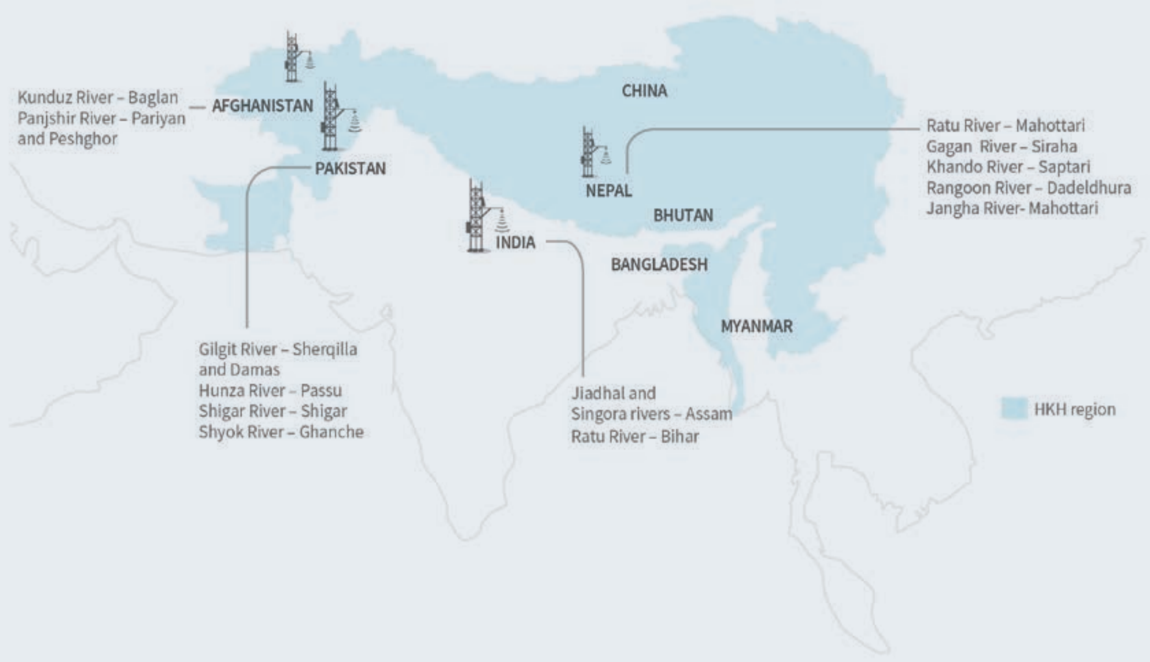


Fig. IV.4: CBFEWS Sites installed across HKH (ICIMOD)

The CBFEWS relies on a set of key stakeholders/players for the successful implementation of the EWS and the timely dissemination of information downstream. These actors include:

- Caretakers who maintain and monitor flood warning systems
- Local disaster management authorities who help circulate information, deploy rescue teams, and communicate the emergency to media outlets
- Focal person or main recipient downstream to transfer information to vulnerable communities
- Local media to publish and broadcast flood warnings
- Flood risk management committee to oversee the coordination, implementation, and preparedness at every step

ZURICH FLOOD RESILIENCE ALLIANCE

Zurich Flood Resilience Alliance is a multi-sectoral partnership which focuses on finding practical ways to strengthen flood risk resilience and support communities in developed and developing countries. The key initiative under the Alliance in Nepal is:

Nepal Ministry of Federal Affairs and Local Development (MOFALD) Flood Resilience Portal: Launched in 2017, the portal is a result of the larger Zurich Flood Resilience Program–an innovative initiative of Zurich Insurance, Wharton Risk Management, Decision Process Centre, International Institute for Applied System Analysis (IIASA), International Federation of Red Cross and Red Crescent Societies (IFRC), and Practical Action. These flood resilience portals are online spaces for sharing practical knowledge on building greater flood resilience and bring together knowledge exchanged through the Zurich Flood Resilience Alliance as well as other research centers. The Nepal portal is one designed for local communities and offers data and information in the national language.

Existing Data Platforms

Nepal Flood Upliftment Portal: Designed to organize and disseminate knowledge and information on flood-related disasters as required.

SAJAG-NEPAL

Sajag-Nepal is a partnership among academic, humanitarian, implementation, and government organizations to influence the way that mountain hazards and risks are managed in Nepal. Sajag-Nepal focuses on linking local knowledge and interdisciplinary approaches to better inform decisions, particularly those which are complex and interactive like earthquakes and monsoon rains. Goals include anticipating and better communicating hazards each year to a wide range of community stakeholders.

Key Initiative

Evidence-based Approach for Strategic Planning for Multi-hazard events: Sajag-Nepal is leading a set of engagements to identify challenges to emergency response in coordination with the UN Humanitarian Country Team. To date, the collaborative approach has hosted a series of focus group discussions to explore successes and gaps in the decision-making process. Relevant identified challenges include data management and scientific data related to major hazards such as earthquakes or monsoons. These focus groups will inform scenario design and risk modeling as a key input for follow-up workshops in September 2022.

GLACIER AND PERMAFROST HAZARDS IN MOUNTAINS (GAPHAZ)

GAPHAZ is a scientific group under the International Association of Cryospheric Sciences and the International Permafrost Association, which consists of more than 45 established scientists and university experts from around the world. GAPHAZ works to improve scientific communications on glacier and permafrost hazards between countries and with government decision-makers, compile and share data and knowledge on hazards in the high mountain regions, and advise media, private sector, and other international and national authorities on relevant developments and in crises. GAPHAZ maintains informational datasets (a KMZ file of glacier/permafrost disasters, a list of relevant experts and contact information) as well as supports dissemination activities such as workshops and seminars, published analysis, and occasional field engagements.

Key Takeaways

Most of the previously profiled institutions and initiatives are data-oriented and do not constitute full early warning systems, but community-level early warning initiatives exist for some river basins and are encouraged and supported by the government agencies involved with disaster response. As the government of Nepal has shifted some of the responsibility for emergency response to municipal authorities, many of these early warning systems are run by local government entities, NGOs, and volunteer corps. The successful evacuation of local communities from the Koshi River flooding in August 2022 serves as an example. Community early warning systems consist primarily of groups like the Volunteer Corps Nepal, which are linked to local government organizations and have access to data portals. When the data points to an imminent flood, as in the River Koshi incident, these volunteers deploy to help share warnings with community members who do not otherwise receive forewarning from text messages or social media.[209]

It is clear from the many parallel systems identified above that there is significant scope for the national government and the broader disaster response community to help address the need for early warning in a more coordinated manner. Approaches are fragmented: early warning systems are led by local leaders, but initial studies indicate that there are significant on-the-ground needs to ensure success. These include direct support such as funding and training for local-level authorities and actors, but also greater national guidance and integration into existing platforms for flood management and warning.[210] This includes greater guidance on the legal side, as currently there is no overarching legal framework that lays out a clear process for how to effectively communicate risk in the lead-up to and during emergency situations.

