

# Insights behind the unexpected flooding in the Budhi Gandaki River, Gorkha, Nepal

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## KEY ISSUES

- On 21 April 2024, a flood from the glacial lake Birendra Tal occurred. This was triggered by a massive ice avalanche after the breaking of ice chunks (known as calving) from the snout (end) of the Manaslu Glacier into the lake water. Manaslu is the eighth-highest mountain in the world at 8,163 metres above sea level (masl), located in west-central Nepal.
- The displacement wave caused the sudden release of water from the lake outlet into the Budhi Gandaki River, in Gorkha district.
- This flood event was not a typical glacial lake outburst flood (GLOF), and the overflows did not breach the moraine dam. There was no significant impact on the dam observed in the post-event images.
- The threat remains. The analysis found significant risk of debris flow and ice/snow avalanches from the left adjacent valley (considering the direction of flow of the lake water), and, together with anticipated temperature rises and glacier retreat, indicate future occurrences could exceed the moderate impact witnessed in the current event. Vigilance from relevant agencies and roles, including Disaster Risk Management Officers, community leaders, national and local governments, is recommended.
- A detailed understanding of glacier dynamics, crevasse formation, and ice detachment processes is crucial to assess the potential risks posed by glacier avalanches and debris flow into the lake. Remote sensing techniques and field-based monitoring, such as GB-InSAR and time-lapse cameras, can provide this information.
- Continuous lake monitoring via satellite imagery and time-lapse cameras, coupled with in-situ sensor installation for lake-level monitoring and establishment of a flood early warning system, is recommended for relevant agencies, in order to mitigate risks and enhance preparedness.
- Weakening glaciers in the region pose risks from various hazards while the countries in the region remain ill-prepared to cope with the rapid pace of these changes. Addressing this issue requires urgent and strong political action to implement effective risk mitigation strategies.

## 1. Birendra Tal (*lake*) and Manaslu Glacier

Birendra Tal, a glacial lake dammed by an end moraine (which forms at the edge of a glacier, marking its maximum advance), sits at 3600 masl at the northeastern base of Mount Manaslu (8,163 masl), along the Manaslu trekking route in Chumanubri Rural Municipality, Gorkha District, west-central Nepal (Figure 1). Initially connected to the Manaslu Glacier, the lake has since detached due to rapid glacier melting. The Manaslu Glacier, originating from Manaslu Peak, extends down to its present snout position at 4,110 metres. The average slope of the glacier is about 30 degrees. The present glacier snout is separated from the lake by exposed bedrock of approximately 600m in height and a slope of roughly 39 degrees. The majority of the glacier surface is characterised by numerous crevasses, suggesting a steeper bed slope. Additionally, the interrupted topography indicates a higher degree of slope and susceptibility to snow and ice avalanches. In the lower section, two distinct steps of topographic interruption can be observed, along with the deposition of icy debris on the surface. The snout of the glacier is heavily crevassed and is prone to avalanches. Icy debris deposits existing between the lower part of the rock slope and the upper reach of the lake manifest frequent ice and snow avalanches.

## 2. Flooding incident

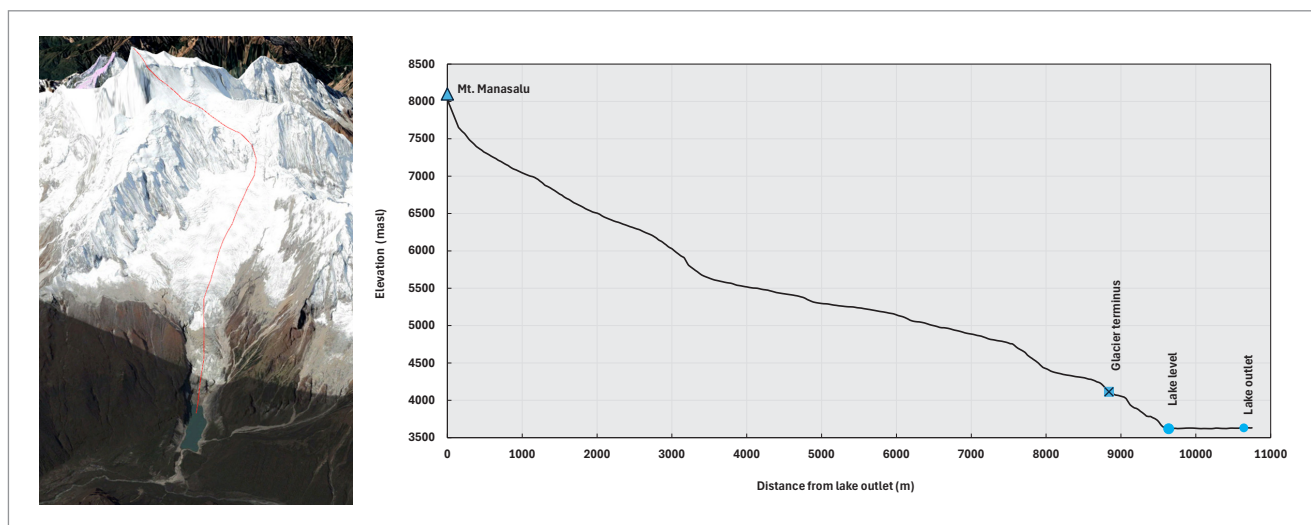
Early on Sunday, April 21, 2024, residents of Samagaun in Chumanubri Rural Municipality, Gorkha, reported a sudden surge in the flow of the Budhi Gandaki River. This surge resulted in the destruction of a wooden bridge on the route from Samdo to Samagaun. Local people had already noticed increasing water levels in the river on Saturday, with a significant rise in flow and sediment load by Sunday morning. At around

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**Figure 1:** A perspective view showing morphological characteristics of Birendra Tal and Manaslu Glacier. The red line represents the central line along the glacier and the plot on the right represents the elevation profile along the line.



09:30 local time on Sunday<sup>1</sup>, trekkers<sup>2</sup> and residents of Samagaun witnessed massive ice avalanches from the Manaslu Glacier snout, which slid and dropped into Birendra Tal. Evidence shows that the displacement wave generated by the event led to the outflow from the lake and subsequent high river flow.

### 3. Mechanism behind the flood

A rapid assessment by ICIMOD and Kathmandu University (KU) with support from the University of Alaska Fairbanks, USA, using satellite images from Planet.com, corroborated the reports by local people, i.e. the flood resulted from the calving<sup>3</sup> of the snout of Manaslu Glacier, which was steep and heavily crevassed, into the lake. The current terminus of the glacier is about 600m above the Birendra Tal water level. This large ice mass swiftly flowed into the Birendra Tal, impacting its upper section and causing the lake water to overflow through the outlet. This resulted in a sudden increase in river flow in the Budhi Gandaki River and downstream.

Glaciers in Nepal are classed as both 'summer accumulation' and 'summer ablation' type. This means that predominant accumulation of snow and ice on the glaciers occurs during the summer (monsoon) season, while they also experience significant ablation (losing snow and ice, mainly through melting) during this season. As the summer approaches, the snow and then glacier ice begin to melt due to increasing temperatures.

The sequential satellite images show a rapid transformation on the landscape around Birendra Tal, showcasing the swift disappearance of fresh snow and

frozen water surface in the area just within a span of a few weeks. The generally increasing temperatures during the period preceding the event are likely to have caused this rapid transformation. This is depicted in the comparative images from Sentinel and PlanetScope Figure 2 below.

As the snow cover on the glacier starts to melt, the underlying glacier surface, having a lower albedo (amount of light reflected back to the atmosphere from the surface) is exposed and also starts to melt. The snow avalanche from the upper reach is also visible in the image comparison of 19 and 20 April. The melting of both the snow surface and the glacier ice allowed meltwater to seep beneath the crevasses, potentially weakening and destabilising the glacier, leading to the detachment of ice masses or seracs – huge blocks or columns of ice that can topple without warning. We hypothesise that similar phenomena prevailed in this case. The ice mass then flowed downward over the exposed rock and through narrow dissected channels, flowing over the ice and debris mixed deposits (or 'apron') and plunging into the lake. This phenomenon was likely of a smaller scale and the flow was confined to the left-hand side of the rock slope and ice and debris apron, as indicated in Figure 3 and Figure 4 dated April 20, 2024, and did not cause significant displacement of the lake water. This corroborates the observation by residents of Samagaon.

