Recurring avalanche hazards at Birendra Lake, Manaslu region: Interdisciplinary insights from the April 21, 2024, avalanche event

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Abstract

On 21 April 2024, a large ice-debris avalanche from the Manaslu Glacier surged into Birendra Lake, triggering overtopping and downstream flooding along the Budhi Gandaki River. Situated below the retreating glacier, Birendra Lake has become increasingly susceptible to avalanche-induced hazards, reflecting the region's shifting climatic pattern and steep topography. This study employed integrated avalanche hazards analysis based on observations, geo-morphological assessments, climatic and hydrological analysis, and community-based interaction to investigate the recurring avalanche hazards in the region and examine the drivers and impacts of the April event. Our findings highlight that rising temperatures, declining precipitation, glacier detachment, and steep and rugged terrain (>30° slopes) are key factors contributing to avalanche susceptibility. While local communities perceive avalanches as routine seasonal events, awareness of their cascading effects, such as lake surges and infrastructure disruption, remains limited. The April event also revealed critical institutional gaps, particularly the lack of real-time hazard information and communication capacity within the region's only formal authority, the Samagaun Police Station. This study highlights the importance of developing localized early warning systems, establishing high-altitude monitoring infrastructure, and implementing community-engaged risk reduction strategies. Strengthening institutional preparedness and integrating scientific analysis with local knowledge are crucial to enhancing resilience. By positioning Birendra Lake as a sentinel site of Himalayan cryospheric vulnerability, this research advocates for co-designed, context-specific approaches to hazard mitigation in avalanche-prone mountain regions.

Keywords: awareness, climate change, cryospheric hazard, susceptibility, vulnerability

Introduction

On 21st April 2024, a massive avalanche consisting of a mixture of ice and debris hit Birendra Glacial Lake with a thunderous sound, as reported by the Samagaun Police Station. The impact of the avalanche caused the lake's water to overflow, resulting in a surge of water flow in the Budhi Gandaki River and triggering a muddy flood downstream. Although there were no casualties or significant infrastructure damage, the event destroyed a wooden bridge connecting the trails of Samagaun and Samdo (the route to Larke Pass). It also inundated the

Samagaun micro hydro-power plant with sediment. This event highlights how even a comparatively small lake ($\approx$ 0.26 km²) can trigger a far-reaching multi-hazard chain now recognised across High-Mountain Asia, where a single snow or ice avalanche can cascade into secondary floods and debris flows (Li et al., 2024; Zhong et al., 2024).

Avalanches, defined as the sliding of snow, ice, rock, or debris down a mountainside, can be triggered by both natural and human activities (Park & Reisinger, 2010). In Nepal, where the northern region is dominated by snow and ice-covered peaks, avalanches are common and frequent, with more than sixty incidents recorded since the 1920s (Thakuri et al., 2020), often resulting in significant human and property losses (McClung, 2016). A recently compiled High Mountain Asia Avalanche (HiAVAL) database documents 681 ice and snow avalanche events between 1972 and 2022, resulting in over 1,331 fatalities, including 508 in Nepal (Acharya et al., 2023). A regional review of satellite and field records by Zhong et al. (2024) found that about 45% of large rock-and-ice avalanches recorded since 2000 have triggered floods or debris flows downstream, demonstrating the causal impact of avalanches to often initiate and cascade into further hazards..

Glacial lakes, particularly those located near retreating glaciers, are at varying levels of risk depending on local geomorphological conditions. Lakes situated on gentle slopes may expand gradually, whereas those near crevassed glaciers or steep slopes are far more vulnerable. Falling ice chunks or avalanches into such lakes can destabilize them, potentially causing moraine dam breaches and catastrophic downstream flooding (Bajracharya et al., 2020). For instance, in Nepal's Barun River valley, a rockfall from a permafrost-degraded slope triggered a debris flow into Langmale Lake, leading to a glacial lake outburst flood. Similarly, the 1985 Dig Tsho disaster in the Everest region, triggered by an ice avalanche into the lake, resulted in a destructive outburst flood (Byers et al., 2022). Moreover, a recent multi-breach model of Birendra Lake shows that even a partial moraine failure could raise peak discharge by roughly a factor of ten relative to the April 2024 overtopping surge, greatly amplifying downstream flood risk (Poudel et al., 2025). Satellite gravimetry reveals that global glaciers lost 273 ± 16 Gt yr^{-1} between 2000 and 2023, a rate that has accelerated by 36 % since 2012 (Hugonnet et al., 2024). Meanwhile, the Manaslu Glacier, which sustains Birendra Lake, has retreated more than 1.5 km and undergone significant thinning since the Little Ice Age (Lee et al., 2021). A recent machine-learning analysis ranked Birendra Lake among the highest-risk, which is 10 % of approximately 3,300 Himalayan lakes in terms of avalanche impacts, mainly due to its steep surrounding slopes and short (< 600 m) glacier-to-shore distance (Steiner et al., 2024).

