Brief Communication: An Ice-Debris Avalanche in the Nupchu Valley, Kanchenjunga Conservation Area, Eastern Nepal

Alton C. Byers,[1] Marcelo Somos-Valenzuela,[2] Dan H. Shugar,[3] Daniel McGrath,[4] Mohan B. Chand,[5] Ram Avtar[6]

[1]Institute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, Colorado USA 80309
[2]Department of Forest Sciences, Faculty of Agriculture and Environmental Sciences, University of La Frontera, Temuco, Chile, 4780000
[3]Water, Sediment, Hazards, and Earth-surface Dynamics (waterSHED) Lab, Department of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta, T2N 1N4
Canada
[4]Department of Geosciences, Colorado State University, Fort Collins, CO, USA, 80523
[5]Department of Environmental Sciences, Patan Multiple Campus, Tribhuvan University, Lalitpur, Nepal
[6]Faculty of Environmental Earth Science, Hokkaido University, Sapporo Japan 060-0810

Correspondence: Alton C. Byers (alton.byers@colorado.edu)

Abstract Beginning in December 2020, a series of small-to-medium, torrent-like pulses commenced upon a historic debris cone located within the Nupchu valley, Kanchenjunga Conservation Area (KCA), Nepal. Sometime between 16 and 21 August 2022 a comparatively large ice-debris avalanche event occurred, covering an area of 0.6 km^2 with a total estimated volume of order 10^6 m^3. The area of the debris cone left by the August 2022 event increased ~~the original area covered by~~the historic debris cone area by 0.2 km^2 (total area: 0.6 km^2). Although no human or livestock deaths occurred, the increase in torrent-like pulses of debris upon this historic debris cone since 2020 exemplifies a style of mass movement that may become increasingly common as air temperatures rise in the region. Although the magnitude of this event was small compared to events like the 2021 Chamoli avalanche, the widespread distribution and frequency of comparable events presents a substantial, and potentially increasing, hazard across High Mountain Asia. ~~suggests that they could be linked to contemporary warming trends in the Nepal Himalaya, similar to larger-scale mass wasting events found elsewhere in the country. Additional future events could also include an increase in glacial lake outburst floods (GLOFs), englacial conduit floods, rockfall-induced rock avalanches, and landlsides. Changing cryospheric conditions throughout the region suggest that~~ .

~~the installation of floodwater diversion technologies for vulnerable villages is warranted, as are improved reporting mechanisms to authorities and the development of early warning systems. More systematic monitoring via remote sensing platforms and hazard mapping by scientists is also indicated.~~

1 Introduction

Large magnitude but low frequency events in the high mountains can include a variety of familiar and poorly understood cryospheric processes, including glacial lake outburst floods (GLOFs) (Lamsal et al. 2014), snow/ice/rock avalanches (Shugar et al. 2021), landslide-induced avalanches and floods (Byers et al. 2019), englacial conduit floods (Rounce et al. 2017), and others (see: Byers et al. 2022). Today, enhanced communications and remote sensing technologies enable rapid identification and location of such events, often within hours of their occurrence. Many, however, remain unreported because of

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My main concern with this study are the risk assessments and monitoring recommendations that are, first, not really careful, or detailed enough grounded, and second….

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their remoteness, inaccessibility, poor communications, and/or absence of people (see: Byers et al. 2020). In this *Brief Communication,* we report on a large ice-debris avalanche that occurred sometime between 16 and 21 August 2022 in the Kanchenjunga Conservation Area (KCA), eastern Nepal. The event is noteworthy not only because of its probable linkages to climate change impacts in the region, but also because local residents only several kilometers down the valley were unaware of its occurrence, as wasere the Government of Nepal and climate change research entities in Kathmandu. Here we briefly document the event and describe its present and future implications for local communities, scientists, and governments.

