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Three Recent and Lesser-Known Glacier-Related Flood Mechanisms in High Mountain Environments

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Glacial lake outburst floods, and specifically those triggered by avalanche-induced seiche waves, have been studied in considerable detail during the past several decades. Less attention has been given to other cryospheric flood phenomena, which include floods sourced primarily from englacial conduits, permafrost-linked rockfall and avalanches, and earthquake-triggered glacial lake floods. The article reviews examples of each phenomenon, based on field sampling and laboratory analyses, that have occurred in the Nepal Himalaya during the past decade, drawing parallels with similar events in other countries throughout the high mountain world. In most cases, the frequency of these events appears to be increasing globally, as is their potential to inflict significant damage downstream. We argue that each type of glacier flood requires more detailed study to develop the most effective prevention, mitigation, and adaptation approaches possible. Such studies will most likely be strengthened if they include a reconnaissance of the event as soon after its occurrence as possible, along with the participation, insights, and experience of local people, in addition to the use of increasingly powerful remote sensing technologies. How scientists can more quickly and effectively share the results of their research with decision-makers, and how decision-makers and governments can deliver more timely mitigation programs, are areas that also require further strengthening.

Keywords: *englacial conduit floods; rockfall-induced floods; permafrost change; earthquakes; high mountains.*

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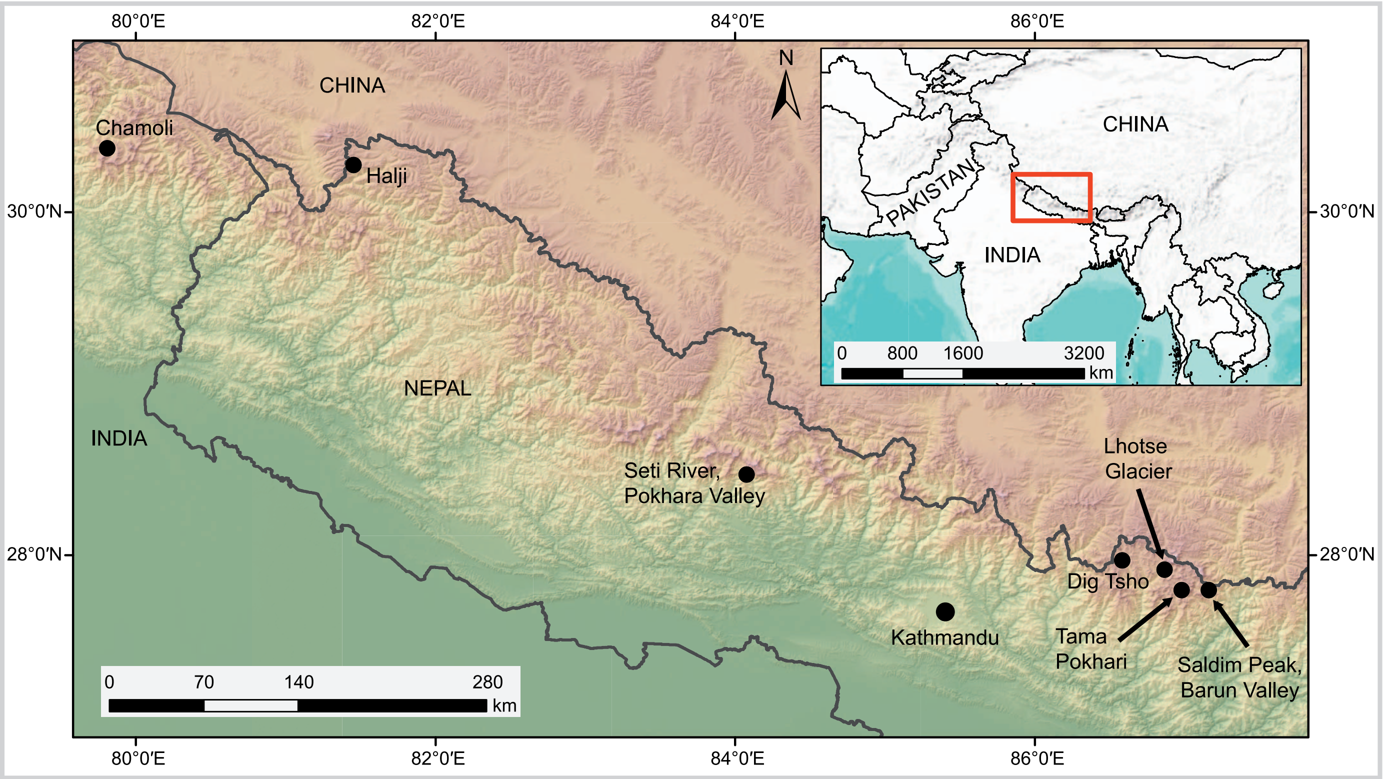
Introduction

