



Beyond a Flash Flood: **The Bhotekoshi-Trishuli Disaster in Nepal**

Preliminary Insights, Lessons Learned & The Way Forward



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DISCLAIMER

This report has been prepared independently by the authors to share preliminary insights, lessons learned, and possible ways forward following the Bhotekoshi-Trishuli disaster in Nepal. The views, interpretations, and conclusions expressed are solely those of the authors and do not necessarily represent the official positions of their affiliated institutions or organizations. The report draws upon data, evidence, and information from multiple credible sources, with appropriate references provided wherever applicable. The findings should be considered preliminary, particularly as the causes and triggering mechanisms of the rock-ice failure associated with the disaster have not yet been fully investigated or scientifically established and require further multidisciplinary investigation. AI tools were used to improve the clarity and presentation of the written text and to assist in preparing one infographic; all substantive content, interpretations, and conclusions were reviewed and finalized by the authors.



DEDICATION

To those who never returned from the river, and to those whose names are still being called across homes, rescue lists, riverbanks, and distant places, this report is dedicated.

To the families who waited for news; to the communities that watched homes, schools, roads, bridges, workplaces, and years of memory disappear beneath water, mud, ice, and debris; and to every rescuer, volunteer, local communities, government agencies, humanitarian workers, and national and international organizations who chose to help.

A disaster can be measured in meters of water depth, kilometers of damaged road, cubic meters of debris, megawatts of lost generation, and the speed of a flood wave. But no graph can carry the weight of an empty chair, an unfinished conversation, a child's belongings left behind, or the silence created by someone who is still missing. Science helps us understand what happened. Remembrance tells us why that understanding matters.

May this report honour lives without reducing them to numbers. May the lessons drawn from this tragedy become earlier warnings, safer infrastructure, stronger cooperation, and decisions made before the next mountain gives way. For every community along the Bhote Koshi–Trishuli corridor: we remember, we rebuild, and we move forward together, not by forgetting what happened, but by carrying its lessons with us.

In memory. In solidarity. In resolve.

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List of Abbreviations

Abbreviation	Full Form
C3S	Copernicus Climate Change Service
CCTV	Closed-Circuit Television
CMIP6	Coupled Model Intercomparison Project Phase 6
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5-Land	ECMWF Reanalysis v5, Land
ESA	European Space Agency
FABDEM	Forest And Buildings removed Copernicus DEM
GCM	General Circulation Model
HEC-RAS	Hydrologic Engineering Center's River Analysis System
ICIMOD	International Centre for Integrated Mountain Development
ISRO	Indian Space Research Organisation
JPL	Jet Propulsion Laboratory
MoFA	Ministry of Foreign Affairs
Mw	Moment magnitude
MW	Megawatt
NASA	National Aeronautics and Space Administration
NDRRMA	National Disaster Risk Reduction and Management Authority
NEX-GDDP-CMIP6	NASA Earth Exchange Global Daily Downscaled Projections, CMIP6
NISAR	NASA-ISRO Synthetic Aperture Radar
NPR	Nepalese Rupee
NPT	Nepal Standard Time
NTC	Nepal Telecom
RAMMS	Rapid Mass Movement Simulation
SAR	Synthetic Aperture Radar
SMS	Short Message Service
SSP	Shared Socioeconomic Pathway
SWE	Snow Water Equivalent
UNDP	United Nations Development Programme
USACE-HEC	U.S. Army Corps of Engineers, Hydrologic Engineering Center
USD	United States Dollar
USGS	United States Geological Survey
UTC	Coordinated Universal Time

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Executive Summary

On 26 August 2026, a catastrophic flash flood occurred in the Rasuwa District of Nepal, causing extensive damage to roads, bridges, hydropower facilities, border infrastructures, and settlements along the Bhotekoshi-Trishuli River corridor. The disaster disrupted transportation, trade, and local livelihoods and demonstrated how events occurring in remote mountain regions can rapidly create severe impacts downstream. This study investigates the causes and development of the flash flood using climate data, seismic records, satellite imagery, reported field observations, and numerical modelling i.e., RAMMS (Rapid Mass Movement Simulation) avalanche and HEC-RAS (Hydrologic Engineering Center's River Analysis System).

The analysis shows that the flood was not triggered by unusually intense rainfall. Instead, evidence indicates that the disaster began when a massive avalanche and landslide of 233.4 million cubic metres failed in the upper catchment. The collapsing mass plunged nearly 1.2 kilometres down slope over, generating enormous energy upon impact. This sudden movement was so powerful that it produced a local seismic signal equivalent to a Mw 5.2 earthquake. The rapid collapse displaced a large volume of water and debris, creating a powerful surge that travelled downstream through the steep Himalayan valleys. As the flood wave moved along the river corridor, it entrained additional sediment, boulders, and debris, significantly increasing its volume and destructive force.

Over the past few decades, the Langtang Lirung area, the source of ice rock avalanche, has become warmer, snow cover has decreased, and the ground has frozen less consistently. These changes may have weakened glaciers, ice-filled cracks, and frozen ground that normally help hold steep slopes together. In the months before the event, conditions were exceptionally warm, with little or no overnight refreezing, which likely further reduced slope stability. At the same time, there was no unusually heavy rain, very little snowmelt, and no evidence of a nearby tectonic earthquake. Taken together, the findings indicate that long-term warming and glacier/permafrost degradation gradually destabilized the slope, leading to a massive rock-ice avalanche that suddenly entered the valley and generated the destructive flash flood downstream.

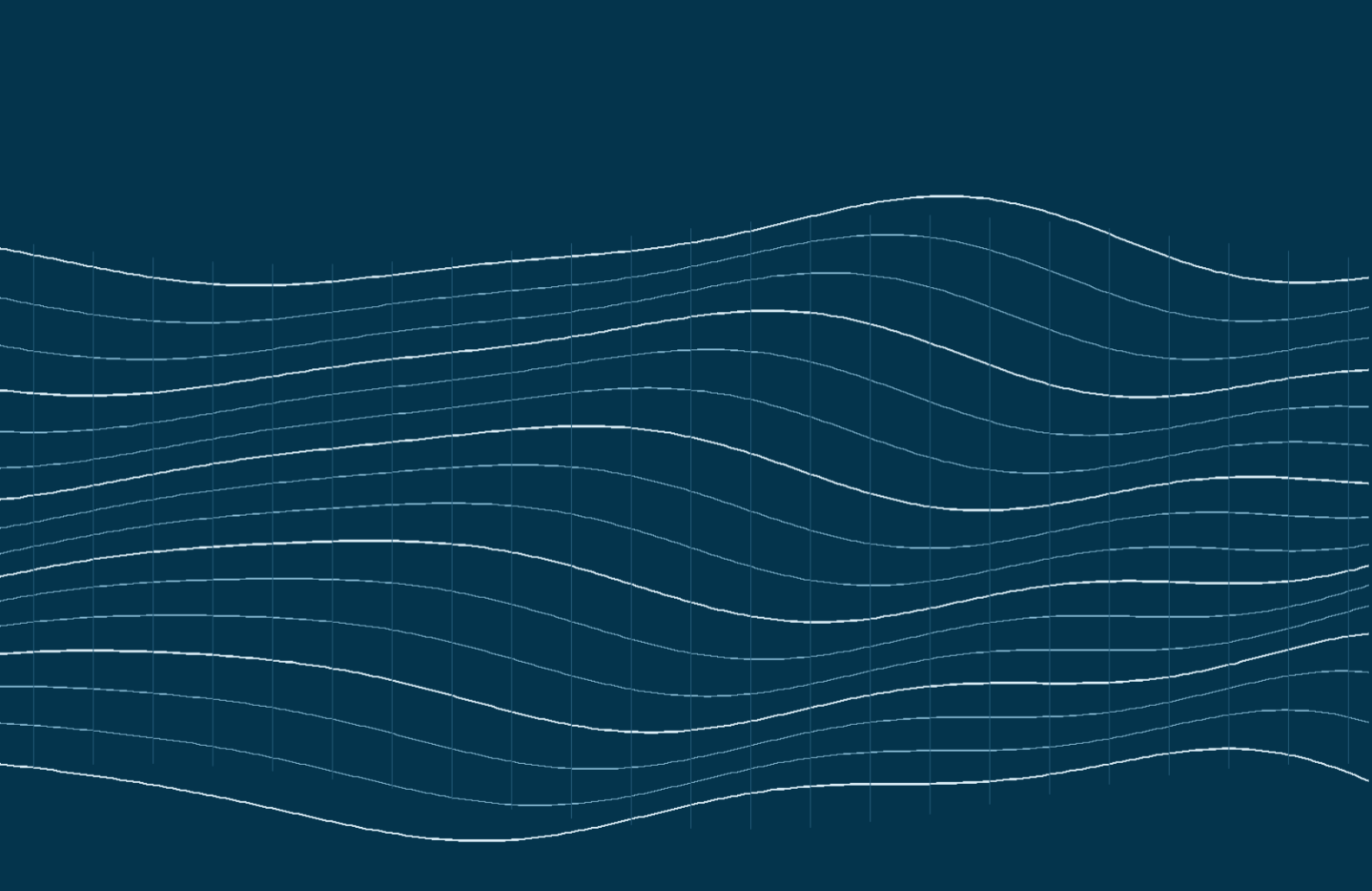
RAMMS-HEC-RAS model simulations successfully reconstructed the flood propagation and showed how the flow accelerated through narrow valleys, transporting large amounts of debris and causing severe erosion and infrastructure damage. The modelling results closely match the observed impact areas and damage patterns along the Bhotekoshi and Trishuli River. The findings highlight the fact that major Himalayan disasters can be triggered by high-mountain slope failures and cascading hazards, even in the absence of extreme rainfall. A localized collapse in a remote upstream area can rapidly evolve into a devastating flood affecting communities and critical infrastructure many kilometres downstream.

This event underscores the importance of real time monitoring of unstable mountain slopes, glaciers, and upstream catchments, particularly in areas with critical infrastructure and settlements. Strengthened remote sensing, multi-hazard early warning systems, cross-border data sharing, and risk-informed infrastructure planning are essential to reduce future losses. Overall, this report concludes that the 26 August 2026 disaster was primarily triggered by a massive rock-ice landslide collapse that generated a sudden downstream flood wave, transforming a remote mountain slope failure into one of the most catastrophic flood disasters in the region's recent history.

Bhotekoshi-Trishuli Disaster in Nepal: At-a-Glance

Date	26 August 2026
Location	Rasuwa District, Nepal-China border; Bhotekoshi-Trishuli corridor
Trigger	Rock-ice avalanche (~233.4 million m ³ adopted volume; magnitude 5.2-equivalent seismic signal); not rainfall-triggered
Deaths	1,395 (as of 16 September 2026)
Missing	5,130 (as of 16 September 2026)
Rescued	13,737 (as of 16 September 2026)
Infrastructure damage	105 bridges destroyed (68 suspension, 37 motorable), 55 km of roads damaged, 13 hydropower projects affected (783 MW capacity), 1 solar plant affected, 2 transmission lines damaged, 20 schools damaged, and 2 municipal offices damaged
Total damage estimate	USD 5 billion (approximately NRs 762 billion)

Source: NDRRMA (2026); Ministry of Foreign Affairs [MoFA] (2026); Khabarhub (2026).



CHAPTER 1

Introduction

BEYOND A FLASH FLOOD | THE BHOTEKOSHI-TRISHULI DISASTER IN NEPAL



1.1 Purpose and Scope

Understanding the causes and evolution of the 26 August 2026 Bhotekoshi-Trishuli flood is important both for explaining this specific disaster and for improving long-term risk management across Nepal's Himalayan river basins. Concern over the stability of high-mountain environments has grown in recent years as climatic warming accelerates glacier retreat and permafrost degradation, while infrastructure and settlement continue to expand into narrow, hazard-prone mountain valleys (Davies, 2026; The Conversation, 2026). Cryosphere specialists have noted that the scale of the August 2026 event exceeded anything previously observed in the region, underscoring how quickly high-altitude slope failures can outpace existing hazard assessments (CNN, 2026b).

The primary objective of this study is to reconstruct the 26 August 2026 event and to identify the processes that controlled its initiation, propagation, and downstream impacts. To achieve this, the study integrates five complementary lines of evidence: (1) meteorological and climate data, to establish the weather conditions prevailing before and during the event; (2) seismic records, to constrain the timing and magnitude of the initial avalanche-landslide collapse; (3) satellite imagery and remote sensing analysis, to identify the source area, associated geomorphic changes, and downstream damage; (4) topographic and terrain data, to evaluate flow pathways and the influence of valley morphology; and (5) RAMMS and HEC-RAS numerical modelling, to reconstruct the avalanche-landslide dynamics and the subsequent downstream flood-wave propagation.

By combining these datasets, this report provides an integrated reconstruction of one of the most destructive mountain disaster events to affect Nepal in recent decades — an event estimated to have killed more than 1,300 people and left thousands more missing across Nepal and China, with direct economic losses estimated in the billions of US dollars (NDRRMA, 2026). Notably, preliminary analyses indicate that no extreme rainfall or unusual meteorological forcing preceded the collapse (Davies, 2026), reinforcing that the flood originated primarily from a high-altitude slope failure rather than from a purely hydrometeorological trigger. The findings are intended to inform multi-hazard monitoring, early warning system design, infrastructure planning, and disaster risk reduction policy across the wider Himalayan region.

1.2 Bhotekoshi-Trishuli River System

The flood travelled through the Lhende Khola-Bhotekoshi-Trishuli system, a river network shared by Nepal and China. The Lhende Khola rises in Gyirong County, Tibet, and flows south into Nepal, where it becomes the Bhotekoshi after crossing the border near Rasuwagadhi. The Bhotekoshi then joins the Trishuli River, which originates near Gosaikunda Lake and continues south through Syabrubesi, Dhunche, Betrawati, and Trishuli Bazaar before draining into the Narayani system.

This corridor loses several thousand metres of elevation over a short horizontal distance, confined within steep, narrow valleys typical of the high Himalaya — terrain that makes the river system highly susceptible to fast-moving floods and debris flows originating far upstream.

The Rasuwagadhi/Gyirong border crossing sits directly on this corridor and hosts the customs office, the Friendship Bridge, and security posts on the valley floor. It is also Nepal's main overland trade route to Tibet, carrying both commercial and Kailash-pilgrimage traffic. Consequently, any

major flood in this system carries serious consequences for regional transportation, trade, tourism, and downstream communities along its length, from Timure and Rasuwagadhi through Syabrubesi to Trishuli Bazaar and beyond (NDRRMA, 2026).

The source area lies on the steep, north-facing slopes of Langtang Lirung (7,227 m), one of the highest peaks in the region, where glacier ice, permanent snow, and degrading permafrost meet. Such high-mountain slopes are known to be inherently unstable and prone to large, episodic rock and ice failures. Langtang Lirung has a documented history of this: the 2015 Gorkha earthquake triggered a glacier collapse that buried Langtang village and killed over 350 people, while a glacial lake outburst flood (GLOF) in July 2025 damaged the same border crossing and claimed nine lives (Malaymail, 2025). Environments of this kind are increasingly recognised as potential sources of large avalanche and landslide events capable of generating destructive downstream floods.

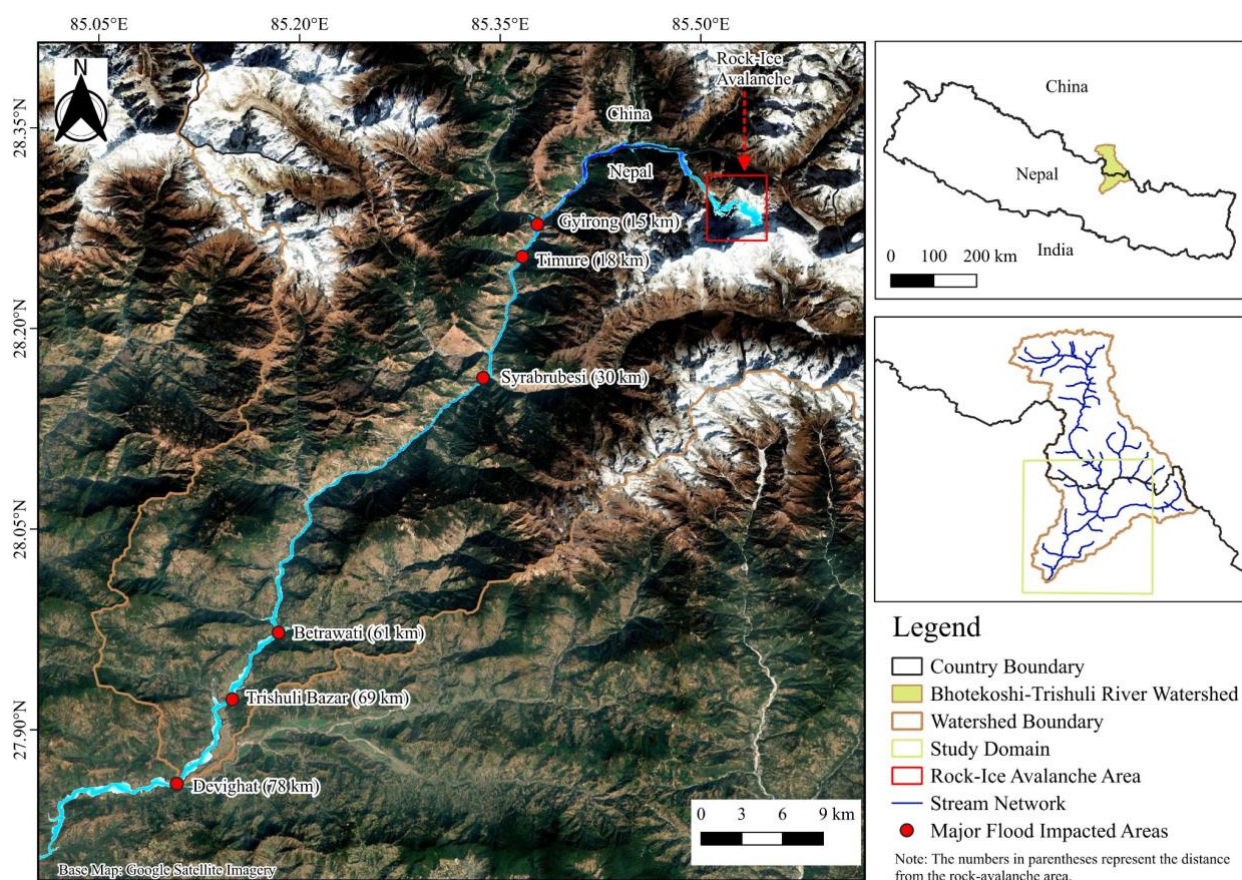
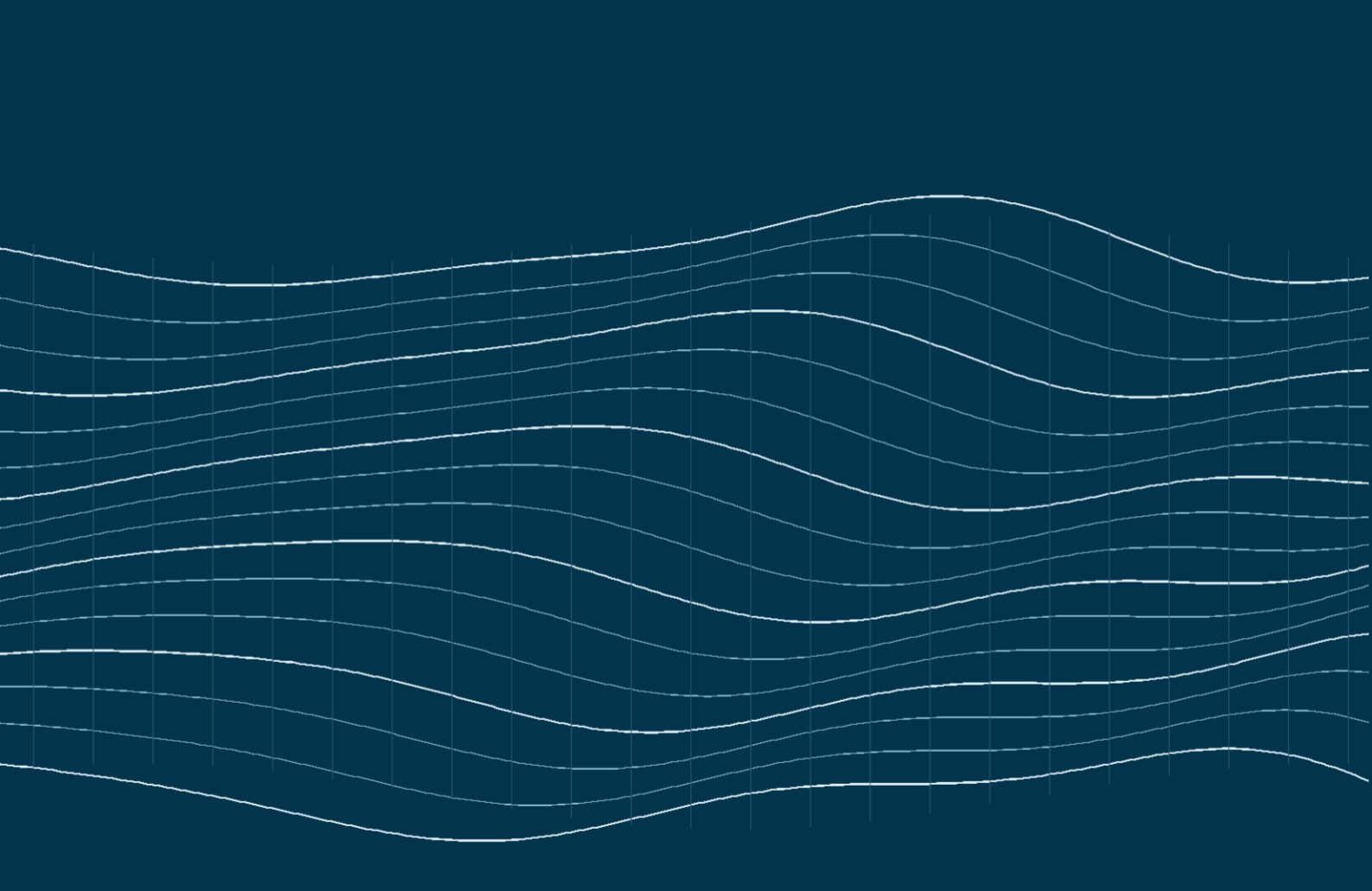


Figure 1: Geographic setting and spatial context of the Bhotekoshi-Trishuli River System in the central Himalaya, showing the river, surrounding high-relief terrain, rock-ice avalanche source area, and key impacted areas.