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2 Setting

The KCA is a 2,035 km² protected area established in 1997 by the Nepalese Department of National Parks and Wildlife Conservation, with management responsibility handed over to local communities in

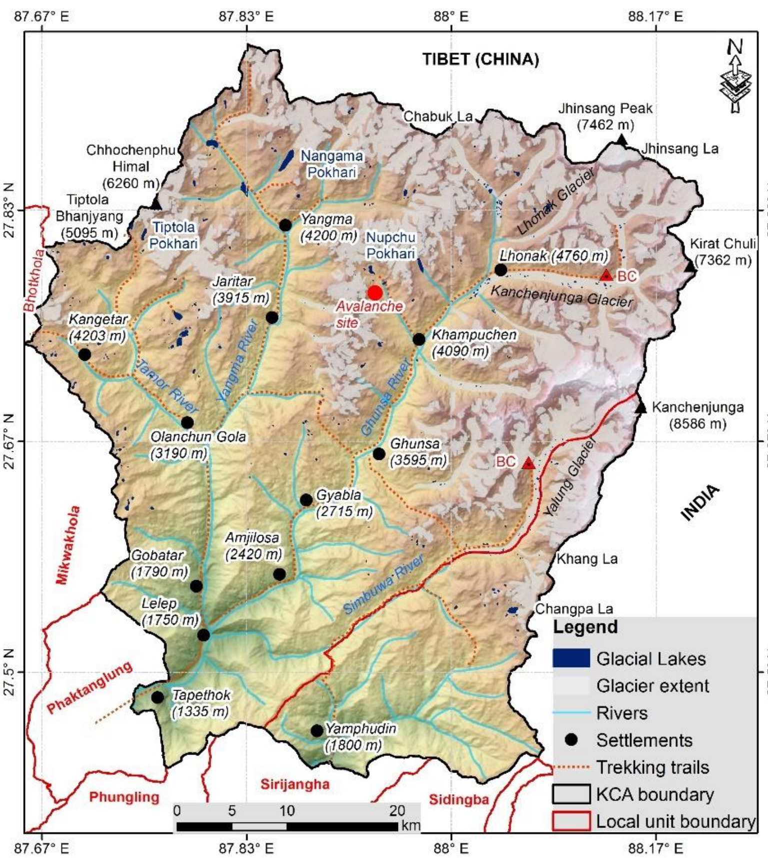

Figure 1. Kanchenjunga Conservation Area and location of the Nupchu ice-debris avalanche. (map by M. B. Chand).

2 Setting

The KCA is a 2,035 km^2 protected area established in 1997 by the Nepalese Department of National Parks and Wildlife Conservation, with management responsibility handed over to local communities in 2006 (WWF Nepal 2018) (Figure 1). It is home to a range of ~~E~~ethnic groups ~~are primarily~~ of primarily Tibeto-Burman origin ~~and~~ that include Limbu, Rai, Tamang, Gurung, Magar, Chhetri, and Sherpa (Thapa 2009). Livelihoods were traditionally based upon agriculture, livestock raising, and trade with Tibet, but globalization, outmigration, and new road construction over the past 15 years has rapidly changed the character of both the social and environmental landscape (~~Byers 2023~~). The South Asian monsoon dominates weather patterns, with most rainfall falling between June and September. ~~High annual rainfall, and the region's location at the intersection of the Indo-Malayan, Palearctic, and Sino-Japanese floristic interface, combine to produce one of the most biologically rich landscapes of the eastern Himalayas~~ (Kandel et al. 2019).

Based upon an analysis of 1962–2000 ~~Landsat ASTER~~satellite imagery, valley and mountain glaciers in the KCA cover approximately 488 ± 29 km^2 and exhibit an overall negative glacier surface area loss of 0.5 ± 0.2% yr^{-1} (Racoviteanu et al. 2015). Valley glaciers are largely debris-covered and have been receding since the most recent maximum during the Little Ice Age. Hooker (1854) for example wrote in 1849 of observing glacial moraines that provided proof "…of glaciers having once descended to from 8,000 to 10,000 feet in every Sikkim and east Nepal valley…" (Hooker 1854: 166). The British alpinist Freshfield (1903: 236) writes of the "glacial shrinkage" he encountered in the Lhonak region in 1899, as well as throughout both the Nepal and Sikkim sides of the Kanchenjunga massif. ~~Valley glaciers are largely debris-covered and have been receding at least as far back as the 1850s (Hooker 1854; Freshfield 1903).~~ Although the Kanchenjunga region received some of the earliest study, exploration, and mountaineering expeditions in Nepal by outsiders (Thapa 2009), relatively little glacier and cryospheric hazards research has been conducted to date. For example, until 2019 only one GLOF event was on record for the region (Watanabe et al. 1998; ICIMOD 2011), although subsequent research revealed that at least seven others had occurred since 1921 (Byers et al. 2020). The Nupchu valley, where the ice-debris avalanche of concern occurred, is used seasonally for yak herding, potato farming, and tourism, with four operational tourist lodges in the village of Kampuchen as of the fall of 2022 (Figure 1).