Many of the actors mentioned above–including People in Need and Sajag-Nepal–are currently actively exploring how risks are communicated and identified as disasters unfold, working to identify ways to improve the risk management system. These engagements are ongoing, but an initial takeaway is an existing lack of resources and local capacity to respond points to a need for dual and parallel actions: to on one continue to expand and improve data collection and data-sharing, and on the other hand to build local capacity to implement early warnings with the data available.

Koshi Disaster Risk Reduction Knowledge Hub (KDKH) Nepal Country Consultation: Building a resilient Koshi Basin. Photo taken by Pradeep Shakya, posted on ICIMOD Kathmandu's Flickr account, and used courtesy of a Creative Commons license.

SECTION V:

Building the System via a Co-Creation Model

Building a national-level risk assessment and early warning system for debris floods will require a co-creation process that involves government authorities, scientists and academic experts, civil society organizations, and earth observation/GIS service providers active in this space, and local community stakeholders. Prior to full implementation at the national level, the system should be piloted or trialed in one or more relevant river systems to test its effectiveness.

To be clear, we want to create a system that works with, builds from, and enhances current systems in place. Our goal is to augment existing programs and bring new tools to bear on wicked questions, not to overwrite or replace existing systems, but to make them work better.

Defining Objectives

1. Avoid a top-down approach and promote inclusive participation of stakeholders and actors from local communities, research/science and academia, and government, and earth observation/GIS service providers authorities alongside international actors.

2. Build a scalable and low cost of ownership system that takes advantage of near-real-time monitoring to replace investment in physical monitoring systems, which are expensive and risky to maintain and analyze, and plow the savings into community capacity building and crowdsourcing efforts.

3. Build an interoperable system based on open standards that provides the opportunity and flexibility to plug in new assessment techniques as novel methods are developed and become more affordable.

4. Enjoin research partnerships to develop shared techniques for risk assessment.

5. Builds local capacity for crowdsourcing, local data collection, and local participation in disaster risk reduction and also communicates risk and early warning messaging in an effective language for beneficiaries.

Our team has identified the following timeline and set of activities to move forward in a collaborative and multi-phase approach to implementing an effective monitoring and early warning system in Nepal:

	Activity	Participants	Duration	Phase
1	Circulate and socialize this baseline report for comment and early partnership recruitment and network building	DRR agencies, ICIMOD/NGOs, Donors, Academics, Stimson	3 months	1
2	Hold local consultations and needs assessments for early warning in context of debris floods, concentrating efforts on diverse groupings of ethnicities and livelihoods	Local communities, Select staff from DRR agencies and possible project partners, Stimson	3-5 local consultations (multi-day) held on-site	1
3	Build nationwide natural dam and debris deposit inventory, collecting basic descriptive data, validation by experts	Stimson and academic partners	6 months	1
4	Recruit academic, NGO, and government partners for Phase 2 participation	Stimson	6 months	1
5	Develop an appropriate set of risk identification indicators for natural dams and debris deposits	Research/Academic/NGO partners, Select staff from DRR agencies, Local communities, Stimson	6 months (Q1-2)	2
6	Develop scoring system for natural dams, segments, and river systems	Research/Academic/NGO partners, Select staff from DRR agencies, Local communities, Stimson	6 months (Q1-2)	2
7	Catalog existing demographic, socioeconomic, and infrastructure layers; conduct a gap analysis and gap fill through the production of necessary data layers	Research/Academic/NGO partners, Select staff from DRR agencies, Local communities, Stimson	6 months (Q1-2)	2
8	Conduct a risk assessment of nation-wide natural dam and debris deposit inventory with scoring system and overlay of aforementioned layers; assign scores, develop risk maps; communicate and socialize results	Research/Academic/NGO partners, Select staff from DRR agencies, Local communities, Stimson (at this point a project team has likely formed)	6 months (Q3-4)	2
9	Hold local co-creation activities and develop plan for local data collection and crowdsourcing, inclusive of feasibility studies and capacity building programs	Project team, Local communities	6 months (Q3-4)	2
10	Establish data sharing partnerships with relevant hydromet agencies	Project team, Relevant agencies	6 months (Q3-4)	2
11	Build central data monitoring platform inclusive of APIs from Nepalese agencies and remote sensing inputs	Project team	1 year (Q3-6)	2
12	Implement a pilot real-time risk monitoring and early warning system (can pilot first to fine tune processes before scaling to national level)	Project team inclusive of local data collectors and communication partners	Ongoing	3
13	Continuous updating of data inventories and risk scores based on pre-determined frequencies; continued capacity building and readiness testing of local data collection stakeholders.	Project team inclusive of local data collectors and communication partners	Ongoing	3

Fig. V.1: Table outlining a three-phase process to co-design, build out and implement a risk assessment and early warning system for debris floods in Nepal.

The table to the left outlines a three-phase process to co-design, build out and implement a risk assessment and early warning system for debris floods in Nepal. These processes emphasize co-creation and collaboration with local community stakeholders, relevant government agencies, NGOs, and the academic community throughout all phases in order to meet the objectives outlined in the beginning of this section. Management of these phases and ownership of the project's outputs will shift from initial oversight from the Stimson Center's team toward an eventual 'project team' formed of an appropriate mix of individuals from communities, government agencies, NGOs, and academics. Eventual ownership and management modality can be worked out through consultation and negotiation as the project progresses.

Phases of Workflow

Phase One will be carried out over a six-month (or a maximum of up to one-year) period and include circulating this report among relevant stakeholders via meetings with relevant stakeholders as well as dissemination of local language and English language versions of this report to socialize its results and generate feedback for future activities and engagements. This activity will also serve as a time to scope future phases with individual experts and potential organizational partners active in the academic, NGO, and government sectors. It is likely and expected that some of these scoped partners will participate in and even help facilitate remaining activities in this phase. The Stimson team will hold some of these meetings in person in Nepal and, with the assistance of scoped partners, hold 3-5 workshops with a diverse set of local community organizations. The workshops will aim to test concepts outlined in this report, assess needs and capacity for disaster risk mitigation and local data collection, and engage in early co-creation activities that will feed into future phases of the project. National government-level stakeholders will also attend these workshops in order to demonstrate the benefits of local co-creation activities and build capacity for strengthened national-local collaboration on this and other projects.