The socio-economic context of high-mountain Nepal amplifies the consequences of such multi-hazard chains. High-altitude regions of Nepal (such as the Manaslu area) are characterized by remote settlements with limited infrastructure and emergency services, as well as non-diversified livelihood options. These factors collectively amplify social vulnerability and constrain resilience. A recent nationwide Vulnerability and Risk Assessment (VRA) by the Government of Nepal (2023), with the second National Adaptation Plan, ranks high-altitude rural municipalities (including Chum Nubri) among the country's most climate risk-prone areas. Indicator-based studies, including a Multidimensional Livelihood Vulnerability Index for the Hindu Kush Himalaya (Gerlitz et al., 2016) and a modified Social Vulnerability Index for Nepal (Aksha et al., 2019), suggest that adaptive capacity factors (e.g., diversified livelihoods, strong social networks, and access to early-warning information) can mitigate some hazard exposure. Strengthening community-based disaster risk reduction, improving access to information, and integrating scientific hazard forecasts with local knowledge have been repeatedly highlighted to build resilience in these regions (Hewitt & Mehta, 2012; Rasul et al., 2021). However, despite these recognized adaptive strategies, real-time avalanche warning systems and adequate studies linking hazard forecasts with local communities remain scarce in these high-altitude communities (Tuladhar et al., 2021).

Therefore, recognizing these challenges, we employ an interdisciplinary approach that combines field observations and semi-structured interviews with geo-morphological, climatic, and hydrological analysis to identify combinations of geomorphological features (e.g., slope angle, terrain roughness) and meteorological conditions that drive the region's frequent avalanches. We also examine how terrain and glacier characteristics influence avalanches in Birendra Lake, and evaluate the extent to which long-term temperature and precipitation trends have influenced avalanche frequency. In addition, we assess how local communities and local authorities (specifically the Samagaun Police Station) perceive, prepare for, and respond to these hazards. Finally, this study tests three hypotheses: First, the 30°- 45° slopes and the detached Manaslu Glacier terminus are the primary physical triggers for frequent avalanches. Second, regional warming and changes in the precipitation pattern have increased avalanche frequency. And third, limited early-warning capacity has led to a normalization of avalanche risk among downstream residents.

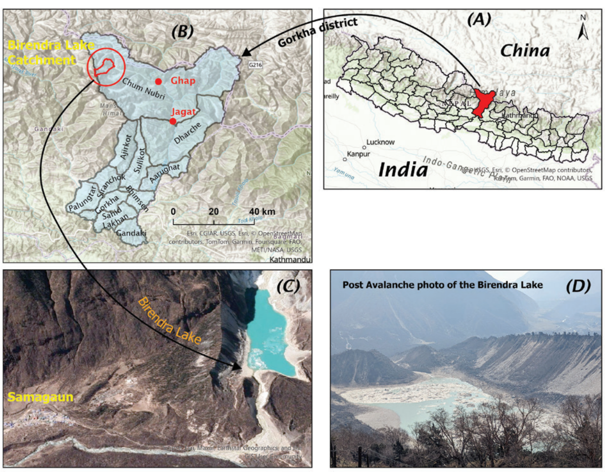
Data and methods

Study area

Birendra Pro-glacial Lake (Figure 1), known as Birendra Tal (Lake), was named by the locals of Samagaun in honor of the late King Birendra Shah after he visited the Manaslu region. Birendra Lake is very popular among trekkers on the Manaslu Circuit, as it lies along the route from Samagaun to Samdo (on the way to Manaslu Circuit). The glacial lake is dammed by an end moraine, situated just beneath Mount Manaslu (8,163 masl) in the Chum Nubri Rural Municipality of the Gorkha district in West-Central Nepal, at an altitude of 3,600 meters above sea level.

Figure 1

Location of Birendra Lake in Gorkha district



Note:

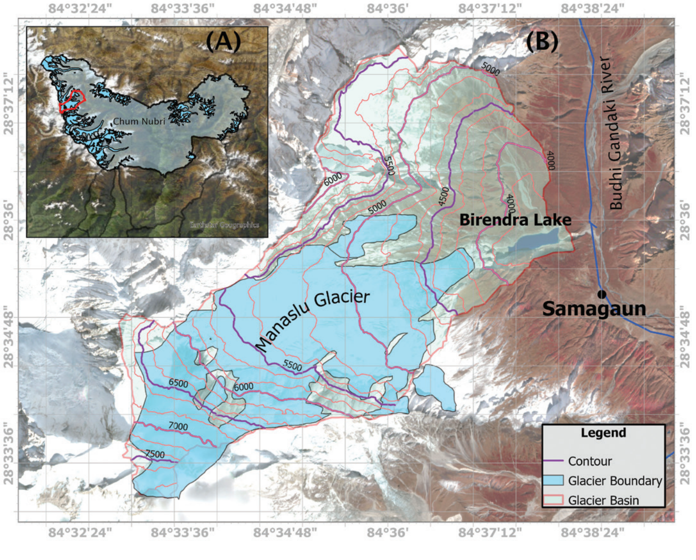
A. Nepal with district boundaries with the location of Gorkha district, B. Local municipalities of Gorkha district with Birendra Lake in Chum Nubri Rural Municipality with Ghap hydrological station 22 km downstream from Birendra Lake and Jagat hydrological station 25 km downstream from Ghap station, C. Google Earth image of Birendra Lake showing its outlet and Samagaun Village; and D. Post Avalanche image of Birendra Lake taken on 23 April 2024.

Birendra Lake is a headwater of the Budhi Gandaki River basin, located in central Nepal between longitudes 82º55' and 85º50' E and latitudes 29º15' and 28º05' N. According to Randolph Glacier Inventory version 7, there are 244 glaciers with a total area of 311.86 km^2 within the Chum Nubri Rural Municipality of the Gorkha district (Figure 2). The glaciers' size ranges from 0.02 km^2 to 32.81 km^2, whereas the size of the Manaslu Glacier is 15.28 km^2.