3 Methods

Field-based observations and assessments of Nupchu Pokhari (glacial lake), other nearby lakes, and the ice-debris avalanche were conducted ~~by A.C. Byers and his field team~~ between 1–20 September 2022. Methods included GPS-based route mapping, photography of avalanche features, oral testimony, and literature reviews. Historic (declassified KH-9 Hexagon satellite imagery; see: Maurer et al. 2019; Dehecq et al. 2020) and recent (Planet Dove and SuperDove) satellite imagery ~~enabled the production of a time series panel between 1975 and 2023 that details the~~revealed the sequence of avalanche/debris flow events between 1975 and 2023 (Figure 2). Numerical simulations of the avalanche were conducted using R.Avaflow version 3 (Mergili and Pudasaini 2014–2023; Mergili et al. 2017), a state of the art software that has been used globally to study ice/rock avalanches events (Zhang 2022). Numerical simulations were used to provide upper limit volume estimation of the avalanche, which were constrained by field observations. We used the parameters from Zhang et al. (2022) to produce a single-phase model scenario for three different volumes: 1, 2.5, and 5 million m^3.

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Commented [DM6]: Landsat AND ASTER?

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Table 1. Summary of satellite imagery used in this study.
Sensor Scene ID Date Spatial resolution Image type
Corona DS009048070DA244 25 Oct 1962 7.5 m Panchromatic
KH4 DS009048070DA243
DS009048070DA242
Landsat ETM+ L7CPF20001001_20001231_07 26 Dec 2000 15 m Pancromatic
28.5 m Visible, shortwave
90 m Thermal infrared
ASTER
AST_L1A#003_12012000051205_07292001131755 1 Dec 2000 15 m Visible
AST_L1A#003_12012000051214_07292001131813 1 Dec 2000 30 m Shortwave
AST_L1A_00311272001045729_02222004173619 27 Nov 2001 90 m Thermal infrared
AST_L1A#00301052002050207_01302002193030 5 Jan 2002 90 m Surface kinetic
AST_L1A#00301052002050216_01302002193046 5 Jan 2002 temperature
AST_08_00310292002045428_20101212181710_16443 29 Oct 2002
QuickBird 1010010004BD8700 1 Jan 2006 2.4 m Visible, 1010010004BB8F00 6 Jan 2006 shortwave
WorldView -2 102001000FBA1D00 2 Dec 2010 0.50 m Panchromatic ...

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For calibration, we modified the internal friction angle of the mixture to match the extension of the debris left by event. For the terrain elevation, an ALOS PALSAR 12.5 m DEM was used (AP_13152_FBD_F0540_RT1) (ASF DAAC 2014).

4 The Event

The investigation of the Nupchu valley was initiated by local concerns about Nupchu Pokhari (27.790708° N, 87.934275° E) as being one of the most dangerous glacial lakes in terms of a potential GLOF (Figure 1). Periodic, smaller floods from the upper Nupchu valley were reported, and assumed locally to have originated in the Nupchu Pokhari, although no supporting evidence was available. Our field reconnaissance results of Nupchu Pokhari on 12 September 2022, however, suggested that the lake only posed a moderate risk of flooding, largely based on the absence of overhanging ice and other potential flood triggers. This assessment corroborates the findings of Rounce et al. (2017) which concluded that the 0.129 km^2 Nupchu Pokhari presented only a moderate risk of flooding because of (a) no apparent growth between 2000 and 2015, (b) absence of avalanche pathways into the lake (i.e., in line with the direction of the lake and its outflow), and (c) absence of landslide pathways entering the lake.

The August 2022 ice/debris avalanche event was unexpected. Field staff had conducted a reconnaissance of the valley below Nupchu Pokhari in early August 2022 to check out potential camping sites, at which time the upper valley was primarily pastureland. When the field team and A.C. Byers returned in early September, the original path was blocked by massive ice-debris avalanche material (27.774328° N, 87.941064° E) that had clearly occurred at some point in the interim (Figure 2). Our team and *dzopkio* (yak-cattle crossbreeds used as pack animals) were nevertheless able to climb up and over the avalanche debris to the upper Nupchu valley, but at the time the source and triggers related to the event remained unknown.