Parallel to the scoping and report socialization, the Stimson team will use the remote sensing techniques outlined in the previous section to develop initial inventories of natural dams and debris floods and collect basic topographical indicators of these hazards. Finally, the Stimson team will recruit and where appropriate establish official collaboration with academic, NGO, and government partners who will participate in Phase two of the project.

Phase Two will be carried out over an 18-month period and include all activities required to design and build out the risk assessment and early warning system for debris floods prior to implementation. During this phase, leadership will transition from the Stimson team to a project team formed of an appropriate mix of the local community, government, NGO, and academic participants. The team will determine the format and the design of the platform to be built during this phase as well. Ownership and future governance and management processes for the system's implementation will be determined during this phase. Ownership modality will influence a host of factors including but not limited to software licensing, data acquisition, operation costs, etc. The Stimson team will work with relevant academic and NGO stakeholders to develop a set of risk indicators for the natural dam and debris flow inventories and conduct a risk assessment to identify the most at-risk river and stream systems in Nepal. While this assessment is carried out, project team members will also collect and compile existing GIS demographic and socioeconomic layers. In support of this process, the team will hold local community-level workshops to identify relevant demographic, socioeconomic, and cultural data that have been excluded from past data collection efforts but would support natural disaster risk monitoring and early warning.

After the most at-risk river and stream systems are identified, the project team will hold co-creation and capacity-building activities with members of the communities within the most at-risk areas. These engagements will establish data collection teams and local crowdsourcing approaches, and determine the most appropriate forms of early warning messaging communication and response–which may differ between communities. Eventually, the team will simulate and test the capacity of risk monitoring and early warning communication once the remaining phase two activities described below are complete.

The project team will establish data-sharing agreements with national and local government authorities and other providers of physical and remote sensing data as needed. As these agreements are being established, the project team will begin to build the central data platform and develop the applications which will collect and analyze incoming data for triggers and continuous risk assessment for hazards in real-time. This process will likely also require the participation of a web platform developer as a contractor. Translation of all project outputs into the Nepali language will also occur during this phase.

At the end of phase two, the system will be ready for implementation. Piloting the system in one or more localities for demonstration, testing, and fine-tuning purposes for 3-6 months will likely help the total system roll-out achieve higher levels of success. This phase will likely require funding from multiple donor sources, and costs can be scoped during phase one.

Phase Three will see the system implemented and operated in real-time by the project team and associated local community, government, NGO, and academic partners. Budget scoping for phase three, which will include annual operation costs and costs related to investment in physical infrastructure and assets related to the project, can be assessed during phase two.

Co-Creation: On Working Partnerships and Community Engagement

All efforts to assess risk and provide early warning to downstream communities must be shaped by talking to local people first. While EWS projects such as ours imagine these folks as vulnerable or as stakeholders/beneficiaries, the fact of the matter is that they are neither. Engaging them as people with their own valuable ideas is critical. Put simply, most Nepalis are highly attuned to changes in the landscape where they live. Many have a depth of understanding shaped by knowledge of what has occurred in the past, information about what is changing and how, and highly informed forecasts of their own about what they might expect from the future.

As an innumerable number of studies have shown, local community stakeholders perceive the dimensions of risk and uncertainty that shape potential natural disasters in ways that often differ from those of scientists and decision-makers from international organizations and national-level institutions. Localized and situated forms of knowledge are extremely valuable in the context of disaster risk reduction and climate change adaptation, as several scholars working in the Himalayan region have suggested.[211] [212] [213] [214] Local oral histories often account for disaster events and latent risks that expert scientific assessments either miss or struggle to understand.[215] [216] Local models of disaster risk and situated strategies of disaster risk reduction can also be critical resources,[217] [218] and cultivating dialogue that creates space for epistemic pluralism is critical.[219] [220] Another recent wave of research on the politics of uncertainty shows that uncertainties are also socially-constructed, culturally organized and highly situated.[221] [222]

At the same time, as many scholars have suggested, we need to avoid orientalizing tropes of "timeless" and "local" knowledge in the Himalayan region.[223] [224] [225] As Hastrup (2015) and others working with indigenous communities across the world suggest, localized knowledge can also be highly cosmopolitan, and people can draw on many different kinds of knowledge frameworks at once.[226]

To be clear: Our project will seek to account for and integrate localized knowledge and situated experiences of disaster risk and uncertainty and to incorporate vernacular understandings into our models in a way that respects cognitive diversity. But we will do so in a way that draws people into dialogue and recognizes their agency as people with their own *contemporary models and strategies* for disaster risk reduction, rather than simply people with "traditional environmental knowledge" or quaint and esoteric beliefs about natural hazards and disasters. In this way, we seek to create space for epistemic difference (and ontological difference, if need be) while also avoiding the pitfalls of an instrumental "insert local knowledge here" approach (which is, regrettably, all too common at the moment).

Further, inclusive and participatory activities can also collect information on when and how past attempts at risk monitoring and early assessment have succeeded or failed. As a handful of critical analyses to date have shown local critiques and perspectives on such interventions can be both enlightening and extremely generative[227]—particularly in Nepal's GLOF EWS space, where heavy-handed community engagement can create anxiety and panic.[228] [229] [230]

ON METHODS: ARTICULATING THE PROJECT LOCALLY

Our community-level engagements will begin by gathering clusters of community stakeholders who have experienced past debris floods or cascading hazard disasters, or who live in communities with a high perceived level of risk for future cascading hazards. These activities will determine baseline levels of local disaster risk reduction capacity and identify knowledge holders and “champions” who we will invite to participate in the co-creation process—throughout all phases or at various points, depending on their preferences. In the early stages of our projects, we will undertake multi-stakeholder participatory mapping exercises that will help us understand situated natural hazard regimes and local patterns of vulnerability, and identify vernacular systems of organizing risk and uncertainty. These exercises and the dialogue that will surround them can help pinpoint preferred methods of communication and action related to early warning. At a later stage, our project team can initiate simulations of early risk response to test the behavioral responses of communities and individuals. Further, the crowd-sourcing and local data collection interests and capabilities of local communities must be assessed and then trained-up prior to implementation of the EWS.

On Institutional Partnerships

For our project, bottom-up consultative and co-creation activities with local communities and local government stakeholders will begin in Phase 1. Top-down initiatives for risk assessment and early warning tend to be poorly translatable and sub-optimally utilized at the local community level even though local community stakeholders are the ultimate beneficiary of such activities. The incorporation and involvement of a diverse set of community-level stakeholders will ensure that communication related to risk assessment and early warning is well designed and appropriately delivered. Technological assets and practices expected to be used by local-level stakeholders also need to be incorporated efficiently and at maximum levels of utilization. Much front-loaded work will be required to communicate the benefits and cost-savings that remote sensing techniques and local community participation can bring to an effective EWS in order to keep the system adaptable and cost-efficient.