Birendra Lake is the moraine-dammed lake fed by the Manaslu Glacier. However, at the present moment, the glacier has since become entirely detached from the lake, exposing a steep slope and bedrock behind it, as illustrated in Figure 3A. The declassified KH-4A satellite image analyzed by Khadka et al. (2024) indicates that Birendra Lake had a size of ~0.25 km^2 at the terminus, indicating its formation began well before the year 1967. Since the Little Ice Age, the Manaslu Glacier has retreated over 1500 meters, and its surface elevation has decreased by more than 200 meters (Lee et al., 2021), significantly contributing to the formation and expansion of the lake. Notably, Khadka et al. (2024) documented a ~0.09 km^2 reduction in lake area between 1977 and 1988, possibly resulting from a glacier collapse or glacial lake outburst event. The lake's terminal moraine exhibits a distinctive V-shaped trench accompanied by a debris fan, suggesting past geomorphological activity likely tied to such events.

Figure 2

Manaslu Glacier Basin



Note:

A.Distribution of glaciers within Chum Nubri Rural Municipality, and B. Manaslu Glacier Basin *showing Manaslu Glacier and Birendra Lake with a contour interval of 200 m and 500 m. The background image is Sentinel-2, dated 26 November 2023.*

Source: RGI version 7

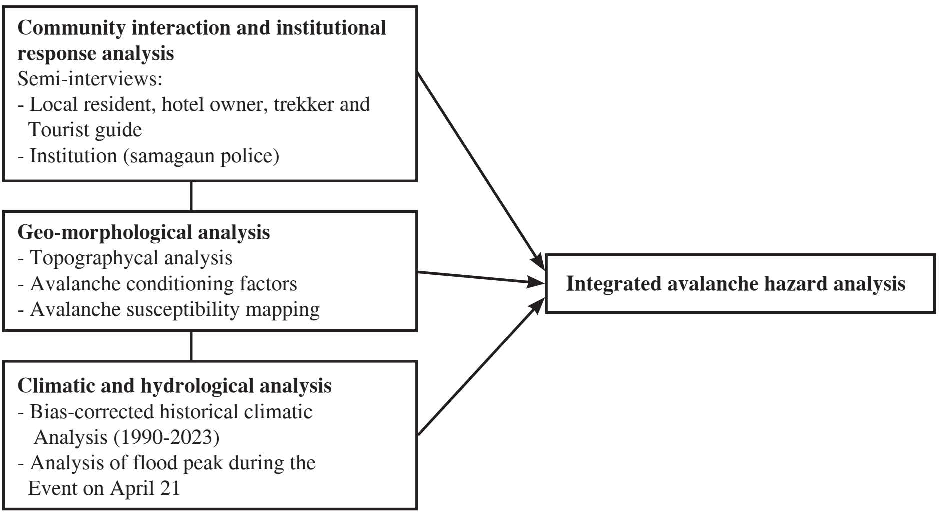
Methods

This study integrates an interdisciplinary methodology to investigate the recurring avalanche hazards in the Birendra Lake region, including the notable event of April 21. The approach integrates field-based observations, geo-morphological assessments, climatic and hydrological analysis, and community-based inquiry to understand the complex interactions between physical and social dynamics contributing to avalanche risk.

We developed a conceptual framework to guide this investigation and illustrate how these diverse components interact to inform an integrated avalanche hazard analysis (Table 1). The framework links three key domains: (i) community interaction and institutional response, (ii) geo-morphological analysis, and (iii) climatic and hydrological analysis. Each study domain contributes complementary insights into the drivers and impacts of avalanche hazards around Birendra Lake.

Table 1

Conceptual framework for integrated avalanche hazard analysis at the birendra lake region



The following sub-sections describe each framework component in detail, outlining the data sources, analytical methods, and field activities used in this study.

Community interaction and institutional response analysis

We conducted a transect walk and semi-structured key informant interviews during a field visit on April 23rd & 24th, 2024, to understand community perceptions and institutional responses to such hazards. This method targeted individuals with long-term experience and functional roles in the Manaslu region, including trekking guides, randomly encountered trekkers, hotel/lodge owners, and officers at the Samagaun Police Station. Each individual offered diverse yet complementary insights shaped by their direct exposure to climatic events and institutional response mechanisms. The interviews aimed to explore personal experiences with avalanche events, observed climate changes, and perceptions of risk and preparedness.

Geo-morphological analysis

To understand terrain-based avalanche susceptibility, a geo-morphological assessment was performed using high-resolution satellite imagery, Google Earth, and a digital elevation model (DEM) based on the slope categories to identify avalanche conditioning factors, highlighting that the Birnedra lake surrounding and the Mansulu region are at a higher risk for the frequent avalanche due to steep slope, rugged terrain, and the proximity to the Manslu Glacier.

Climatic and hydrological analysis

Temperature and precipitation data were bias corrected for the climatic analysis using observed datasets from the Ghap meteorological station, located approximately 22 km downstream of Birendra Lake. Precipitation data from Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) were also bias-corrected using the multiplicative scaling method (Sperna Weiland et al., 2010), expressed as:

$$P_{corrected\_MOD} = \left(\frac{\overline{P}_{obs}}{\overline{P}_{MOD}}\right) P_{MOD} \qquad \text{------------------------(I)}$$

Where P represents the monthly precipitation (mm), and $\overline{P}$ denotes the monthly average precipitation. In this study, CHIRPS is referred to as the modeled dataset (MOD).