The development of glacial lakes from receding glaciers, contained by either terminal moraines or bedrock, is commonly linked with global warming trends that have occurred since the end of the Little Ice Age (LIA) (Emmer et al 2020) and are thought to be increasing in number and size (Shugar et al 2021). Such lakes are prone to sudden and catastrophic drainage of their water, popularly known as glacial lake outburst floods (GLOFs). Dam breakage can result from rapid lake area expansion rates, dead-ice melting in moraines, destabilizing seepage processes, sudden lake water level change, and surge waves created by rockfall or ice calving (Watanabe et al 2009). The stored lake water that is released can cause, and has caused, enormous devastation downstream, including high death tolls, loss of homes and farmland, and destruction of costly infrastructure (eg hydroelectric facilities, roads, bridges). Many countries with glaciated mountain ranges have experienced devastating GLOF events during the past century. Affected areas include the Nepal Himalaya (Bajracharya and Mool 2009; ICIMOD 2011; Bajracharya 2020), the Himalaya of India, the Tibet Autonomous Region of China, and Bhutan (Richardson and Reynolds 2000; Bajracharya 2020; Schmidt et al 2020) (Figure 1), the Peruvian, Bolivian, and Chilean Andes (Carey 2005, 2010; Dussaillant et al 2010; Chevallier et al 2011; Carey et al 2012; Mark et al 2017; Kougkoulos et al 2018), the Swiss Alps (Huggel et al 2003), the Canadian Rockies (Clague and Evans 2000), and the Juneau and Kenai Peninsula regions of Alaska (Abdel-Fattah et al 2021). GLOFs have also been linked to sudden advances—surges—of glaciers and damming of rivers, especially in the Karakoram (eg Rounce et al 2017; Bhambri et al 2020) and northwest North America (eg Kochtitsky et al 2019).

Glacial lake formation and GLOF occurrence since the LIA have been shown to be spatially heterogeneous and asynchronous (eg Harrison et al 2017; Veh et al 2019). For example, LIA-linked glacial lake formation in the Peruvian Andes was active by the beginning of the 20th century, with disastrous GLOFs occurring in the early 1940s (Carey 2005). In the Himalaya, the accelerations in glacier retreat, formation of glacial lakes, and GLOF frequency is associated with the mid-1960s to early 1970s (ICIMOD 2011) (Figure 2). Zhang et al (2015) reported an increase in total lake area in

FIGURE 1 Overview of the major study areas discussed in this article. (Map by Mohan Bahadur Chand)



the Third Pole region of about 13% between 1990 and 2010, which is similar to the estimate of Nie et al (2017) of 14% between 1990 and 2015. Zheng et al (2021, supplementary figure 4), on the other hand, found an increase in glacial lake area of 7% between the 1990s and 2015 but disproportionately influenced by moraine-dammed lakes, which increased ~31% in area. In western Greenland, How et al (2021) found an increase of ~75% in lake frequency since 1985. In Alaska and neighboring Canada, Rick et al (2022) reported an increase in lake area of 57% between 1984 and 2019, whereas Shugar et al (2021) found a 55% increase between 1990 and 2018.

A majority of 32 GLOFs that are recorded for the Cordillera Blanca of Peru were caused by ice avalanches or landslides into the lakes (Emmer et al 2020). These have also been a common trigger of the 34 known GLOF events, as of 2010, for Nepal, Tibet Autonomous Region/China, and Bhutan (ICIMOD 2011: 4; Kirschbaum et al 2019). The actual number of GLOFs that have occurred since the end of the LIA, however, is difficult to determine with precision. This can be linked to the lack of remote sensing technologies before the latter half of the 20th century, historical travel and research prohibitions (eg Tibet, Nepal), steep terrain and poor communication technologies in remote high mountain regions, and monitoring preference and attention given to larger glacial lakes because of their visibility and relative ease of monitoring. Even today, high mountain regions that have only one GLOF event on record since the mid-1960s (eg Watanabe et al 1998) have, in fact, been shown to have experienced many more in the interim (see Byers et al 2020). Current lists of known GLOF occurrences in high mountains (eg Carey 2005, 2010; Harrison et al 2017; Bajracharya 2020) are thus most likely underestimates.

A number of lesser studied cryospheric processes that can also result in major landslide, debris flow, hyperconcentrated slurry, and/or other major glacier-related flood events are beginning to receive attention. In the current article, we briefly examine and focus on 3 of these lesser-known and less well documented phenomena—englacial conduit floods (Rounce et al 2017), permafrost-linked rockfall and debris flows (Byers et al 2019), and earthquake-triggered floods (Byers et al 2017)—based on recent field studies and the first-hand experience of several of the authors. Detailed descriptions of the methods employed for each interdisciplinary study can be found in the respective citations above. While recognizing that all examples could fall under an overarching "glacier flood" or "cascading hazard process" heading, we argue that each type of event still needs more focused research to achieve the best understanding of their causes, consequences, and mitigation opportunities. Although englacial conduit floods are rare in the Peruvian Andes, they are becoming increasingly common in glaciers throughout the other high mountain regions of the world; changes in permafrost, and consequential catastrophic events, have been documented not only for the Himalaya, but also for the European Alps, Andes, and other high mountain regions; and earthquakes remain a constant and potential trigger for GLOFs throughout the high mountain world. Finally, the authors also believe that the 3 case studies presented, individually and collectively, provide valuable lessons learned that could have applications to other high mountain regions of the world. They include (1) the need to study catastrophic events as soon after their occurrence as possible, given the ephemeral nature of geomorphic evidence; (2) the importance of combining field-based work with state-of-the-

FIGURE 2 (A) Tama Pokhari in the Makalu-Barun National Park, Nepal, provides a good example of a lake where a glacial lake outburst flood (GLOF) was triggered by an ice avalanche from overhanging ice (far right of the photograph). The flood occurred on 3 September 1998. In 2010 the breached terminal moraine can be seen to the far left. (B) One of the only known photographs of a GLOF in progress at its source. Water can be seen cascading over the Tama Pokhari's newly breached terminal moraine, which reportedly was repeated in a series of distinct waves. (C) The same general location in 2010, showing the extensive damage caused to what had been the northeastern section of Tagnag village (4350 m). Downstream impacts were also considerable. (Photos A and C by Alton C. Byers; B by Lhakpa Sherpa)

art laboratory technologies; and (3) the importance of including local communities in the research and analyses processes. At the same time, the wisdom of constructing major and costly hydropower and other projects in dynamic high mountain regions is questioned, and the continued need to improve communications between scientists and decision-makers is stressed.

