

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

Alton C. Byers^{1*}, Dan H. Shugar², Mohan Bahadur Chand³, Cesar Portocarrero⁴, Milan Shrestha⁵, David R. Rounce⁶, and Teiji Watanabe⁷

* Corresponding author: alton.byers@colorado.edu

¹ Institute of Arctic and Alpine Research (INSTAAR), University of Colorado at Boulder, Campus Box 450, Boulder, CO 80309-0450, USA

² Water, Sediment, Hazards, and Earth-surface Dynamics (waterSHED) Lab, Department of Geoscience, University of Calgary, Calgary, Alberta, T2N 1N4, Canada

³ Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan, and Local Action for Global Health and Environment Training and Research Center, Dhangadhi, Sudurpaschim 10900, Nepal

⁴ Civil Engineer and Consultant, Jirón 28 de Julio 924, Huaraz, Peru

⁵ School of Sustainability, Arizona State University, PO Box 877904, Tempe, AZ 85287-7904, USA

⁶ Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213-3890, USA

⁷ Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Hokkaido 060-0810, Japan

© 2022 Byers et al. This open access article is licensed under a Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>). Please credit the authors and the full source.

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.

Received: 25 August 2021

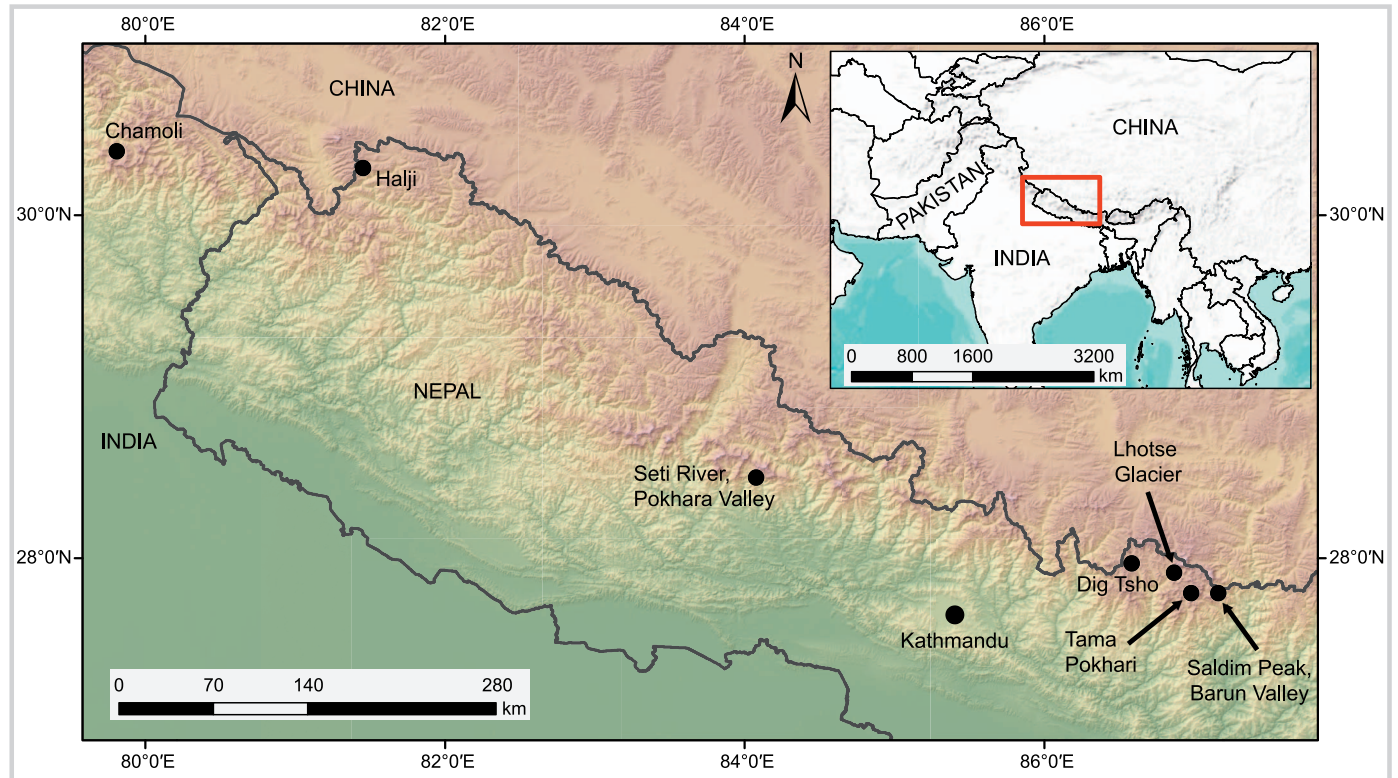
Accepted: 17 February 2022

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 $\sim 31\%$ in area. In western Greenland, How et al (2021) found an increase of $\sim 75\%$ 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)