The original historic debris cone was found to have covered an area 0.402 km^2 that had been relatively stable for at least 45 years, based upon the oldest satellite imagery available (i.e., 1975) (~~Amaury~~Dehecq et al. 2020) (Panel A, Figure 2). Time series satellite images revealed the periodic occurrence of surficial debris flows upon this original deposition. That is, ~~B~~beginning in 2020, ~~however,~~ a series of small-to-medium, torrent-like pulses commenced (Panel C through G, Figure 2), culminating in the relatively large event that occurred sometime between 16 and 21 August 2022 (Panel H, Figure 2). The area of the debris cone left by the August 2022 event increased the original area covered by 0.2 km^2 (total area: 0.6 km^2). Of the three different volume estimates tested (1, 2.5, and 5 million m^3) using R.Avaflow, an avalanche volume of 1 x 10^6 m^3 most consistently matched the extent (red line) and depth of the new debris cone deposited as determined by our field observations (Figure 3).

Our team was unable to locate the event on any seismographs, most likely related to the absence of instrumentation in this part of the eastern Himalayas. Based upon direct field observations as well as satellite imagery, the avalanche had clearly blocked and temporarily dammed the water from the Nupchu Khola (river) at its onset, which was nevertheless able to cut down through the ice and sediment deposited to form a steep canyon estimated at >10 m depth. The presence of shrubs (e.g., *J. indica*) fully stripped of their bark was testimony to the high velocities of the flood- and meltwater produced by frictional forces during the event, a phenomenon reported for other rockfall-induced landslides in Nepal (Byers et al. 2019).

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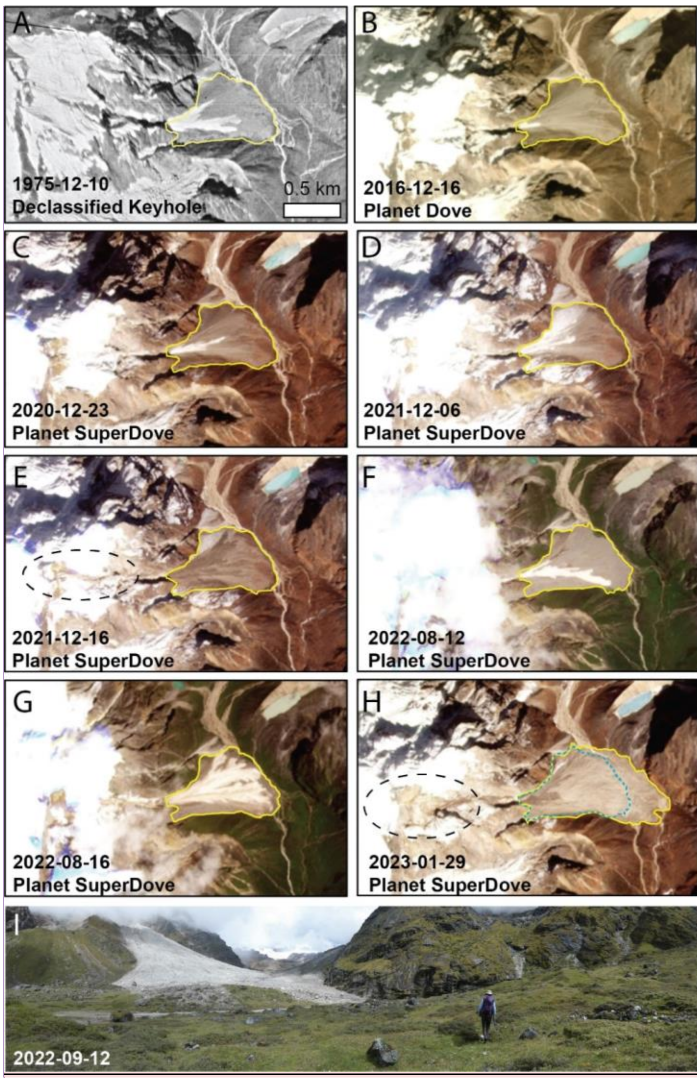

Figure 2. Time series satellite images showing the periodic occurrence of surficial debris flows upon the original deposition. These appear to have accelerated in both frequency in magnitude beginning several years ago, leading up to the main event that occurred between 16 and 21 August 2022. Blue dashed outline in panel H is the 1975 outline of the debris cone, while the dashed black circle identifies the failure zone. The photograph at the bottom provides an oblique view of the ice/debris avalanche about three weeks after it occurred (photograph by A. Byers). Panel H shows an image from early 2023, as imagery from immediately after the ice-avalanche in mid-August 2022 were partially obscured by clouds (KH-9 imagery courtesy of USGS; Planet Dove and SuperDove imagery courtesy of Planet Lab PBC~~; panel by D.H. Shugar~~).