Three lesser-known glacier flood mechanisms

Englacial conduit floods

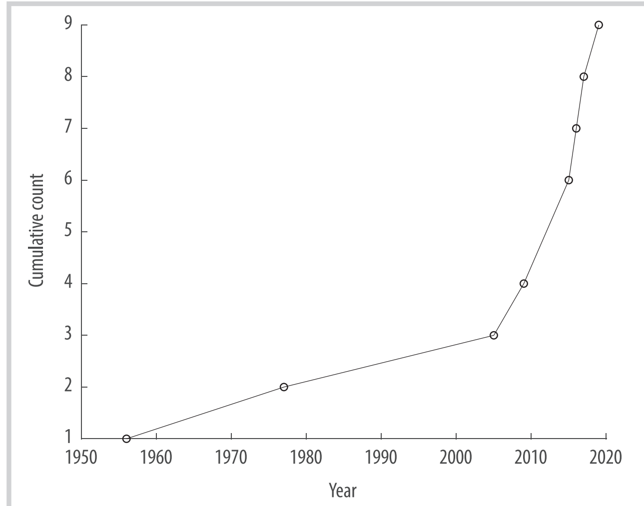
Debris-covered glaciers with gradients steeper than 2° are prone to meltwater drainage as opposed to the pooling and development of large glacial lakes (Quincey et al 2007). Consequently, they often develop a network of englacial conduits, or cave-like features, within the glacier itself (Benn et al 2012). The conduits may be interconnected as well as linked to the surficial meltwater ponds characteristic of stagnating and ablating debris-covered glaciers (Gulley and Benn 2007). These conduits are usually water filled during the summer months, contained within the glacier by an ice lens or dam located below the exterior debris cover. They are water free during the winter months (Gulley et al 2009; Rounce et al 2017).

Flood triggers can include the rapid drainage of a surficial meltwater pond directly into water-filled conduits; overland floods from high precipitation events, where floodwaters enter surficial sinkholes that connect directly to the conduits; or the sudden discharge of water from one internal conduit to another. Once the discharge of water begins, retaining ice lenses located at the glacier/debris cover interface can fracture from the increased hydrostatic pressure, with flood waters emerging directly out of the glacier itself. The discharged water from multiple conduit outlets can then merge to create significant downstream flood activity, with peak discharges in the range of several hundred cubic meters per second (Rounce et al 2017). These floods, while considerably smaller than most known and recorded GLOFs, can nevertheless result in damage downstream to bridges, agricultural fields, and/or structures located in the flood path.

On 12 June 2016, we witnessed and videoed one such flood event from Lhotse glacier, Sagarmatha National Park and Buffer Zone, eastern Nepal, that passed dangerously close to the tourist village of Chukhung (5550 m) (see Rounce et al 2017) (Figure 3). A similar flood had occurred a year earlier on 25 May 2015 in the same location (Byers et al 2017). Both events flooded the ground levels of at least 3 lodges. Lodge owners informed us that such floods had been a fact of high-elevation life for as long as anyone could remember. For example, a larger flood in the early 1950s destroyed over half of the grazing land of the then-small and

FIGURE 3 Gabions constructed near Chukhung village in 2016, following a threatening englacial flood from the Lhotse glacier in 2015. Local lodge owners credited the gabions with protecting the village during a second flood in 2016. (Photo by Alton C. Byers)

FIGURE 4 Known englacial conduit flood frequency in the upper Imja Khola watershed region, Khumbu, Nepal, since the 1950s (data based on the informal oral histories of local informants).



seasonal grazing settlement of Chukhung. Likewise, the Swiss-Canadian glaciologist Fritz Müller was nearly forced to leave Khumbu in 1956 when, during what were most likely englacial conduit floods that destroyed a number of *ghatta*, or water-driven mills, villagers insisted that his glacier research work had angered the gods (Müller 1958). Fortunately, the then 14-year-old Abbot of Tengboche, who had formed a close friendship with Müller, intervened.

Lodge owners also reported that, during the 1950s and 1960s, englacial conduit floods occurred "about every 15 years" (L. Sherpa, personal communication, 14 June 2016). Since the early 2000s, however, the frequency of englacial floods within the Khumbu region appears to have been increasing, based on informal data collected by the authors for the upper Imja Khola watershed (Figure 4), although this may also be related to recent improvements in communications, media coverage, and research trends. Unfortunately, flood paths and damage are difficult to reconstruct using remote sensing, and the floods are rarely reported to park authorities and/or the national media by local people because of their small size. One exception was the 25 May 2015 flood from Lhotse, which caused widespread panic throughout Khumbu, primarily because of the mistaken belief that it was an earthquake-triggered GLOF from Imja Tsho glacial lake (5550 m) (Byers et al 2017). The fact that the flood occurred during the night, when it could be heard but not seen, was also reported by local people to have exacerbated the confusion and fear surrounding the event. By comparison, the 12 June 2016 Lhotse glacier event, which commenced in late morning in full daylight, caused little immediate local or downstream concern.