CHAPTER 2

What Happened?

BEYOND A FLASH FLOOD | THE BHOTEKOSHI-TRISHULI DISASTER IN NEPAL



2.1 Chronological Narrative — Event Timeline

This timeline reconstructs the sequence of events on 26 August 2026 based on media reports, updates from the Department of Hydrology and Meteorology (DHM) Flood Forecasting Division of Nepal, river-gauge records, CCTV footage, and other available observations (NDRRMA, 2026). The reconstruction should be considered preliminary and may be revised as additional official information and observations become available from DHM, NDRRMA, and other relevant agencies.

Two features of the event are particularly noteworthy. First, the flood propagated exceptionally rapidly, travelling from the source area to Devghat, approximately 100 km downstream, in less than 10 hours, while the initial ~20 km was reportedly traversed within only a few minutes (CNN, 2026a; NDRRMA, 2026). Such rapid propagation differs substantially from the behaviour of a typical monsoon flood, which generally develops progressively as rainfall accumulates and runoff increases over time. Instead, the observed timing and rapid downstream propagation are more consistent with a sudden, large-scale mountain-collapse event that rapidly displaced and released a substantial volume of water and debris into the river system (Davies, 2026).

Second, the river gauge at Syabrubesi (30 km from source area) was reportedly destroyed by the flood at approximately 08:50 NPT, before the first public flood warning was issued at around 09:15 NPT (NDRRMA, 2026). Thus, the flood reached and disabled a critical monitoring station before the warning could be disseminated downstream. This substantially reduced the available response time for communities, infrastructure, and other facilities along the Trishuli river corridor. The sequence highlights a critical limitation of conventional river-based early warning systems in steep Himalayan catchments, where sudden mass-movement-generated floods can travel faster than monitoring and warning systems are able to detect, communicate, and respond to the hazard.

Table 1. Timeline of the 26 August 2026 flood event, from the initial rock-ice avalanche to the flood wave's arrival at Devghat. All times are in Nepal Standard Time (UTC+5:45). Source: DHM Flood Forecasting Division, as compiled in NDRRMA (2026).

Time	Event
08:37	A shock equal to a magnitude 4.4 earthquake is recorded (Department of Mines & Geology). This was later re-examined by the USGS and identified not as a tectonic earthquake, but as the seismic signal of a magnitude 5.2 mountain collapse (EarthSky, 2026).
08:40	Last data received from the Bhotekoshi gauge at Syabrubesi: water level 1.62 m (warning level 6 m, danger level 7 m) — a completely normal reading (NDRRMA, 2026).
08:50	The Syabrubesi station stops transmitting. The gauge was destroyed — just 13 minutes after the mountain collapse (NDRRMA, 2026).
09:00	The first human reports reached DHM, from the Rasuwa District Administration Office and staff at the Betrawati station (NDRRMA, 2026).
09:15	DHM confirms the flood and issues its first advisory for Rasuwa, Nuwakot, Dhading, and Chitwan, with a high alert extending down to Mugling (NDRRMA, 2026).
09:16	Mass warning text messages begin going out via Nepal Telecom and Ncell — 679,295 messages in total (435,635 from NTC, 243,660 from Ncell) (NDRRMA, 2026).
09:20	The Betrawati station (45 km downstream) stops transmitting. Last reading: 3.55 m (warning level 4.1 m, danger level 5.0 m) (NDRRMA, 2026).
10:28	The flood front reaches the Dhading-Galchhi area. Fresh alerts are issued for the Prithvi Highway and the Mugling-Narayanghat road (NDRRMA, 2026).
11:26	Water level at Furke (Malekhu) rises past the warning level (NDRRMA, 2026).
11:43	Water level at Furke passes the danger level — moments later, the station itself and its bridge are swept away (NDRRMA, 2026; Mappr, 2026).
11:50	The flood front reaches Malekhu bazaar, with the wave expected to reach Mugling in about 30 minutes. Riverside markets are told to evacuate (NDRRMA, 2026).
13:00	The flood front passes Mugling. Alerts are extended further downstream to Devghat (NDRRMA, 2026).
13:20	Water level at Devghat reaches 4.76 m. DHM forecasts the main flood wave to arrive around 15:30, potentially reaching a level of about 8 m (NDRRMA, 2026).
13:35	Reports from the Chinese side indicate the lake behind the debris blockage has not fully drained, meaning the risk of further flooding is not yet over (Davies, 2026; NDRRMA, 2026).
14:14	Water level at Kalikhola passes the danger level (12.1 m) and continues rising, eventually peaking at 12.3 m (NDRRMA, 2026).
15:20	The flood wave is detected at the automatic monitoring station where the Narayani meets Devghat (NDRRMA, 2026).
16:00	Water level at Devghat peaks at 6.57 m — about 1.4 m lower than forecast — before beginning to recede (NDRRMA, 2026).
18:30	Water level at Devghat returns to around 4 m. The extra volume of water that passed through Devghat during the event is estimated at roughly 20 million cubic metres (NDRRMA, 2026).

2.2 Human, Infrastructure, and Economic Toll

As of 16 September 2026, the Bhotekoshi flood has left 1,395 confirmed dead, 5,130 people reported missing, and 13,737 rescued alive, and 2712 displaced (Khabarhub, 2026; MoFA, 2026; CGTN, 2026). The flood has destroyed 105 bridges — 68 suspension and 37 motorable — and damaged 55 km of roadway (MoFA, 2026; The Independent, 2026). It has also knocked out 783 MW of hydropower capacity across 13 hydropower projects, one solar plant, and two transmission lines, and damaged 20 schools and 2 municipal offices (MoFA, 2026).

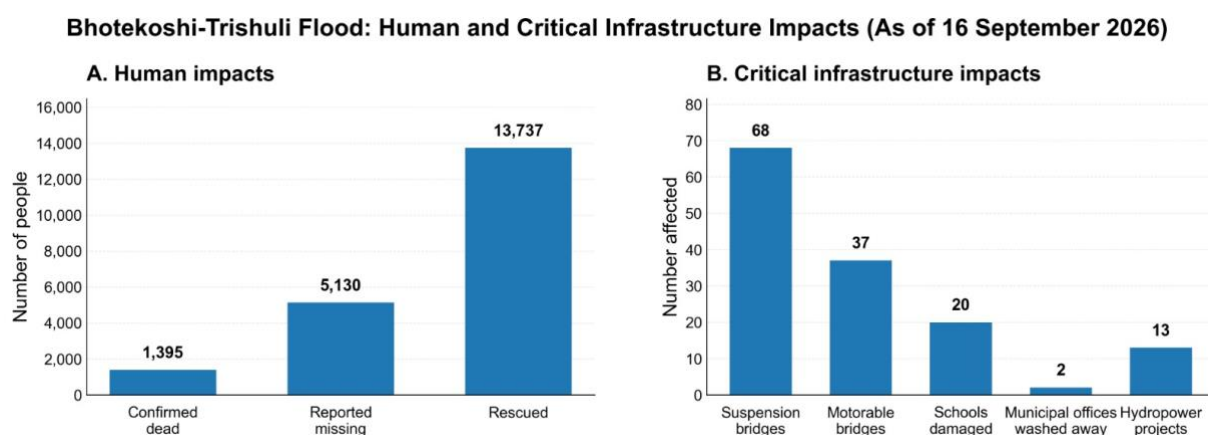


Figure 2: Human and critical infrastructure impacts of the 26 August 2026 Bhotekoshi-Trishuli catastrophic flash flood, Nepal. (A) Human impacts, including deaths, missing persons, and rescues; and (B) critical infrastructure impacts, including bridges destroyed, public facilities and hydropower projects damaged. Figures are provisional and based on official situation updates available as of 12 September 2026 (Sources: NDRRMA, 2026; MoFA, 2026).



Figure 3: Impact of Bhotekoshi-Trishuli Catastrophic flash flood in the downstream communities.

CHAPTER 3

Primary Process: The Rock-Ice Avalanche

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At 08:37 NPT on 26 August 2026, a mass of bedrock and glacier ice detached from the north slope of Langtang Lirung at an estimated elevation of 5,200-5,400 m and fell approximately 1.2 km into the Lhende Khola valley. This study adopts a source volume of 233.4 million m³ for the analysis; published estimates for the collapse currently span a wider provisional range of roughly 197-492 million m³ (Figure 4; Davies, 2026; EarthSky, 2026).

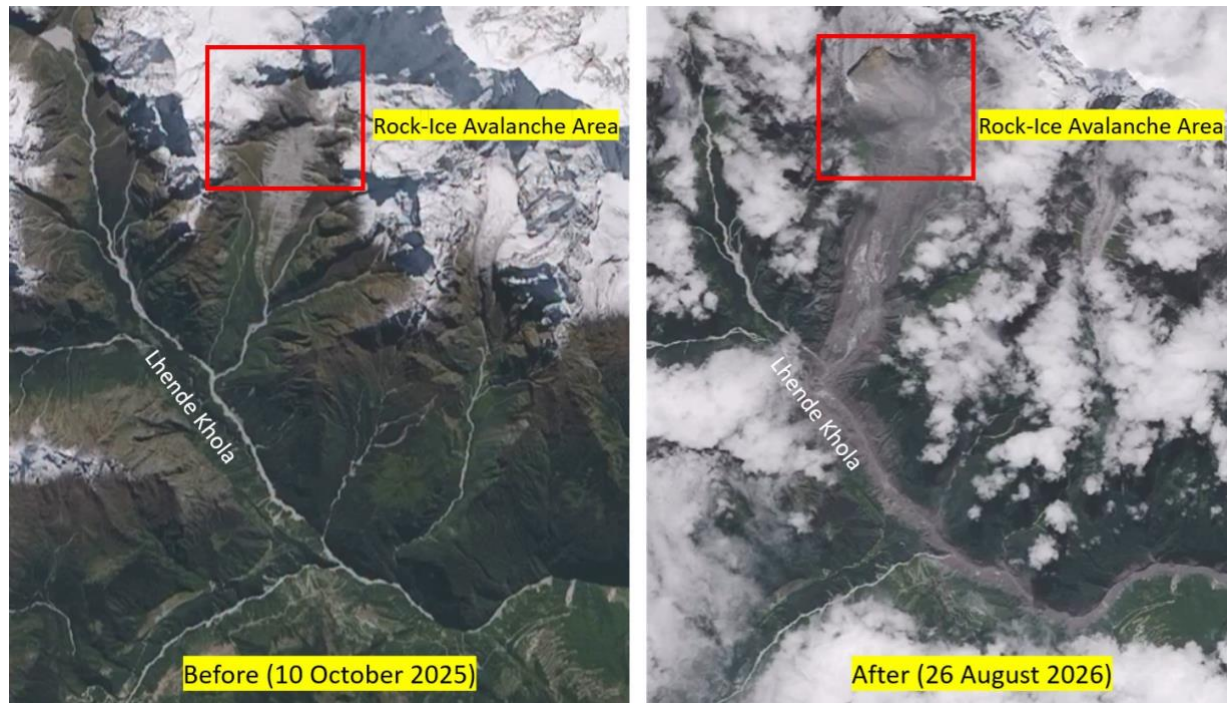


Figure 4: Satellite imagery © 2026 Planet Labs PBC; reproduced via Reuters. Pre-event (10 October 2025) vs Post-event (26 August 2026).

The collapse generated a strong seismic signal, initially misclassified as a magnitude 4.4 tectonic earthquake before reanalysis of long-period surface waves led USGS to reclassify it as a magnitude 5.2 landslide at zero depth (EarthSky, 2026). The transition from collapse to debris flow was effectively instantaneous. Frictional heating generated during the fall flash-melted a substantial fraction of the entrained glacier ice, and the resulting rock-ice-water mixture scoured additional sediment and boulders from the valley floor, bulking the flow considerably beyond its initial detached volume. This mechanism is consistent with the interpretation that the first flood pulse was driven directly by sudden ice-melt at the point of impact, rather than by the delayed failure of a landslide-dammed lake: the ~7-minute transit time to Gyirong Port is too short to accommodate a dam-formation-and-breach sequence, and this is treated as ruling out a dam-break origin for the first pulse. Reported peak flow velocities reached 216 km/hr near Gyirong Port (Davies, 2026; CNN, 2026a), placing this event among the most mobile rock-ice avalanche-to-debris-flow transformations yet documented in the Himalaya (Davies, 2026).

The collapse debris also blocked the upper Lhende Khola, impounding a barrier lake near the source zone (Figure 5 and 6). Rather than failing catastrophically, this lake released water intermittently over the following days, with renewed outflow observed around 30 August (NDRRMA, 2026). Of the two lakes formed during the event sequence, this upper lake proved the more persistent and remained an active hazard for the longest period.

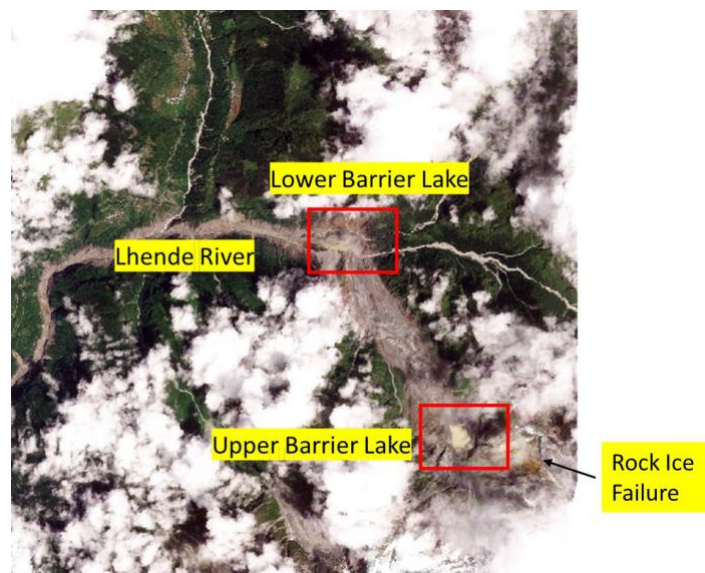


Figure 5: Satellite image showing the formation of two landslide-dammed lakes following the mass-movement event.

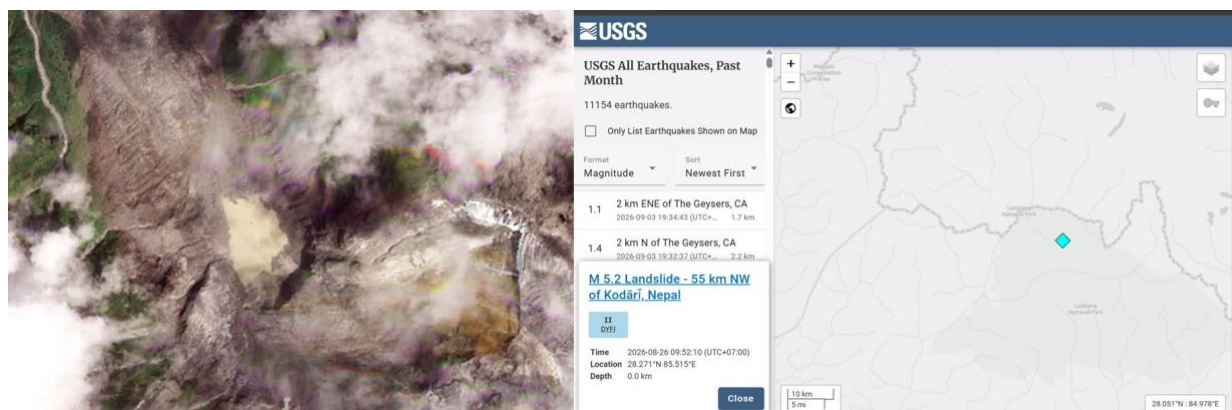


Figure 6: Source area of the ice rock collapse and the upper barrier lake, Langtang Lirung north slope, Seismicity reported by USGS.

Approximately three hours after the initial collapse, at roughly 11:37 NPT, a second and smaller landslide occurred along the same valley system, recorded by USGS as a magnitude 4.2 landslide signal. Based on this reconstruction, this failure is located approximately 7 km downstream of the Event 1 source area. This second failure coincided with an additional surge of water and debris moving downstream, compounding the flood already generated by Event 1.

Debris from this second landslide temporarily blocked the river, forming a lower barrier lake near the confluence of the Chhochhen Khola and Purepu Tsangpo in Tibet (Figure 7). Unlike the catastrophic first flood, this lower lake produced only a limited overflow on 28 August, raising water levels downstream (NDRRMA, 2026). The lake drained progressively and had largely disappeared by 30 August, marking it as the shorter-lived and less hazardous of the two barrier lakes formed during the event sequence.

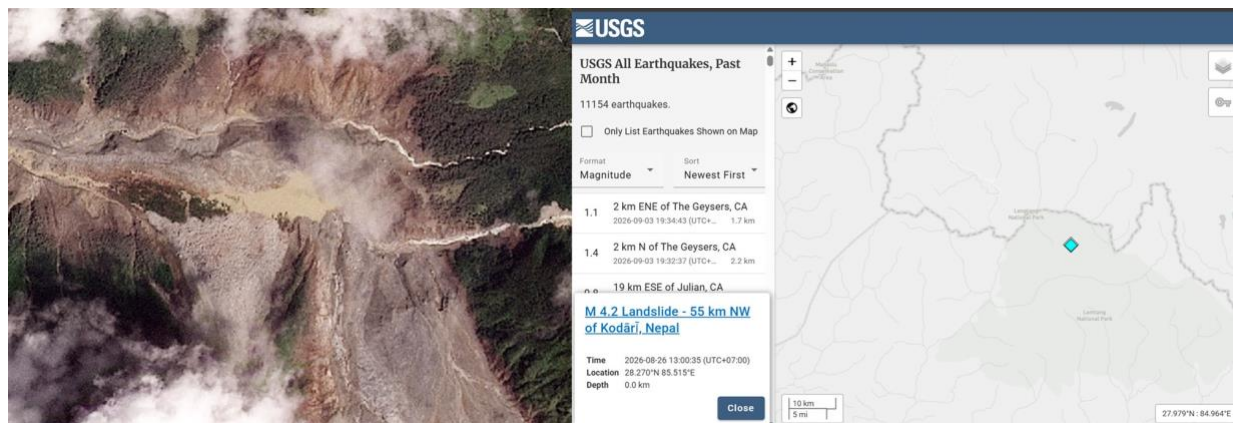


Figure 7: Landslide source area and the lower barrier lake, located approximately 7 km downstream of the upper rock-ice avalanche collapse area, with reported seismicity based on USGS earthquake records.