The event of 21 April was likely of a much larger magnitude with the avalanche covering the whole width of the rocky slope. According to our analysis of the 21 April event, detachment of a massive ice mass from the extensively crevassed part of the glacier snout occurred. This is clearly seen in the textural changes in the PlanetScope satellite images from 19 to 21 April

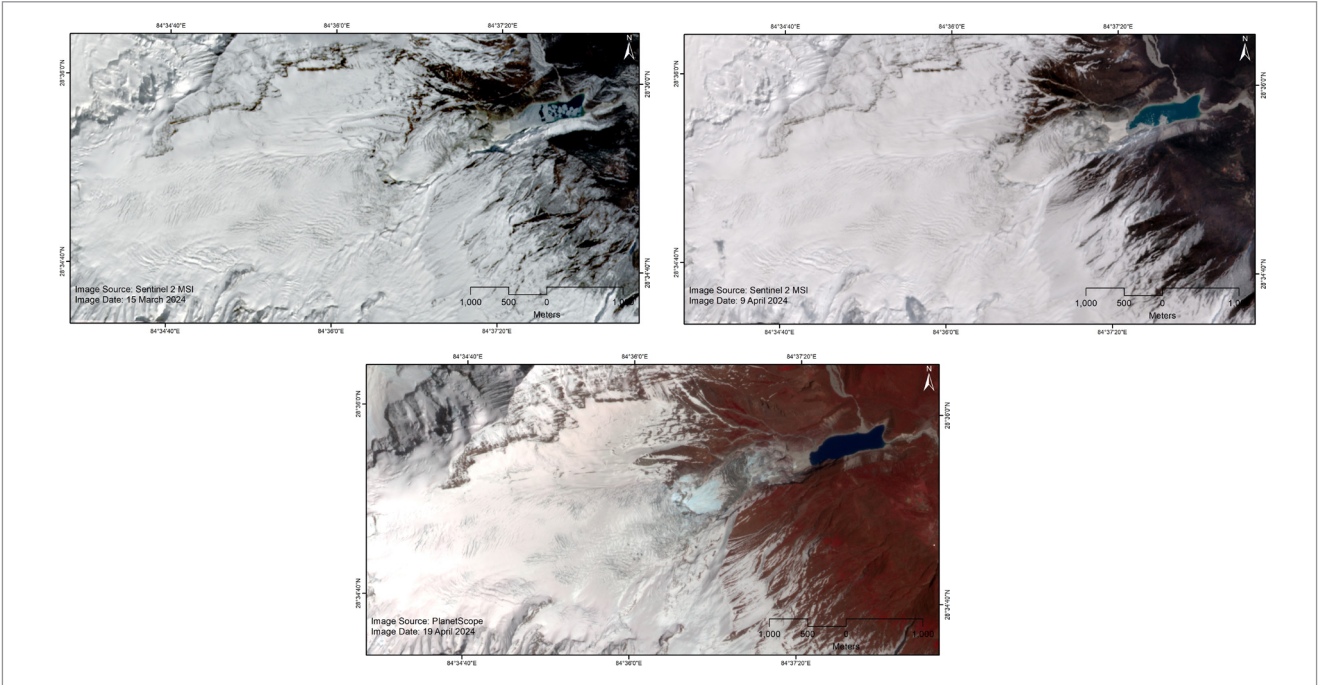
<sup>1</sup> Ministry of Home Affairs urged to be vigilant in the coastal area of Budhigandaki :: Setopati Correspondent: Setopati ([www.setopati-com.translate.goog](http://www.setopati-com.translate.goog))

<sup>2</sup> <https://english.onlinekhabar.com/eyewitness-statement-we-saw-the-critical-situation-in-birendra-glacier-lake-we-were-saved-by-luck.html>

<sup>3</sup> Avalanching glacier instabilities: Review on processes and early warning perspectives - Faillettaz - 2015 - Reviews of Geophysics - Wiley Online Library



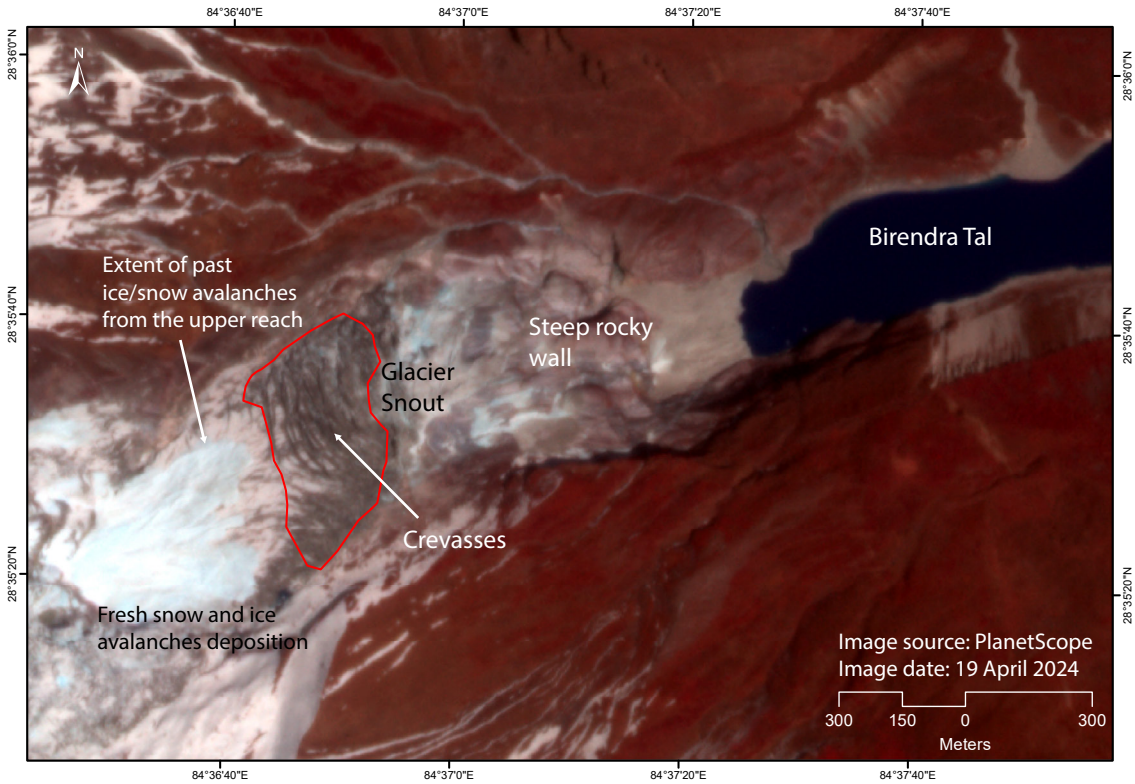
**Figure 2:** Sentinel 2 MSI image dated 15 March 2024 (top left), 09 April 2024 (top right) and PlanetScope image dated 19 April 2024 (Bottom) shows the major disappearance of snow cover in the valley and glacier surface at a lower elevation and melting of the frozen lake surface.



2024 (the source area is labelled and marked by a orange arrow in the image dated 21 April; see Figure 3, Figure 4 and Figure 5). The propagation of ice in the lake water can be seen in the images of 21 and 22 April (Figure 5 and Figure 6). The displacement wave created by the huge mass of ice falling into the lake caused

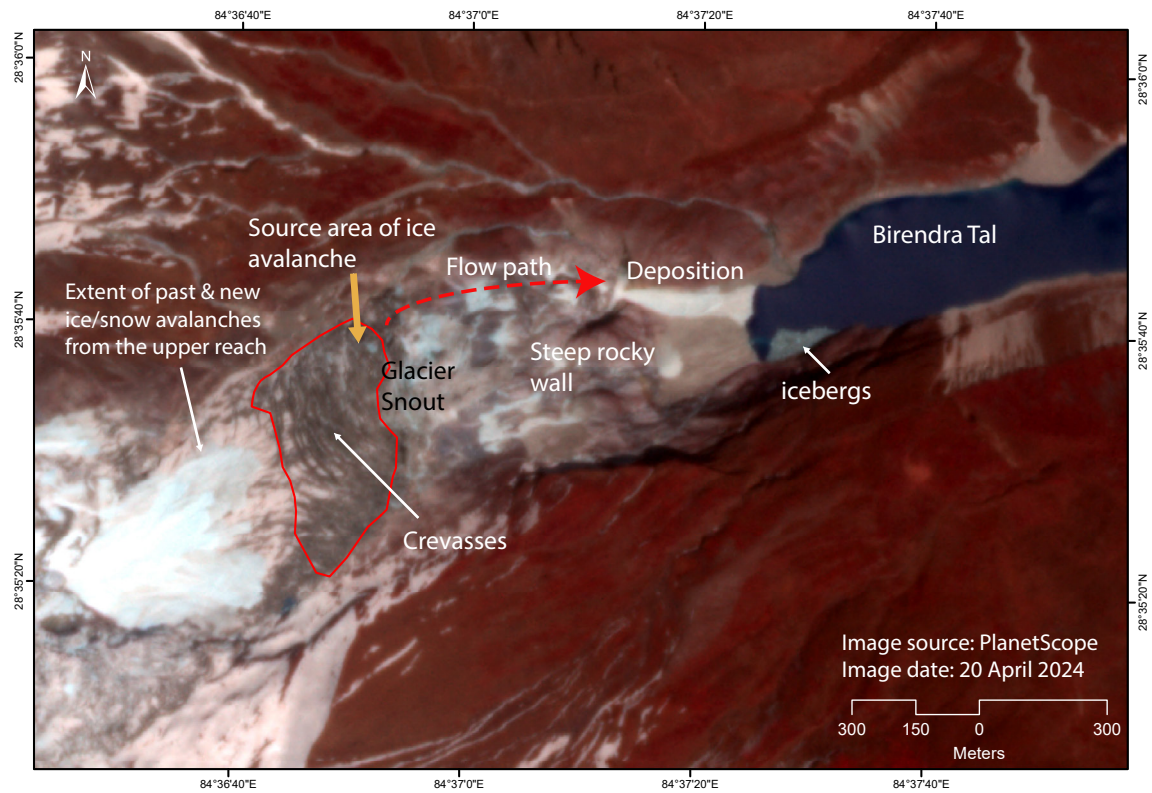
the water to overflow, which produced flooding in the immediate downstream area. The evidence from the image showing the number of icebergs floating on the lake water also proves that it was predominantly an avalanche of ice rather than snow, as some initial speculations had suggested.