We imagine that initial community engagements might be facilitated by experts with prior experience and relationships in these communities—such as NGOs that focus on community-oriented disaster risk reduction such as People in Need, Practical Action, or ICIMOD, as well as academics who have conducted research in these communities or the surrounding areas in the past. We have already built a network of colleagues during this initial study process, and our team member Austin Lord is very active within the Himalayan Studies community.

As the risk assessment outputs associated with Phase Two are produced, then a more fine-tuned approach to identifying at-risk communities with which to engage can be implemented. Importantly, this engagement should involve local government officials at multiple scales: local officials at the municipality or ward, mid-level government officials from provincial and district disaster risk reduction units, and staff from the NDRRMA. For the purpose of building effective EWS programs and protocols as well as understanding local patterns of disaster risk exposure, working with local government officials is *critical*. As one disaster risk reduction practitioner we spoke to said: “Talking to politicians at the Ward level rather than the Kathmandu level is important. Their buy-in is strong. They just don’t have money to scale anything. But they understand the problems better than anyone.”

At all levels of our work, forging technical and on-ground partnerships will be governed by a goal of achieving efficiency and avoiding problematic bureaucratic and political drama which might bog down progress in the design and implementation of the system. Government partnerships are essential (if sometimes frustrating). We hope that project partners and local supporters such as community leaders with buy-in will help in managing the political valences of government and institutional engagement. Recent critical disaster studies literature suggests that truly transformational approaches to EWS are those which seek to reckon with and rectify socio-historically produced patterns of inequity and structural exclusion, which often requires engaging the state. While working with the famously bureaucratic Government of Nepal may prove challenging, we feel this is essential.[231]

EWS ON THE KARNALI RIVER DURING 2014 FLOODS

In her study of community-based early warning systems in the floodplains of the Karnali River in Nepal’s Tarai region, human geographer Sierra Gladfelter (2018) proposes a useful middle path when considering the involvement of government officials. Drawing from research conducted in the wake of the 2014 Karnali Floods,[232] she highlights the need for NGOs working on EWS to not only acknowledge the power of the state but also to draw government officials into the program. In short, Gladfelter argues that NGOs working on EWS need to avoid interventions that reallocate responsibility for disaster risk reduction away from the state because doing so only assists in reproducing chronic conditions of vulnerability. Bypassing the state and focusing on programs that increase or generate the burden on Nepalis to “become resilient” unto themselves a) doesn’t fix the structural problems that create vulnerabilities and shape disasters and b) partially excuses the state for lapses in responsibility.[233] The middle path proposed: by working with government authorities there is an opportunity to work *on* power relations that marginalize local people and create vulnerabilities rather than working *around* them. Doing so can enhance the capacity of government officials and also create opportunities to rework the relation between at-risk communities and the state - which is often a major factor that shapes the vulnerability of these communities.

Here, Gladfelter foregrounds the ways in which the approach of the INGO Practical Action has led over time toward a community-oriented model that more effectively empowers community members vis a vis the state: “Practical Action, with its eight-year history of working in the Karnali Basin and even longer commitment to DRR in Nepal, provides an example for how INGOs can effectively invest not only in vulnerable people, but also in governments so that their community-based solutions to disasters do not erode or prevent the extension of state programs, but rather serve to complement and enable them." (p.129).

On a broader note, drawing from the political ecology approach to disaster studies (cf. Oliver-Smith & Hoffman 1999), Gladfelter also elegantly articulates the central critique of disaster studies in the context of EWS in Nepal when she writes that "treating disasters as an objective phenomenon that can be anticipated and prevented through better calculation and dissemination" (p.130) will have less impact than programs which recognize the socially-produced nature of disasters. Therefore, "precluding disasters will require not only focusing on technologies of predicting hazards, but also working with the state through a discourse of rights, social justice, and entitlements to serve and secure the most vulnerable communities long before hazards strike (p.130)."

Overall, these critiques are meant to be generative, and Gladfelter is also highlighting the value of Practical Action's evolving approach. Indeed, as another report (written by ISET in collaboration with Practical Action) states, when reviewing the value of these EWS systems: "In spite of complications and points of failure, these systems were instrumental in saving lives and assets during the 2014 floods. There is a clear opportunity to strengthen and scale up these systems country-wide" (Venkateswaran et al 2015). We agree that there are lessons to be learned from the success of these programs and the adaptive process of learning that the 2014 floods provoked, and we agree that there is an opportunity to build EWS systems at a broader scale, using a blend of new technologies and insights from the social sciences.[234]

ON SCOPING PROJECT PARTNERS

In the early stages of this study, we have done a great deal of work to understand the institutional landscapes that shape disaster risk reduction efforts in Nepal, to familiarize ourselves with previous and ongoing EWS programs, and to build a network of peers and potential partners. This process has been extremely educational and useful. For example, we are happy to say that we have been invited to join the Landslides Working Group convened by People In Need.

At the time of writing, we have already begun the work of scoping potential project partners for the upcoming phases of this project. Achieving success will require numerous partnerships and as the project matures, actors should emerge who can help develop specialized partnerships, particularly in the areas of data sharing and access, data and communication platform building, and those who focus on local engagement. Additionally, partnerships will be required to unlock further funding resources to help this project achieve success. It is impossible for one core partner to possess all of these capabilities and required talents. Likely high-level partners in this effort will be the NDRRMA, ICIMOD, and People in Need– but the capabilities and interests of these and other partners must be assessed and tested.

Ownership of the risk monitoring and early warning system for debris floods eventually must be housed within a Nepal-based entity. The ownership transition pathway for project outputs and a system of governance should be worked out in due course of phase one and two activities. Co-ownership models which involve local-level community organizations and localities should be emphasized and explored (or even required).

**See the Annex for a working list of potential contacts*

Acknowledgments

The research and analysis presented in this report would not be possible without the interest and assistance from our funders, partner organizations, and the various friends and colleagues who were generous with their time and insights during the process of project development. We are particularly grateful to the McConnell Foundation which provided the genesis and majority funding support for this effort. We are also grateful to the Prudence Foundation which provided additional funding support.

In addition, we would like to thank several colleagues, friends, and interviewees working in Nepal and in the disaster risk reduction and earth observation sectors for their time and willingness to share their insights. In particular, we would like to thank Jakob Steiner, Vera Exenerova, Sanchita Neupane, Karen Bennett, Kaushal Gnyawali, Calvin Kwon, Oliver Cottray, and Salim Sawaya for their advice throughout this process and for serving as peer reviewers of earlier drafts of this report. Additionally, we are indebted to the work of the many natural and social scientists and institutions which have produced a robust reservoir of literature on geohazards and EWS in the Hindu-Kush Himalayan Region. We have learned a great deal throughout this study and we look forward to future conversations, to engaging others, and to learning more as our work continues to evolve.