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The intelligence community used Keyhole (KH) designators to describe system characteristics and accomplishments. The CORONA systems were designated KH-1, KH-2, KH-3, KH-4, KH-4A, and KH-4B. The ARGON systems used the designator KH-5 and the LANYARD systems used KH-6. Mission numbers were a means for indexing the imagery and associated collateral data.

https://www.usgs.gov/centers/eros/science/usgs-eros-archive-declassified-data-declassified-satellite-imagery-1

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Commented [DM19]: I thought we had a image from 8/21 that was used to constrain the timing? Or was that image partially cloudy and hence the Jan 29 2023 image is included instead?

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~~most consistently matched the extent (red line) and depth of the new debris cone deposited (Figure 3). Our team was unable to locate the event on any seismographs, most likely related to the absence of instrumentation in this part of the eastern Himalayas. Based upon direct field observations as well as satellite imagery, the avalanche had clearly blocked and temporarily dammed the water from the Nupchu Khola (river) at its onset, which was nevertheless able to cut down through the ice and sediment deposited to form a steep canyon estimated at >10 m depth. The presence of shrubs (e.g., *J. indica*) fully stripped of their bark was testimony to the high velocities of the flood- and meltwater produced by frictional forces during the event, a phenomenon reported for other rockfall-induced landslides in Nepal (Byers et al. 2019).~~

5 Discussion

Interestingly, individuals in the community of Kampuchen, only 5 km downstream of the event, were unaware of the avalanche. Yak herds had already returned from the high pastures to the village by early August, the community was busy harvesting potatoes and preparing for the fall tourist season, and no obvious changes in the Nupchu Khola had been observed (e.g., ~~see:~~ Kargel 2014 for a description of changes in the Seti Kosi prior to the catastrophic flooding of 5 May 2012). Thus, authorities in Taplejung and Kathmandu were also unaware of the event as of September 2022, which is typical of many large-scale cryospheric events in remote regions of the Himalayas (~~see~~e.g.,~~:~~ Byers et al. 2022).

Still, the acceleration of torrent-like pulses of debris upon the historic debris cone since 2020 suggests that they could have been linked to contemporary warming trends, similar to larger-scale mass wasting events found elsewhere in the Himalaya ~~Still, the acceleration of torrent-like pulses of debris upon the historic debris cone since 2020 suggest that they may have been linked primarily to contemporary warming trends, similar to larger-scale mass wasting events found elsewhere~~ (e.g., Shugar et al. 2021; Kääb et al. 2021; Taylor et al. 202~~2~~3). If these increase in frequency as well as magnitude in the coming decades within the Kanchenjunga region, they could include such events as new GLOFs, englacial conduit floods, rockfall-induced rock avalanches, and other phenomena (~~see:~~e.g., Byers et al. 2017, 2022).~~These can be expected to increase in frequency as well as magnitude in the coming decades within the Kanchenjunga region, and could include new GLOFs, englacial conduit floods, rockfall-induced rock avalanches, and other phenomena.~~ Vulnerable villages, such as Kampuchen, may ~~want~~ wish to consider the installation of preventative floodwater diversion mechanisms, such as the rock-filled gabion walls currently protecting tourist lodges in the Mt. Everest region (e.g., Rounce et al. 2017; Byers et al. 2022) using participatory processes as outlined in Watanabe et al. (2016). ~~In the short term, the melting of deposited ice during the coming monsoon season may cause temporary access problems for yak herds, which have relied on the upper Nupchu valley as grazing land for centuries (Thapa 2009). Likewise, access for tourist groups may be delayed for some time until the ice within the debris avalanche has melted.~~

5 Conclusion

~~Despite local concerns, the 0.129 km² Nupchu Pokhari was found to present only a moderate risk of flooding because of (a) no apparent growth between 2000 and 2015, (b) absence of avalanche pathways into the lake, and (c) absence of landslide pathways entering the lake.~~ Beginning in 2020,