**Figure 3:** PlanetScope image dated 19 April 2024 (pre-event) show a clear view of Birendra Tal, ice and debris deposits (apron) in between the steep rocky wall and the lake boundary, extensive crevasses on the glacier terminus (red polygon), snow and ice avalanche deposits from the upper section of the Manaslu Glacier.

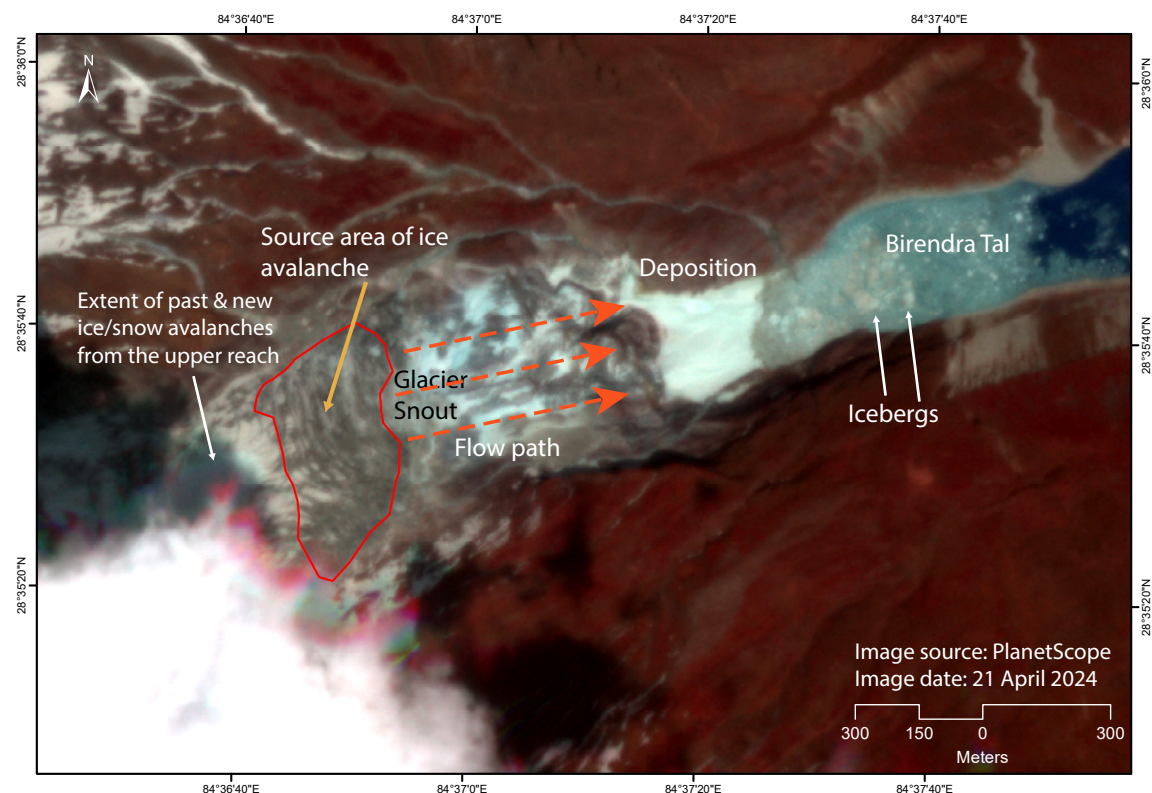




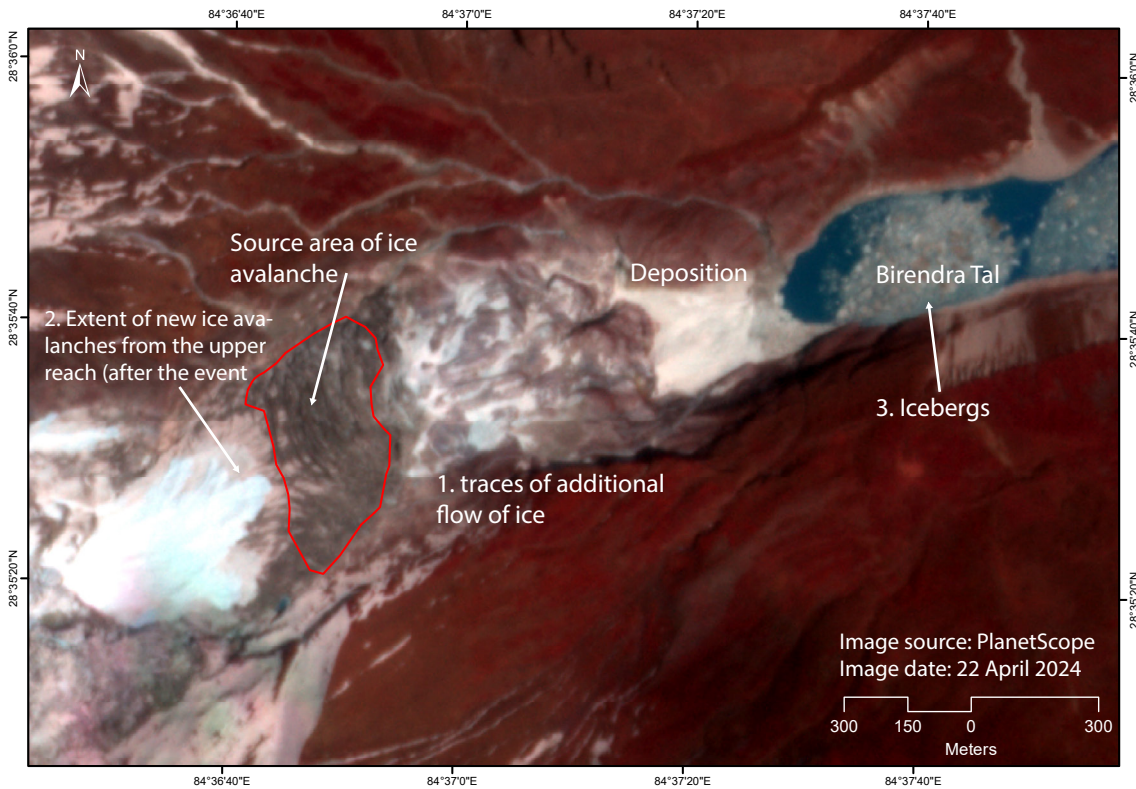
**Figure 4:** PlanetScope image dated 20 April 2024 (one day before the main event) show the dry calving area marked by an orange arrow, the ice avalanche flow path through the narrow-dissected channel at the left side of the steep rocky wall, deposits along the ice and debris apron, and floating ice at the left upper reach corner of the lake.



**Figure 5:** PlanetScope image dated 21 April 2024 (during the main event) show the source of a dry calving area marked by orange arrow, the ice avalanche flow path throughout the steep rocky surface and the narrow-dissected channel (red arrows) and deposits covering the full width of the ice and debris apron and floating ice covering one third of the lake surface. The red polygon showing the heavily crevassed snout of the glacier and source area of avalanches.



**Figure 6:** PlanetScope image dated 22 April 2024 (after the main event) shows – 1) traces of the additional flow of ice from the glacier snout area; 2) deposits of new ice and snow avalanches from the upper reach of the glacier, and 3) the movement and melting of icebergs on the lake.



#### 4. Tracking GLOF evidence from the past

The high-resolution satellite images from Google Earth clearly depict a glacial lake outlet spanning approximately 30–50 metres wide (Figure 7). The V-shaped cross-section of the channel shown in Figure 8 presents a profile among the crest of the end moraine dam from ALOS 30m DEM; high-resolution satellite images in Google Earth show that an open channel outlet exists in the lake that is able to release a certain amount of flow safely (Figure 7 and Figure 8). The channel could have been created by lake outflow or by past GLOF events. The open channel is over 700 metres long measured from the rim of the lake to the moraine dam toe (Figure 9). The channel drops by 50m within this distance, giving it a slope of around 4 degrees. The outer side of the dam is covered by vegetation, indicating a more compact and stable slope. The present overflow was also from the same outlet with no significant impact on the dam, which is clearly visible in the images of 19 April, 2024 and 21 April 2024 shown in Figure 10 below.