CHAPTER 4

Potential Pre-Trigger Conditions of Rock-Ice Avalanche

BEYOND A FLASH FLOOD | THE BHOTEKOSHI-TRISHULI DISASTER IN NEPAL



4.1 ERA5-Land Data Source and Processing

Pre-trigger hydroclimatic conditions at the Langtang Lirung source area were evaluated using ERA5-Land Hourly reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the Copernicus Climate Change Service (C3S) (Muñoz-Sabater et al., 2021). ERA5-Land provides a continuous hourly record from 1950 onward on a $0.1^\circ \times 0.1^\circ$ (10 x10 km) regular latitude-longitude grid. The analysis used the grid cell centred near the Langtang Lirung source area (approximately 28.250° N, 85.550° E) for the period 1950-2026.

The variables used directly from ERA5-Land were 2-m air temperature, total precipitation, snowfall, snow depth, and snowmelt (Annex 1). Temperature was converted from kelvin to degrees Celsius, while precipitation, snowfall, and snowmelt were converted from metres of water equivalent to millimetres. Rainfall was estimated as total precipitation minus snowfall. Rainfall and snowfall fractions were then expressed as percentages of annual total precipitation. Daily minimum, maximum, and mean temperatures were derived from the hourly record. A freeze-thaw day was defined as a day with minimum temperature below 0°C and maximum temperature above 0°C , whereas a positive-temperature day was defined as a day with daily mean temperature above 0°C . The temperature anomaly was calculated relative to the 1950-1975 mean annual temperature. Annual means were used for air temperature and snow depth; annual totals were used for precipitation, snowfall, and snowmelt; and annual counts were used for freeze-thaw and positive-temperature days.

4.2 Long-Term Temperature and Precipitation Regime

The annual 2-m air-temperature record shows a gradual warming of the Langtang Lirung area. Mean annual temperature increased from -5.21°C during 1950-1975 to -5.14°C during 1975-2000 and to -4.89°C during 2000-2026 (Figure 8). In absolute terms, the most recent period is about 0.31°C warmer than the 1950-1975 mean. The upward linear tendency and the cluster of relatively warm years after 2020 provide a consistent long-term warming signal at the source area.

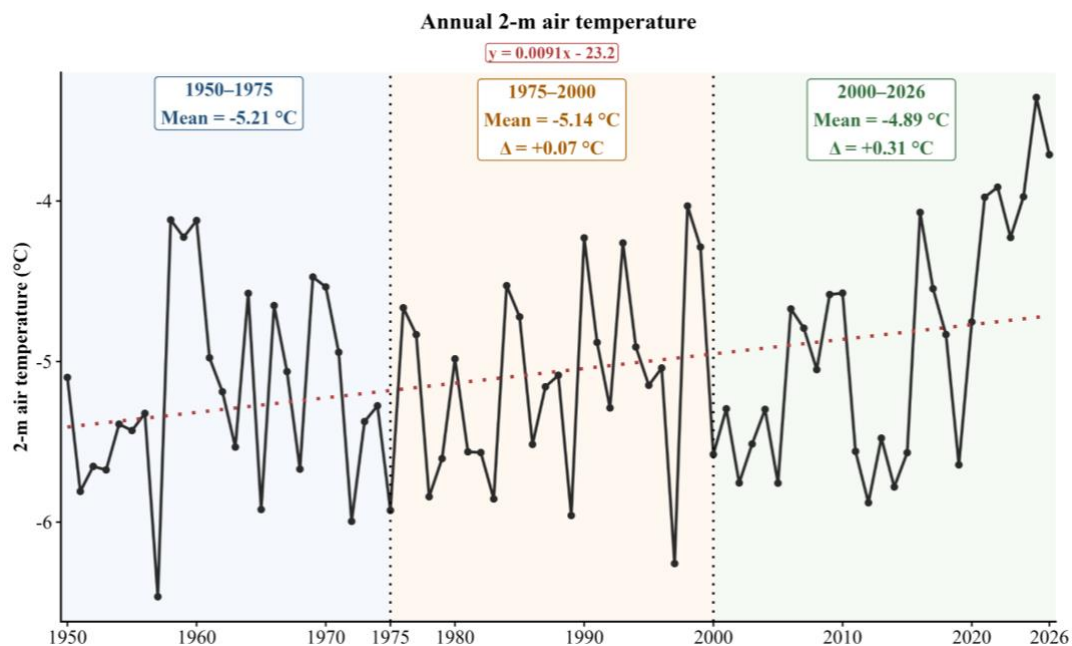


Figure 8: Annual 2-m air temperature at the Langtang Lirung source area, 1950-2026. Shaded intervals show the three analysis periods; boxes report period means and the dotted red line shows the overall linear trend.

Annual total precipitation varies substantially from year to year and does not show the same monotonic change as temperature. The period mean decreased from 1,683 mm during 1950-1975 to 1,496.2 mm during 1975-2000, before increasing to 1,621.2 mm during 2000-2026 (Figure 9). Thus, the recent period is wetter than 1975-2000 but remains below the earliest-period mean. This pattern indicates that the long-term shift in pre-trigger conditions is better characterized by precipitation phase and snow storage than by a simple increase in total precipitation.

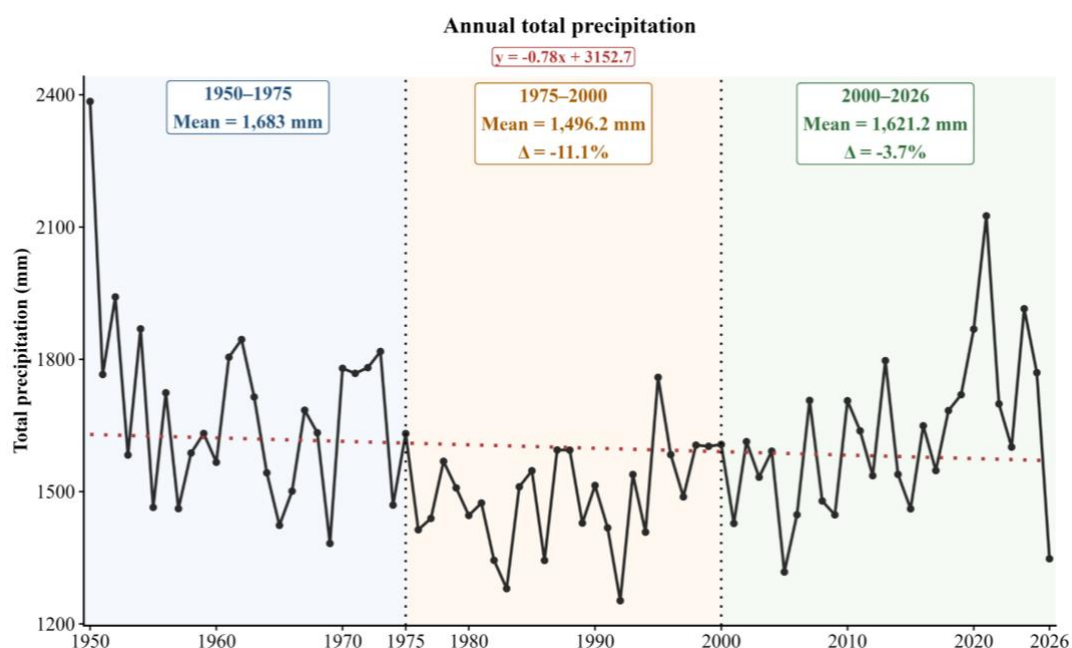


Figure 9: Annual total precipitation at the Langtang Lirung source area, 1950-2026, with period means and overall linear trend.

A clearer long-term change is evident in the precipitation phase. The mean rainfall fraction increased from 57.03% during 1950-1975 to 60.11% during 1975-2000 and 63.41% during 2000-2026 (Figure 10). Conversely, the snowfall fraction declined from 42.97% to 39.89% and then to 36.59% over the same periods (Figure 11). These complementary changes show that a progressively larger share of precipitation is represented as rain rather than snow in the ERA5-Land record.

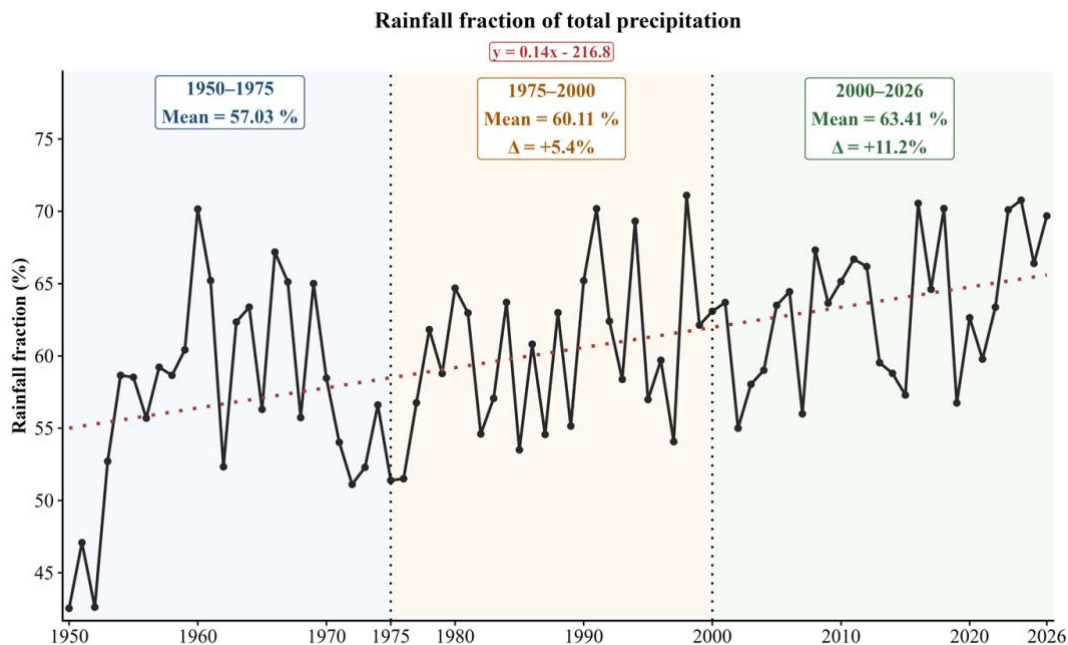


Figure 10: Annual rainfall fraction of total precipitation at the Langtang Lirung source area, 1950-2026.

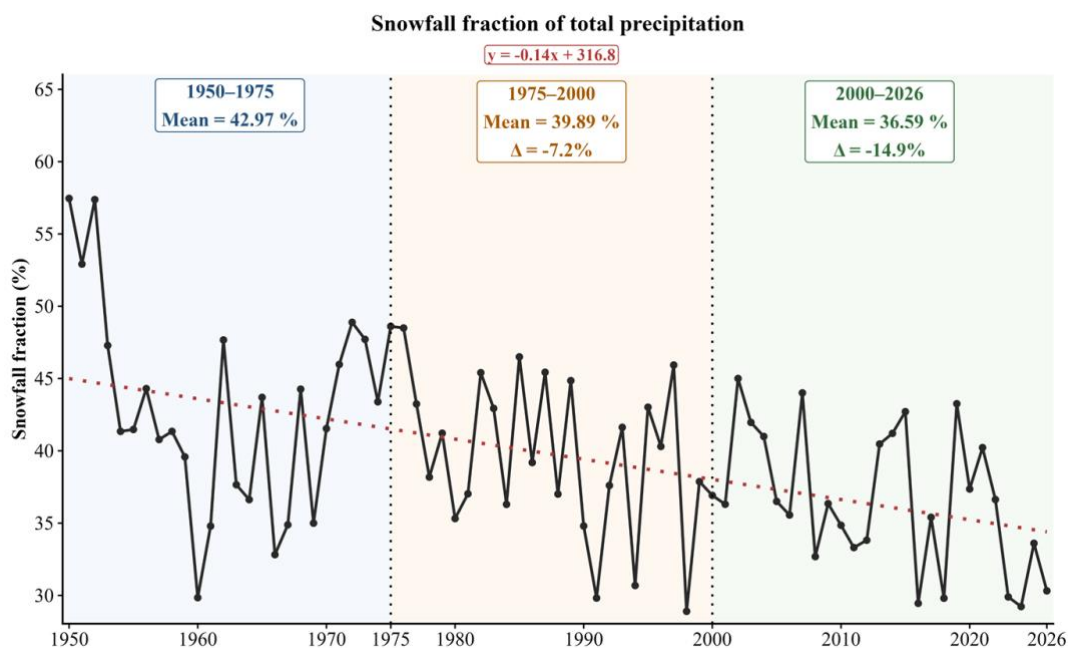


Figure 11: Annual snowfall fraction of total precipitation at the Langtang Lirung source area, 1950-2026.

4.3 Snow Accumulation and Melt

The snow-related variables consistently indicate reduced snow storage and reduced annual snow fluxes through time. Mean snow depth declined from 0.41 m during 1950-1975 to 0.34 m during 1975-2000 and 0.26 m during 2000-2026 (Figure 12). This represents a marked reduction in the average depth of the snowpack represented by ERA5-Land.

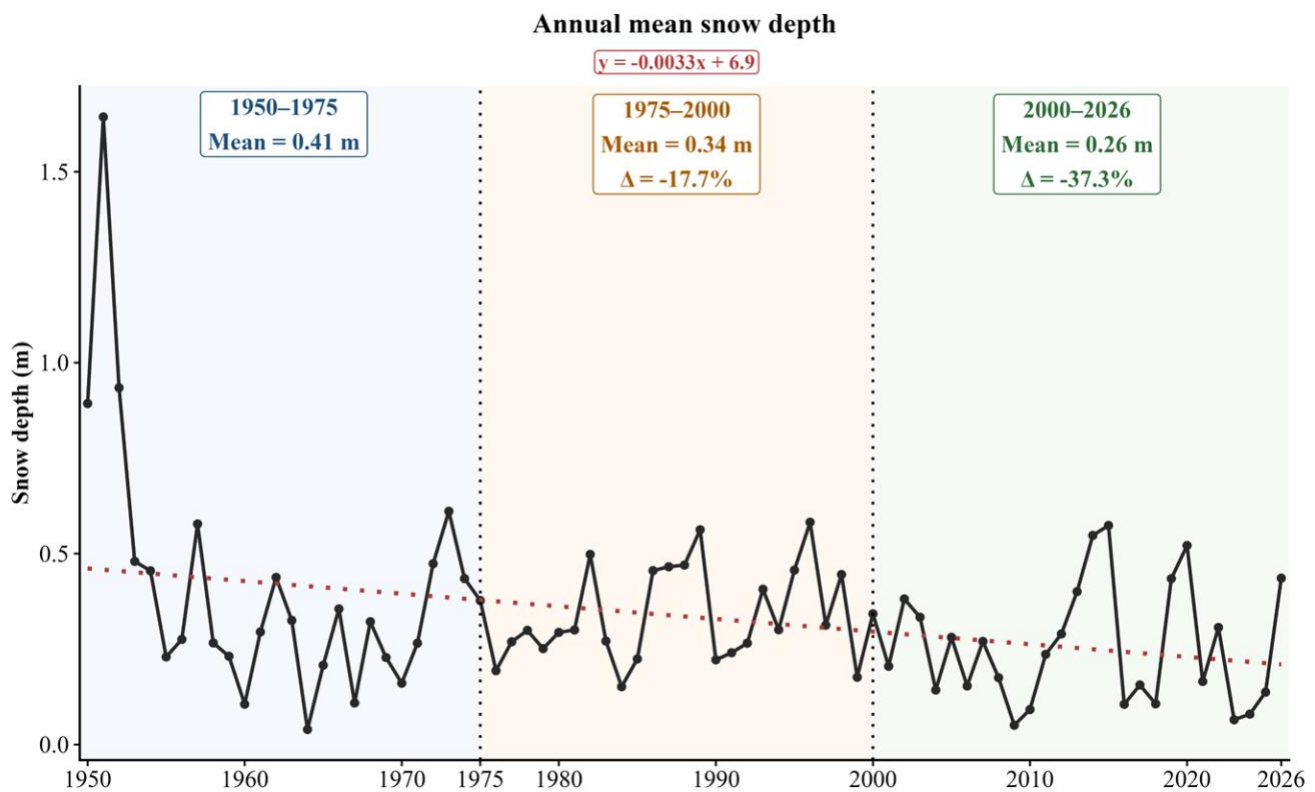


Figure 12: Annual mean snow depth at the Langtang Lirung source area, 1950-2026.

Annual total snowmelt also decreased, from a periodic mean of 721.2 mm water equivalent during 1950-1975 to 583.4 mm during 1975-2000 and 576.5 mm during 2000-2026 (Figure 13). A decline in annual snowmelt does not imply reduced thermal forcing by itself; in a progressively snow-limited environment it can also reflect a smaller amount of seasonal snow available to melt.

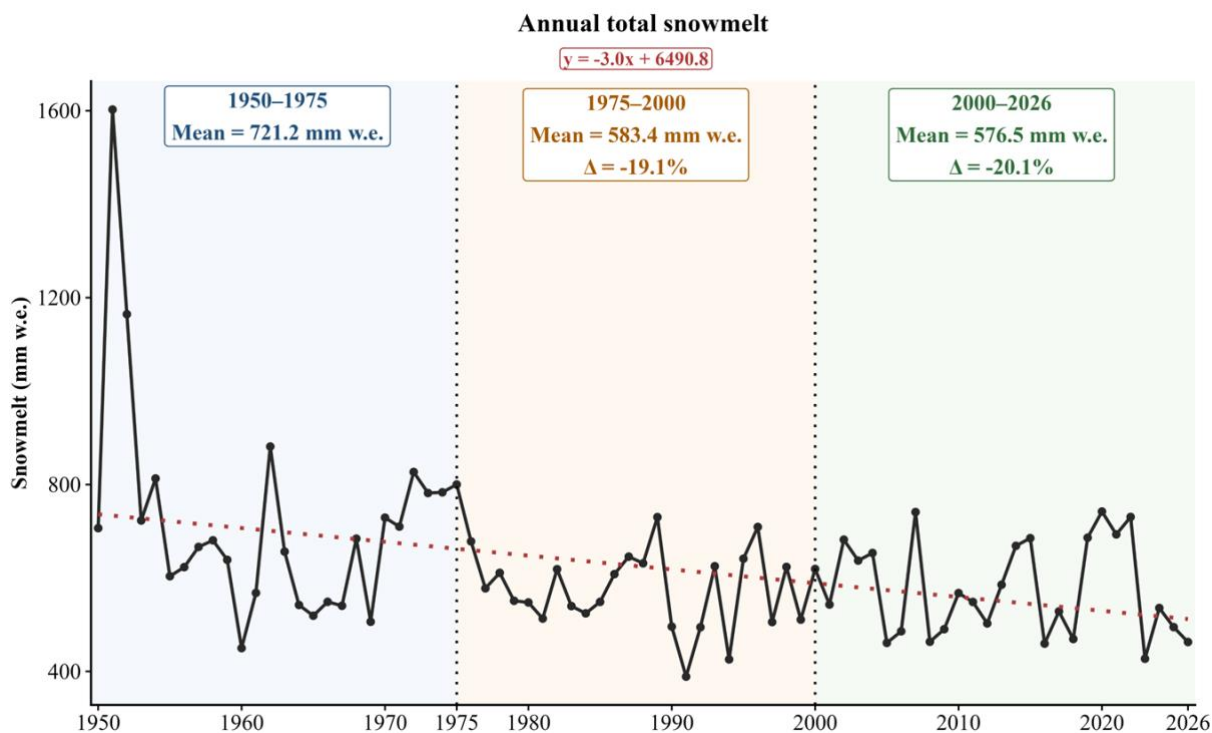


Figure 13: Annual total snowmelt at the Langtang Lirung source area, 1950-2026.