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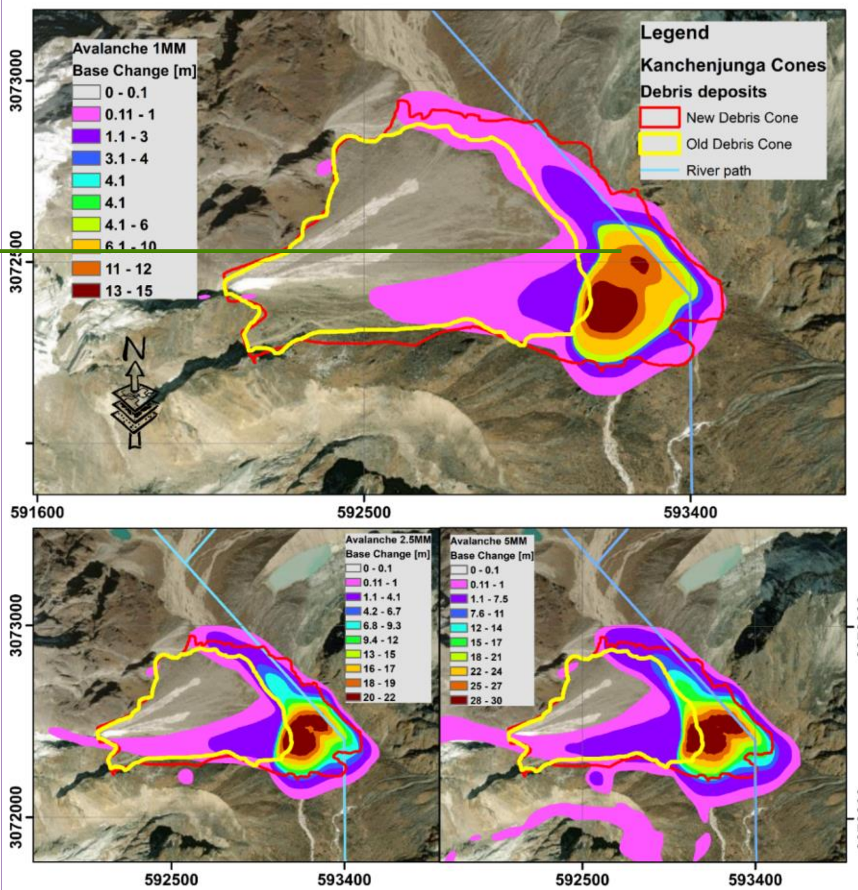
~~however,~~ a series of small-to-medium, torrent-like pulses commenced upon a historic debris cone located approximately 2 km down valley from the lake, culminating in a relatively large avalanche event that occurred sometime between 16 and 21 August 2022. The August 2022 event deposited debris with an area of 0.6 km^2 and estimated volume in the order of 10^6 m^3. No fatalities from the event occurred because of the absence of humans and livestock in the vicinity when the event occurred. Likewise, no impoundment of the Nupchu Khola, and formation of a potentially dangerous backwater lake, occurred as a result of debris blockage, although such scenarios happen routinely in high mountain environments. ~~The installation of preventative floodwater diversion mechanisms, such~~