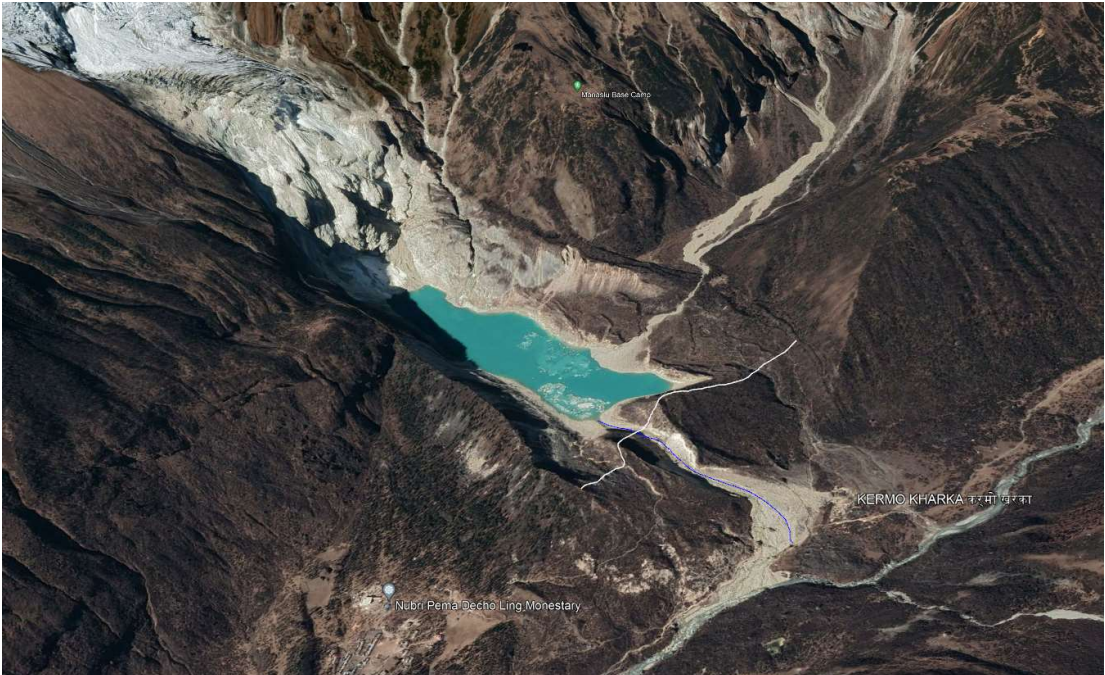
To determine if the open channel was formed from past GLOF events, we analysed historical Landsat satellite images to track the formation of the V-shaped open channel on the moraine dam.

The Landsat image dated 28 October 1976 shows the distinct channel opening, whereas the image from 2 January 1973 (Figure 11) shows the position of the lake but the lake outlet is not distinctly visible. We further tracked the high resolution historical declassified satellite photographs from Corona (8 Nov 1967) and Hexagonal (16 Nov 1973), which confirm the open channel of the lake with erosion and deposition along the moraine dammed area (Figure 12 and Figure 13). However, we cannot find any significant changes in the downstream river flow area, indicating erosion or deposition of flow sediments due to flash floods over time from the late 1960s onward. This suggests that the lake either experienced a breach prior to the late 1960s or the channel was opened during the glacial process of melting, deposition of debris and formation of lakes. Understanding and tracking these processes require obtaining and analysing further historical aerial photographs and other sources of satellite images before and after the lake formed.

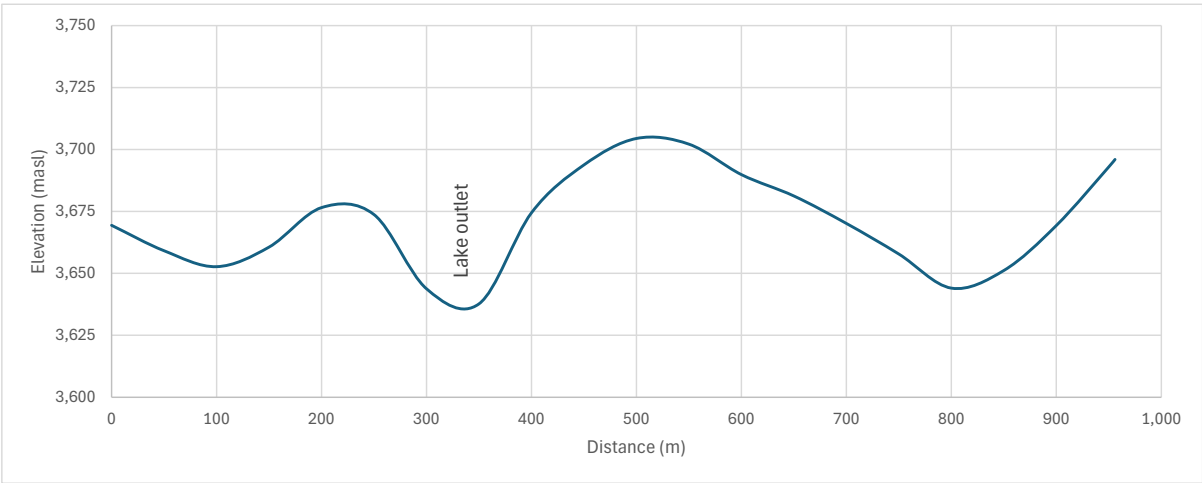
The significant debris deposition on the left side of the lake is also observed, which flows from the left adjacent valley and through the left lateral moraine of the lake. There is also high potential for debris flow and ice and/or snow avalanches from the adjacent valley from the left.



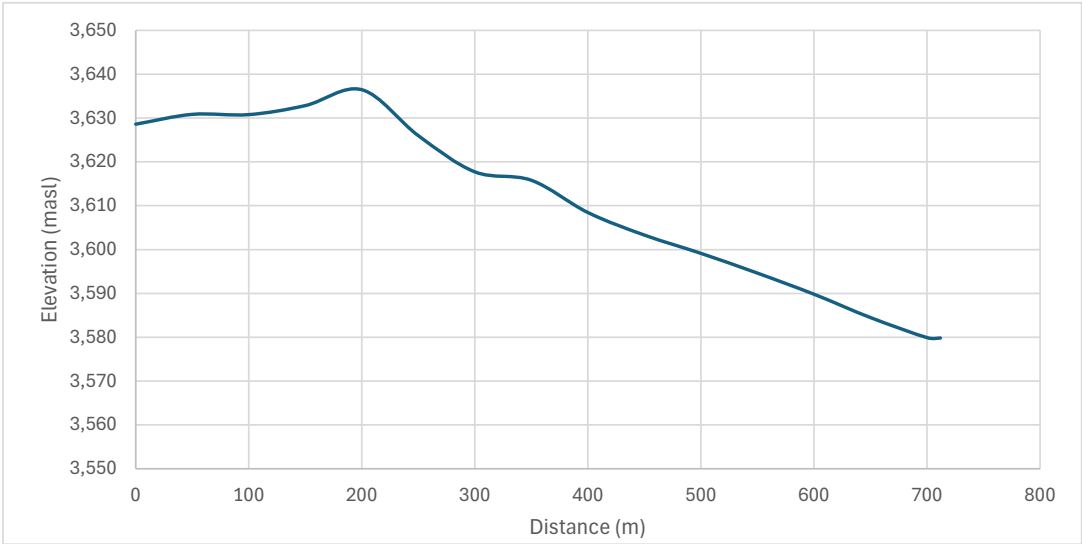
**Figure 7:** High-resolution satellite images from Google Earth show the open channel and fan deposits at the foot of the end moraine dam, indicating the lake was breached in the past.



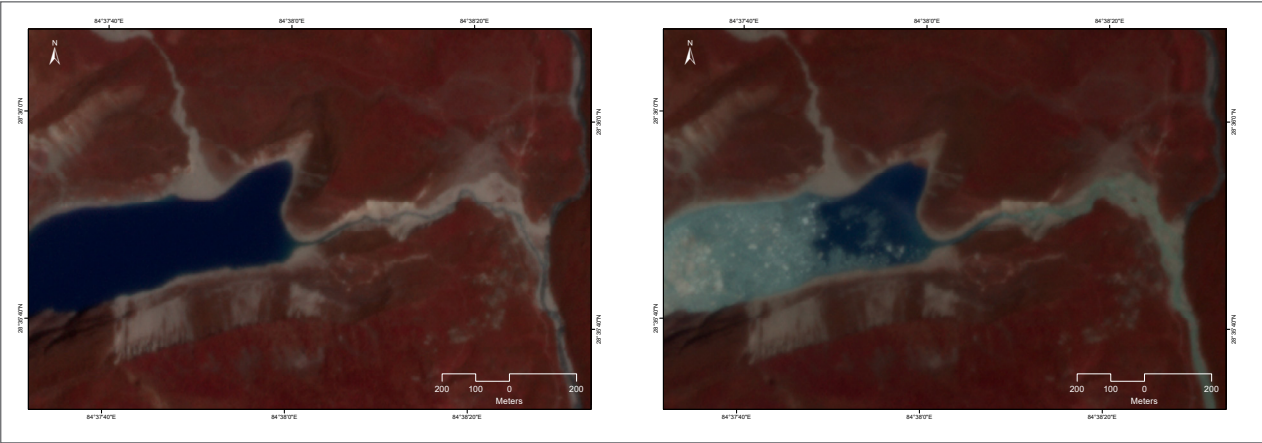
**Figure 8:** Crest profile of the dam showing the V-shape outlet of the lake.