As another example, since 2004, Halji village in northwestern Nepal has experienced 6 recurrent glacier floods from the 6.5-km-distant Halji glacier. The first recorded flood occurred in 2004, followed by 5 events between 2006 and 2011. The floods have appeared regularly at the end of June or beginning of July, remarkably within a 1-week period of each other (TMI 2011; Kropáček et al 2015; Singh 2018). Each of the floods has damaged large parts of Halji village and valuable agricultural land, with the 30 June 2011 flood being the most destructive. The floods have also directly threatened the Rinchen Ling Monastery, believed to be among the oldest in Nepal (Hovden 2012; Vallangi 2019), through continuous river bank undercutting processes (Kropáček et al 2015). The actual causes of the floods remain poorly understood and are the focus of an ongoing research effort funded by the Deutsche Forschungsgemeinschaft in Germany since 2019 (Scherer and Schneider 2019).

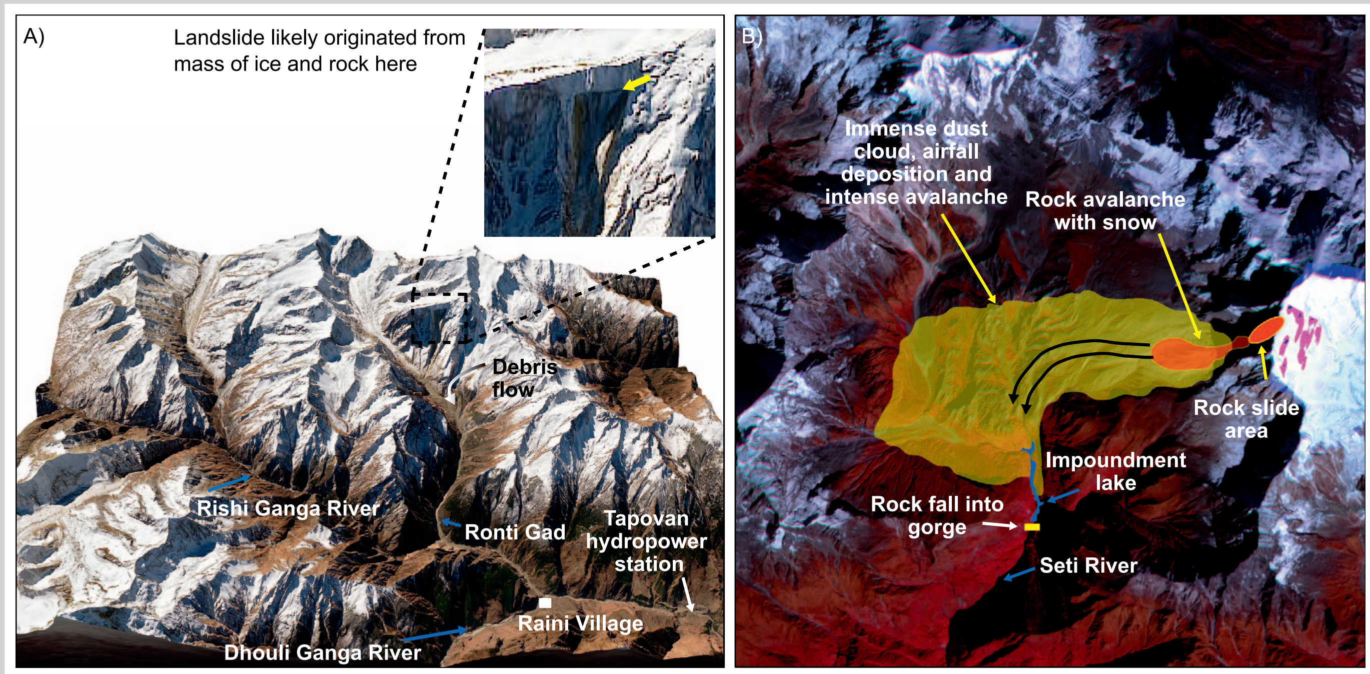
In both cases, the flood prevention response has consisted of the building of gabions, or rock-filled wire cages measuring approximately 1 m (height) by 3 m (width), in an effort to divert future flood flows and damage (see Figure 3). In general, the practice of building preventive gabions appears to have grown throughout much of the Khumbu region during the past decade, as well as within villages located adjacent to major rivers throughout Nepal.

Permafrost-linked, rockfall-induced GLOFs and debris flows

The impacts of global warming trends can be particularly conspicuous in glaciated landscapes, notably in the form of rapidly receding glaciers and the formation of glacial lakes (Shugar et al 2021). Growing evidence suggests that similar changes are also occurring at above 6000 m elevations, in the form of thawing permafrost that can impact the mechanical strength and hydraulic permeability of high elevation rock faces (Haeberli et al 2017). Massive rockfall from these rock faces, previously constrained by millennia of year-round freezing temperatures, can set in motion a cascade of catastrophic processes below, including rockfalls, debris flows, explosive impact with glaciers below, massive dust clouds, and high winds, in addition to triggering glacier-related floods downstream (Figure 5).