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Stimson's Energy, Water, and Sustainability Program has achieved significant impacts in the disaster risk reduction and transboundary water management sectors via its partnership with Eyes on Earth, Inc through the Mekong-U.S. Partnership-supported Mekong Dam Monitor, a flagship project of the Mekong Water Data Initiative. The Mekong Dam Monitor won The Prudence Foundation's 2021 Safe Steps Disaster Tech 1st prize for its pioneering work in using remote sensing processes to provide early warning on sudden changes to river levels caused by upstream dam operations to vulnerable communities in the Mekong. The Mekong Dam Monitor also won the 2021 Special Achievement in GIS Award from ESRI, the Renewable Natural Resources Foundation 2021 Outstanding Achievement Award, and was a 2022 finalist in the Roy Family Award for Environmental Partnerships sponsored by Harvard University's Belfer Center for Science and International Affairs.

The Energy, Water, and Sustainability Program also convenes the Water Security in the Himalayan Region project, which in cooperation with the Konrad-Adenauer-Stiftung delivers impactful high-level multi-stakeholder dialogues to foster trust-building between key riparian states in South Asia. In addition to these dialogues, the project regularly convenes closed-door joint working group sessions with high-ranking officials from transboundary river commissions as well as with EU officials on issues and challenges faced by high water stress regions like South Asia, Central Asia, and the Middle East.

Austin Lord is an environmental anthropologist whose work focuses on disaster, disaster risk reduction, climate change, natural resource management, infrastructural politics, and the production of environmental knowledge in the Himalayan region. He spent roughly five of the last ten years in Nepal and has worked as a Consultant for the United Nations Development Programme (UNDP), as Lead Social Scientist on the 2018 Karnali River Expedition, and with several other organizations including the International Centre for Integrated Mountain Development (ICIMOD) and Lutheran World Relief. In 2015, he helped Kathmandu Living Labs develop the HydroMaps platform, and he has conducted extensive research on geophysical hazards and critical infrastructure in Nepal. Austin holds a PhD in Anthropology from Cornell University and a Master of Environmental Science from Yale University.

Eyes on Earth, Inc. was founded in 2013 to service the agricultural and insurance industry on climate-related investments, as well as monitor food and water resources around the world. Eyes on Earth is a corporation established to conduct business in the climate monitoring sector. Eyes on Earth has joint ownership with Global Environmental Satellite Application of proprietary software to generate satellite-derived land surface products on wetness, temperature, and snow cover from a series of microwave sensors.

Annex/Appendix A

This Appendix expands on some of the data initiatives and organizations profiled above in Section IV: Overview of Early Warning Systems and Active Organizations. Below are noted potential points of contact at individual organizations as well as further details on some of the additional relevant datasets, data platforms, or ongoing programming which are mentioned above.

Government Initiatives

NEPAL DISASTER RISK REDUCTION PORTAL

Potential Points of Contact

- Bikram Shrestha Zoowa, Senior Divisional Hydrologist, Department of Hydrology and Meteorology

Incident maps

- Tracks district-level summary data on disaster incidents, including details on number of deaths, injuries, houses damaged or destroyed, and affected families.These statistics are sortable by the type of incident.

List of Recent Incidents (Last 7 days):

- Tracks recent incidents and allows for review by type, including heavy rainfall, landslides, flash floods, etc. This is manually updated by the Government of Nepal based on reported incidents with details on date, location (district/municipality), deaths, affected families, damages, etc. This list likely accounts for some incidents which are small enough they are not reflected on the Incident Maps.

BIPAD

Potential Points of Contact

- Anil Pokhrel, Executive Chief and Dr. Dijan Bhattarai, Under Secretary/Spokesperson/Information Officer

Operation

- When a user goes to the site, the platform's initial loading screen shows ongoing alerts, which are updated every minute in real-time. Displayed alerts and other data is directly pulled in from other government agencies: disaster incident data is drawn from the NEOC and Nepal Police; data for rainfall and water levels are drawn from DHM; earthquake data comes from the Department of Mines and Geology; pollution information is drawn from DoFE; and forest fire and streamflow data is integrated from the non-governmental organization ICIMOD (profiled below).

- One of the modules is specifically devoted to risk analysis, allowing a user to look at a particular region to view risk of floods or other hazards to specific localities. This module allows the user to look at the likelihood of potential events, specific exposure of infrastructure and buildings in areas of effect, a range of vulnerability indicators, and relevant institutions with potential response capacity.

- There is an opportunity for users and the public to crowdsource information–for instance, they can report an incident filling out as much information as possible from their phone or computer to prompt review by NDRRMA.

- The platform was first published in 2019 and is likely to evolve in future in response to user feedback, new data, and technological advancements. Short-term updates are expected to help streamline the incident reporting system process.

- A study supported by UK Aid in 2020 indicated that there were a few obstacles to effective institutionalization and use of the BIPAD portal. One is a need for clarification on which organizations are responsible for which activities and a priority sequence for individual responses in the case of an emergency.[235]

Multi-stakeholder Partnerships

SERVIR

Potential Points of Contact

- Birendra Bajracharya, Chief of Party—SERVIR-HKH
- Rajesh Bahadur Thapa, Capacity Building Scientist for Geospatial Solutions
- Kabir Uddin, GIS and Remote Sensing Specialist for Geospatial Solutions
- Manish Shrestha, Hydrologist for Water and Air
- Sudan Bikash Maharjan, Remote Sensing Analyst—Crysophere for Geospatial Solutions

Additional programs

National Land Cover Monitoring System of Nepal uses Landsat remote sensing data along with Google Earth Engine to generate land cover maps which are updated on an annual basis and which track changes to land use, including glaciers as well as snow, water bodies, riverbed, forest, cropland, etc.

SAJAG-NEPAL

The Sajag-Nepal team works directly with the UN Resident Coordinator's Office and Humanitarian Country Team as well as the NDRRMA on the BIPAD portal. Most Sajag-Nepal members are associated with other organizations, including Durham University, Northumbria University, and the National Society for Earthquake Technology-Nepal.