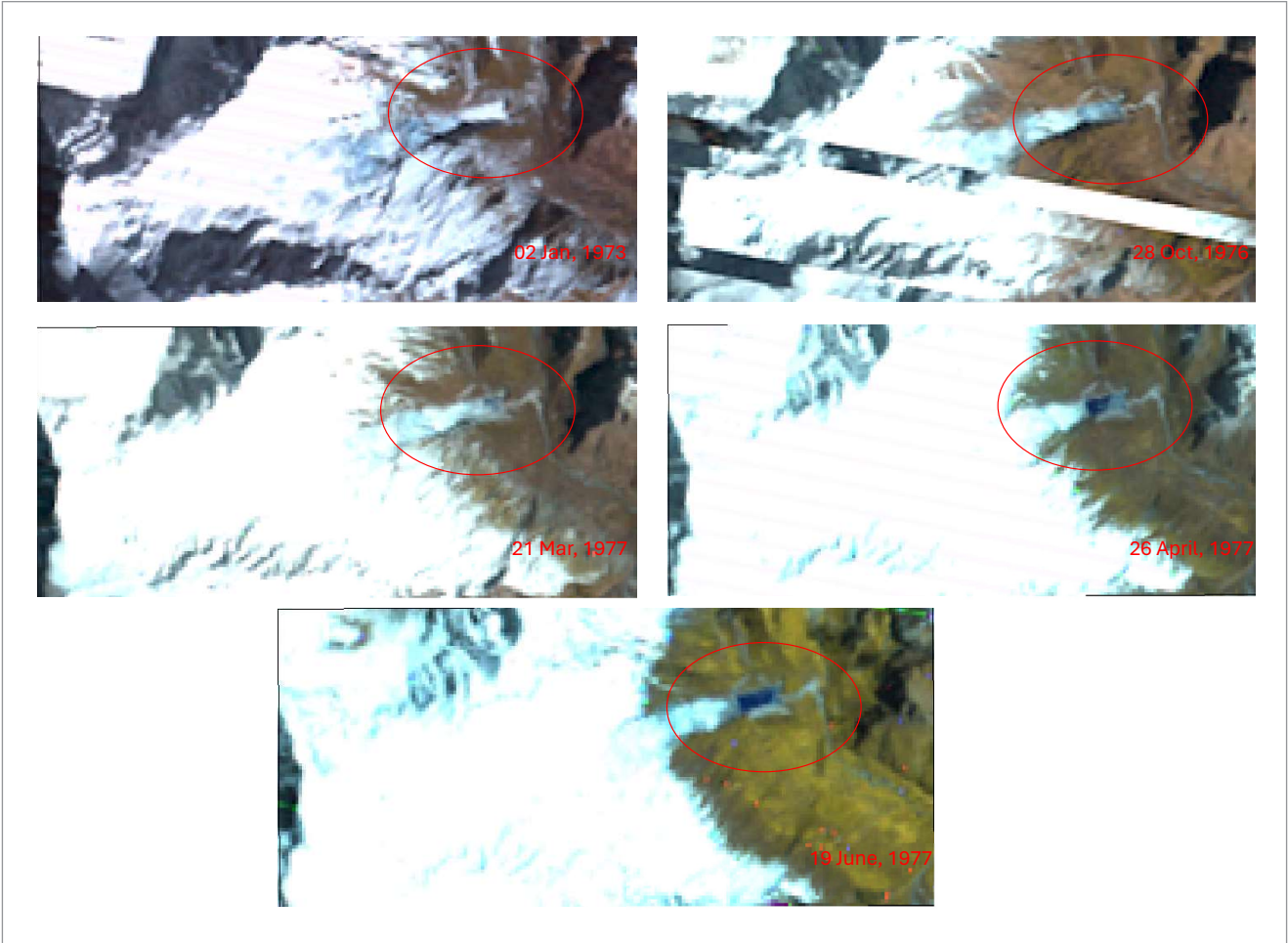
**Figure 9:** Longitudinal profile from the lake edge to the toe of the end moraine dam along the outlet channel centreline.



**Figure 10:** PlanetScope image dated 19 April 2024 (left) shows the open outlet of the lake and an image dated 21 April 2024 taken at 10:54 NPT/05:09 UTC (right) shows an increase in the outlet water flow without significant impact on the dam.



**Figure 11:** The Landsat MSS satellite images show clear drainage and sediment erosion at the end moraine dam of the lake after 28 October 1976; the Landsat image of 1973 shows the position of the lake, but the lake outlet is not distinctly visible.





**Figure 12:** Declassified hexagonal telescopic satellite photograph (KH9-7, ground resolution 20–30 feet) dated 16 Nov 1973 shows the opened channel of the Lake and fresh debris at the lower section of the dam. No trace of flood is visible along the river in the downstream. The blue line shows the lake boundary mapped from the Landsat MSS satellite images of 1973. (The image is georeferenced but not orthorectified).



**Figure 13:** Declassified corona telescopic satellite photograph (KH-4A, ground resolution 9 feet) dated 8 Nov 1967 shows the opened channel of the Lake and fresh debris at the lower section of the dam. There is no distinct indication of a flood along the river in the downstream area. (Note: This image is not in scale, nor is it geo-rectified/orthorectified. In this case, the rivers and other features are not properly oriented as in other geo-rectified images above. Due to the rapid nature of this assessment, it has not been possible to geo-rectify/orthorectify these images as this is a lengthy process.)





## 5. Lake development and tracking of similar past events

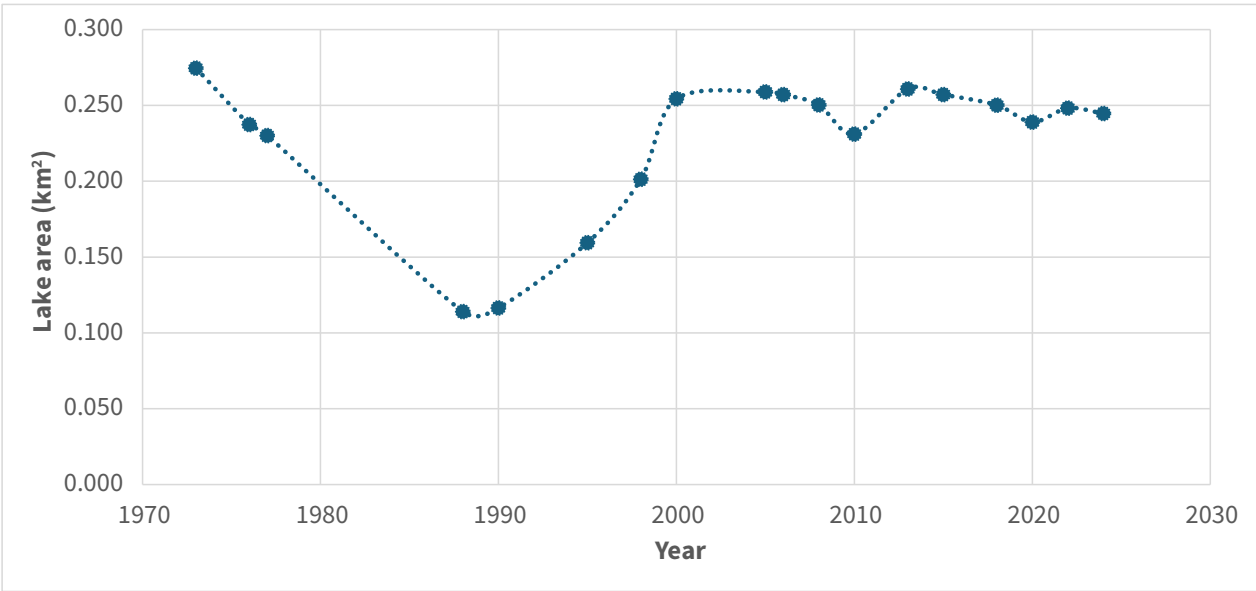
The analysis of the Landsat and PlanetScope images spanning from 1973 to 2024 reveals significant fluctuations in the area covered by the Glacial Lake (Figure 14 and Figure 15). Initially measuring around 0.27 square kilometres (km<sup>2</sup>) in 1973, the lake area decreased to approximately 0.24 km<sup>2</sup> by 1976. Notably, a drastic reduction occurred, with the area halving to 0.11 km<sup>2</sup> by 1988 within a ten-year period. Following a period of stability until 1990, the lake area began to rapidly increase, reaching its maximum extent and covering 0.25 km<sup>2</sup> by 2000. Slight fluctuations in subsequent years are observed, which may be attributed to overflows caused by avalanches or debris flow from the glaciers and their adjacent valley. Some past events are also visible in the satellite images shown below (Figure 16 and Figure 17), and were also covered in the media<sup>4</sup>.