On 20 April 2017, a flood from the remote Barun River valley, Makalu-Barun National Park and Buffer Zone, eastern Nepal, reportedly blocked the confluence of the Barun with the Arun River to the east, resulting in a potentially dangerous, 2–3-km-long lake upstream (Shakya 2017) (field reconnaissance in 2019, however, suggested that the lake had actually been less than 200 m in length). Our helicopter reconnaissance of the Barun valley on 3 May 2016 revealed that the source of the flood was the <0.1 km^2 Langmale

FIGURE 5 Schematic diagram of the origins of the (A) Chamoli flood, Uttarakhand, India, 7 February 2021, and (B) Seti River flood, Nepal, 5 May 2012. (Chamoli flood diagram courtesy of NASA, 2021; Seti River image courtesy of Planet, 27 October 2020)



glacial lake, too small to be included within the potentially dangerous glacial lake studies of Rounce et al (2017) and others (eg Bajracharya 2020). In spite of its small size, the estimated 1.3×10^6 m^3 volume flood that resulted caused extensive downstream damage to forests, pastureland, and some infrastructure, from Langmale Lake to the flood's attenuation point in Yangle Kharka.

Follow-up field studies revealed a fine, white rock powder covering on all surfaces—juniper shrubs, rocks, *mani* walls, buildings—fanning out over an approximately 40 km^2 region from the now-drained glacial lake to points west and south. The source of the dust covering became clear once local people identified the trigger of the flood, a rockfall that began as a massive breakage of solid rock from the east face of Saldim Peak (6388 m). The resultant rock, ice, and debris landslide plummeted 1200 m downward to the Langmale glacier, reportedly creating a massive explosion upon impact characterized by the dust cloud and high winds—processes similar to those reported for the 2012 Seti River flood north of Pokhara (Kargel et al 2013; SANDRP 2014). A 1.1 million m^3 debris flow of ice, debris, and sediment then cascaded directly into the Saldim glacial lake below. The resultant surge wave triggered a hyperconcentrated slurry outburst flood that grew progressively larger and more destructive as it continued down the valley. Among the casualties were 24 yak and *dzo* (yak–cattle crossbreeds) and the loss of valuable forest and pastureland, 4 tourist-related structures, trails, and bridges.

This particular event has been covered in detail by Byers et al (2019). Not covered in our article, however, is the fact that massive rock failure from Saldim Peak could have been linked to changes in mechanical strength and hydraulic permeability of high elevation rock faces caused by permafrost degradation (Haeberli et al 2017; W. Haeberli, personal communication, 15 November 2019; Etzelmüller et al 2020; Haeberli and Weingartner 2020). Using recent examples from the Swiss Alps, Cordillera Blanca in Peru, and Mt Everest region of Nepal, Haeberli et al (2017, 2018) also suggest that the probability of similar flood events will systematically increase with the continued formation of new glacial lakes near, or even at the foot of, large mountains such as Saldim Peak. Changes in this "cryospheric glue" may also have been one of the triggers of the 2010 and 2020 rock/ice avalanche and flood from Lagunas 513 and Salkantaycocha in the Cordilleras Blanca and Salkantaycocha of Peru (Haeberli et al 2017; Vilca et al 2021) and of the 2012 Seti River flood near Pokhara, Nepal, that claimed more than 70 lives (Kargel et al 2013), as well as the more recent Uttarakhand glacier flood that left more than 70 people dead with 134 missing and heavily damaged the unfinished Tapovan Vishnugad Hydropower Plant (Mashal and Kumar 2021; Shrestha et al 2021; Shugar et al 2021) (Figure 5). The possibility of increased frequencies of similar high mountain slope instabilities, wisdom of continued construction of large hydropower projects in increasingly unstable high mountain landscapes, and need to examine the destructive power of even small glacial lakes are all topics that need further study.

Earthquake-induced GLOFs

Seismic activity has been regularly cited in the literature as a potential trigger of GLOFs (Kargel et al 2016; Byers et al 2017). The fragile and unconsolidated nature of most terminal moraines suggests that they can be easily damaged in the event of a medium- to large-scale earthquake, releasing millions of cubic meters of water downstream as a result.

On 25 April 2015, a magnitude 7.8 earthquake leveled parts of Kathmandu and caused more than 9000 deaths throughout the country, followed by a magnitude 7.3 aftershock on 12 May (Kargel et al 2016). Known as the

"Gorkha earthquake," massive landslides wiped out entire villages, rivers were dammed by landslides, and the geologic and geomorphic integrity of high elevation mountains and glaciers was further destabilized. Concern was expressed by both scientists and the Government of Nepal (GON) that the seismic activity could also trigger a series GLOFs throughout the country through the further weakening of terminal moraines, destabilization of GLOF triggers (eg overhanging ice, rock, soils; see Kargel et al 2016), and effects of the imminent monsoonal rains (eg melting ice, soil saturation). At the request of the GON's Department of Hydrology and Meteorology (DHM) and the International Centre for Integrated Mountain Development (ICIMOD), our team spent the summer of 2015 (May–August 2015) conducting a field-based study of the impacts of the earthquake on 3 glacial lakes identified as being potentially dangerous: Imja, in Khumbu, Tsho Rolpa, in Rowaling, and Thulagi, in Manaslu (Byers et al 2017).