Key Personnel

- Simon Dadson, Professor at Oxford (hydrology modeling)
- Alex Dunant, Durham University (disaster risk preparedness)
- JC Gaillard, University of Auckland (participatory tools)
- Rachel Middleton, Sajag-Nepal Project Administrator
- Shobhana Pradhan, Country Director, BBC Media Action
- Maximillian Van Wyck de Vries, University of Oxford (remote sensing and datasets for risk management)

CBFEWS

In Nepal, the Department of Hydrology and Meteorology piloted CBFEWS in the Ratu and Gagan rivers of the Koshi basin in Nepal and the system worked well for the 2017 floods as well. Further, in 2018 Oxfam, with ICIMOD's support, also implemented a CBFEWS at the Rangoon River in Dadeldhura, Nepal.[236]

Figure A.1: CBFEWS - How does it work? (2019) ICIMOD. Available here.

Non-government Organizations and Initiatives

ICIMOD

Potential Points of Contact

- Neera Pradhan, Programme Coordinator Koshi Ad-Interim, River Basins and Cryosphere
- Vijay Khadgi, Flood Early Warning and Energy Analyst, Water and Air
- Mandhira Singh Shrestha

HI-RISK

The HYCOS User Phase builds on work from 2010 to 2016 during which 38 hydrometeorological stations were set up across Bhutan, Bangladesh, Nepal, and Pakistan. These stations worked to ensure that there was regional and national flood information available as near real-time data for flood-vulnerable communities. This project phase has three major action areas: pathways to flood information and better user connectivity, develop better communication strategies for equitable dissemination of early warnings, and improved regional cooperation and outlook on shared challenges like flood issues.

HYCOS-RFIS

The main project priorities were to strengthen the framework for cooperation on flood information sharing, establish a flood observation network in river basins between countries, enhance sharing of real-time data and increase lead time, build flood-forecasting capacity for governments and partners, and develop a well-rounded regional project to facilitate flood mitigation in all participating regional countries. The project, however, met with some pertinent technical challenges in terms of station operations and database managements. There are also capacity challenges owing to high variability in forecasting measures as well as weak linkages between science-backed data and policy implementation. As a part of the HKH-HYCOS project, the Depart of Hydrology and Meteorology has upgraded 11 hydrometeorological stations in the Koshi Basin, Nepal to improve flood forecasting and provide early warnings in real-time.

The Cryosphere Initiative

Overviewed in the main report includes the following programs and initiatives:

- **Regional Database System:** The RDS portal was established as a part of ICIMOD's efforts to have a central and accessible data repository for different thematic areas in the Hindu Kush Himalayan (HKH) region. The portal is designed so that the users have the ease to search by any titles, keywords, or themes. See Figure below (to be added)

- **HI-AWARE:** An initiative led by ICIMOD and in collaboration with other regional partners, is designed to execute efforts in the Indus, Upper Ganga, Gandaki, and Teesta river basins, looking at a wide range of elements from altitudes to hydro-meteorological conditions. The research and potential adaptation measures devised under HI-AWARE aim to identify the following:

    - Critical Moments: Timelines with the highest climate risks and need for interventions
    - Adaptation Turning Points: identifying the need for innovation and new measures
    - Adaptation Pathways: policy actions that respond to adaptation turning points

Koshi Basin Information System (KBIS)

Portal under the Koshi DRR Knowledge Hub which provides research and knowledge sharing for better understanding and evidence-based decision-making on transboundary water-related disaster risk reduction (DRR). The KBIS application allows users to view resource layers such as land cover, wetlands, and drainage networks in the Koshi basin. See figure below (To be added)

PEOPLE IN NEED

Potential Points of Contact

- Vera Exenerova, Country Director PIN Nepal, Relief and Development Department
- Bharat Shreshta, Head of Programs
- Sanchita Neupane, DRR specialist

PIN Nepal's DRR programming in Nepal

- **Durable Solutions—facilitating the implementation of durable solutions for households at risk of or displaced by geohazards and floods.** Durable Solutions I, II and III played a major role in advancing a policy that made earthquake-affected landless households eligible for the NRA's relocation and housing reconstruction grants – with up to 13,091 landless households made eligible. The project unlocked approximately NPR 5.2 billion (c. GBP 32 million) worth of government grants including for relocation, housing reconstruction, and public infrastructure construction for over 14,000 of the targeted households. Currently, Durable Solutions III, specifically focuses on landless Households at risk or displaced by Floods in Madhesh Pradesh.

- **Pratibaddha I: Risk Informed landslide Management in Nepal's hill areas.** The project supported local and federal authorities including NDRRMA, MoFAGA, DDMCs, DAO, LDMCs develop critical guidelines pertaining to rural road construction, geohazard assessment of landslides and identification of safer areas for landslide affected households.

Similarly, it also supported municipalities prepare a monsoon preparedness plan and temporarily relocated households that were at high risk to landslides. Further, the project also supported working municipalities prepare Disaster Preparedness and Response Plan (DPRP) to strengthen preparedness against future disasters at local level.

- **Pratibaddha II: Landslide preparedness and early action in Nepal's hill areas.** Pratibaddha II focuses on households at risk, especially marginalized and indigenous families towards improved and inclusive disaster preparedness and early action. At first, the project entails engaging municipality representatives, communities at risk, and key stakeholders across three tiers of the government to commit and work together. This includes supporting the local government in decision-making through the categorization of settlements as per Government of Nepal (GoN) guidelines into CAT II in need of mitigation, and CAT III in need of relocation. Secondly, the project will focus on localizing landslide forecasting (including EWS) and also on developing early action protocols to strengthen the capacity of local government and at-risk communities for early action. The activities will facilitate knowledge exchange among experts and practitioners on landslide forecasting and early warning system. Additionally, Pratibaddha II project will collate knowledge, understanding and evidences for Shock Responsive Social Protection (SRSP).

- **Climate Change Toy Model.** PIN aims to strengthen climate change adaptation planning at local level through the development of an interactive tool that enables local-level authorities to identify transient and long-term climate change impacts, which subsequently underpin adaptation policies. The project integrates elements of co-production of knowledge that seeks to enhance community inclusion and local-level climate vulnerability assessments to feed into the primarily large-scale top-down models.

- **EWS dissemination-Global Investment Fund (GIF).**The proposed project aims at identifying and addressing the gaps and barriers in the current early warning message dissemination modality targeting the most vulnerable population during the extended monsoon period. PIN Nepal aims at designing early warning messages for vulnerable people for the pilot of the design anticipatory tool and early warning dissemination channels via different possible modalities like Interactive Voice Response (IVR) and Last Mile Communication (LMC) methodologies.

INTERNATIONAL FEDERATION OF RED CROSS AND RED CRESCENT SOCIETIES

Potential Points of Contact

- Padmini Nayagam, Senior Programme Officer (Asia Pacific);
- Finau Heuifanga Leveni, Asia Pacific Disaster Law Coordinator

Existing Projects

- **IDRL Guidelines**: The IFRC has compiled a series of recommendations for governments around the world to support preparation for disaster laws and mitigation of regulatory challenges when disasters occur and international responses are needed. There are a series of guidance documents, checklists, and online training courses available to support legal review and updates.