However, recent observations from 19 April 2024, just before the event, indicate a slight decrease in the lake area to approximately 0.24 km<sup>2</sup> and no significant changes in the lake area after the event based on a PlanetScope image dated 22 April 2024 (0.22 km<sup>2</sup>)

except the ice deposition part on the upper reach of the lake. These findings underscore the dynamic nature of glacial systems and the importance of continuous monitoring to understand their response to changing environmental conditions.

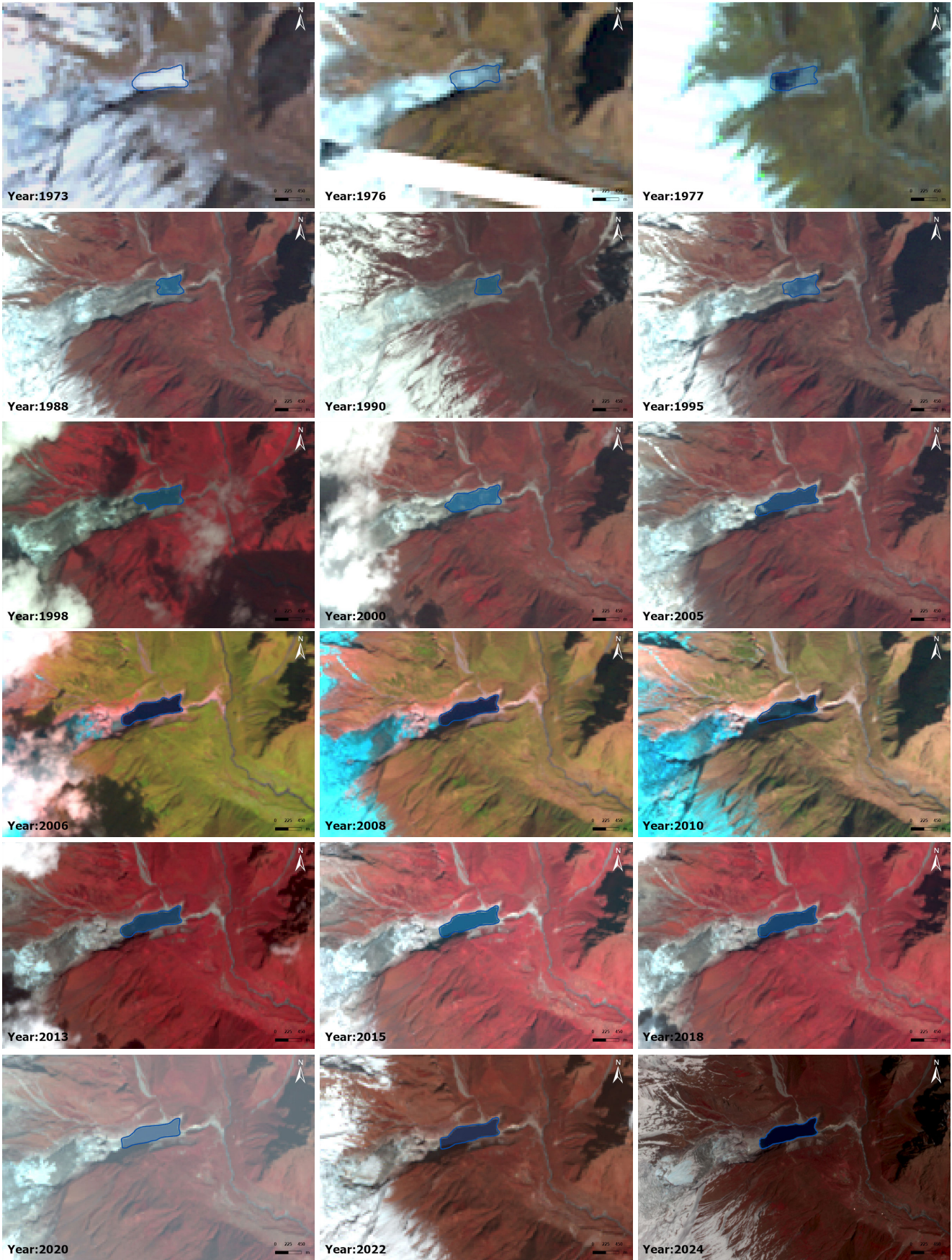
The comparative images on 28 September, 14 and 30 October 2006, and 1, 8 and 9 April 2022 in Figure 16 and Figure 17 show evidence of similar events that occurred in the past. This serves as an illustration, to highlight the recurring nature of avalanches from the Manaslu Glacier. Such events are attributed to the morphological condition of the glacier, its processes, and presence of densely covered crevasses on its surface. The fluctuation in the lake surface area, shown in Figure 14 and Figure 15, also offers insights into the frequency of these kind of events. This underscores the importance of delving into the intricate physical process governing glacier movements as well as the dynamics of the formation and detachment of crevasses. Achieving this understanding necessitates continued monitoring of the glacier, utilising high spatio-temporal resolution satellite images alongside field-based monitoring such as time-lapse camera or ground-based interferometric synthetic aperture radar (InSAR) including monitoring of climate/weather in the catchment.

**Figure 14:** Development of the lake surface area over time spanning from 1973 to 2024 based on the Landsat and PlanetScope images



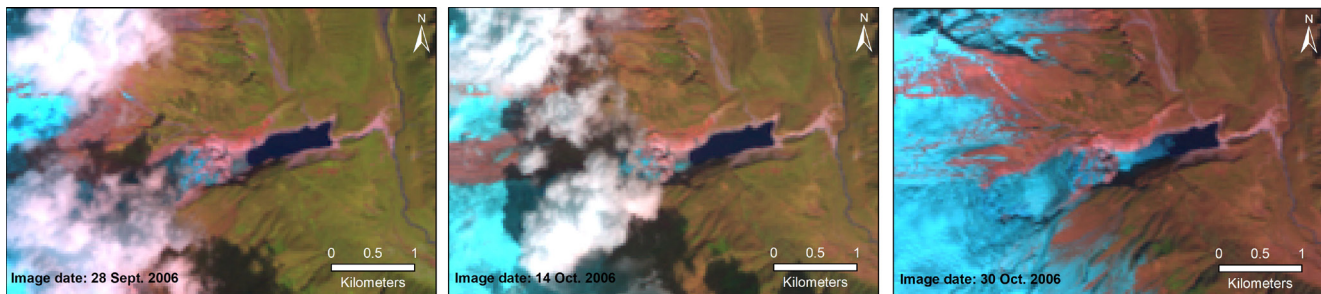
<sup>4</sup><https://kathmandupost.com/national/2015/04/10/melting-of-glacial-lake-threatens-life-property>

**Figure 15:** Landsat and PlanetScope images showing development of the Birendra Tal (glacial lake) over a 48-year period

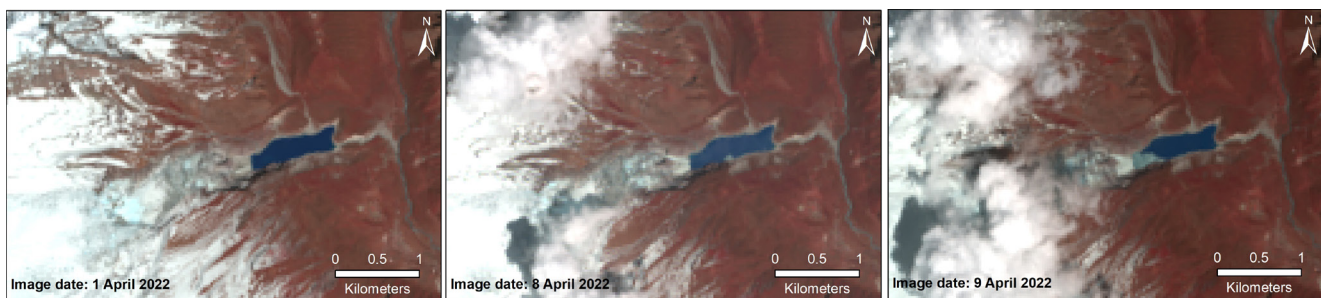




**Figure 16:** Landsat images from 28 September 2006 to 30 October 2006 shows similar events of avalanches from the Manaslu Glacier impacting Birendra Tal. The impact of the ice avalanche on the lake and ice deposit on the upper section of the lake is clearly seen in the image of 30 Oct 2006.



**Figure 17:** Landsat images from 1 April 2022 to 9 April 2022 also shows avalanche from the Manaslu Glacier area and their impact on the upper reach section of Birendra Tal. The deposits of ice and floating masses of ice (icebergs) are clearly visible in the images of 8 and 9 April 2022.