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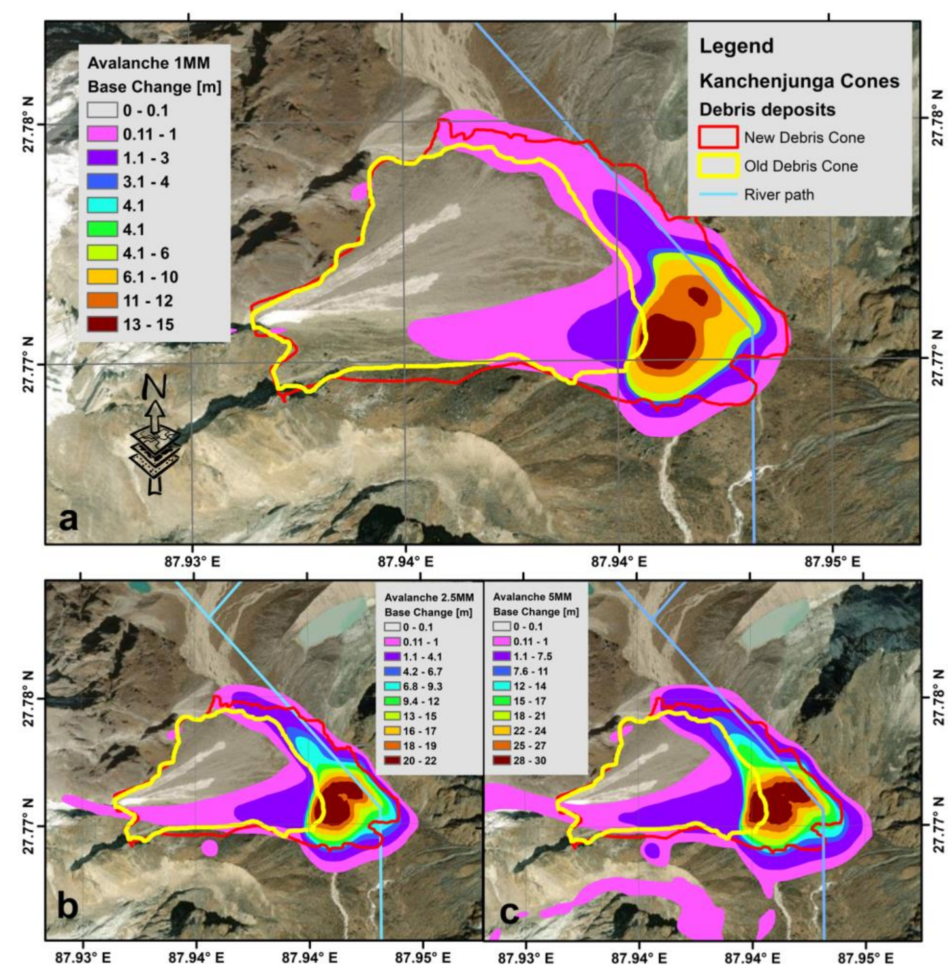

Figure 3. Base change modeled with R.Avaflow for three different avalanche volumes: 1 x10^6 m^3 (top), 2.5 x10^6 m^3 (bottom left) and 5 x10^6 m^3 (bottom right). Of the three estimates, 1 x 10^6 m^3 most consistently matched the extent and depth of the new debris cone deposited in August 2022 (red line; the yellow line represents the extent of the historic debris cone ~~(figure by M. Somos-Valenzuela)~~).

~~as the rock-filled gabion walls currently protecting infrastructure in flood prone regions throughout Nepal, may be warranted to protect vulnerable villages in this specific region.~~ The improvement of remote area event reporting mechanisms, especially to authorities in the capital, Kathmandu, could help with the development of hazard mitigation technologies and response. Likewise, more systematic monitoring of cryospheric events by scientists, using remote sensing platforms and hazard mapping tools, could help with the development of more effective early warning systems for vulnerable communities, livestock, and adventure tourists. Ultimately, this could lead to a minimization of losses and damage due to multi-hazard events.

Data availability. Declassified KH-9 Hexagon satellite imagery is available at https://earthexplorer.usgs.gov/. Planet Dove and SuperDove satellite imagery is available at https://www.planet.com/explorer/. The ALOS PALSAR DEM "AP_13152_FBD_F0540_RT1" used for the R.Avaflow is available at https://asf.alaska.edu.

Author contributions. ACB conceived the study and wrote the original narrative, with contributions from MS-V, DS, DM, MBC, and RA. MBC created Figure 1, DS and RA created Figure 2, and MS-V created Figure 3. MS-V conducted the numerical simulations of avalanche volumes shown in Figure 3. All authors revised and contributed to the final manuscript.

Competing Interests. The contact author has declared that none of the authors has any competing interests.

Acknowledgements. The Fulbright Nepal Scholar Program is thanked for its support of A.C. Byers during his six-month field study of contemporary impacts on alpine ecosystems in the Kanchenjunga Conservation Area, eastern Nepal. The Department of National Parks and Wildlife Conservation, Kanchenjunga Conservation Area, Department of Geography at Tribhuvan University are also thanked for their interest in and support of the project. Support for M. Somos-Valenzuela during the preparation of this paper was provided by the Chilean Science Council (ANID) through the Program of International Cooperation (PII-180008). Support for D.H. Shugar was provided by the Natural Sciences and Engineering Research Council of Canada (DG-2020-04207) and Alberta Innovates. Support for D. McGrath was provided by NASA award 80NSSC20K1343.~~The ca. 1975 KH-9 Hexagon satellite image of the original debris cone was provided by Dr. Summer Rupper (Maurer et al., 2019).~~

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