- The Nepal Municipal Risk Governance Assessment Tool supports the localization of IDRL guidance from the national level to the local level to support disaster management and climate change laws and policies. The tool is being piloted through the end of 2023 in coordination with the Ministry of Federal Affairs and General Administration.[237]

CHINA NATIONAL CRYOSPHERE CENTER

Potential Points of Contact

- Wu Lizong from Northwest Institute of Eco-Environment and Resources, China Academy of Sciences (Dataset Author)
- Min Yufang from Northwest Institute of Eco-Environment and Resources, China Academy of Sciences (Dataset Manager)

Relevant Platforms

- **Glacial Catalogue Dataset of Nepal**: Coordinated with ICIMOD and UNEP, this dataset uses Landsat remote sensing to catalog glaciers in Nepal as of 2000; it was last updated in 2019.
- **Ice Lake Catalogue Dataset of Nepal**: Coordinated with ICIMOD and UNEP, this dataset uses Landsat remote sensing to track ice-covered lakes in Nepal as of 2000; it was last updated in 2019.

FLYING LABS

Potential Points of Contact

- Uttam Pudasaini, Executive Director
- Binod Parajuli, Risk Management Advisor
- Pukar Parajuli, Head of GIS & Drones
- Suraj Gautam, Co-Founder & DRR Lead

Relevant Project

Using Drones to Study Glaciers: In collaboration with the Himalayan Cryosphere, Climate, and Disaster Research Center at Kathmandu University, Nepal Flying Labs helped map the Ponkar Glacier for the first time in 2015 and has conducted annual surveys since to support ongoing research. This approach shows the viability of using drones to track changes in the field.

IWMI

Potential Points of Contact

Pabitra Gurung, Senior Research Officer - Water Resources
Aditi Mukherjee, Principal Researcher (New Delhi)
Santosh Nepal, Researcher - Water Resources and Climate Change
Sanju Koirala, National Researcher - Social Science, Water, & Natural Resources

Additional Programs

- **ADB Project on Watershed Resilience:** IWMI Nepal staff mapped 135 upland watersheds in Nepal to identify vulnerability, identifying spring water sources, deforestation, and potential conservation efforts. This data is not available on their website but may be available upon request for engagement.

- **Flood Risk Mapping:** IWMI's flood risk spatial datasets contain estimated maximum flood inundation extent for South Asia, Southeast Asia and Nigeria. The South Asia portal includes maximum flood inundation extents as gathered from optical imagery with low-resolution analysis in 2012. It highlights vulnerability to floods of both communities and crops, and can be used to inform government response planning.

- **Climate Change Impacts and Adaptation in Nepal** is an online data tool to run analysis on climate sensitivity, exposure, vulnerability, and adaptability in Nepal. This IWMI tool uses data from UN agencies, the Asian Disaster Preparedness center, and additional analysis on human and ecological sensitivities to identify priority sub-basins and watersheds in Nepal particularly vulnerable to climate change. The results could be useful for focusing the initial application of an early warning system.

WORLD BANK

The project's four key components are as follows:

- Institutional strengthening, capacity building, and implementation support of the Department of Hydrology and Meteorology (DHM).

- Modernization of the observation networks and forecasting.

- Enhancement of the service delivery system of DHM so information services for climate-vulnerable communities could be improved

- Creation of an Agriculture Management Information System (AMIS) at the Ministry of Agriculture Development (MoAD).

Academic Actors

DURHAM UNIVERSITY INSTITUTE OF HAZARD, RISK, AND RESILIENCE

Potential Points of Contact

- Alexander Densmore, Professor and Deputy Head of Geography Department
- Dave Petley
- Ivo Pink, PhD Student; PhD Dissertation: Modelling and Mapping Flood Hazards in Data Poor Environments: The Case of Nepal.

Datasets or Projects

- The Action on Natural Disasters project focuses on earthquake-induced landslides in Nepal, and includes numerous PhD research projects with partner organizations on the ground in Nepal.

- Professor Alexander Densmore has received numerous grants for analysis on landslides in Nepal triggered by earthquakes, many of which have focused on the use of satellite data and automation to analyze landslides after earthquakes.

- Ivo Pink's PhD dissertation and focus on utilizing remote sensing and geospatial modeling on flood hazard patterns in Nepal are directly relevant to the type of analysis and risk mapping that would be necessary for an early warning system as envisioned in this report. He could be a potential peer reviewer of methodology.

- Katy Burrows, 2019 graduate, focused on the use of satellite radar to identify earthquake-triggered landslides. Her research created a dataset of landslides from 2014-2018 in Nepal which would be useful background data.

NORTHUMBRIA UNIVERSITY DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL SCIENCES

Potential Points of Contact

- Katie Oven, VC Senior Fellow for Geography and Environmental Science
- Dr. Matt Westoby, Assistant Professors for Geography and Environmental Sciences

Datasets or Projects

- Katie provides support to the People in Need project on post-earthquake reconstruction in Nepal, and has a lengthy list of published articles relating to disaster risk and the changes to landslide hazards as a result of the 2015 Nepal earthquake. Her field work in Nepal in recent years has included hazard inventories to identify shifts in landslide instances over time since 2015. The data collected during her field engagement could be a useful input to identification of high-risk areas in Nepal if an early warning system project moves ahead.

- Dr. Matt Westoby has supported numerous analyses on glaciers using satellite data and has also done reconstructions of previous GLOFs in the Himalaya region.

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[65] Adhikari and Tian, 2021.

[66] Ibid.

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[84] See Penna et al (2021) for more analysis of airblasts caused by large slope collapses - basically they occur when the mass is moving at a high speed into a constrained topographic space.

[85] According to Gnyawali et (2020: 8) the Langtang Avalanche carried about six times as much fluid volume as solids volume, and the estimated basal friction angle was 13°and density of this turbulent mixture was around 850 kg/m³. The combination of low basal friction and high fluid content is the reason This is why it moved so fast (~36 m/s average velocity), carrying so much destructive force. In this way, the constitution of the Langtang Avalanche was similar to the massive co-seismic Huascaran avalanche that buried the city of Yungay, Peru in 1970 – the deadliest avalanche in recorded history.

[86] Kargel et al., 2015.

[87] Fujita et al., 2017.

[88] Gnyawali et al 2020.

[89] LaCroix 2016.

[90] Fujita et al., 2017.

[91] And as Lord (2022) would argue—one potentially shaped by climate change.

[92] Note: Here we use the term climatological rather than just meteorological because we are talking about the ways patterns of snow accumulate or ablate over time.