Similarly, temperature data from ERA5 Land developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) were bias-corrected using the Cumulative Distribution Function (CDF) matching method in equation (II) proposed by (Piani et al., 2010), expressed as:

$$T_{corrected\_MOD} = F^{-t}{}_{obs}\left(F_{MOD}(T_{MOD})\right) \text{ -----------------(II)}$$

Where F_{MOD} and F_{obs} are the CDFs of the modeled and observed temperature distributions, respectively, and F^{-1} represents the inverse CDF. Here, T_{MOD} and $T_{corrected\_MOD}$ denote the raw and bias-corrected temperature data, respectively.

Additionally, the hydrological analysis included the interpretation of the flood peak associated with the April 21 avalanche event, using the data recorded at the Water Level Radar Stations at Ghap and Jagat.

Integrated analysis approach

The outputs from the community-level assessments, geomorphological modeling, and climate-hydrological corrections were utilized to produce a comprehensive avalanche hazard profile for Birendra Lake. This integrated analysis informed the understanding of physical vulnerabilities, local adaptation capacities, and institutional gaps in hazard management.

Data sources

This study integrates multiple data sources to assess the avalanche hazard of the Birendra Lake region. Remote sensing data were primarily obtained from Google Earth and Sentinel-2 imagery (dated 26 November 2023) to observe changes in glacier morphology and lake development. For terrain analysis, an ALOS PALSAR Digital Elevation Model (DEM), a radiometric terrain corrected and with a 12.5-meter resolution, was acquired from the Alaska Satellite Facility dataset to generate a slope-based avalanche susceptibility map.

Climatic datasets were sourced from two major reanalysis products: ERA5-Land, which provides temperature data from 1990 to the present (Muñoz-Sabater et al., 2021). It is widely used in climate change studies to capture warming trends and regional variations (Amjad et al., 2020). Similarly, CHIRPS is a satellite-based precipitation dataset with a high spatial resolution of 0.05° grid, which offers precipitation data from 1981 to the present and the capability to detect changes in precipitation patterns over time. It can effectively capture precipitation variability, which can be used for bias correction (Du et al., 2023).

Hydrological data were obtained from automatic radar water level sensors installed by the Himalayan Cryosphere, Climate and Disaster Research Center (HiCCDRC), Kathmandu University. These included real-time water level records from Ghap and Jagat stations, which captured significant surges during the April 21, 2024, avalanche event. The dataset is illustrated in Table 2.

Table 2

Summary of the dataset

Data type	Source	Timeframe	Purpose/Use
Satellite imagery	Google Earth, Sentinel-2 (ESA)	2019, 2023	Morphological analysis and mapping
Digital Elevation Model (DEM)	ALOS PALSAR (12.5 m resolution)	2009	Slope analysis for avalanche susceptibility mapping
Temperature data	ERA5-Land (ECMWF)	1990–2023	Long-term temperature trend analysis
Precipitation data	CHIRPS (Climate Hazards Group)	1981–2023	Long-term precipitation pattern analysis
Ground station data	Ghap Station (Kathmandu University)	2024/01/01-2025/02/28	Bias correction for reanalysis datasets
Photographs	Field survey	2024/4/23	Geomorphic characterization
Hydrological data	Water Level Radar Stations at Ghap and Jagat (HiCCDRC, KU)	April 2024	Observe the water surge during the avalanche event
Qualitative data	Semi-structured interviews (locals, police, guides)	23rd to 25th April 2024 (field visit)	Understanding community perception and institutional response

Results and discussion

Field observation

During the aftermath visit to the Birendra Lake on the third day following the avalanche event, the lake's water level had visibly dropped with numerous ice chunks (mixed with debris) floating on the lake's surface (Figure 3). Some of these chunks, comparable in size to rocks (as shown in Figure 3D), were scattered around the lake above its water level. Despite the overtopping, the lake’s outlet remained structurally intact, though the outlet size had forcefully increased after the event. Additionally, continuous debris flow was observed entering the lake from the left side of the valley, adjacent to Birendra Lake and the Manaslu

Glacier, suggesting an ongoing sediment influx. Notably, how the incident was circulated raised questions about the lack of a prompt scientific investigation. Without clear communication or immediate research, the cause of the April 21 avalanche event remained ambiguous, leading to varied interpretations among local residents, tourist guides, and the media. While some attributed the event to rockfalls, others pointed to glacier collapse or snow avalanches. Figure 4 and 5 show the surroundings of Birendra Lake and avalanche source.

Figure 3

The condition of Birendra Lake after the avalanche event

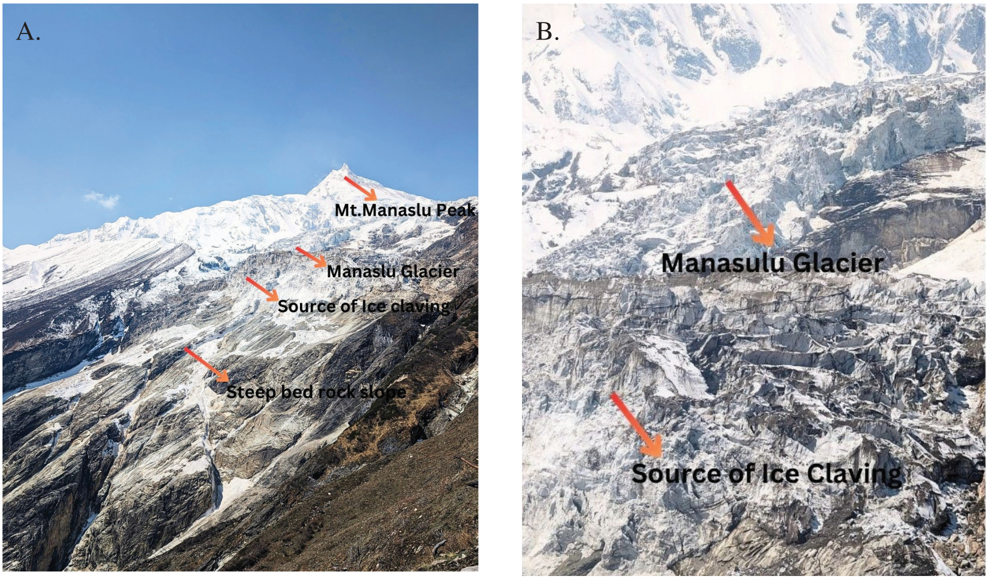
Note:

A. B. & D. show ice debris deposition on the lake's surface three days after an avalanche event, and C. shows a chunk of the mass of ice away from the lake.