Annual snowfall shows a similar pattern. Mean snowfall decreased from 731.7 mm water equivalent in 1950-1975 to 597.0 mm in 1975-2000 and 593.7 mm in 2000-2026 (Figure 14). When considered together with the declining snowfall fraction and snow depth, the snowfall record indicates a long-term reduction in snow accumulation at the source-area grid scale.

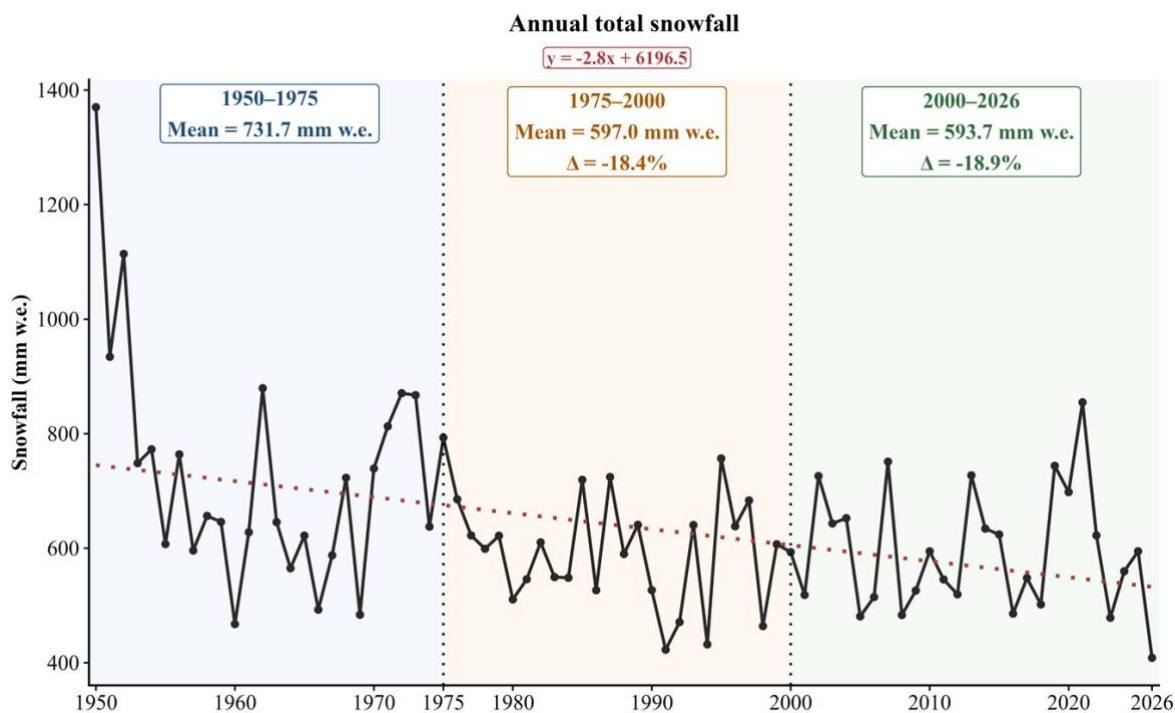


Figure 14: Annual total snowfall at the Langtang Lirung source area, 1950-2026.

4.4 Temperature Anomaly and Thermal-State Indicators

The temperature-anomaly series, calculated relative to the 1950-1975 mean, reinforces the warming signal. The mean anomaly is approximately 0.00 °C for the baseline period, 0.07 °C during 1975-2000, and 0.31 °C during 2000-2026 (Figure 15). Positive anomalies become particularly prominent in the most recent years, indicating that the later part of the record is generally warmer than the historical baseline.

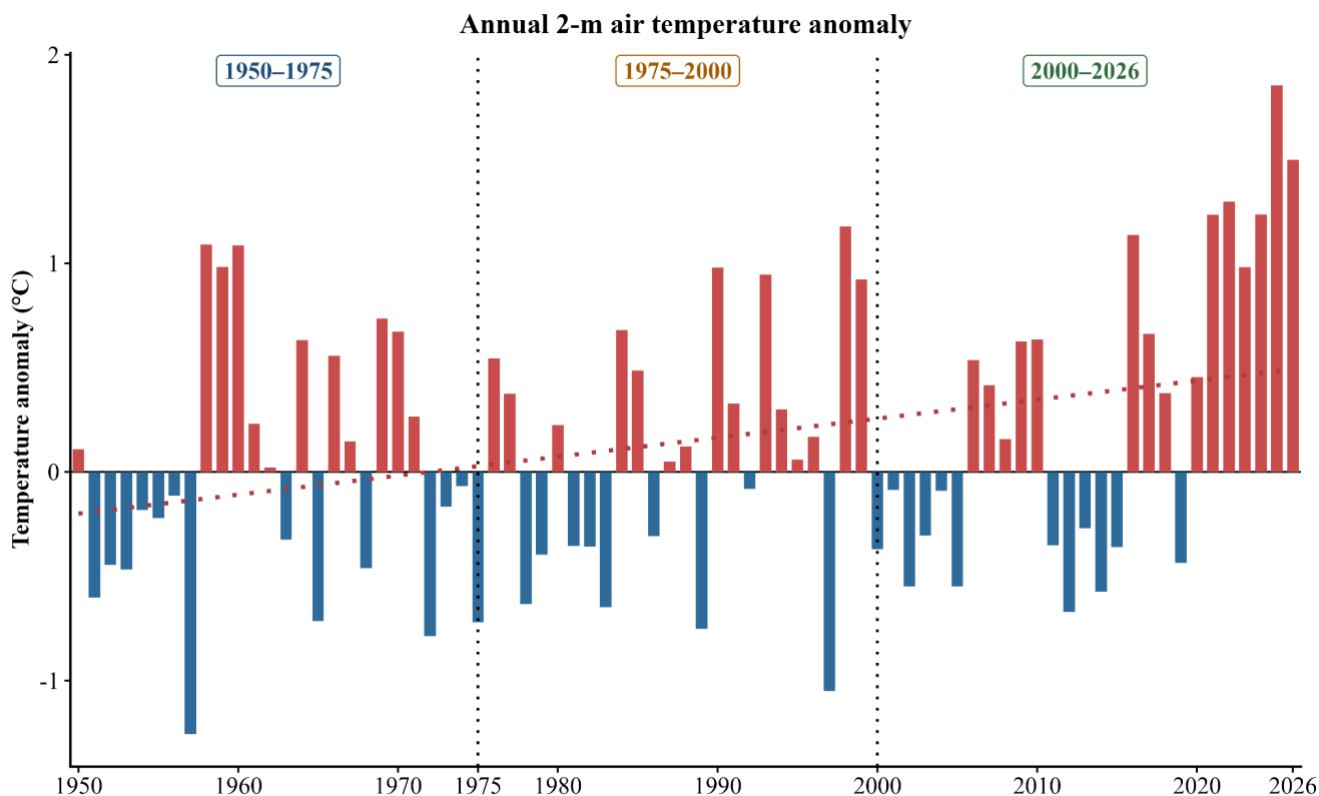


Figure 15: Annual 2-m air-temperature anomaly relative to the 1950-1975 mean at the Langtang Lirung source area.

Freeze-thaw activity remained similar between the first two periods, with mean values of 81.65- and 82.15-days yr^{-1} , but decreased to 75.41 days yr^{-1} during 2000-2026 (Figure 16). This recent reduction indicates fewer days crossing the 0 °C threshold within a single day. In a high-mountain setting, this change is consistent with a shift in the thermal regime, although freeze-thaw counts alone cannot distinguish all processes affecting glacier ice, permafrost, or fractured bedrock.

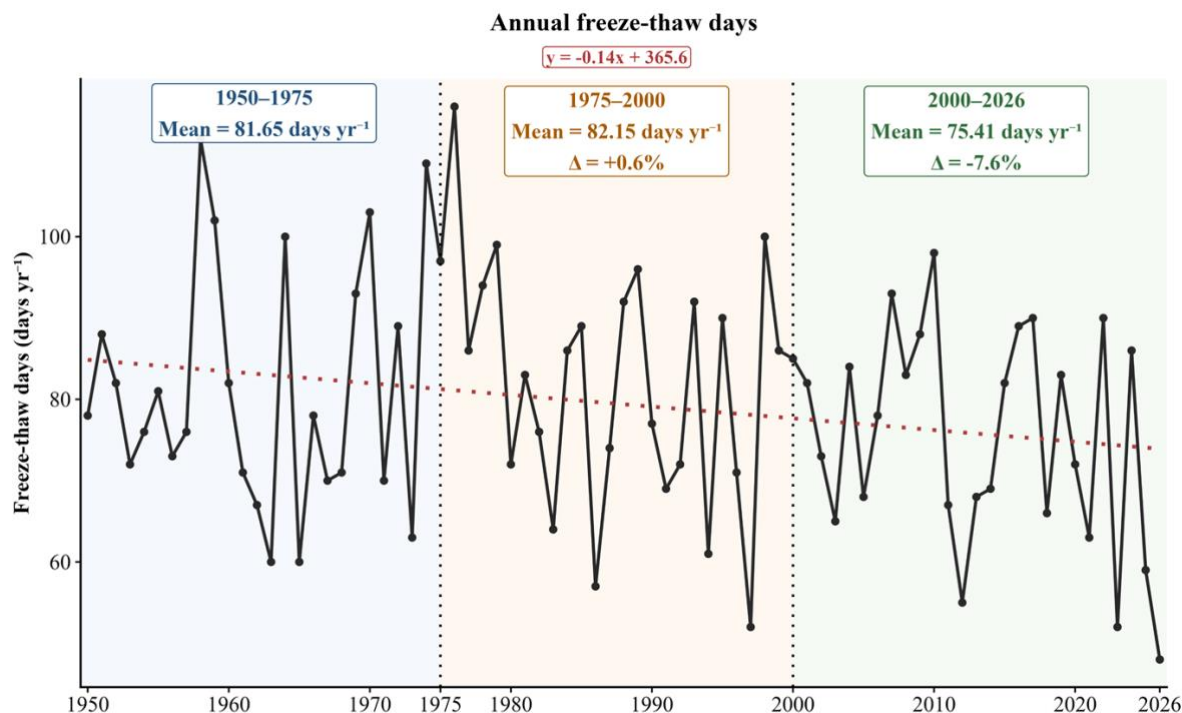


Figure 16: Annual freeze-thaw days at the Langtang Lirung source area, 1950–2026. A freeze-thaw day is defined as $T_{min} < 0\text{ }^{\circ}\text{C}$ and $T_{max} > 0\text{ }^{\circ}\text{C}$.

The number of positive-temperature days does not show a corresponding long-term increase. Period means are 119.2, 117.1, and 116.6 days yr⁻¹ for 1950–1975, 1975–2000, and 2000–2026, respectively (Figure 17). Therefore, the warming signal in this record is expressed more clearly by higher mean temperatures and positive temperature anomalies than by a greater number of days with daily mean temperature above 0 °C.

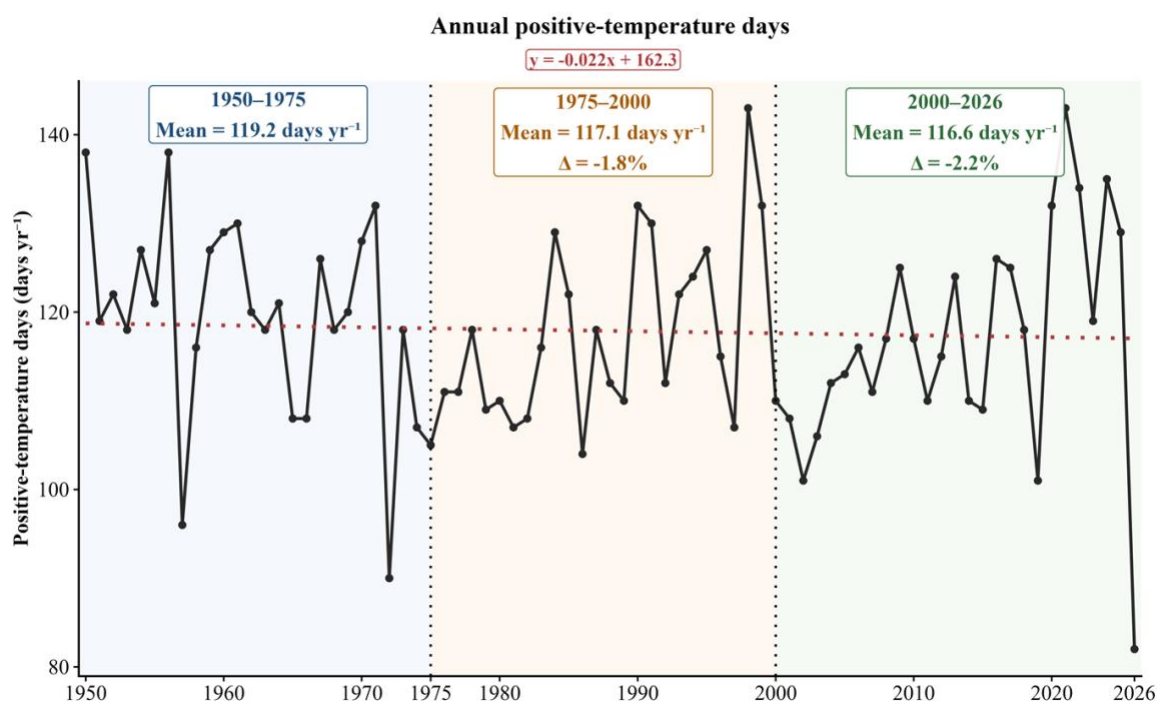


Figure 17: Annual positive-temperature days at the Langtang Lirung source area, 1950–2026. A positive-temperature day is defined as a day with daily mean 2-m air temperature $> 0\text{ }^{\circ}\text{C}$.

Table 2. Period-wise changes in key hydroclimatic indicators at the Langtang Lirung source area during 1950-2026.

Parameter	Unit	Baseline (P1): 1950-1975	P2: 1975-2000	P3: 2000-2026	Δ P1→P2 (%)	Δ P1→P3 (%)
Annual 2-m air temperature	°C	-5.21	-5.14	-4.89	1.25	6.03
Annual total precipitation	mm	1683.03	1496.23	1621.25	-11.1	-3.67
Rainfall fraction of total precipitation	%	57.03	60.11	63.41	5.40	11.19
Snowfall fraction of total precipitation	%	42.97	39.89	36.59	-7.17	-14.86
Annual mean snow depth	m	0.41	0.34	0.26	-17.69	-37.30
Annual total snowmelt	mm w.e.	721.2	583.35	576.53	-19.11	-20.06
Annual total snowfall	mm w.e.	731.7	597.05	593.71	-18.4	-18.86
Annual freeze-thaw days	days/yr	81.65	82.15	75.41	0.61	-7.65
Annual positive-temperature days	days/yr	119.23	117.08	116.59	-1.81	-2.21

The analysis shows that these environmental changes are not only continuing but are becoming stronger over time. Over the last decade, warming temperatures, melting conditions, and short periods of intense snow and ice melt have all increased more rapidly than in previous decades. In contrast, these trends were much weaker, and sometimes even absent, during the 1980s to early 2000s.

Taken together, the results show that the Langtang Lirung source area is warming faster, retaining less snow, receiving more rain instead of snow, and refreezing less frequently than before. These changes are creating increasingly unstable conditions on the mountain slope. The evidence suggests that long-term warming and the accelerated loss of snow and frozen ground gradually weakened the rock and ice mass, helping to create the conditions that eventually led to the large rock-ice avalanche.

4.5 Satellite-Based Pixel Change Detection for Rock-Ice Avalanche Area

The NISAR Track 98 pixel-offset analysis for 8 June-19 August 2026, ending seven days before the 26 August collapse, revealed a distinct and spatially coherent zone of pre-failure slope deformation (NASA/JPL-Caltech & ISRO, 2026) (Figure 18; Annex 2). Conversion of the slant-range and azimuth offsets to horizontal east-north displacement showed cumulative movement of approximately 12-14 m within the area that subsequently failed. The zone of strongest deformation closely coincided with the mapped slide area, indicating that substantial slope movement was already occurring well before the final collapse.

The displacement vectors were predominantly aligned with the downslope direction, indicating coherent movement of the unstable slope mass rather than spatially incoherent measurement noise. Deformation was also spatially heterogeneous. The greatest displacement was concentrated in the upper-central part of the slope, close to the mapped breach zone, while displacement generally decreased toward the margins of the slide and remained comparatively limited outside the eventual failure boundary.

The spatial correspondence between the highest pre-failure displacement and the subsequent breach zone suggests that this part of the slope experienced the most rapid deformation and represented the principal zone of instability before failure. Overall, the NISAR observations indicate that the 26 August collapse was preceded by at least 10 weeks of measurable slope deformation, rather than occurring as an abrupt failure without detectable antecedent movement. The close agreement between the satellite-derived deformation zone and the eventual source area further supports the use of NISAR pixel-offset tracking for identifying and delineating actively deforming slopes prior to catastrophic failure.

Temporal Evolution of NISAR-Derived Horizontal Surface Displacement and Velocity

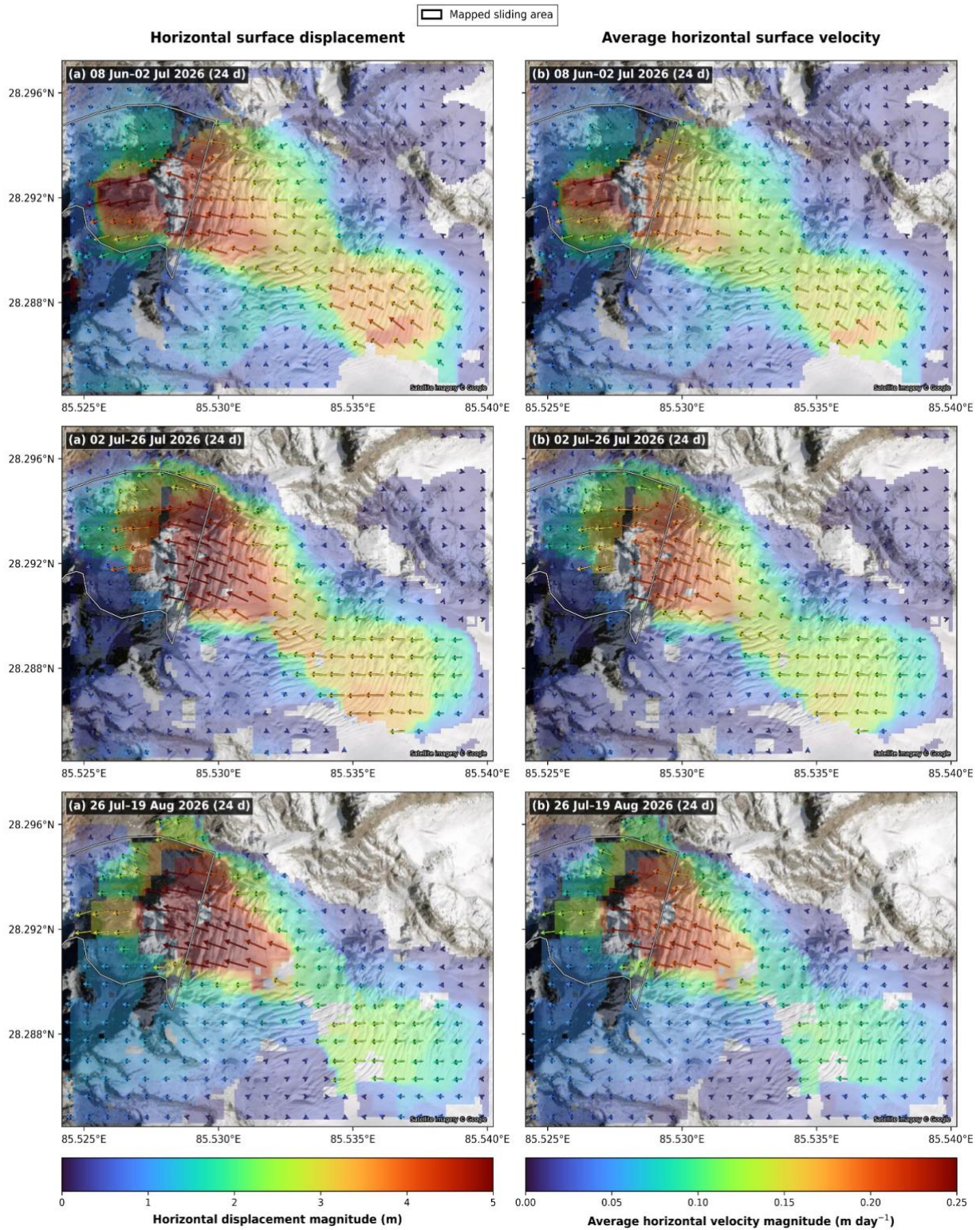


Figure 18: Temporal evolution of NISAR Track 98-derived pre-failure horizontal surface displacement and average horizontal velocity for three consecutive 24-day periods: 8 June-2 July, 2-26 July, and 26 July-19 August 2026. The left column shows horizontal displacement magnitude, while the right column shows the corresponding average horizontal velocity. Colour contours represent displacement or velocity magnitude, and vectors indicate the direction of horizontal ground movement derived from the NISAR slant-range and azimuth offsets. The mapped sliding area is outlined in each panel.