## 6. Estimation of peak outflow discharge

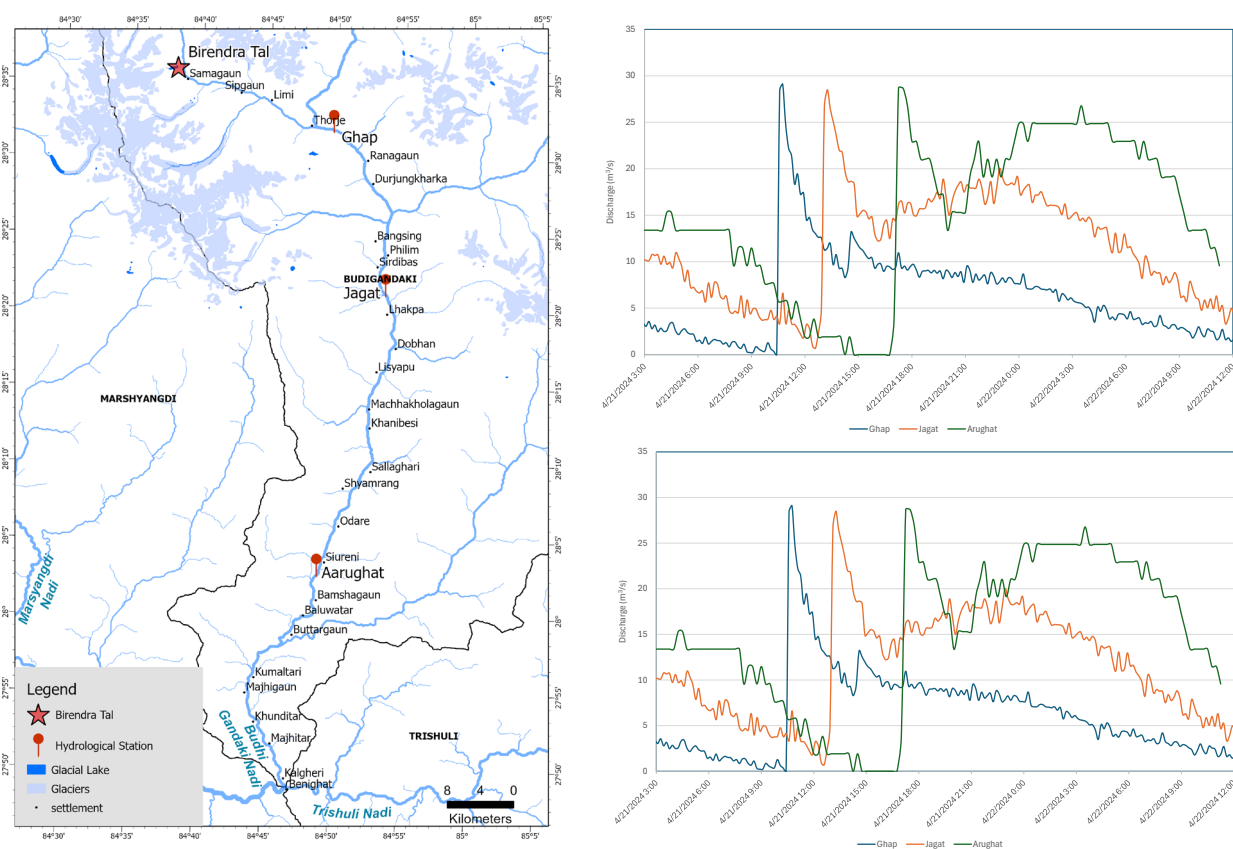
To estimate the peak discharge of the lake overflow, we conducted a back analysis using water level data from Ghap and Jagat, collected by a team from KU, and data from Arughat, collected by members of the Department of Hydrology and Meteorology (DHM), and we generated cross-section information utilising 2m DSM access through the SERVIR Program. These hydrological sites are located at 22, 48, and 87 km downstream from the lake, respectively (see Figure 18). The data shows that the flood reached Ghap at 10:45AM, Jagat at 01:15 PM, and Arughat at 05:30 PM after it was reported at 9:30 AM by an eyewitness<sup>5</sup> (Figure 18).

We estimated the flow velocity, based on the travel time and abrupt water level rise measured by these hydrological stations and considering the average slope of the channel between the locations. The 1D-hydrodynamic model was set up in DHI Mike 11

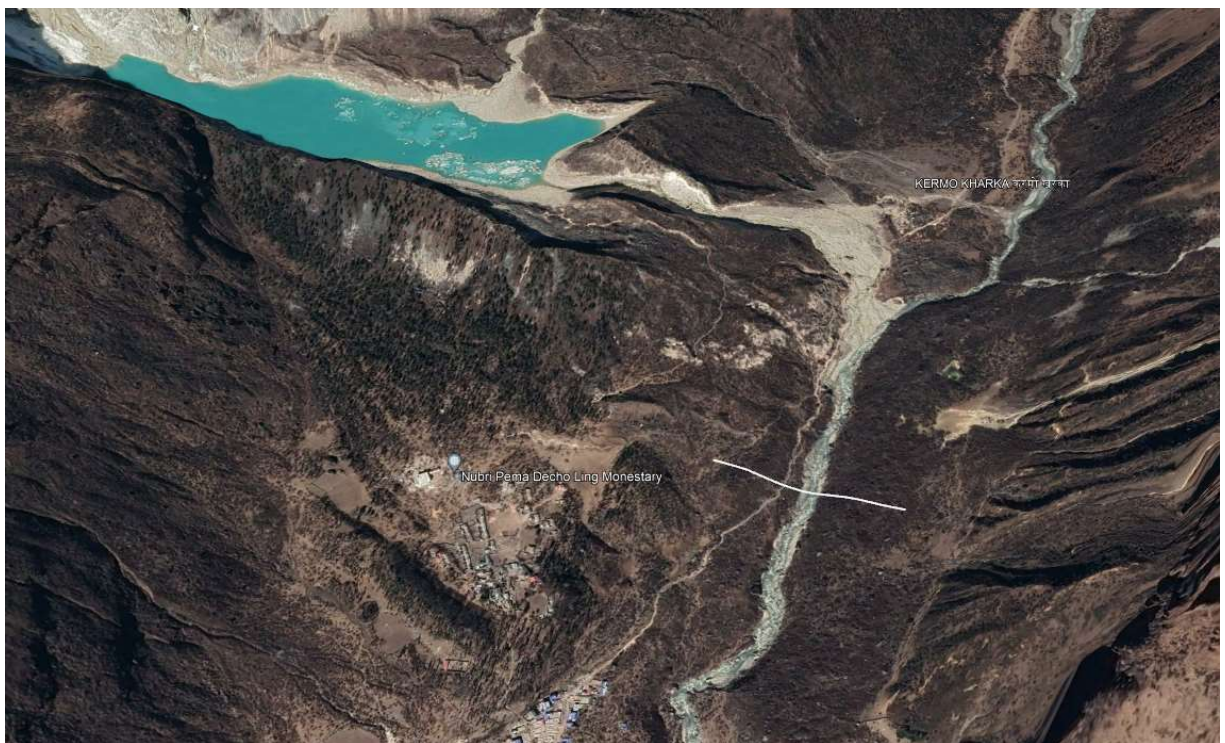
software, integrating the cross-section of the river channel generated using 2m DSM and calibrated using the closest station data (Ghap station) to estimate the peak overflow discharge at the lake outlet. The results show that the peak flow discharge at the lake outlet was 32 cubic metres per second; this is shown in Figure 18. Additionally, the cross-sectional plot showing the simulated water level from just below the moraine dam, close to Sama village and at the Ghap station in Figure 19 and Figure 20 below, indicates that the flow is insufficient depending on channel morphology, to cause major damage in the downstream riverbank. However, factors such as flow velocity, river morphology and geomorphology, and sediment characteristics on the riverbed and banks also play a critical role in determining the impact of the flow along the river. This also clearly suggests that the present event was an overflow of lake water sparked exclusively by ice avalanches from the calving of the glacier snout, not by a breaching of the lake. Therefore, this event is not classed as a GLOF.