@Manavi Chaulagain on 24 April 2024.

Figure 4

Manaslu glacier and Ice avalanche source



Note:

A. Mt. Manaslu peak and glacier, and B. Manaslu glacier and ice avalanche source, photo taken from the Manaslu base camp.

@Manavi Chaulagain on 24 April 2024.

Figure 5

Debris deposition and farsight view of Birendra Lake

Note:

A. Farsight view of Birendra Lake, and B. Debris deposition flowing from the adjacent valley to the left side of Birendra Lake.

@Manavi Chaulagain on 24 April 2024.

Observations and insights from Samagaun people on the event

Before reaching Samagaun, where Birendra Lake is situated, we were preoccupied with thoughts about the avalanche event: its potential impact, the local community's response, and the broader atmosphere in the aftermath of the avalanche. However, upon reaching Samagaun, we observed how normal everything seemed for the communities, as there were no visible concerns among the residents about the avalanche. For the people of Samagaun, avalanches are not unusual; they occur annually and are regarded as a regular part of their lives. The only recurring loss they face each year is the destruction of the wooden bridge that connects the trekking trails from Samagaun to Samdo. Every year, an avalanche sweeps away the bridge, and each time, the community rebuilds, which has become a regular scenario and practice for them. This attitude towards the event demonstrated a cycle of adaptation that reflects both resilience and normalization of hazard exposure for the people of Samagaun.

Insight from the local authority about the avalanche

In Samagaun, the only official governmental body present to ensure the security and well-being of the residents in case of any natural events like avalanches is the 'Samagaun Police Station'. The police station is a small unit with just seven officers, yet they have to cover the extensive area of 1,648.65 km² of Chum Numbri Gaupalika. Despite their limited numbers and scarce resources, these officers performed a wide range of duties crucial to the region's safety. They are involved in rescue operations as the first responders in emergencies. For instance, when tourists go missing during treks along the circuit, this small team mobilizes to find and bring them back to safety. They also play a key role in ensuring the general security of the local population and maintaining peace and order in the community. Additionally, they are tasked with making the community aware of various threats, from environmental hazards to potential social issues.

The police station in Samagaun does not have the authority to circulate news and information directly. They must first report every piece of information to the Arughat division responsible for disseminating news and early warning cautions. Though the protocol and chain of command are crucial for maintaining order and ensuring accurate communication, this hinders a swift response to the disaster. When we inquired about how they provide weather information to tourists who seek information and guidance about the conditions at the base camp or the high range, the response was disheartening. The officers admitted they had no answers due to the absence of weather forecast information and their lack of knowledge about weather conditions. The officer expressed hope that if the concerned authorities showed interest in making them aware of weather forecasts and climate change, it would greatly benefit their work.

Despite the event's significance, no stakeholders, agencies, NGOs, or INGOs showed concern for understanding the situation at Birendra Lake and the affected community until the third day, when media hype peaked about the event.

Insight while reaching Manaslu Base Camp

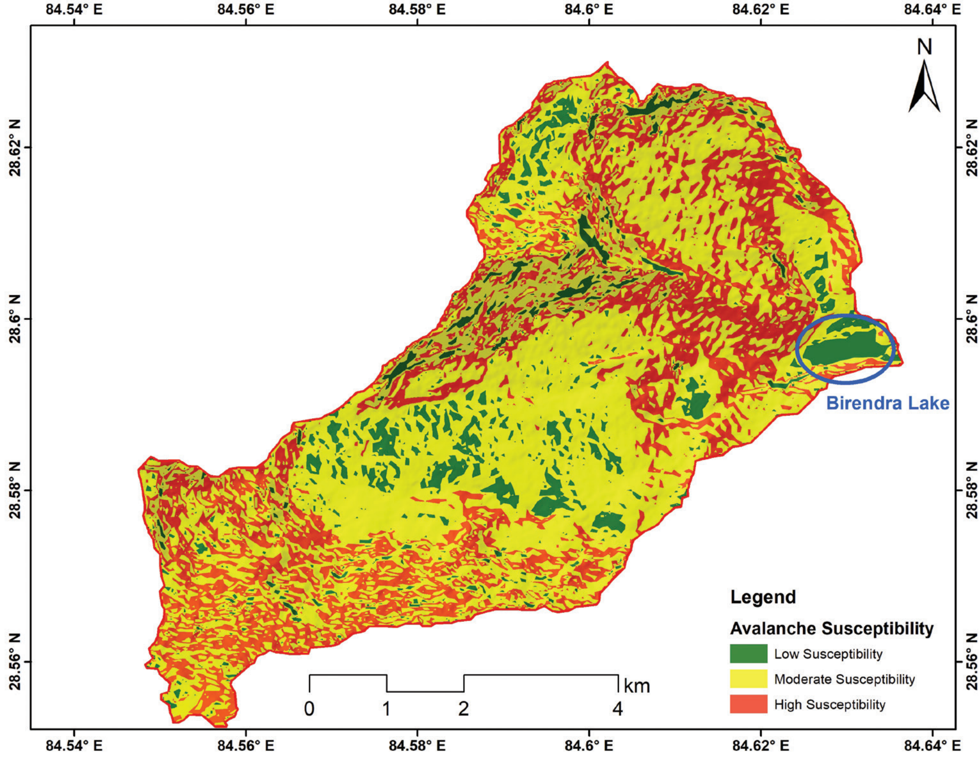
During the visit to Manaslu Base Camp, multiple snow avalanches were observed, reflecting the recurring nature of such events in the region, as reported by the locals. Within four hours, approximately seven to eight avalanches were heard, likely small in scale, as they did not appear to displace water from the nearby lake. Yet, they produced loud, resonating sounds across the area. Conversation with people in Samagaun emphasized that such avalanches are a frequent phenomenon in the area, underscoring the region's dynamic and unstable nature. These firsthand observations highlighted the urgency of understanding the frequency and impact of such events to develop effective risk mitigation strategies for both locals and trekkers.