4.6 Past 30 days (27 July-25 August 2026) climatic state

To characterize the hydroclimatic state immediately preceding the 26 August 2026 event, conditions during the 30-day antecedent period (27 July-25 August 2026) were compared with the same calendar window for 1950-2025 (Figure 19). The 2026 period was markedly warmer than the historical baseline, with a mean air temperature of 5.09 °C compared with 3.90 °C, while accumulated positive degree-days increased from 117.11 to 152.60 °C Day. All 30 days remained frost-free, compared with a historical mean of approximately 28 days, indicating persistent positive-temperature conditions. Total precipitation reached 383.17 mm, about 6.1% higher than the historical mean of 361.27 mm. In contrast, total snowmelt declined sharply to 11.48 mm w.e., approximately 81% below the historical mean, while mean snow depth decreased from 0.026 m to only 0.002 m. Collectively, these conditions indicate an unusually warm and nearly snow-depleted pre-event environment accompanied by moderately enhanced precipitation. The reduced snowmelt despite higher temperatures reflects the limited snow available for melt, rather than weak thermal forcing. These antecedent conditions therefore suggest substantial preconditioning of the source area, although they should be interpreted as contributing environmental conditions rather than evidence of a single direct trigger.

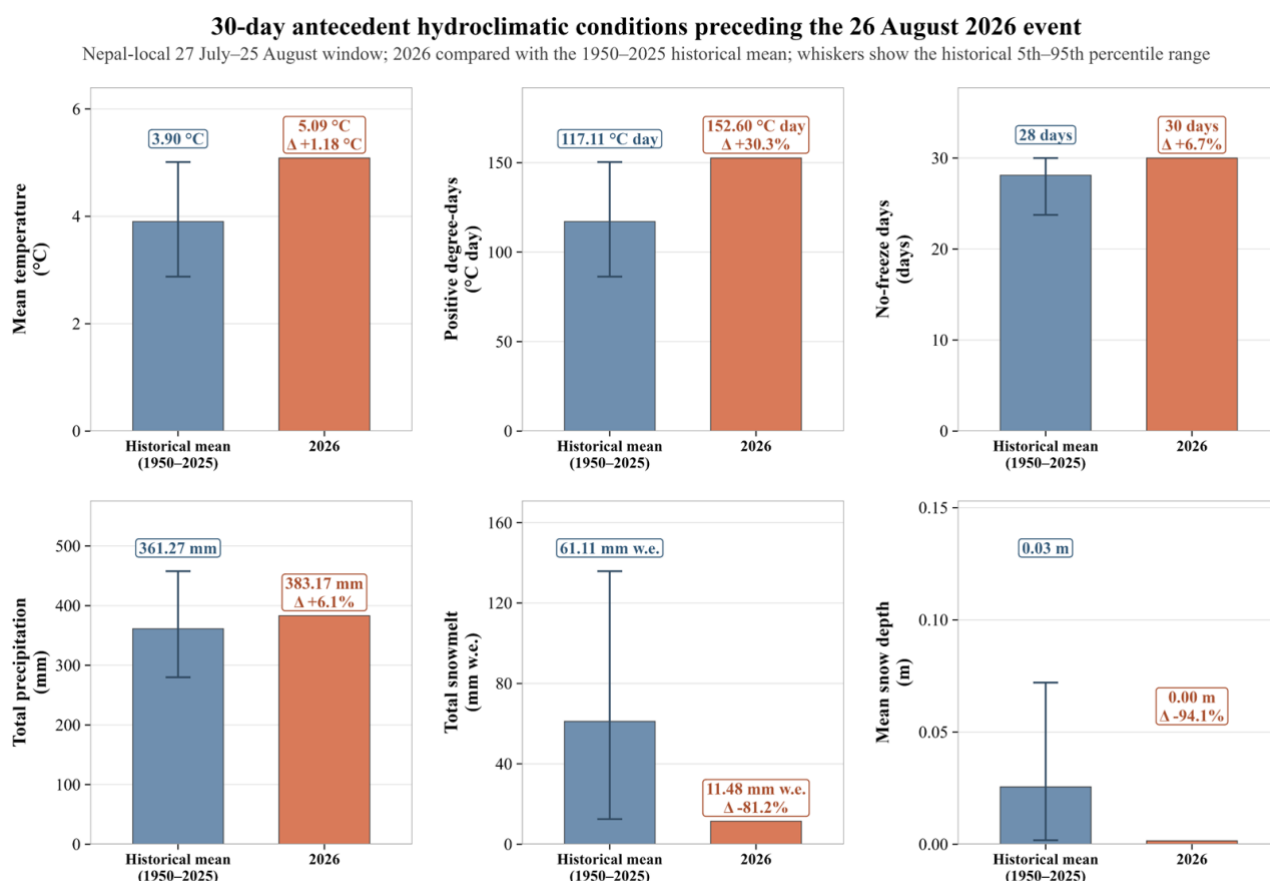


Figure 19: Comparison of 30-day antecedent hydroclimatic conditions during 27 July-25 August 2026 with the corresponding 1950-2025 historical mean at the Langtang Lirung source area.

4.7 Regional Seismic History (2010-2025)

The spatial distribution of regional seismicity from 2010 to 2025 demonstrates a pronounced geographical clustering, characterized by intense activity along major tectonic structures well away from the study area alongside total local quiescence (Department of Mines and Geology, National Seismological Center, 2026; USGS, 2026). While hundreds of low-to-moderate magnitude events (M_w 3-5) were recorded across the broader 100 km domain, the primary concentration of seismic activity occurred 60 to 100 km south and southeast of the site (Figure 20). This cluster represents the 2015 Gorkha earthquake sequence, which includes the dataset's highest-magnitude events — such as the 25 April M_w 7.8 mainshock and its 12 May M_w 7.3 aftershock, situated 78.2 km and 75.3 km away from the source area, respectively. In fact, all major regional events ($M_w \geq 6.0$) occurred at distances exceeding 69 km from the site, confirming that regional seismic hazards are strictly governed by distant fault systems rather than local structures beneath Langtang Lirung.

Crucially, the area within the innermost 5 km radius of the Bhotekoshi site remained completely devoid of any tectonic earthquakes throughout the entire 15-year observation period. This absence of local seismicity, paired with a standard global frequency-magnitude distribution across the broader region, indicates no anomalous local stress accumulation or active faulting beneath the source area. Because there is no tectonic precedent for local ground motion, the seismic signal recorded on 26 August 2026 cannot be attributed to a conventional earthquake. Instead, the results support a non-tectonic surface origin — specifically, the sudden detachment and rapid downhill movement of a massive rock-ice avalanche that subsequently triggered downstream flooding.

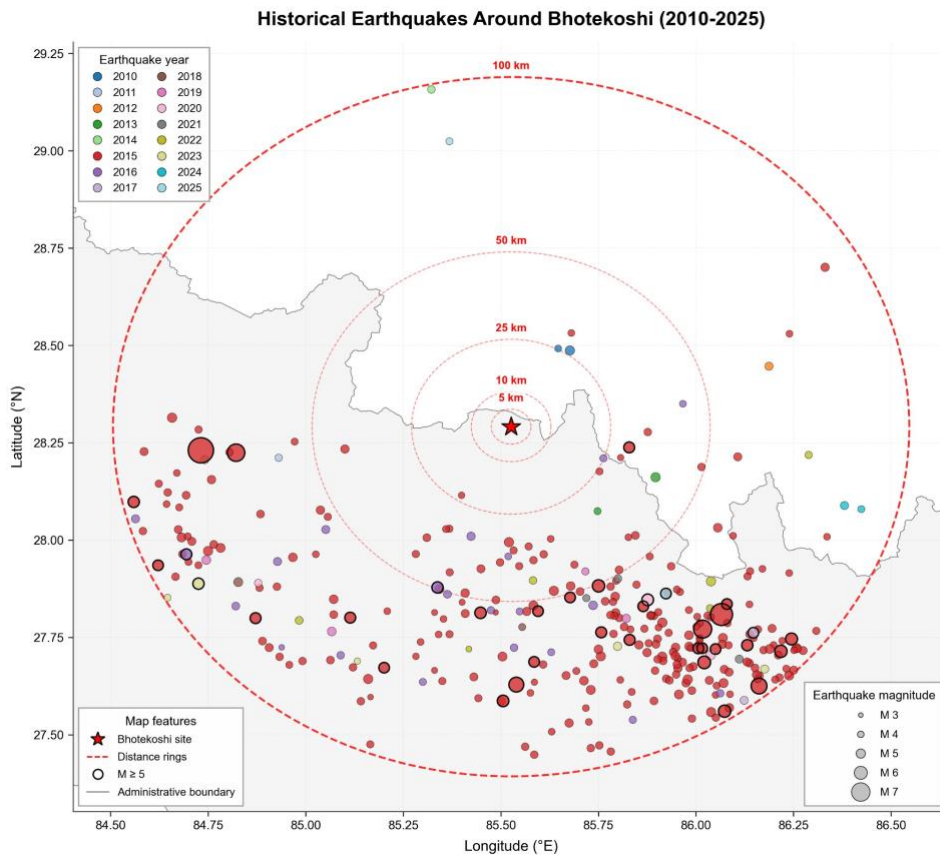


Figure 20: Regional seismicity within 100 km of the Langtang Lirung site, 2010-2025: event locations and magnitude (Data sources: National Seismological Center of Nepal and USGS).

Table 3. Top 10 highest-magnitude earthquake events within a 100 km radius of the rock-ice failure zone, showing their location, depth, magnitude, and distance from the source area (Data sources: National Seismological Center of Nepal and USGS).

Date	Location	Latitude (°)	Longitude (°)	Depth (km)	Magnitude (Mw)	Distance (km)
2015-04-25	67 km NNE of Bharatpur, Nepal	28.23	84.73	8.22	7.8	78.16
2015-05-12	Nepal	27.80	86.07	15	7.3	75.34
2015-04-26	21 km SSE of Kodari, Nepal	27.77	86.01	22.91	6.7	75.27
2015-04-25	71 km NNE of Bharatpur, Nepal	28.22	84.82	10	6.6	69.43
2015-05-12	42 km SSE of Kodari, Nepal	27.62	86.16	15	6.3	96.85
2015-04-25	0 km NNW of Dhulikhel, Nepal	27.62	85.54	10	6.1	73.70
2015-04-25	31 km SSE of Kodari, Nepal	27.68	86.02	10	5.6	83.03
1997-11-03	31 km SSE of Saga, China	29.07	85.38	33	5.5	88.61
2015-04-25	22 km WSW of Kodari, Nepal	27.88	85.75	10	5.5	50.51
2015-05-12	37 km SE of Kodari, Nepal	27.71	86.21	13.01	5.5	93.40

CHAPTER 5

Future Climate of Langtang Lirung (1985-2100)

BEYOND A FLASH FLOOD | THE BHOTEKOSHI-TRISHULI DISASTER IN NEPAL



To understand how climatic conditions at the Langtang Lirung source area may change in the future, this study used a NEX-GDDP-CMIP6 downscaled five General Circulation Models (GCM) (Annex 3; Eyring et al., 2016) covering the period 1985-2100. The GCM outputs were bias-corrected against ERA5-Land reanalysis data using the quantile mapping technique to improve their consistency with historical climate conditions. Two future climate scenarios were examined: SSP2-4.5, representing a moderate-emissions pathway, and SSP5-8.5, representing a high-emissions pathway. Results were analysed for the near future (2031-2050), mid future (2051-2070), and far future (2071-2100).

The projections show that the source area is expected to become significantly warmer and wetter during the 21st century. Annual mean temperature, which was historically about -2.3°C , is projected to increase by 3.7°C under SSP2-4.5 and by 6.1°C under SSP5-8.5 by the end of the century (Figure 21). This continued warming is expected to further reduce overnight refreezing, accelerating glacier thinning and permafrost degradation.

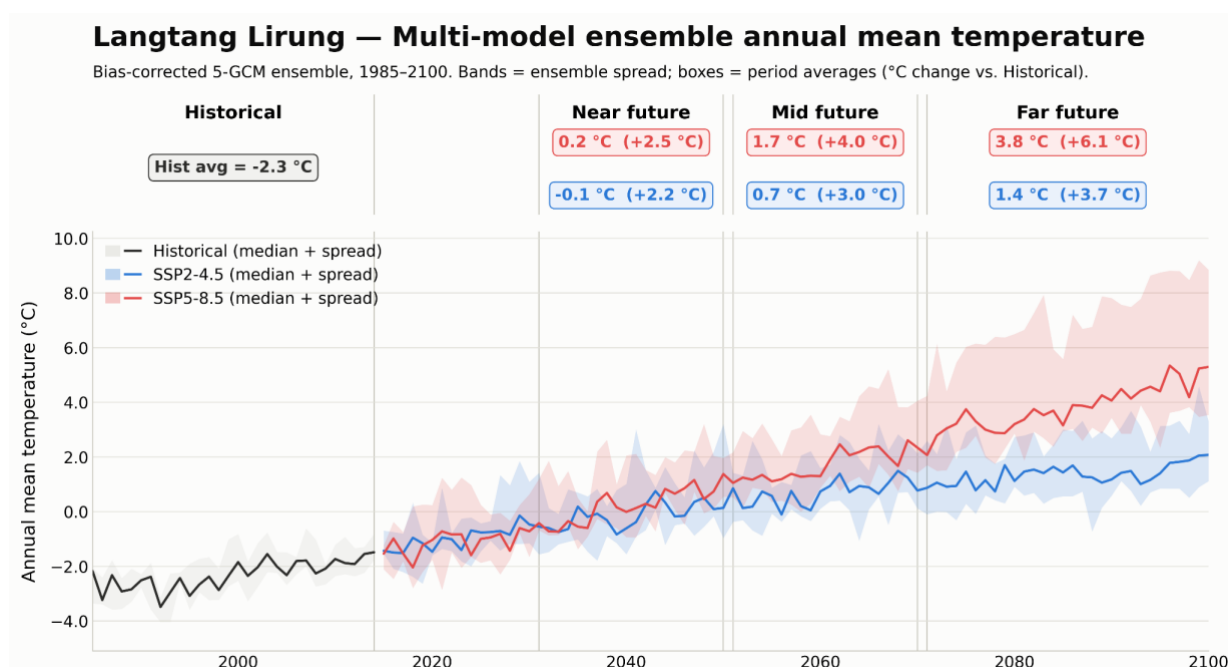


Figure 21: CMIP6 multi-model ensemble annual mean temperature, 1985-2100, SSP2-4.5 and SSP5-8.5 (bias-corrected 5-GCM ensemble).

Annual rainfall is also projected to increase substantially. Compared with the historical average of 1,306 mm per year, rainfall could reach about 1,560 mm (+19.5%) under SSP2-4.5 and 1,935 mm (+48.2%) under SSP5-8.5 by the end of the century. Increases are already evident in the near-future period, with rainfall rising by about 10% by 2050 (Figure 22). Combined with the observed decline in snowfall, these projections indicate that a larger share of future precipitation will fall as rain rather than snow. Overall, the results suggest that the source area will experience continued warming, less persistent snow cover, more rainfall, and increasing slope instability. Although the 26 August 2026 event was not triggered by extreme rainfall, these future conditions could increase the likelihood of similar rock-ice avalanches and related flood hazards in the Himalayan region.

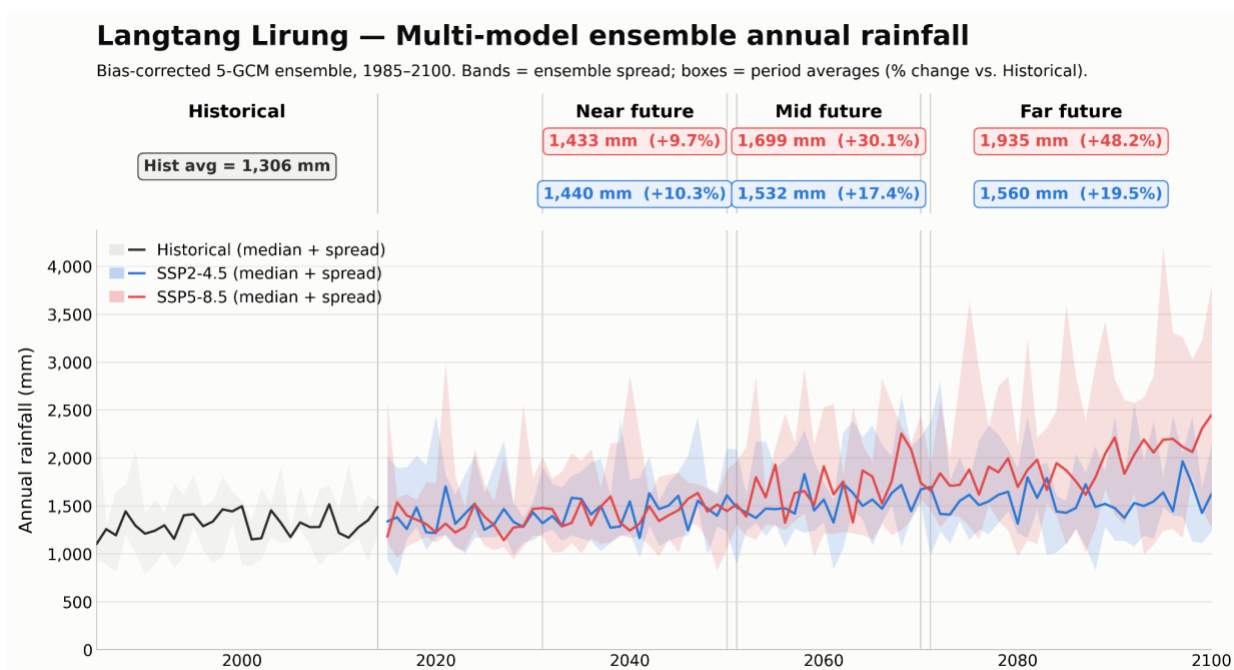


Figure 22: CMIP6 multi-model ensemble annual rainfall, 1985–2100, SSP2-4.5 and SSP5-8.5 (bias-corrected 5-GCM ensemble).

The annual freeze-thaw days show an initial increase under both scenarios, rising from a historical average of 216.9 days/year to 226.3 and 225.3 days in the near future and 228.6 and 232.6 days in the mid-future under SSP2-4.5 and SSP5-8.5, respectively (Figure 23). In the far future, freeze-thaw days remain elevated at 229.7 days under SSP2-4.5 but decline to 225.1 days under SSP5-8.5. This indicates that moderate warming may sustain freeze-thaw cycling, whereas stronger warming increasingly reduces sub-zero conditions, shifting toward predominantly unfrozen conditions. The late-century decline under SSP5-8.5 may influence freeze-thaw weathering, rockfall, slope stability, and related geohazards.