<sup>5</sup> <https://shorturl.at/hPQS0>

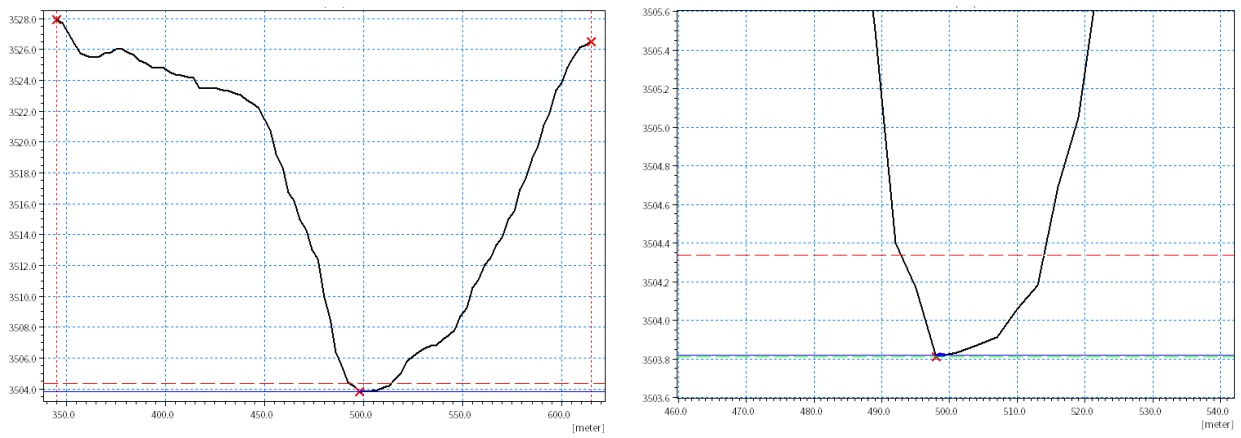
**Figure 18:** Location map (left) of the Birendra Tal and hydrological stations operated by KU (Ghap and Jagat) and DHM (Arughat); the water level measured by these stations (upper right graph), and the



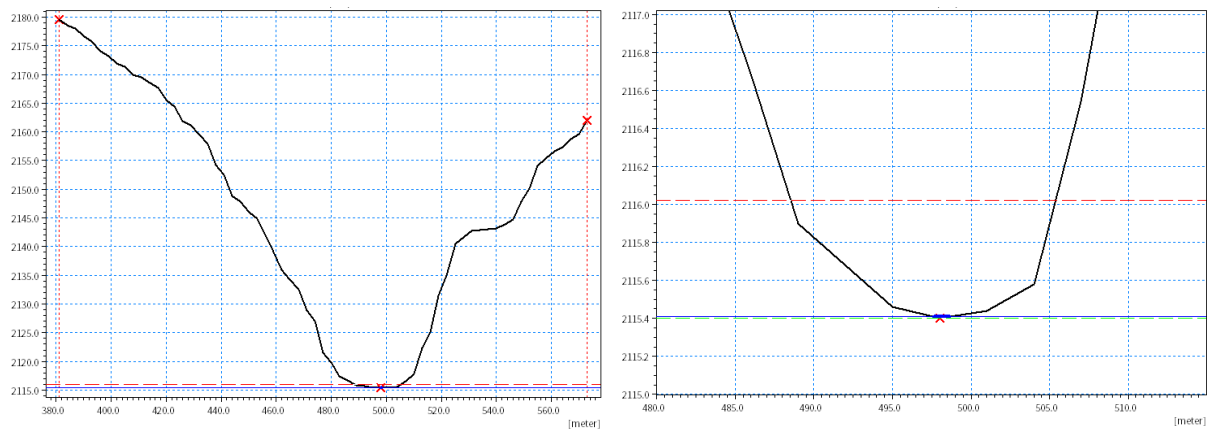
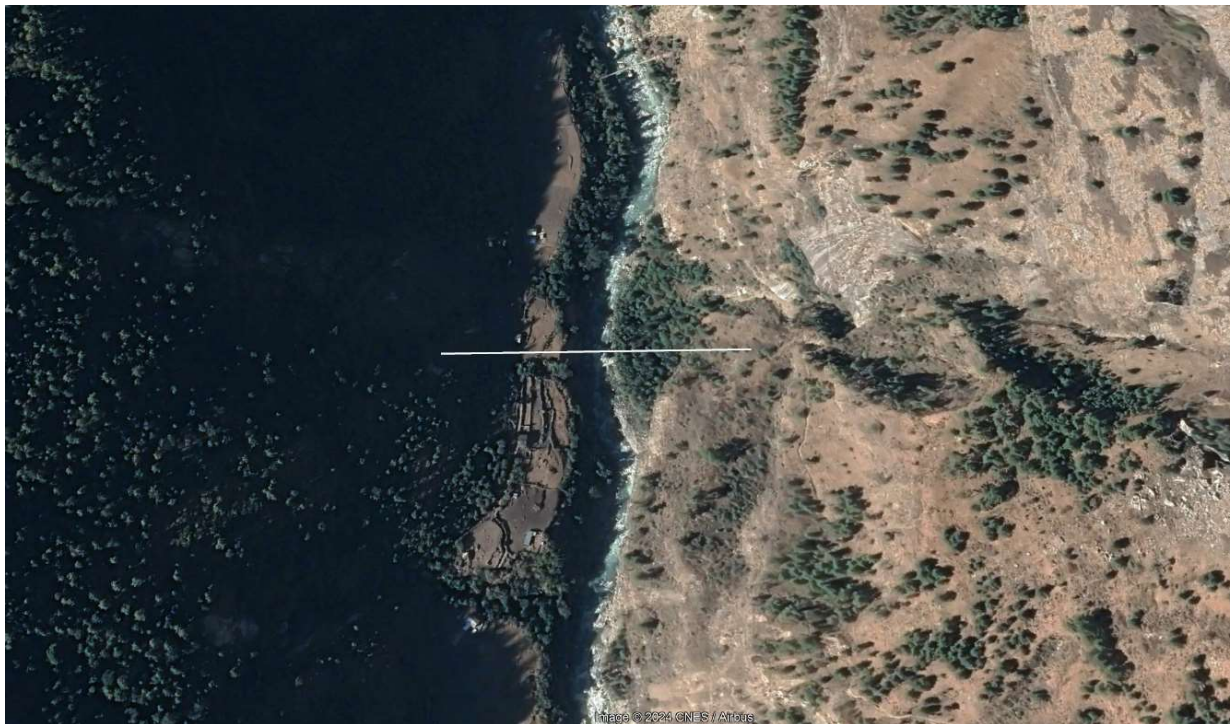
**Figure 19:** Cross-section (white line on the top image) and simulated water flow level (lower graphs) just below the moraine dam and near to Sama village, showing the water level increased to approximately 60cm (red dotted line indicates the simulated water level and the blue solid line is the base flow estimated using the high-resolution image from Google Earth); flow width is around 22 metres







**Figure 20:** Cross-section (white line in top image) and simulated water flow level near the Ghap station showing the water level increased to approximately 60cm and flow width is around 20m (the red dotted line indicates the simulated water level and the blue solid line is the base flow estimated using the high resolution image from Google Earth)



## 7. Conclusion and recommendations

Based on preliminary analysis using satellite data, the flood event on 21 April 2024 originating from Birendra Tal, was attributed to the ice avalanches due to the dry calving of the Manaslu Glacier snout, which sparked the lake overflow.

The magnitude of the overflow was influenced by various factors including the volume of ice and snow released, the manner of the fall, distance from the drop point to the lake, and the channel geometry.

Although the 21 April event was moderate in scale and did not result in significant downstream damage, it's essential to note that both the steep and crevassed frontal section and the crevasses over the whole of the Manaslu Glacier have a historical propensity for dry calving. With projected temperature increase and glacier retreat, future events could surpass the moderate impact observed in this instance.

There is also high potential for debris flow and ice and/or snow avalanches from the left adjacent valley of the lake. The significant debris deposition on the left side of the lake is also observed, which flows from the left adjacent valley and through the left lateral moraine of the lake.

Assessing the potential risk posed by avalanches from glaciers and debris flow from the adjacent valley into the lake and understanding the scale and extent of their impact on the lake, is essential for evaluating the potential magnitude of future disasters. This necessitates a detailed understanding of glacier flow velocity, crevasse formation dynamics, and ice detachment processes. Such information can be acquired through remote sensing techniques and field-based monitoring, such as Ground-based Interferometric Synthetic Aperture Radar (GB-InSAR) or the installation of time-lapse cameras.

To mitigate such risks, continuous monitoring of the lake using satellite imagery and field monitoring by installing a time lapse camera is recommended. Additionally, implementing in-situ sensors for lake-level monitoring and establishing a flood early warning system would enhance preparedness and response capabilities. As the results presented here are derived from rapid analysis, it is imperative that they be substantiated by more detailed assessments, potentially supported by field investigations.

Rising temperatures and rapid glacier retreat are growing concerns across the region. As they pose risks from various mountain hazards similar to the current avalanches triggering overflow from the lake, an extensive event (GLOF) could happen from much larger glacial lakes in the region. The countries in the region remain ill-prepared to cope with the rapid pace of these changes. Addressing this issue will require urgent and strong political action to implement effective risk mitigation strategies as well as investment in scientific research to generate robust data. ICIMOD continues to work with our regional member countries to ensure line agencies have the required skillsets and access to the latest technology to monitor risks and analyse their data to feed into the decision-making process.

## Acknowledgements

This rapid analysis has been conducted based on the Planet satellite imagery accessed through SERVIR-HKH. SERVIR is a joint initiative of [NASA](#), [USAID](#), and leading geospatial organisations in Asia, Africa, and Latin America. ICIMOD implements the SERVIR Hindu Kush Himalaya (SERVIR-HKH) Initiative regional hub in its regional member countries in the HKH region. We have also used other freely accessible satellite images and photographs through USGS portals (Glovis and Earth Explorer). The 2m Digital Surface Model (DSM) utilised for back analysis was accessed through SERVIR. Data from the hydrological stations were accessed through our close collaboration with KU and DHM.

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