Morphological analysis

The avalanche susceptibility of Birendra Lake and its surrounding terrain has been assessed by categorizing slope gradients, with large portions falling within moderate-to-high-risk zones (Figure 6). Studies suggest that slopes greater than 30° are particularly susceptible to avalanches (Corona & Stoffel, 2017). This key feature is also evident in our study of slope-based susceptibility mapping of the region.

Figure 6

Avalanche-susceptible zone map based on the slope category around Mt. Manaslu and Birendra Lake



The developed avalanche susceptibility map of the Birendra Lake region classifies the terrain into three distinct zones: high (30 - 45 degrees), moderate (10-30 degrees and 45-60 degrees), and low susceptibility (<10 degrees and > 60 degrees).

The map divides the terrain into three distinct zones based on slope angles:

- **High susceptibility (30–45°):** These steep, unstable slopes, highlighted in red, are most prone to avalanches, especially near glacier fronts or snowfields where snow can accumulate. Birendra Lake lies within this high-risk area, surrounded by steep terrain that makes it especially vulnerable to frequent avalanches.

- **Moderate susceptibility (10–30° and 45–60°):** Represented in yellow, these zones are characterized by slightly less steep slopes or more stable terrain. While the risk is lower than in high-susceptibility zones, avalanches can still occur under extreme weather conditions, such as heavy snowfall or seismic activity.
- **Low susceptibility (<10° and >60°):** Marked in green, these zones have gentler slopes or very steep areas where snow accumulation is minimal, resulting in a relatively low avalanche risk.

Further analysis by Maharjan et al. (2024) also highlights the Manaslu glacier's average slope of around 30 degrees and its snouts, which are separated from the lake by about 600 meters with a slope of approximately 39 degrees, emphasizing the lake's susceptibility to frequent avalanches. Furthermore, the proximity of the Budhi Gandaki River raises concerns about potential downstream impacts from avalanche-induced water surges, as evidenced during the April 21, 2024, event. These findings underscore the importance of implementing risk management strategies, including monitoring high-risk zones and establishing early warning systems to mitigate potential hazards.

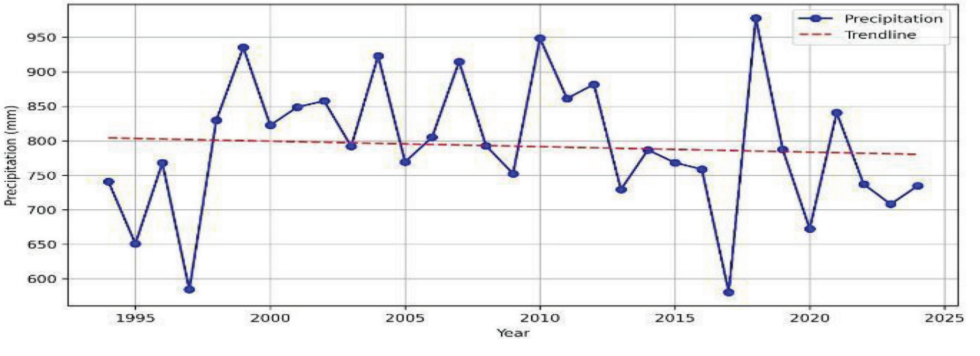
Climatic analysis

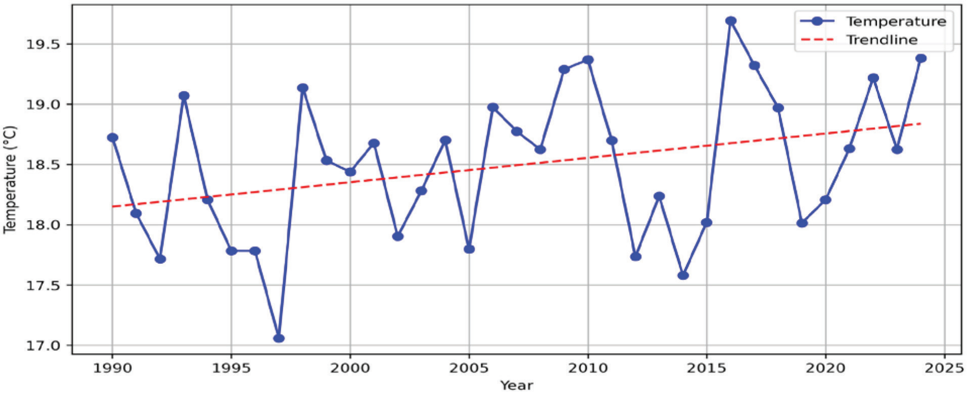
Following the bias corrections of ERA5-Land and CHIRPS, the results indicate a consistent warming trend in mean temperature over the years (Figure 7A). In contrast, the precipitation trend (Figure 7B) displays a slight decreasing pattern; however, this trend is statistically insignificant, suggesting no definitive change in total precipitation amounts over time.