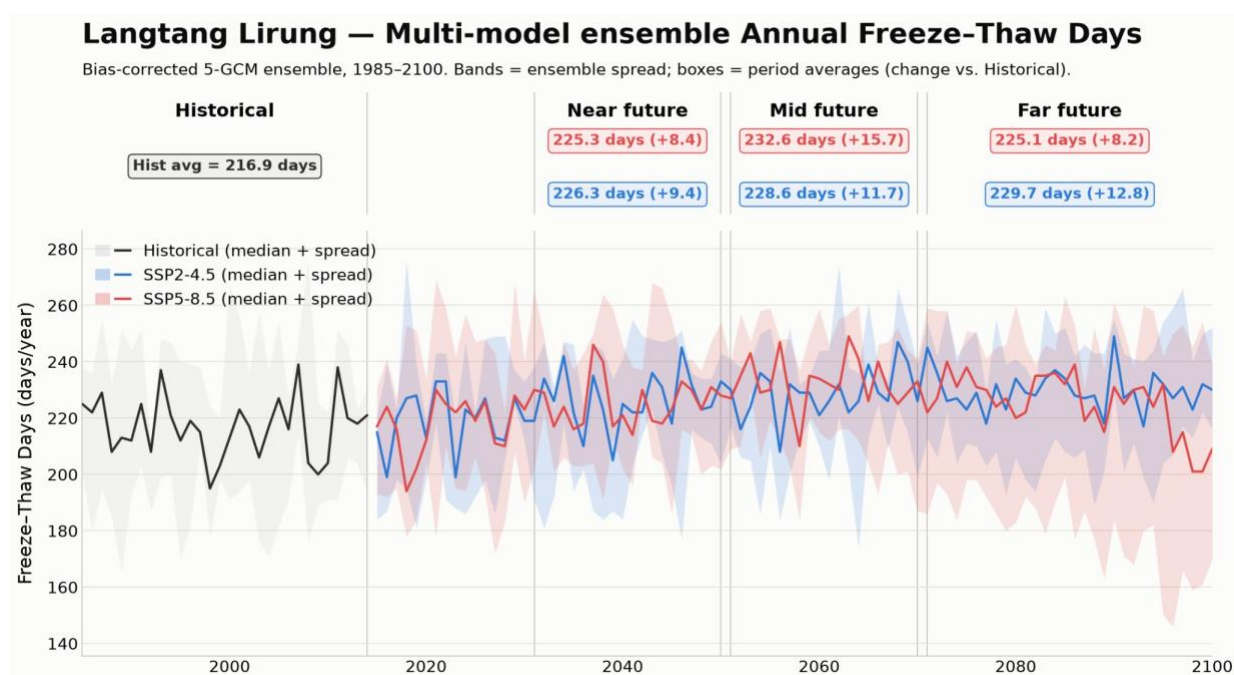


Figure 23: CMIP6 multi-model ensemble median annual freeze thaw days, 1985–2100, SSP2-4.5 and SSP5-8.5 (bias-corrected 5-GCM ensemble). A freeze-thaw day is defined as $T_{min} < 0^{\circ}\text{C}$ and $T_{max} > 0^{\circ}\text{C}$.

Annual positive-temperature days show a strong and continuous increase under both scenarios, rising from a historical average of 143.3 days/year to 172.7 and 180.6 days in the near future and 190.2 and 205.1 days in the mid-future under SSP2-4.5 and SSP5-8.5, respectively (Figure 24). By the far future, above-freezing days reach 201.9 days under SSP2-4.5 and 255.5 days under SSP5-8.5. The results indicate substantial warming across the Bhotekoshi-Trishuli Basin, with a much stronger increase under SSP5-8.5. The expansion of above-freezing conditions suggests a prolonged warm season, potentially accelerating snow and ice melt, permafrost degradation, glacier retreat, and related landslide and GLOF hazards.

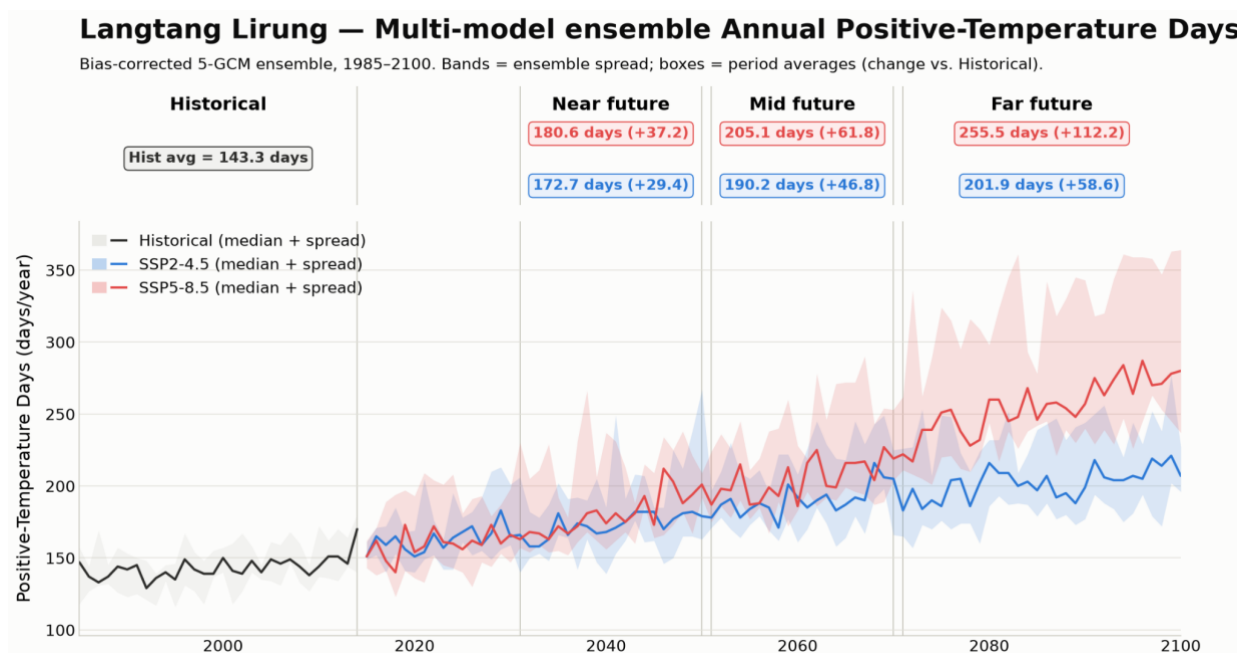
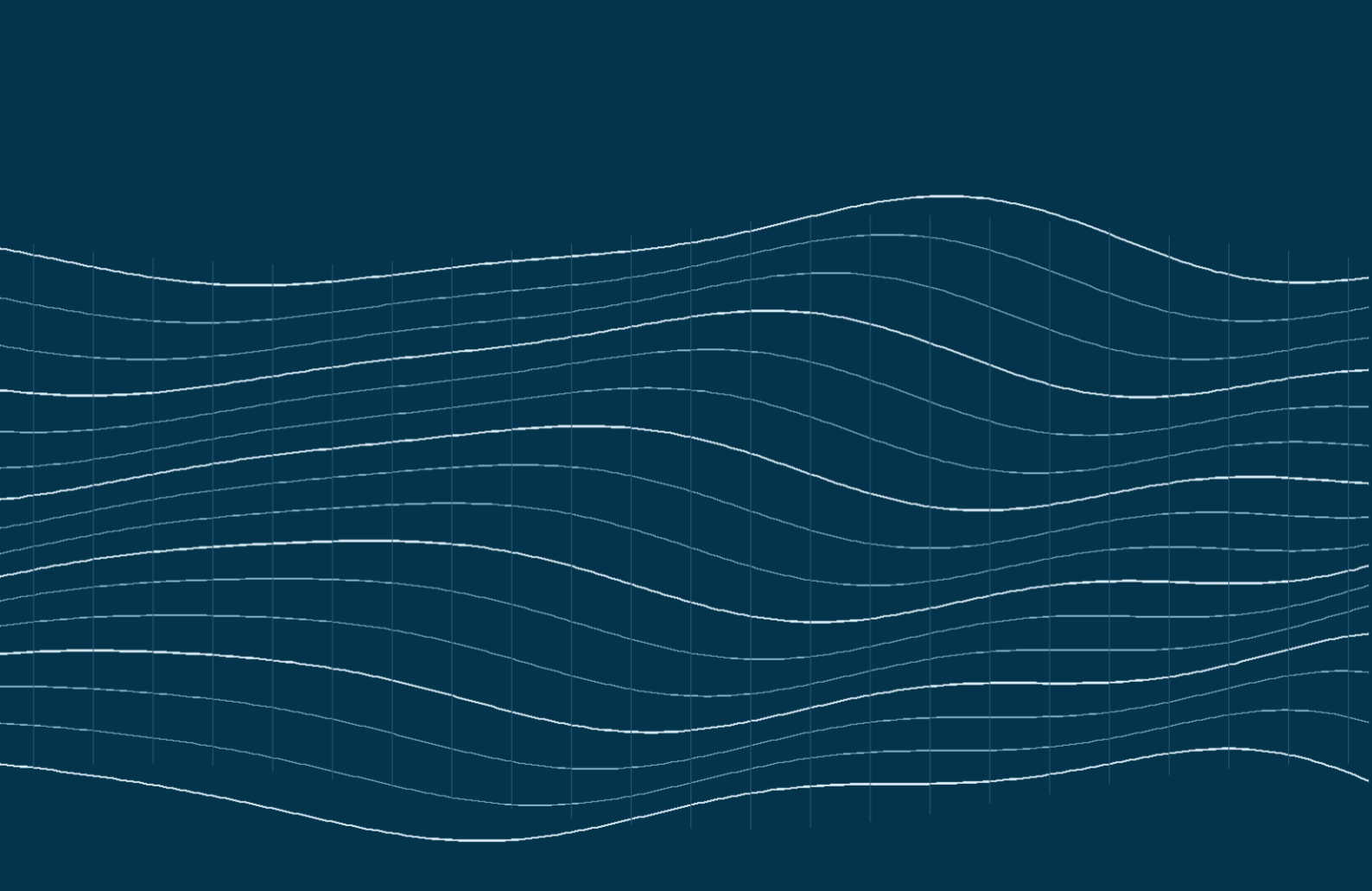


Figure 24: CMIP6 multi-model ensemble median positive temperature days, 1985-2100, SSP2-4.5 and SSP5-8.5 (bias-corrected 5-GCM ensemble). A positive-temperature day is defined as a day with daily mean 2-m air temperature $> 0^{\circ}\text{C}$.



CHAPTER 6

Reconstruction of the Bhotekoshi-Trishuli Disaster through Modelling and Simulation

BEYOND A FLASH FLOOD THE BHOTEKOSHI-TRISHULI DISASTER IN NEPAL



6.1 Overall Methodology

To reconstruct how the 26 August 2026 source-area collapse evolved into the destructive downstream event, a coupled RAMMS-HEC-RAS modelling framework was developed. RAMMS model was used to simulate the initial rock-ice mass movement from the Langtang Lirung source area and its propagation toward the valley, while HEC-RAS 2D was configured for non-Newtonian debris-flow simulation to model the subsequent downstream movement of the highly sediment- and debris-laden surge through the Bhotekoshi-Trishuli river corridor. This approach allowed the transition from the source-area rock-ice failure to the downstream debris-flow/flood process to be represented within a physically connected modelling framework.

The purpose of reconstructing the disaster through modelling was to understand how the rock-ice failure evolved into the downstream destructive flow and to estimate key flow characteristics, particularly flood/debris-flow depth, velocity, arrival time, and inundation extent at different locations along the river corridor. Because direct observations were not available continuously throughout the affected area, the coupled modelling framework provided spatially distributed information on flow conditions between and beyond the available observation points. Following validation against satellite imagery, field observations, high-flood marks, and documented event timing, the reconstructed model can also provide a transferable framework for investigating similar cascading multi-hazard events in other mountainous regions.

RAMMS (Rapid Mass Movement Simulation) is a numerical modelling system designed to simulate rapid gravitational mass movements over complex terrain (Christen, Kowalski, & Bartelt, 2010). The model represents the movement of the flowing mass using depth-averaged governing equations and a Voellmy-type resistance formulation, in which the friction parameters μ and ξ control basal resistance and velocity-dependent turbulent resistance, respectively. In this study, RAMMS was applied to reconstruct the release, acceleration, runout, flow depth, velocity, and downstream movement of the rock-ice mass originating from the Langtang Lirung source area. Terrain information, reconstructed release geometry, material properties, and friction parameters were used as the principal model inputs.

The RAMMS simulation produced an estimated downstream outflow volume of approximately 233 Mm³. This simulated outflow constituted the coupling variable between the two models and was transferred to the HEC-RAS model as the upstream input for the debris-flow simulation. RAMMS model therefore represented the source-area rock-ice mass movement and runout, whereas HEC-RAS model represented the downstream propagation, spreading and attenuation of the debris-laden flow through the river corridor.

HEC-RAS (Hydrologic Engineering Center's River Analysis System) model was used to simulate the downstream propagation of the event in two dimensions. Because the reconstructed surge contained a substantial mixture of water, sediment, rock and debris, the flow was represented as a non-Newtonian debris flow rather than as conventional clear-water flooding. In non-Newtonian flow, the relationship between shear stress and deformation differs from that of ordinary water and is influenced by the concentration and rheological behaviour of the transported material. The HEC-RAS 2D simulation therefore incorporated the adopted non-Newtonian flow representation to reproduce the propagation of the debris-laden surge through the steep and confined Bhotekoshi-

Trishuli valley. Model outputs included maximum flow depth, velocity, water/debris-flow surface elevation, arrival time and inundation extent.

The overall modelling sequence therefore consisted of four stages: (1) reconstruction of the Langtang Lirung rock-ice failure, (2) RAMMS model simulation of mass movement from the source toward the valley and estimation of the downstream outflow volume, (3) transfer of the approximately 233 Mm³ RAMMS-derived outflow to HEC-RAS model as the upstream hydraulic forcing, and (4) HEC-RAS 2D model simulation of downstream flood propagation and inundation (Figure 23). Model outputs were subsequently evaluated using available satellite imagery, field observations, high-flood marks, documented event timing, and observed impacts along the river corridor.

Terrain and geometric information required for the simulations was derived from the available DEM and river-channel data, while land-cover information was used to support hydraulic roughness parameterization. Satellite imagery was used both to reconstruct the source and affected areas and to compare the simulated downstream flood extent with the observed inundation pattern.

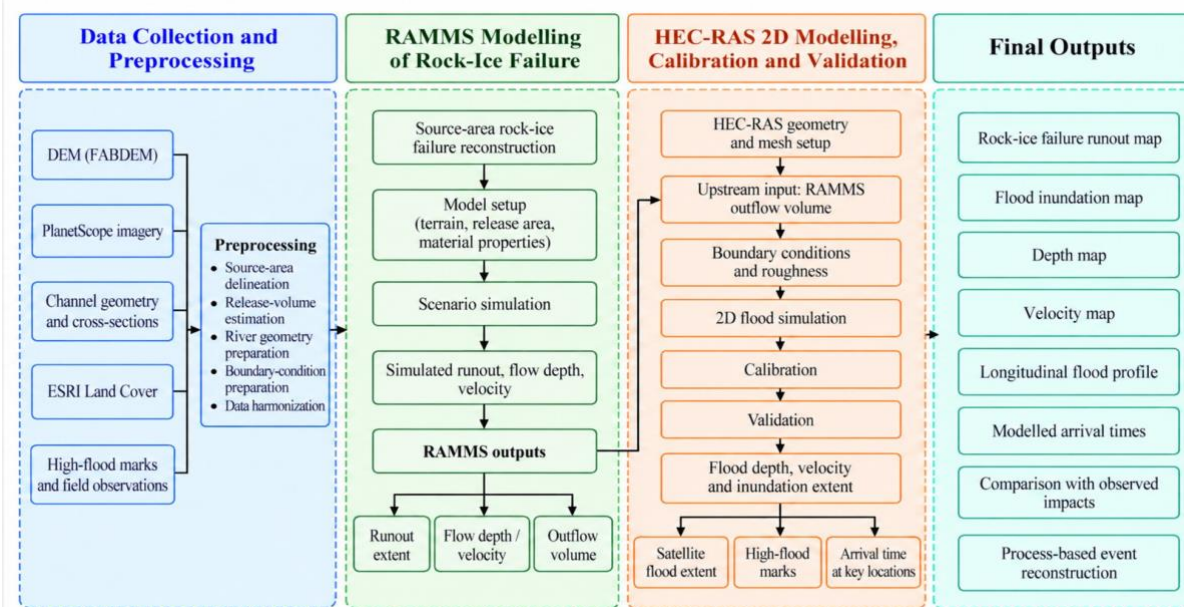


Figure 25: Overall methodological framework of the RAMMS-HEC-RAS modeling framework, showing the key input data, data processing, modelling steps, and resulting final outputs.

6.2 Modelling Outputs

The coupled RAMMS-HEC-RAS modelling framework was used to reconstruct the initial rock-ice mass movement and the subsequent downstream propagation of the resulting debris-flow surge. RAMMS represented the source-area failure and generated an estimated outflow volume of approximately 233 Mm³, which was subsequently introduced into HEC-RAS 2D for downstream debris-flow simulation.

6.2.1 Avalanche Simulation Outputs

The RAMMS model simulation indicates that the avalanche originated from the Langtang Lirung glacier area at an elevation of approximately 5,200 m. The failed rock-ice mass descended about 1.2 km vertically before entering and mixing with the Lhende River. The simulated flow then continued downstream through the steep and confined valley toward Gyirong Port.

The maximum flow-height map shows the largest flow depths in the upper release and runout zone, where the moving mass was strongly confined by the terrain. Local flow heights approached 150 m, while the simulated maximum depth at Gyirong Port was about 94 m (Figure 26). Near Gyirong Port, which acts as a junction in the river corridor, the map also shows a small zone of backflow or flow spreading, indicating local flow interaction and temporary accumulation caused by the valley geometry. The maximum-velocity map shows that the avalanche accelerated rapidly after leaving the Langtang Lirung source area, with local velocities approaching 100 m/s (350 km/hr) along the steep upper slope. The velocity gradually decreased as the mass moved downstream and became more channelized within the Lhende River. At Gyirong Port, the simulated maximum velocity was approximately 60 m/s (216 km/h), indicating that the surge still retained very high kinetic energy at the junction (Figure 27).