[93] The major difference was that the trigger was different - the Langtang Avalanche was co-seismic, whereas the Chamoli Disaster was not. Details in Shugar et al., 2021.

[94] Scientists continue to debate about the extent to which the Chamoli Disaster might have been shaped by climate change. While this gets into the complexities of attribution science, we can say, in any case, that this event speaks the scale of what might be possible under climate change, and that it is causing people to reevaluate and recalibrate their models of geohazards and disaster risk reduction.

[95] "High seismicity coupled with the globally changing climate is expected to increase the number of debris flows, ice, and snow avalanches in high-altitude regions." Gnyawali et al., 2020: 1.

[96] Gariano and Guzzetti, 2016.

[97] Lord 2022.

[98] Byers et al., 2021.

[99] Ives 2004.

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[101] Ives 1986.

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[103] Maharjan et al 2021.

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[106] ICIMOD 2011

[107] Byers et al., 2015.

[108] Mool et al., 2001

[109] Shrestha et al., 2013.

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[116] Watanabe et al.

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[134] Ibid.

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[142] Ives 2004.

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[147] Kirschbaum et al, 2019.

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[149] Dhital et al., 2016.

[150] Hungr and Evans 2004.

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[152] U.S. Geological Survey, "Frequently Asked Questions: What is a Debris Flow?," accessed October 25, 2022, https://www.usgs.gov/faqs/what-debris-flow.

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[167] Lord 2016.

[168] McAdoo et al., 2018

[169] Acharya, 2021.

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[172] Government of Nepal, 2015.

[173] Vuillez et al., 2018.

[174] McAdoo et al. (2018)

[175] (cf. Butler & Rest 2017; Huber 2020; Lord 2018)

[176] Put differently, assets built in the main channel are considered at risk, so much so that it's considered worth the cost to build the whole powerhouse underground (read: this is considered a worthwhile investment in the mitigation of risk from potential hazards).

[177] Schwangart et al 2019.

[178] Lord 2018.

[179] Dongfeng Li, Xixi Lu, Desmond E. Walling, Ting Zhang, Jakob F. Steiner, Robert J. Wasson, Stephan Harrison, et al., "High Mountain Asia hydropower systems threatened by climate-driven landscape instability, *Nature Geoscience*, Vol. 15, No. 7 (2022): 520-530.

[180] Li et al., 2022.

[181] Several new multi-stakeholder patterns indicate motion in the direction of basin-scale planning and full-spectrum hazard assessment – programs supported by the International Finance Corporation in the Trishuli Basin and WWF in the Karnali Basin and across the country. These are critical steps forward, but, sadly, this is not yet the general practice and strategic planning is still plagued by multiscalar coordination problems. For these reasons, a significant opportunity for the development of orchestrated disaster risk reduction efforts that involve infrastructural players exists - and as hazards continue to occur, those players seem increasingly receptive to such ideas. We believe that a co-creation process around a project and toolkit like the one we are proposing (which may engage the private sector too) can serve as a catalyst.

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[187] Kelman & Stough 2015;

[188] Lord et al, 2016.

[189] Interview with Sanchita Neupane, People in Need Nepal, 2022.

[190] Lord et al, 2016.

[191] We should note that several members of our team have significant experience conducting field-based work that seeks to unpack these situated vulnerabilities.

[192] Maharjan et al 2021.

[193] Some experts refer to these events as the Melamchi Floods because of the preceding rain and flooding events and the fluid nature of these flows - but we are focused on the primary and final stage of this cascading disaster, which manifested itself as a debris flood.

[194] Maharjan et al., 2021.

[195] Maharajan et al 2021

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[206] Virtual interviews with Vera Exnerova and Sanchita Neupane from People in Need, June and September 2022.

[207] Virtual interviews with Vera Exnerova and Sanchita Neupane, September 2022.

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[212] Mukherji et al., 2019.

[213] Sherpa 2014.

[214] Yeh et al., 2014.

[215] Byers, A. C., Chand, M. B., Lala, J., Shrestha, M., Byers, E. A., & Watanabe, T. (2020). Reconstructing the History of Glacial Lake Outburst Floods (GLOF) in the Kanchenjunga Conservation Area, East Nepal: An Interdisciplinary Approach. *Sustainability*, *12*(13), 5407.

[216] Soden & Lord 2018

[217] Gladfelter 2018

[218] Lord 2022

[219] Nightingale 2016;

[220] Yeh 2016

[221] Scoones, I., & Stirling, A., Eds. (2020). *The Politics of Uncertainty: Challenges of Transformation*. Taylor & Francis.

[222] Mehta et al 2019.

[223] Gagne 2016;

[224] Nusser & Baghel 2016;

[225] Sherpa 2014.

[226] Lord (2022) has certainly found this to be the case in the Langtang Valley, where local people are now engaged in dialogue with a variety of different scientific teams, integrating scientific risk assessments with more traditional and situated modes of risk assessment (cf. Hastrup 2013).

[227] Gladfelter 2018.

[228] Gyawali & Dixit 2001.

[229] Sherpa 2014.

[230] Sherry et al 2018.

[231] While it may often be easy to dismiss Nepalese state institutions as ineffective and overly bureaucratic (or even corrupt) bypassing the state is not a sustainable or ethical long-term solution. Working with the state, while acknowledging its capacity gaps, bureaucratic frustrations, and shortcomings is the best path forward. That said, thoughtfully and pre-emptively working to craft relations and shape those interventions focused on relations with the state is critical. ICIMOD understands this well, and this is what is behind their DHM partnerships on CBEWS. The creation of the NDDRMA means an opportunity to work with a new and dynamic institution.

[232] MacClune, Karen, Shobha Yadav, Kanmani Venkateswaran, Rajani Maharjan, Kanchan Mani Dixit, and Sumit Dugar. “Urgent case of recovery: what we can learn from the August 2014 Karnali River floods in Nepal.” (2014).

[233] See also Seira Tamang (2015) for more insightful commentary on the dangers of celebrating “resilience” in Nepal, written in the context of the 2015 Gorkha Earthquake.

[234] Gladfelter 2018.

[235] Ibid, page 2.

[236] Community-based flood early warning system: The story from then to now (2018)) ReliefWeb. Available at: https://reliefweb.int/report/nepal/community-based-flood-early-warning-system-story-then-now

[237] Jonathan Ulrich, “Nepal’s Municipal Disaster Risk Governance Assessment Tool: A Case Study on Strengthening Disaster Risk Management,” *Prevention Web*, January 25, 2022, at https://www.preventionweb.net/news/nepals-municipal-disaster-risk-governance-assessment-tool-case-study-strengthening-disaster.

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