While total precipitation does not show a significant trend, the implications of climate change may be more significant. A key concern is the potential shift in the phase and timing of precipitation, with increased temperatures possibly causing a higher proportion of precipitation to fall as rain rather than snow. This shift can have critical impacts on the hydrological regime, including earlier snowmelt, reduced snowpack stability, and an increased frequency of rain-on-snow events, all of which can enhance avalanche risk and contribute to glacier mass imbalance.

Figure 7

Temperature and precipitation trend of Chum-Numbri Municipality





Note:

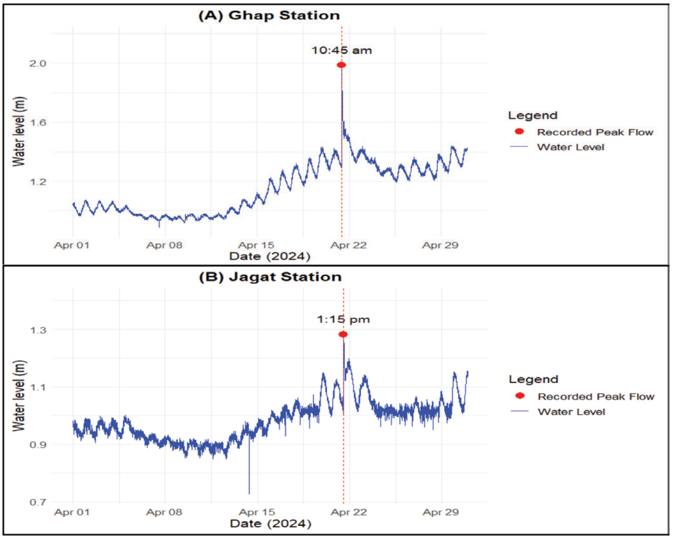
A. Mean annual temperature trend of Chum-Numbri Municipality, and B. Total annual precipitation trend of Chum-Numbri Municipality.

Peak water level recorded by the water level radar stations during the incident

According to the water level data available from the two automatic water level radar stations in Budhigandaki River at Ghap (2,089 m), 22 km downstream from the lake, the water level increased from 1.29 m at 10:25 am to 1.98 m at 10:45 am (a total of 69 cm increase). Similarly, the water level recorded at Jagat (1,350 m), 25 km downstream from the Ghap station, shows that the water level increased from 1.02 m at 12:45 pm to 1.28 m at 1:15 pm (a total of 26 cm increase) on April 21.

Figure 8

Peak water level at Ghap and at Jagat



Note:

A. Peak water level recorded by the water level radar station at Ghap, 21 April 2024. and B. Peak water level recorded by the water level radar station at Jagat, 21 April 2024.

Discussion

This study highlights the heightened vulnerability of Birendra Lake and the broader Manaslu region to avalanche-induced hazards, driven by a convergence of steep and rugged topography, proximity to the Manaslu Glacier, and dynamic climatic conditions. The April 21, 2024, avalanche incident further exemplifies how these factors converge to pose serious downstream risks. Although the lake is relatively small in surface area, 0.26 km^2, it holds substantial hazard potential, as evidenced by displacing a significant volume of ice and debris that generated the surge waves, raising water levels by 69 cm and 26 cm at Ghap and Jagat stations, respectively.

Using the volume estimation equation proposed by Zhang et al. (2023) (V = 42.95 × A^1.408), a hypothetical breach of Birendra Lake could release approximately 6.44 million m^3 of water. Though not extremely large, this volume would be sufficient to trigger significant flooding impacts downstream.

A comparative analysis with other Himalayan glacial lakes, such as Imja Lake in the Everest region, reveals both similarities and disparities. While both are moraine-dammed and located near retreating glaciers, Imja has undergone significant mitigation efforts, including a 3.4 m drawdown project in 2016 to reduce GLOF risk (ICIMOD, 2017; Somos-Valenzuela et al., 2016). In contrast, Birendra Lake, despite being categorized as high-risk due to its steep surrounding slopes and <600 m glacier–lake distance (Rounce et al., 2017; Zhang et al., 2023; Steiner et al., 2024) it has not been the focus of systematic monitoring or mitigation efforts yet. This discrepancy reflects a gap in hazard prioritization and preparedness strategies.

Birendra Lake presents a distinct multi-hazard cascade, where an avalanche may trigger lake overtopping, potentially leading to flash floods downstream. This layered hazard profile echoes past events like the 1985 Dig Tsho disaster in Nepal and the Laguna 513 flood in Peru, both triggered by icefalls into glacial lakes, resulting in catastrophic GLOFs (Byers, 1986; Carey et al., 2012). These events and the April 2024 avalanche demonstrate that even smaller-volume lakes can unleash destructive forces when subjected to sudden slope failure. The Table 3 offers a comparative overview of significant avalanche events in the Himalaya, showcasing diverse triggers, estimated volumes, and varying downstream effects.