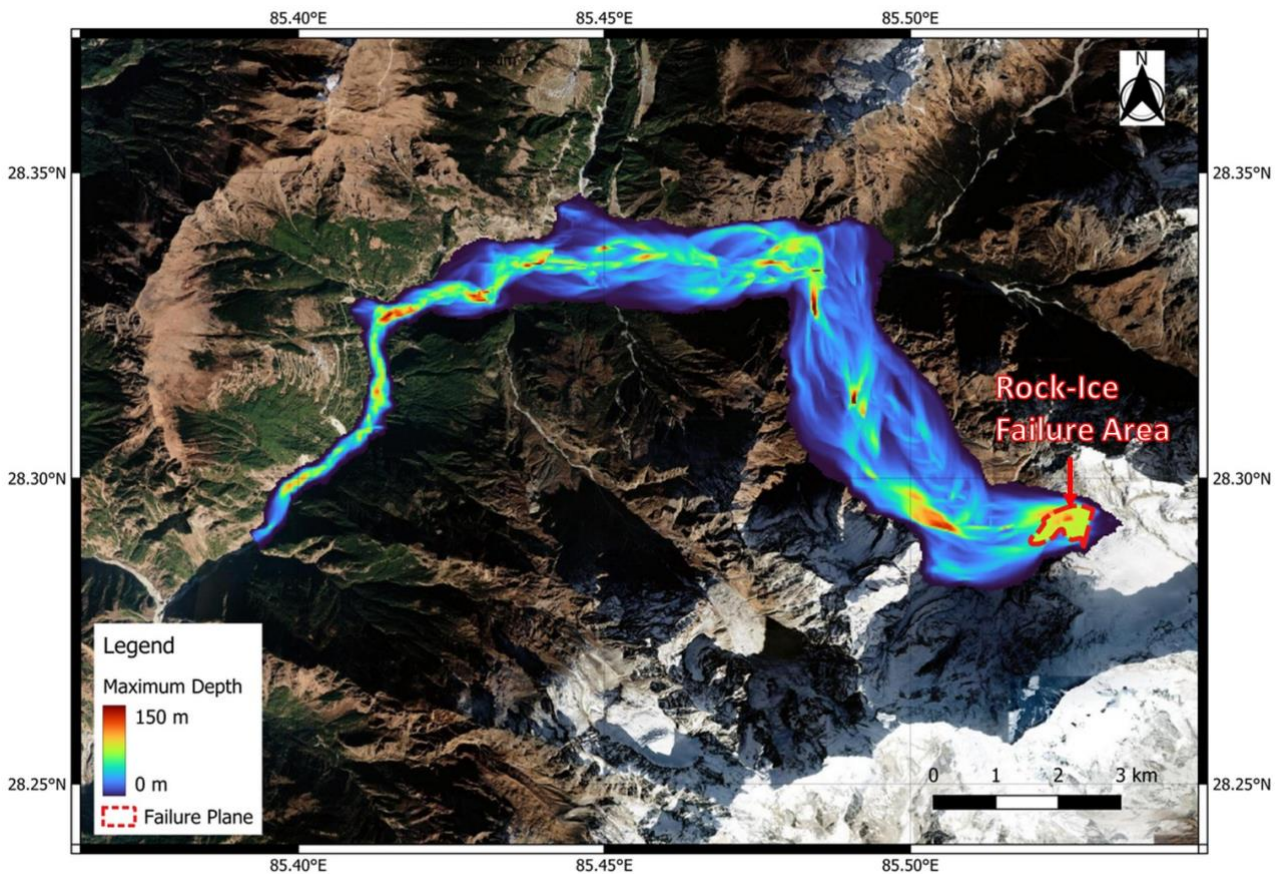


Figure 26: RAMMS model simulated maximum flow height of the Langtang Lirung rock-ice avalanche.

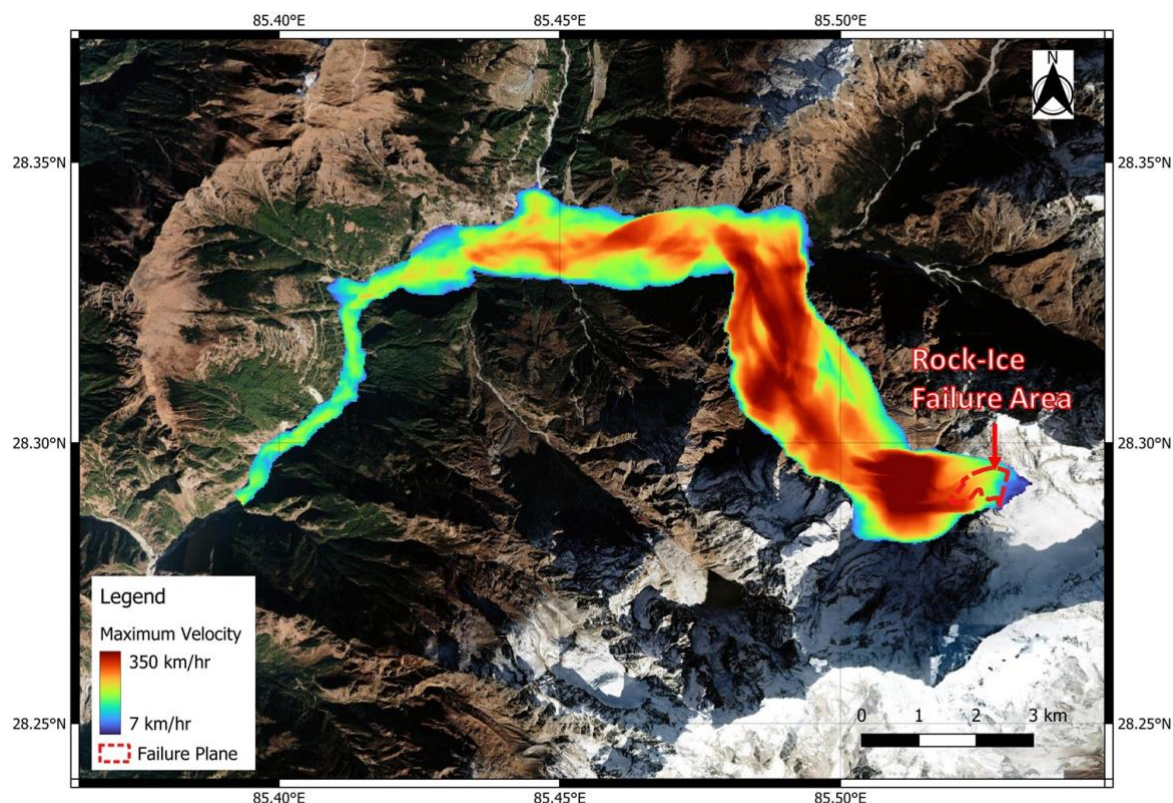


Figure 27: RAMMS model simulated maximum flow velocity of the Langtang Lirung rock-ice avalanche.

6.2.2 Downstream Debris Flow Propagation and Inundation

The HEC-RAS 2D non-Newtonian model simulation was used to propagate the approximately 233 Mm³ RAMMS model derived outflow through the Bhotekoshi-Trishuli river corridor. The simulation represents the event as a debris-laden surge rather than conventional clear-water flow, accounting for the rheological behaviour associated with the transported sediment and debris. Simulated depth and velocity varied considerably along the river owing to changes in valley confinement, channel width, longitudinal slope and local topography. The simulated flood arrived at Gyirong Port (22 km from source area) at 08:48 NPT, with a maximum modelled depth of 94 m and velocity of 60 m/s (216 km/h). At Timure (25.6 km from source area), the simulated arrival time was 08:51, with a maximum depth of 56 m and velocity of 38 m/s (136.8 km/h). At Syabrubesi (30 km from source area), the flood arrived at approximately 08:57, with a maximum depth of 56 m and velocity of 32 m/s (115.2 km/h). Farther downstream, the flood reached Betrawati (67.6 km from source area) at approximately 09:20, where the model produced a maximum depth of 35 m and velocity of 23 m/s (82.8 km/h). At Trishuli (75.3 km from source area), the simulated arrival time was approximately 09:30, with a maximum depth of 32 m and velocity of 18 m/s (64.8 km/h). At Devighat (84.7 km from source area), the modelled wave arrived at approximately 09:42, with a maximum depth of 32 m and velocity of 12 m/s (43.2 km/h) (Figure 28).

Overall, the results show a clear downstream reduction in flow velocity. The simulated velocity decreased from 60 m/s near Gyirong Port to 12 m/s at Devighat. This indicates that the initial surge was extremely energetic in the steep upper valley but gradually lost momentum as it moved through the wider and less steep downstream river reaches.

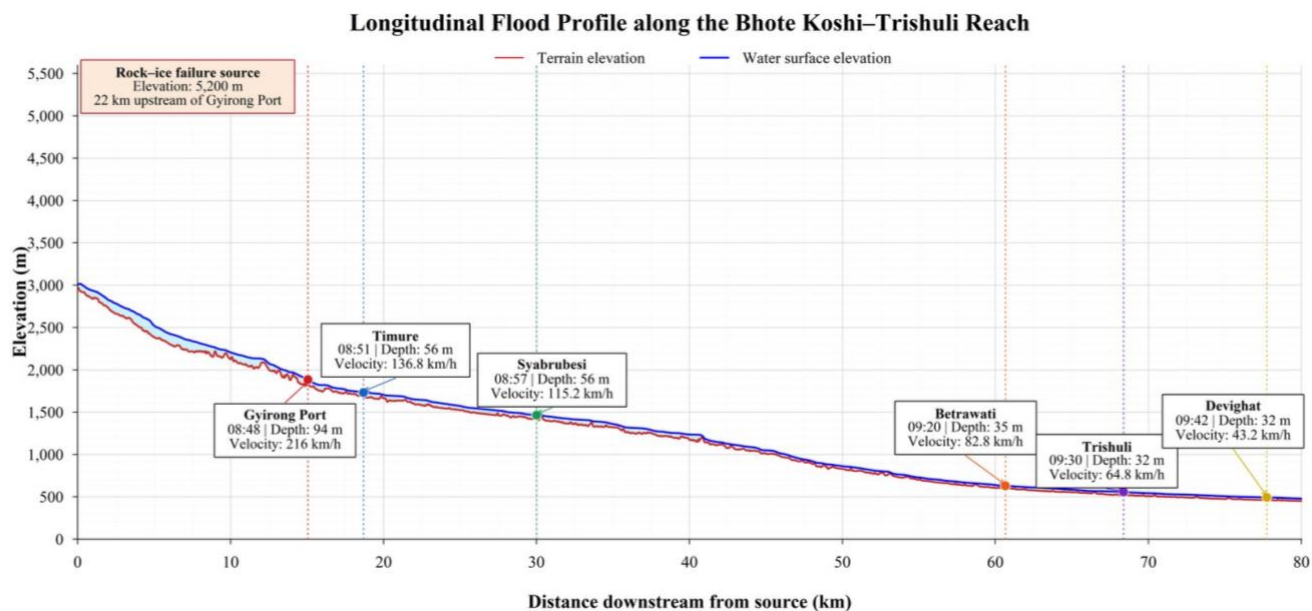


Figure 28: Longitudinal profile of the HEC-RAS 2D debris-flow simulation along the Bhoté Koshi–Trishuli corridor, showing terrain elevation, simulated flow-surface elevation, and modelled arrival time, maximum depth and velocity at key locations.

6.2.3 Comparison of Modelled Flood Inundation Extent and Against Observed Impacts

The model results were compared with satellite imagery and post-flood field photographs at six key locations: Gyirong Port, Timure, Syabrubesi, Betrawati, Trishuli, and Devighat (Figure 29). The simulated inundation pattern shows good spatial agreement with the observed affected river corridor and damaged areas. The comparison also confirms the downstream progression of the flood, with simulated arrival time, maximum depth, and velocity decreasing progressively from the steep upper reach toward Devighat. This agreement between the model outputs and observed impacts supports the overall reliability of the flood reconstruction.

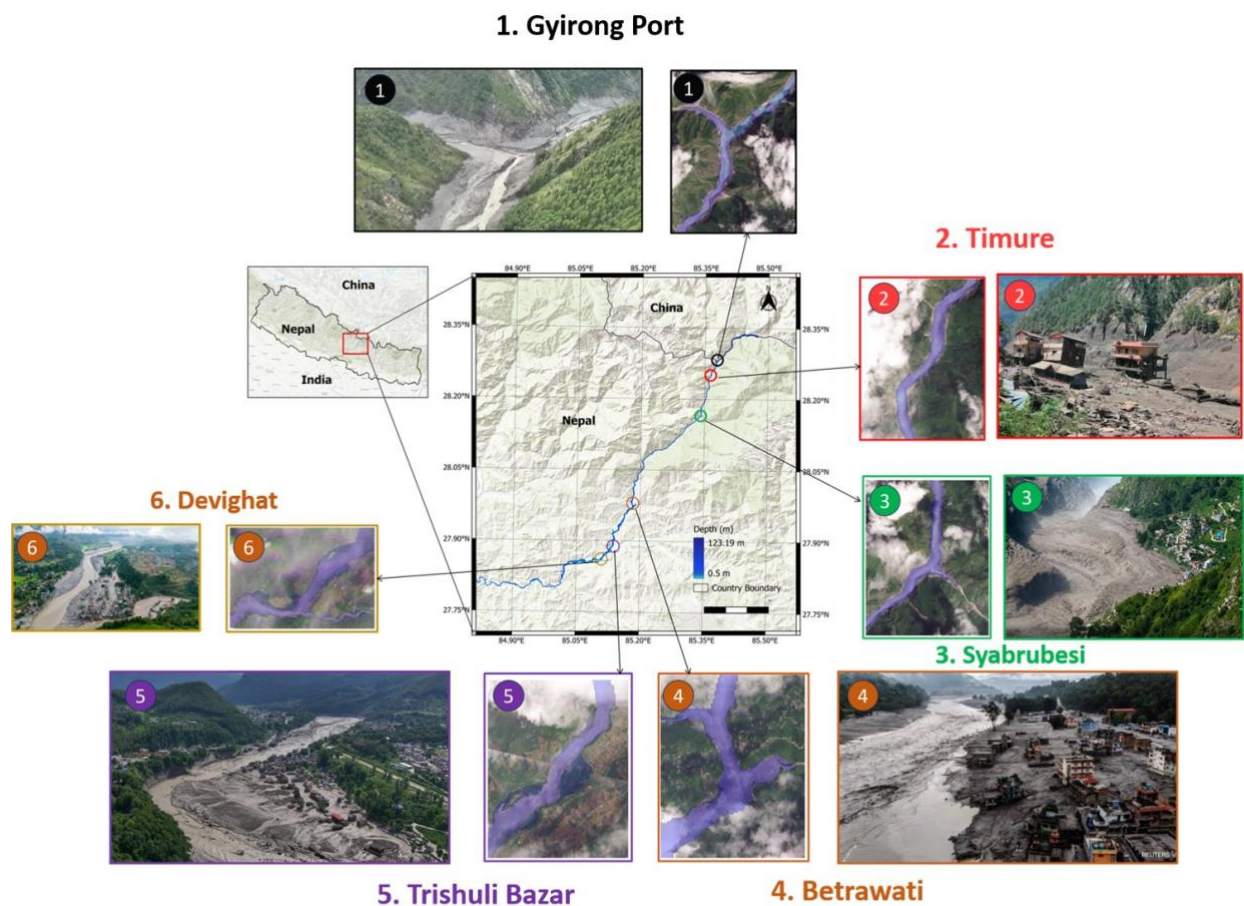
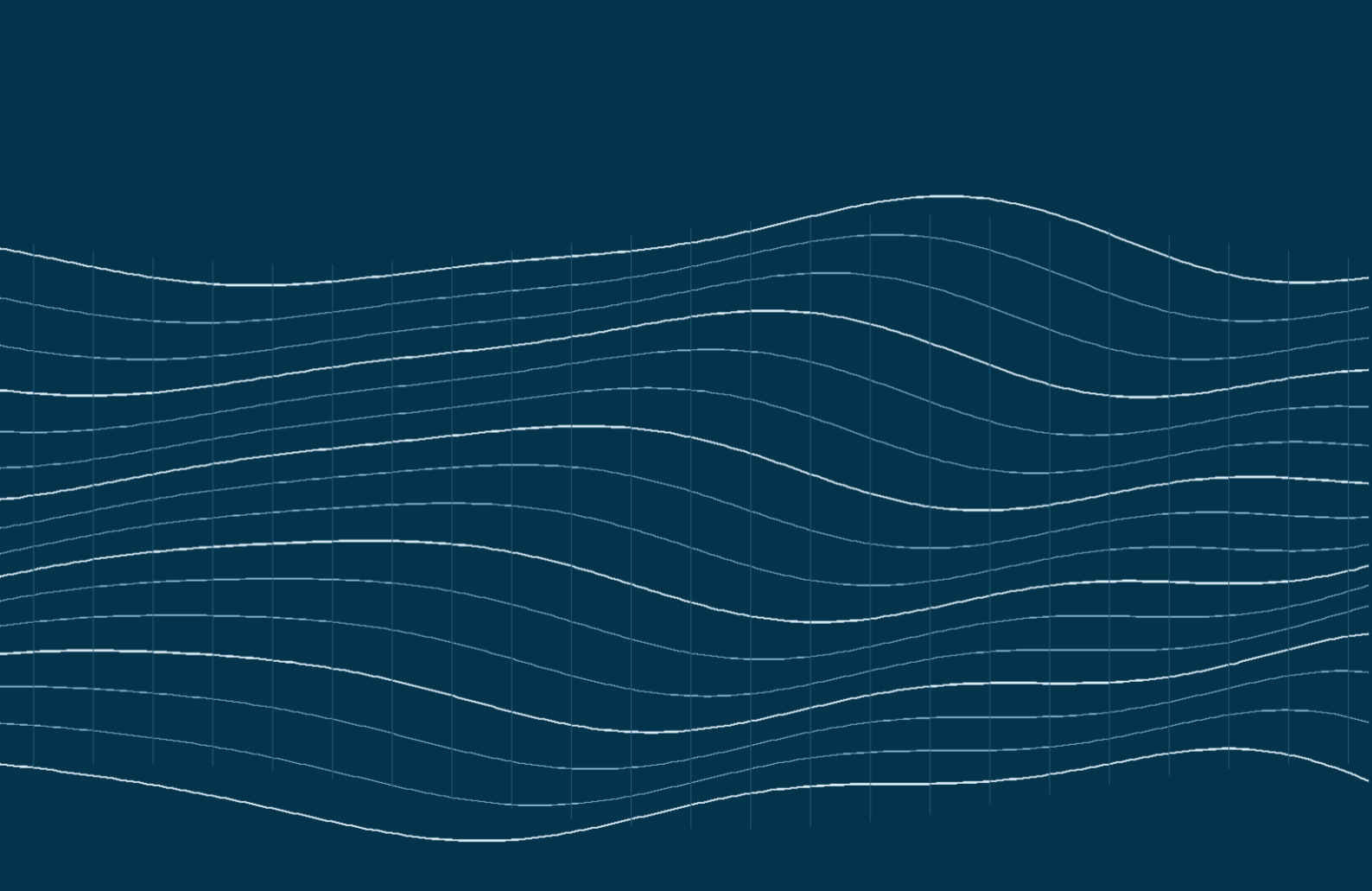


Figure 29: Comparison of RAMMS-HEC-RAS model simulated inundation extent against satellite imagery and post-flood field photographs at Gyirong Port, Timure, Syabrubesi, Betrawati, Trishuli, and Devighat.

Table 4. Comparison of Modelled and Observed Flood Arrival Times, Maximum Depth, and Velocity at Key Locations Along the Bhotekoshi-Trishuli Corridor.

S.N.	Location	Modelled Arrival Time (NPT)	Observed Arrival Time (NPT)	Modelled Max. Depth (m)	Modelled Velocity
1	Gyirong Port	08:48	08:44	94	60 m/s (216 km/h)
2	Timure	08:51	08:53	56	38 m/s (136.8 km/h)
3	Syabrubesi	08:57	~08:55-09:00	56	32 m/s (115.2 km/h)
4	Betrawati	09:20	09:20	35	23 m/s (82.8 km/h)
5	Trishuli	09:30	~09:30-09:35	32	18 m/s (64.8 km/h)
6	Devighat	09:42	09:42	32	12 m/s (43.2 km/h)



CHAPTER 7

Lessons Learned and the Way Forward

BEYOND A FLASH FLOOD | THE BHOTEKOSHI-TRISHULI DISASTER IN NEPAL



The Bhotekoshi-Trishuli Flash Flood Disaster provides important lessons for disaster risk management in Nepal and across the Hindu Kush Himalayan region. The event demonstrated that disasters in high-mountain environments can evolve rapidly, involve several interacting hazards, and produce impacts far beyond those anticipated from conventional flood-risk assessments. The following key lessons emerge from the disaster.