In addition to the severe trauma experienced by the loss of loved ones, property, and livelihoods, many hundreds of thousands of Nepali people were understandably concerned about the possibility of earthquake-triggered GLOFs within their respective locales. The GON, in-country research organizations, and international research groups were quick to assuage these concerns through a number of rapid reconnaissance measures. Based on evidence derived from several helicopter flyovers, the DHM and Ministry of Science, Technology and Environment concluded that Nepal's "major glacial lakes—Tsho Rolpa of Dolakha, Imja of Solukhumbu, and Thulagi of Manang—are normal" and ruled out an "immediate" risk of outburst floods (Samiti 2015). ICIMOD confirmed that a helicopter fly over and remote sensing analyses of Tsho Rolpa, considered to be one of Nepal's most dangerous glacial lakes, showed "no disturbance to the moraine dam or to the engineered structures that have been used to lower and control the lake level" (Byers et al 2017: 27). A team of international remote sensing specialists led by scientists at the University of Arizona mapped coseismic and postseismic landslides on a daily basis (total: 4312) in an effort to assist the GON in the identification of potential hazards (Kargel et al 2016). A total of 491 glacier lakes were also surveyed for earthquake damage, finding 9 landslide-impacted lakes but no visible satellite evidence of GLOFs. The lack of GLOFs was attributed to the impacted region's extreme topography, which may have played a role in buffering the potentially destructive impacts of the shock waves (Kargel et al 2016).

In fact, on 25 April 2015, what was apparently an earthquake-triggered avalanche of ice and rock was dislodged from the Langmoche glacier above Dig Tsho glacial lake. The avalanche created a 4.2–8.2 m seiche wave and small outburst flood within the Bhote Kosi (river) downstream (Figure 6). Although the flood was largely contained within the river channel, several bridges were destroyed. Dig Tsho first experienced major GLOF activity on 4 August 1985 as a result of a similar ice avalanche from the Langmoche glacier. In this case, the avalanche created a surge wave that breached the terminal moraine, unleashing an estimated 5 million m^3 of water that caused extensive downstream damage, including the loss of 5 lives (Vuichard and Zimmermann 1986). The 2015 repeat event is important because it demonstrates that even though a glacial lake has already experienced an outburst flood, it can still be dangerous, subject to additional flooding activity in the future, and in need of regular monitoring.

Other flood events that may or may not have been related to the earthquake and aftershock include the previously mentioned englacial conduit flood from Lhotse glacier on 25 May 2015 and a large discharge event reported from the Hongu Khola hydrological station, Makalu-Barun National Park and Buffer Zone, in late June 2015, whose origins remain unknown. Likewise, the moraines of Imja Tsho, Tsho Rolpa, and Thulagi displayed a range of earthquake-related impacts that included cracks, displaced boulders, slumps, landslides, soil liquefaction, and outlet channel expansion. It is likely that the 2015 Gorkha earthquake further destabilized their already deteriorating moraines and capacity to contain lake water, and regular monitoring, both satellite- and ground-based, of the lakes was recommended by our study (Byers et al 2017). In fact, the 14 June 2021 flood in Melamchi bazar of Sindhupalchok District of Nepal, a region heavily impacted by the 2015 earthquake, was linked to heavy rainfall-induced landslides that blocked sections of the Malemchi and Indrawati Rivers, causing massive destruction downstream when backed-up river water was released (DHM 2021). This event was similar to a 2016 flood in the Upper Bhote Kosi/Sun Kosi watershed that has been described by Cook et al (2018).

Discussion

Most high mountain countries have clearly entered an era of accelerated glacier and high mountain hazards, most of them poorly understood. Although rock or ice avalanche-triggered proglacial GLOFs have been studied in considerable detail during the past several decades, less attention has been given to other cryospheric flood phenomena such as englacial conduit floods, permafrost-linked rockfall and avalanches, earthquake-triggered glacial lake floods, and recurrent flooding of seasonal proglacial lakes (Figures 6 and 7).

Englacial conduit floods tend to be small, localized, and underreported. What is apparently an increase in their frequency, however, could result in an increase in risks for downstream infrastructure, agricultural fields, and grazing land. The periodic and recurrent release of water from proglacial lakes, formed each warm season by accumulations of meltwater, represents an additional type of glacier flood that may also be increasing geographically. For example, such processes have been reported as being particularly problematic for different high mountain regions of Central Asia (eg Mergili and Schneider 2011; Komatsu and Watanabe 2013; Narama et al 2018; Theule et al 2018; Daiyrov et al 2020).