Table 3

A comparative overview of avalanche events in the Himalayas

Date	Location	Trigger type	Estimated volume	Impacts	Reference
21 April 2024	Birendra Lake, Gorkha	Ice and debris avalanche	~0.2 million mÂ^3	Lake overtopping, downstream flooding, the bridge, and the hydropower plant affected	Field observation
12 February 2021	Mount Dhaulagiri, Myagdi	Winter storm avalanche	Unspecified	7 fatalities, including climbers, major avalanche from snowstorm	BBC News (2021); Himalayan Times

13 October 2015	Langtang Valley, Rasuwa	Earthquake-triggered snow avalanche	Unspecified	Village buried, 243 fatalities, massive destruction	Kargel et al. (2016); ICIMOD report (2015)
20 Aprril 2014	Everest Base Camp, Khumbu	Icefall avalanche	50,000 mÂ³	16 fatalities at Everest Base Camp, triggered by a serac fall	Fujita et al. (2017); Media sources
5 November 1995	Manang District	Heavy snowfall-induced	Unspecified	Multiple injuries and livestock loss, houses damaged	Thakuri et al. (2020)
4 August 1985	Dig Tsho, Everest Region	Ice avalanche into the glacial lake	~10 million mÂ³ (with GLOF)	A glacial lake outburst flood destroyed the hydropower plant and bridges	Byers (1986); ICIMOD archive

Climatic trends across the Hindu Kush Himalaya (HKH) add a further dimension of risk. Regional warming rates of +0.28°C per decade since 1951 (ICIMOD, n.d.) are outpacing the global average, with temperature increases in HKH reaching 1.8±0.4°C for every 1.5°C of global warming. Although long-term precipitation trends remain statistically insignificant, our bias-corrected climatic analysis confirms a steady warming trajectory (Figure 7). Rising temperatures are shifting the phase and timing of precipitation, reducing snowfall and increasing erratic rainfall, impacting avalanche formation and snowpack stability. The decreased persistence of snow, increased rain-on-snow events, and earlier melt cycles collectively exacerbate slope instability and glacial retreat. For instance, in Jumla, residents have observed a noticeable reduction in snowfall over the past several years. What once accumulated as deep snow lasting for weeks now melts within a day, indicating a shift toward rain-dominated winter precipitation (Practical Action Nepal, 2010). Such localized changes support the notion that precipitation phase transitions, even without significant changes in total volume, are critical to understanding evolving avalanche and hydrological risks in high-mountain environments.

Despite the clear signs of a changing hazard landscape, the April 2024 event, one of the largest recorded in the region according to the resident, highlights several gaps in the scientific and social framework. The lack of continuous monitoring at Birendra Lake left local communities and authorities ill-equipped to interpret or respond to the incident in real time. Conflicting reports from local sources and media about labeling the event alternately as an avalanche or GLOF illustrate a significant gap in scientific communication. This ambiguity, compounded by the absence of real-time hazard data, created confusion among residents and trekkers, disrupting livelihoods that depend heavily on tourism.

Community resilience, while admirable, reveals deeper issues. The routine reconstruction of wooden bridges after flood damage indicates strong adaptive responses, yet also reflects a lack of understanding about the increasing frequency and complexity of such hazards. The assumption that "nature will heal itself" may hinder proactive adaptation. Furthermore, information bottlenecks within institutional channels, such as delays caused by hierarchical communication protocols at the Samagaun Police Station, impede timely disaster response and public alerting.

This study argues for an integrated, forward-looking risk framework incorporating avalanche dynamics into the broader glacial lake and climate hazards context. Strengthening early warning systems, expanding high-elevation monitoring infrastructure, and fostering media literacy in hazard communication are crucial. Moreover, prioritizing Birendra Lake for active study and intervention is not just justified; it is urgent, given the lake's demonstrated potential for initiating complex hazard cascades.

Conclusion

This study reveals the acute vulnerability of Birendra Lake and its surrounding terrain to avalanche-induced hazard cascades, underscored by the 21 April 2024 event. Through a multi-method approach integrating remote sensing, climatic analysis, field observations, and community interviews, we identified the critical interplay between geomorphic settings, changing climatic conditions, and limited institutional preparedness. The findings demonstrate that despite its small size, Birendra Lake can generate significant downstream impacts due to its steep adjacent slopes, proximity to the retreating Manaslu Glacier, and debris inflow factors that heighten its hazard profile within a changing Himalayan cryosphere.

Our assessment shows that the event exemplifies a multi-hazard cascade, avalanche leading to lake overtopping and downstream flooding, aggravated by insufficient early warning mechanisms and institutional constraints. Although Birendra Lake has been classified as high risk in previous regional hazard assessments, it has remained under-monitored, with limited scientific focus and no real-time data infrastructure. These gaps contributed to public confusion during the April 2024 event and disrupted the tourism-based economy due to misinformation and a delayed response.

The study emphasizes the urgent need for improved early warning systems, including the establishment of high-altitude weather and hydrological monitoring stations and real-time data communication channels. Furthermore, fostering community-based participation in hazard monitoring and preparedness can bridge scientific knowledge and local resilience. Strengthening institutions like the Samagaun Police Station with training, resources, and streamlined communication protocols is also essential to improve response efficacy during crisis events.

Finally, translating scientific evidence into actionable and accessible knowledge for policymakers, practitioners, and the media remains critical. Doing so will support proactive planning and foster climate-risk literacy at both institutional and grassroots levels. Addressing these gaps through integrated scientific, social, and institutional strategies is vital for building long-term resilience in high-risk, glacially influenced mountain regions like Manaslu.

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