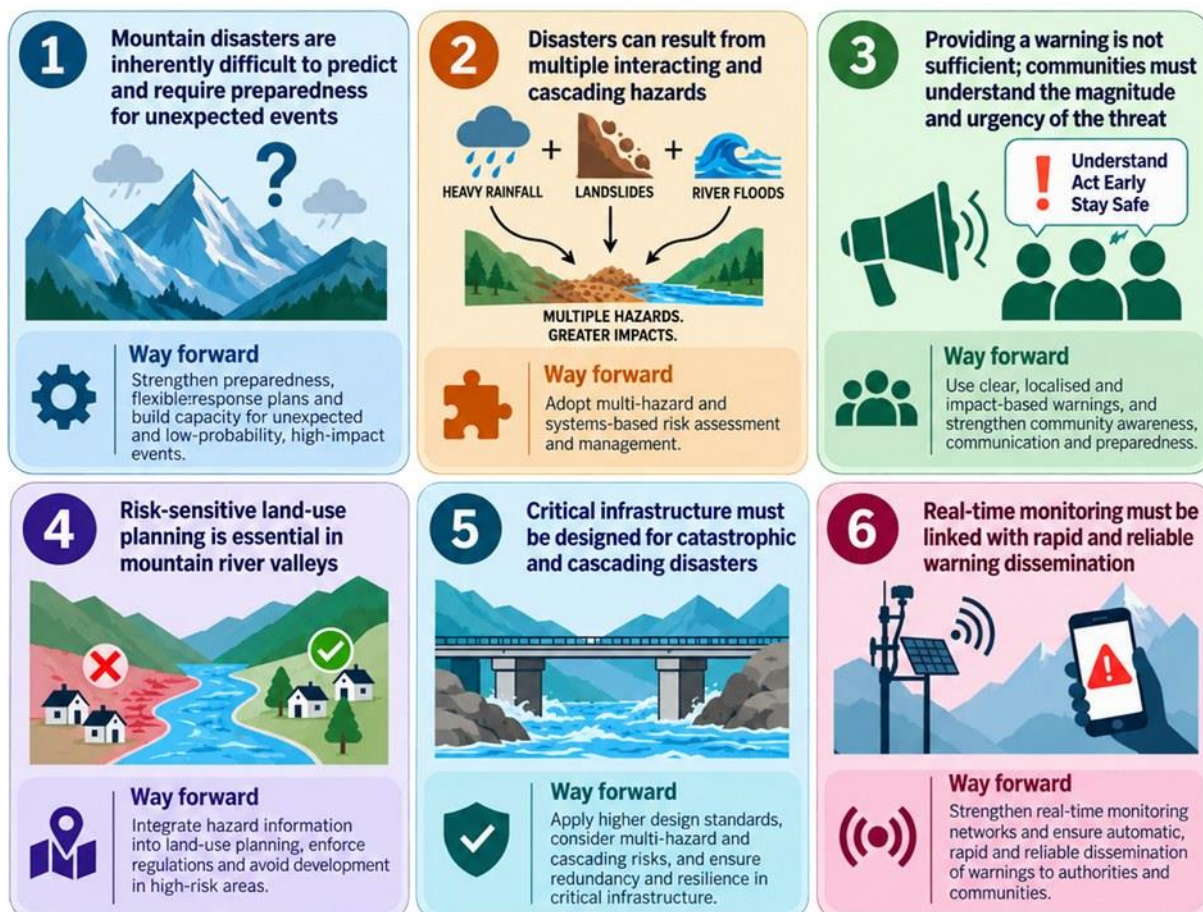


Figure 30: Lessons learned and way forward for reducing risks from Bhotekoshi-Trishuli flash flood disaster.

1. Mountain Disasters Are Inherently Difficult to Predict and Require Preparedness for Unexpected Events

Mountain regions such as the Himalayas are characterized by steep and unstable terrain, glaciers and snowfields, rock slopes, narrow valleys, difficult accessibility, and limited monitoring infrastructure. These conditions make it extremely challenging to observe all potential hazards continuously or predict precisely when a catastrophic event will occur.

The Bhotekoshi-Trishuli disaster illustrates this challenge. The initiating processes occurred in a remote high-mountain environment where direct observation and ground-based monitoring were limited. The situation developed rapidly, leaving very little time or no time to understand the event and respond downstream. Conventional rainfall and river monitoring alone may therefore be insufficient for detecting such complex mountain hazards.

The important lesson is that disaster preparedness cannot depend solely on our ability to predict a specific event. Monitoring systems should combine satellite observations, remote sensing,

weather and hydrological monitoring, seismic and geohazard information, field observations, and emerging AI-based techniques. At the same time, emergency plans should consider extreme scenarios that may not have occurred previously or may not be represented in historical records.

2. Disasters Can Result from Multiple Interacting and Cascading Hazards

The Bhotekoshi-Trishuli disaster should not be viewed simply as a conventional flash flood. Preliminary observations indicate that several physical processes interacted within a very short period. A rock-ice avalanche and associated mass movement appear to have contributed to river blockage and temporary impoundment of water. The subsequent sudden release generated a highly destructive flood containing large quantities of sediment, rocks and debris.

As the flood travelled downstream, it caused further erosion, channel changes, destruction of settlements and damage to infrastructure. The failure of roads, bridges, communication systems and other facilities subsequently created additional difficulties for rescue, evacuation and relief operations.

The disaster therefore demonstrates that one hazard can trigger another, creating cascading impacts that become much larger than the initial event. Future risk assessments in Nepal and other Himalayan countries should consequently move beyond single-hazard approaches. Floods, landslides, avalanches, glacial hazards, earthquakes, river blockage, debris flows and infrastructure failures need to be considered as interconnected processes.

3. Providing a Warning Is Not Sufficient; Communities Must Understand the Magnitude and Urgency of the Threat

Warnings were reportedly communicated during the event, but one of the major challenges was that communities could not fully anticipate the extraordinary magnitude and destructive nature of what was approaching. People living along the river are familiar with seasonal floods and fluctuations in river levels. Consequently, a general warning about a "flood" may not have communicated that an exceptionally large, fast-moving and debris-laden event could arrive within a very short period.

This highlights an important distinction between receiving a warning and understanding what that warning means for immediate action. When people hear the word "flood," they may interpret it according to their previous experience. If the approaching event is fundamentally different from anything experienced before, conventional terminology may fail to generate the necessary sense of urgency.

Future warning systems should therefore use impact-based communication. Messages should clearly explain the expected consequences, the urgency of evacuation, where people should move, and what actions they should avoid. For extreme events, communities should be instructed to evacuate immediately to predetermined safe areas rather than waiting to observe changes in the river.

The disaster also raises the broader question of whether conventional terminology adequately communicates catastrophic mountain hazards. Public awareness and warning protocols may need distinct categories or terminology for exceptionally destructive cascading events so that

communities immediately recognize that the situation is fundamentally different from a normal flood.

4. Risk-Sensitive Land-Use Planning Is Essential in Mountain River Valleys

Many settlements and economic activities in Himalayan valleys are located close to rivers because relatively flat and accessible land is scarce. However, this creates significant exposure to floods, debris flows, erosion and sudden changes in river channels.

The Bhotekoshi-Trishuli disaster demonstrated the consequences of development in highly exposed river corridors and floodplain areas. Houses, businesses and other facilities located close to the river experienced severe impacts when the scale of the event exceeded what communities had previously experienced or anticipated.

A major lesson is that historical experience alone should not determine where future development is permitted. Land-use planning should be based on multi-hazard risk assessments that consider not only conventional river flooding but also extreme floods, debris flows, landslides, natural river blockages, channel migration and other cascading hazards.

Post-disaster reconstruction provides an important opportunity to correct existing vulnerabilities. Highly exposed areas should be identified as restricted-development or no-build zones where appropriate. New settlements and important public facilities should be located in safer areas. Reconstruction should therefore follow the principle of building back safer and, where necessary, relocating to safer locations.

5. Critical Infrastructure Must Be Designed for Catastrophic and Cascading Disasters

The disaster caused severe disruption to roads, bridges, health facilities, schools, hydropower facilities and other infrastructure. The experience demonstrates that critical infrastructure in mountain valleys may be designed to withstand conventional floods but remain highly vulnerable to extreme events involving debris, sediment, erosion, channel changes and very high flow velocities.

The consequences of infrastructure failure extend far beyond the physical damage itself. For example, the loss of a bridge can isolate communities and prevent rescue teams, ambulances and relief supplies from reaching affected areas. Damage to roads can significantly delay emergency response. Damage to hospitals and health posts can reduce medical capacity at precisely the time it is most urgently required. Similarly, disruption of electricity and telecommunications can affect warning dissemination and coordination of emergency operations.

Critical infrastructure should therefore be subjected to multi-hazard and extreme-event stress testing. The location and design of bridges, roads, hospitals, schools, hydropower facilities and communication infrastructure should consider catastrophic scenarios beyond conventional design floods. Redundancy should also be incorporated so that the failure of one road, bridge, power supply or communication system does not completely isolate affected communities.

6. Real-Time Monitoring Must Be Linked with Rapid and Reliable Warning Dissemination

The Bhotekoshi-Trishuli disaster reinforces the importance of real-time monitoring, particularly because catastrophic mountain events can develop and travel downstream extremely quickly. However, monitoring by itself is not sufficient. Information must be rapidly interpreted, converted into an actionable warning, communicated through responsible authorities and received by communities with enough clarity to trigger immediate action.

A comprehensive system should integrate satellite and remote-sensing observations, weather monitoring, river gauges, glacier and slope monitoring, seismic information, hydrological and hydraulic modelling, and other relevant observations. Information from these sources should be continuously analysed to identify abnormal conditions and rapidly estimate potential downstream consequences.

Equally important is the last-mile communication system. Warnings should reach local governments, emergency responders and communities through multiple channels, including mobile alerts, sirens, radio, social media and community networks. Clear institutional responsibilities should determine who issues the warning, who communicates it locally, and who orders or facilitates evacuation.

Because the Bhotekoshi-Trishuli is part of a transboundary Himalayan system, timely exchange of upstream information across national boundaries is also critical. Strengthened regional cooperation on monitoring, data sharing and emergency communication could substantially increase the warning time available to downstream communities.

Overall, Lesson: A Paradigm Shift in Himalayan Disaster Risk Management

The Bhotekoshi-Trishuli disaster demonstrates that we may not always be able to predict exactly when, where and how a catastrophic mountain disaster will occur. However, we can prepare for the unexpected.

The experience calls for a fundamental shift from conventional flood management toward multi-hazard and cascading disaster-risk management. Future approaches should recognize that extreme mountain disasters can originate from several interacting processes, develop extremely rapidly, cross administrative and national boundaries, and simultaneously affect communities, infrastructure and essential services.

The key lesson is therefore not simply to improve flood forecasting. It is to build an integrated system in which science and technology, real-time monitoring, risk-sensitive land-use planning, resilient infrastructure, effective risk communication, community preparedness, rapid evacuation and transboundary cooperation work together.

The Bhotekoshi-Trishuli disaster should ultimately serve as a turning point for strengthening preparedness not only in Nepal but throughout the Hindu Kush Himalayan region, where similar low-probability but high-consequence disasters may occur in the future.

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Annexes

Annex 1: ERA5-Land Reanalysis Dataset

This annex sets out the ERA5-Land variables, derived climate indicators, unit conversions, and annual aggregation methods used in the hydroclimatic analysis presented in Section 4 (Muñoz-Sabater et al., 2021).

Table A1. ERA5-Land variables, derived climate indicators, unit conversions, and annual aggregation methods used in the analysis.

Variable / Indicator	ERA5-Land Source / Derivation	Unit / Conversion	Annual Aggregation / Definition
2-m Air Temperature	Directly from ERA5-Land hourly 2-m air temperature	Kelvin → °C	Annual mean temperature
Total Precipitation	Directly from ERA5-Land total precipitation	m water equivalent → mm	Annual total
Snowfall	Directly from ERA5-Land snowfall	m water equivalent → mm	Annual total
Snow Depth	Directly from ERA5-Land snow depth	m	Annual mean
Snowmelt	Directly from ERA5-Land snowmelt	m water equivalent → mm	Annual total
Rainfall	Total precipitation – snowfall	mm	Annual total
Rainfall Fraction	Rainfall / total precipitation × 100	%	Annual percentage
Snowfall Fraction	Snowfall / total precipitation × 100	%	Annual percentage
Daily Minimum Temperature	Minimum of hourly 2-m air temperature for each day	°C	Used to derive freeze-thaw days
Daily Maximum Temperature	Maximum of hourly 2-m air temperature for each day	°C	Used to derive freeze-thaw days
Daily Mean Temperature	Mean of hourly 2-m air temperature for each day	°C	Used to derive positive-temperature days
Freeze-Thaw Days	Days with $T_{min} < 0\text{ °C}$ and $T_{max} > 0\text{ °C}$	days/year	Annual count
Positive-Temperature Days	Days with daily mean temperature $> 0\text{ °C}$	days/year	Annual count
Temperature Anomaly	Annual mean temperature – 1950-1975 mean annual temperature	°C	Annual anomaly

Annex 2: NISAR Synthetic Aperture Radar Data

NISAR Synthetic Aperture Radar data were used as an additional source of information for investigating surface displacement and geomorphic change within the Langtang Lirung source region (NASA/JPL-Caltech & ISRO, 2026). Radar observations are particularly useful in the Himalayan monsoon environment because image acquisition is not dependent on daylight and is substantially less restricted by cloud cover than optical imagery. The SAR observations were therefore used to complement optical satellite interpretation of the source-area failure.

Annex 3: NEX-GDDP-CMIP6 Climate Model Data

Future climate conditions were assessed using the NASA Earth Exchange Global Daily Downscaled Projections from CMIP6 (NEX-GDDP-CMIP6) dataset (Eyring et al., 2016). The dataset provides statistically downscaled daily climate projections from CMIP6 general circulation models on a common $0.25^\circ \times 0.25^\circ$ spatial grid. The downscaled product was selected to provide spatially consistent climate information for the Langtang Lirung source region and surrounding high-mountain environment.

Two scenarios were considered:

SSP2-4.5 — intermediate-emission pathway, reaching about 4.5 W m^{-2} radiative forcing by 2100.

SSP5-8.5 — very high-emission pathway, reaching about 8.5 W m^{-2} by 2100.

Table A2. The five bias-corrected CMIP6 general circulation models (GCMs) used in the ensemble are referenced in Section 4.8.

S.N.	Climate Model	Institution
1	ACCESS-CM2	Australian Community Climate and Earth System Simulator
2	ACCESS-ESM1-5	Australian Earth System Model
3	BCC-CSM2-MR	Beijing Climate Center Climate System Model
4	CanESM5	Canadian Earth System Model
5	EC-Earth3	European Earth-System Climate Model

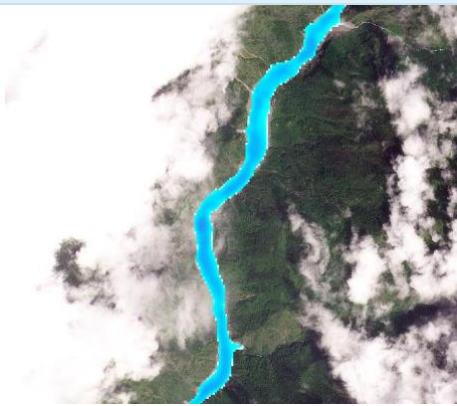
Annex 4: Summary of Data Sources

Table A3 summarizes the datasets, sources, coverage periods, and spatial/temporal resolutions used throughout the reconstruction of the 26 August 2026 event (Section 5).

Table A3. Summary of data sources, spatial resolution, and temporal coverage used in this reconstruction.

S.N.	Dataset / Variable	Source	Period / Coverage Used	Spatial Resolution	Temporal Resolution / Acquisition
1	Air temperature, precipitation, snowfall, snowmelt, snow depth and SWE	ERA5-Land, ECMWF/Copernicus	1950-2026	$0.1^\circ \times 0.1^\circ$	Hourly
2	NEX-GDDP-CMIP6 climate projections: ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, EC-Earth3	NASA NEX-GDDP-CMIP6	Historical: 1950-2014; SSP2-4.5 and SSP5-8.5: 2015-2100	$0.25^\circ \times 0.25^\circ$	Daily
3	NISAR SAR imagery	NASA-ISRO NISAR	Pre-event 2026	3-10 m (mode dependent)	~12-day repeat
4	PlanetScope optical imagery	Planet Labs	Pre- and post-event around 26 Aug 2026	~3 m	Acquisition dependent
5	Sentinel-1 SAR imagery	ESA/Copernicus	Pre- and post-event around 26 Aug 2026	10 m pixel spacing	Acquisition dependent
6	Digital Elevation Model (FABDEM)	FABDEM	Static	~30 m	Static
7	Land-cover data	ESA WorldCover	2021	10 m	Static
8	High-flood marks and field observations	Post-event field / observations	Post-event 2026	Site specific	Event based
9	Observed flood arrival times and impact information	Field observations and documented event records	26 Aug 2026	Location specific	Event timing
10	Satellite-derived flood extent at six key locations	Sentinel-1 / PlanetScope imagery	Post-event 2026	Sensor dependent	Event based

Annex 5: Comparison Maps of Satellite-Derived Flood Extent and Model Outputs

	
Gyirong Port	
	
Timure	
	
Syabrubesi	

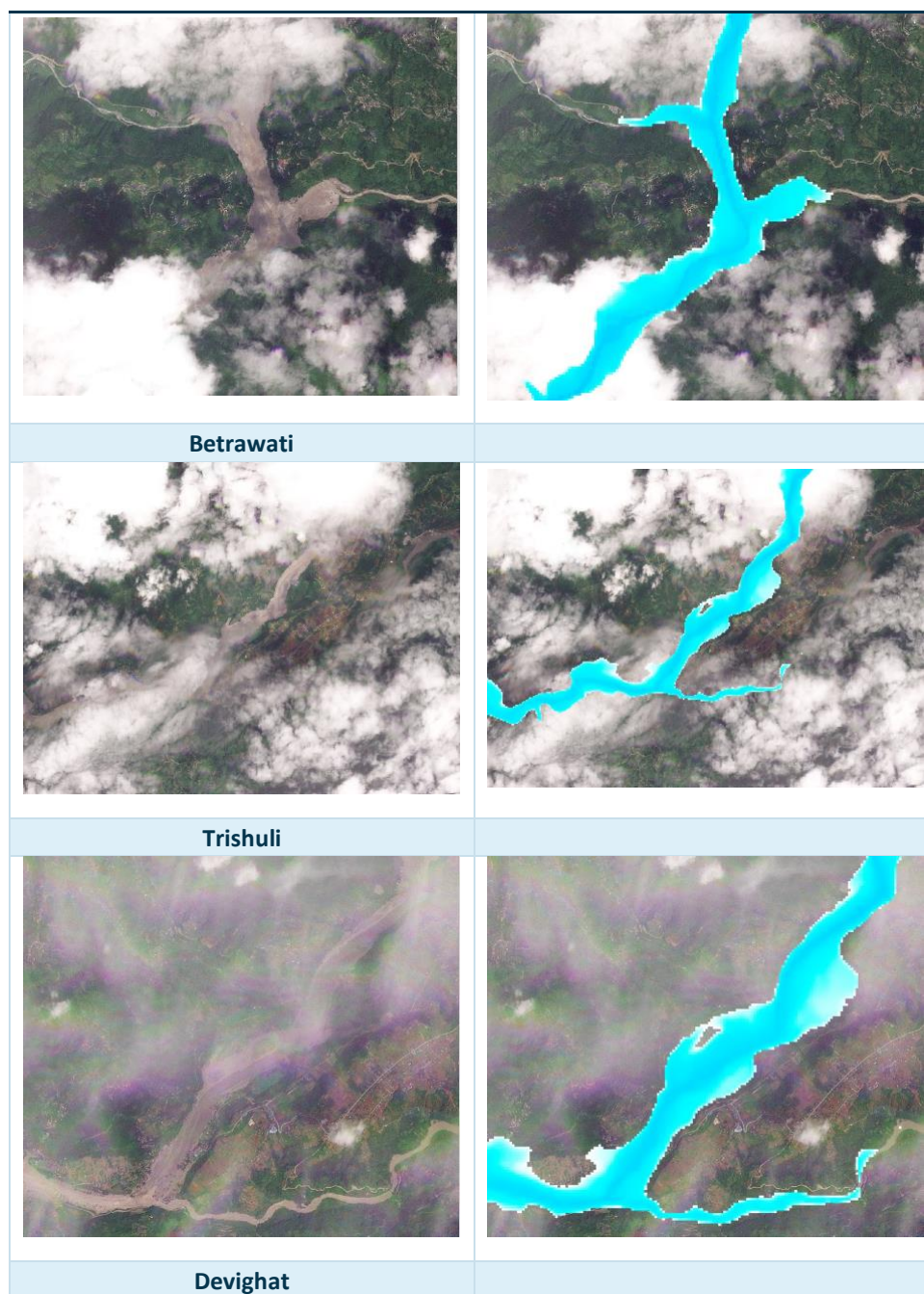


Figure A1: Comparison of RAMMS-HEC-RAS-simulated inundation extent and flow characteristics against satellite imagery and post-flood field photographs at Gyirong Port, Timure, Syabrubesi, Betrawati, Trishuli, and Devighat.



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