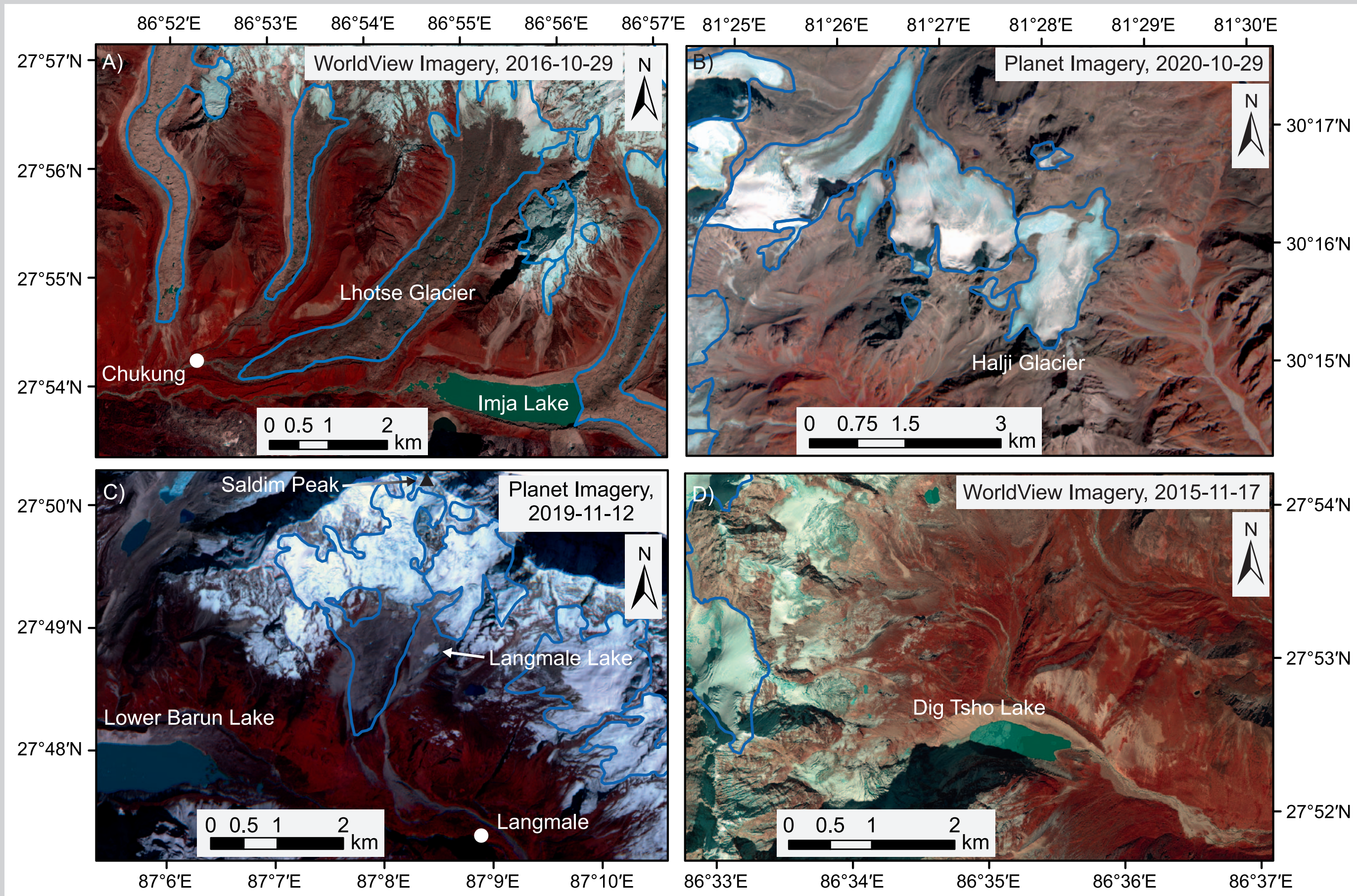
Recurrent proglacial and englacial conduit floods are not so common in the tropical Peruvian Andes because of the steepness of the rock bed gradient (Portocarrero, personal communication, July 2021). Massive rock fall events there at high elevations, however, have been linked to changes in high elevation permafrost, as well as in other major mountain ranges (Hubbard et al 2005; Haeberli and Whiteman 2021; Gruber et al 2017). These events also appear to be increasing in frequency worldwide (Haeberli et al 2017; Coe et al 2018). They are capable of triggering a range of processes that include the explosive forces of tons of rock and ice hitting glaciers, the resultant generation of massive

FIGURE 6 Images of (A) Dig Tsho, Khumbu, Nepal, after the 25 April 2015 earthquake and resultant glacial lake outburst flood (GLOF), the second GLOF the lake has experienced since 1985; (B) Saldim Peak after the 17 June 2017 separation of rock from the north-facing face; and (C) Lhotse glacier, Khumbu, Nepal. (Photos A and B by Alton C. Byers; C by Lhakpa Sonam Sherpa)

dust clouds and aerial debris, winds capable of leveling entire forests, the generation of additional flood waters through frictional heat and melting processes, the release of water contained in englacial conduits, and the formation of debris flows and/or hyperconcentrated slurry floods. Although small (<0.1 km^2) lakes have thus far been omitted from most dangerous glacial lake surveys, it is clear that they are nevertheless capable of causing massive downstream damage, as shown by the example of the 2017 Langmale flood in the Barun valley. Improved understanding of the location of both present and future glacial lakes, of all sizes and characteristics, represents an important area of future research. Standardized methods for assessing the relative dangers presented by different glacial lakes could also help to reduce present levels of uncertainty (eg Rounce et al 2016).

Earthquakes continue to be listed as one of the main potential GLOF triggers in most glacial lake studies. Even though the 2015, 7.8 magnitude earthquake in Nepal resulted in little GLOF activity, earthquakes remain a serious threat in terms of their potential to trigger major flood events from terminal moraine collapse or breakage, and through their destabilization of surrounding hillslopes that can cause avalanches and/or rockfalls. Glacial lakes that have experienced major flood events once can also flood again, as shown by the 25 April 2015 GLOF from Dig Tsho in the Sagarmatha National Park. The destabilizing impacts of the 2015 earthquake on glacial lake slope stability has been discussed by Byers et al (2017) and for landslide-prone hillslopes by Fort et al (2019). It can be further argued that slope stability in many high mountain regions has also been compromised by contemporary anthropogenic activities, such as annual foliage burning (Dixit 2021), inappropriate road building (McAdoo et al 2018; Coburn 2020), and decisions regarding the location of infrastructure and human settlements. Unusually heavy rainfall events, such as those experienced in Nepal in June 2021, can accelerate and exacerbate the damage and impacts of such land use practices (Allen et al 2016). Continued interdisciplinary and participatory research will be important to understanding the complexity of these hazards, their triggering mechanisms, resultant impacts, and risk reduction management options (lowering, early warning systems, zoning, disaster training).

FIGURE 7 Satellite imagery and locations of (A) Lhotse glacier, eastern Nepal; (B) Halji glacier, western Nepal; (C) upper Barun Khola region, eastern Nepal; and (D) Dig Tsho glacial lake, eastern Nepal. (Image by Mohan Bahadur Chand)



On a more positive note, local communities are already responding and adapting to many of these hazards and impacts. Technologies include building higher bridges over flood-prone rivers, constructing gabions along river or floodplain channels to divert flood flow, and building lodges, religious buildings, and villages on higher ground that is well beyond floodplains. Major damage to villages and infrastructure is already being reduced by simple, informal zoning measures, where valuable infrastructure is now being constructed away from floodplains, torrents, and other indicators of recent hydrologic or geomorphic activity. Many mountain communities have also made increasing use of mobile telephone and other wireless communication media to communicate potential flooding threats and risks—while they are happening—to downstream communities. Examples include the 2013 Seti River flood (Kargel 2014; Kargel et al 2016), 2015 Lhotse englacial conduit flood (Byers et al 2017), and 2021 Melamchi floods (Dixit 2021).

Large hydropower projects, however, are particularly vulnerable to the impacts of glacier floods, as has been demonstrated repeatedly in recent years (Shugar et al 2021). These projects need to recognize and plan for these glacier-related events, which have thus far been largely ignored within the preconstruction feasibility and environmental impact study process (USAID 2014). Transboundary research and cooperation will also be essential to minimizing the impacts of future GLOFs, particularly in countries bordered by similarly GLOF-prone nations, such as Nepal and Tibet (Khanal et al 2015). Overall, the vulnerability of multimillion dollar, mega-hydropower projects to climate change (Bocchiola et al 2020) and natural hazards (Shugar et al 2021) also argues for the promotion of local, smaller-scale hydropower technologies that can be situated away from major rivers (Adhikari 2011; Upadhya 2021).

In recent years, international cooperation and efforts to obtain digital elevation model and other satellite imagery immediately after major catastrophic events have been encouraging and praiseworthy (eg Kargel et al 2016; Shugar et al 2021). While remote sensing and modeling technologies have provided major advances to our understanding of high mountain cryospheric processes and hazards, there nevertheless remains a need to verify such results through the use of field-based measurements and experience. Additionally, field research activities should begin as soon afterward an event as possible, as physical evidence of the causes, damage inflicted, and even eyewitness testimony is ephemeral by nature and is quickly lost (Higman et al 2018; Byers et al 2019). The experience and insight of local people can also play major roles in the mitigation of current and future cryospheric events, not only by participating in research programs designed to better understand the range of cryospheric hazards and threats, but also by helping to develop preventive technologies and responses (see Gagné 2016; Watanabe et al 2016).

Regardless of the thoroughness and participatory nature of future glacier flood studies, results will be meaningless if governments do not take appropriate remedial action. Lake

Palcacocha in the Cordillera Blanca of Peru, for example, has been known to represent a particularly high threat to the city of Huaraz for at least a decade (Portocarerro 2014; Somos-Valenzuela et al 2016), and yet little in the way of concrete action has been taken by the central government. Likewise, Tsho Rolpa, still considered to be "the most dangerous glacial lake in Nepal" 20 years after its lowering by 3 m in 2000, has yet to receive further action related to its recommended lowering of 20 m (Reynolds 1999; Rana et al 2000; Byers et al 2017). How scientists can most effectively share the results of glacier flood research with decision-makers, and how decision-makers can encourage more effective and timely follow-on action, will most likely remain as major challenges for actual climate change mitigation opportunities for the foreseeable future.

Conclusion and recommendations

Although GLOFs continue to dominate the focus of peer-reviewed scientific and popular articles, a range of other cryospheric processes exist that require further research attention, mitigation technologies, and awareness building among the general public. Those discussed in the current article include englacial conduit floods, permafrost-linked rockfall and debris flows, and earthquake-linked glacier floods.

In recent years, remote sensing and modeling technologies have provided major advances to our understanding of high mountain cryospheric processes and hazards. Nevertheless, there remains a need to verify such results through the use of field-based measurements and experience. The rapid reconnaissance of glacier flood events as soon after their occurrence is critical to obtaining the most accurate understanding of the complex processes that were involved. The concurrent integration of the insights and experiences of local people can strengthen the assessment process, as has been demonstrated in each of the case studies mentioned. Nevertheless, the wisdom of constructing major and costly hydropower and other projects in dynamic high mountain regions is in need of re-examination. How scientists can more quickly and effectively share the results of their high mountain hazards research with decision-makers and how decision-makers and governments can deliver more timely mitigation programs are areas that also require further strengthening.

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OPEN PEER REVIEW

This article was reviewed by Marcus Nüsser and Suraj Mal. The peer review process for all MountainAgenda articles is open. In shaping target knowledge, values are explicitly at stake. The open review process offers authors and reviewers the opportunity to engage in a discussion about these values.

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