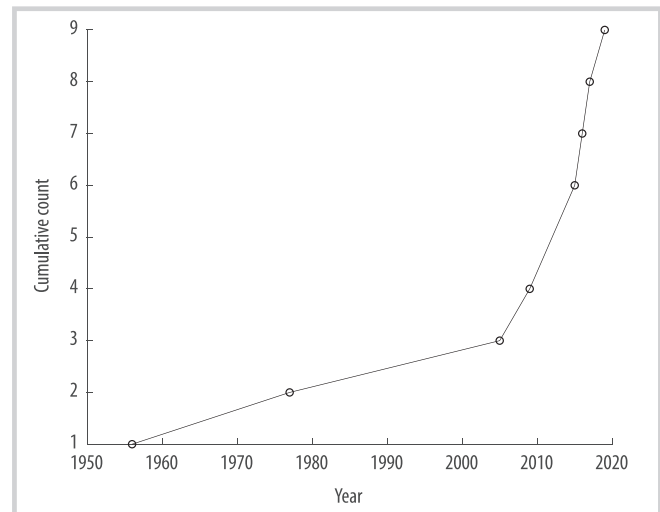


seasonal grazing settlement of Chukhung. Likewise, the Swiss-Canadian glaciologist Fritz Müller was nearly forced to leave Khumbu in 1956 when, during what were most likely englacial conduit floods that destroyed a number of *ghatta*, or water-driven mills, villagers insisted that his glacier research 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

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).



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).

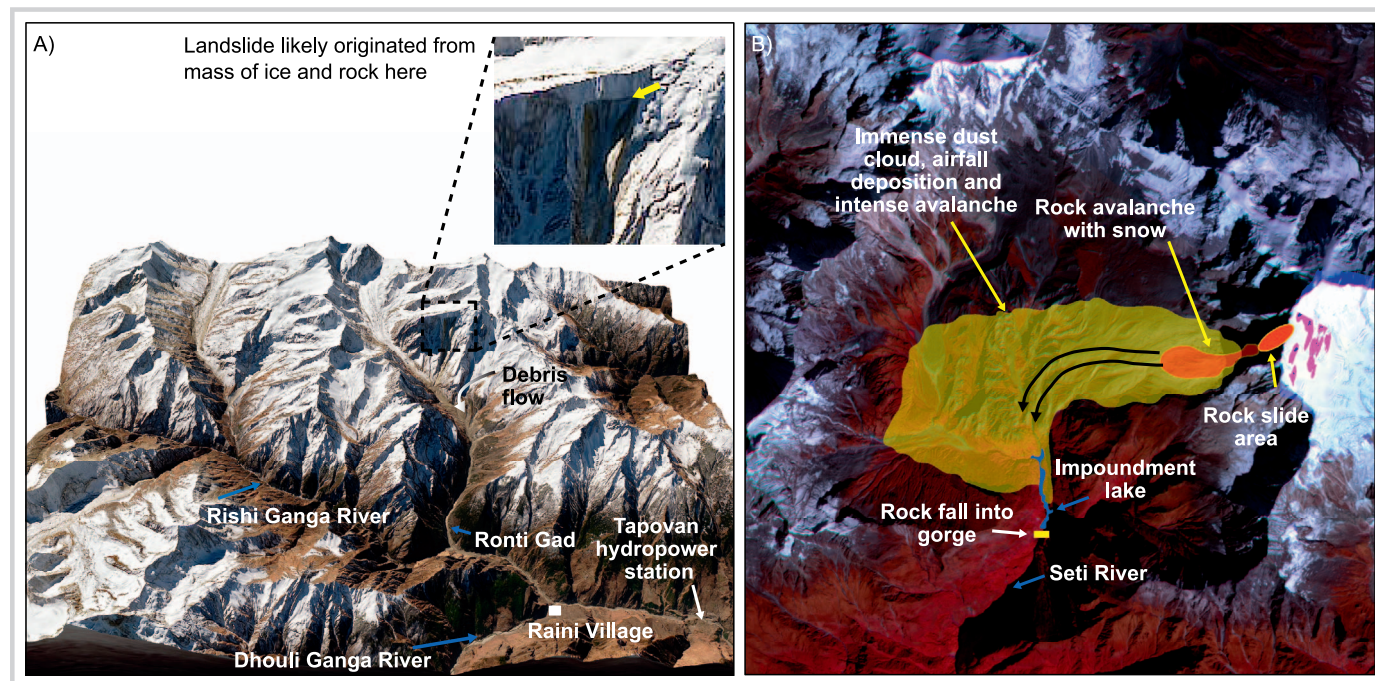
In both cases, the flood prevention response has consisted of the building of gabions, or rock-filled wire cages measuring approximately 1 m (height) by 3 m (width), in an effort to divert future flood flows and damage (see Figure 3). In general, the practice of building preventive gabions appears to 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 km² 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 $1.3 \times 10^6 \text{ m}^3$ 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; Etzelmueller 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 of 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 m³ 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).

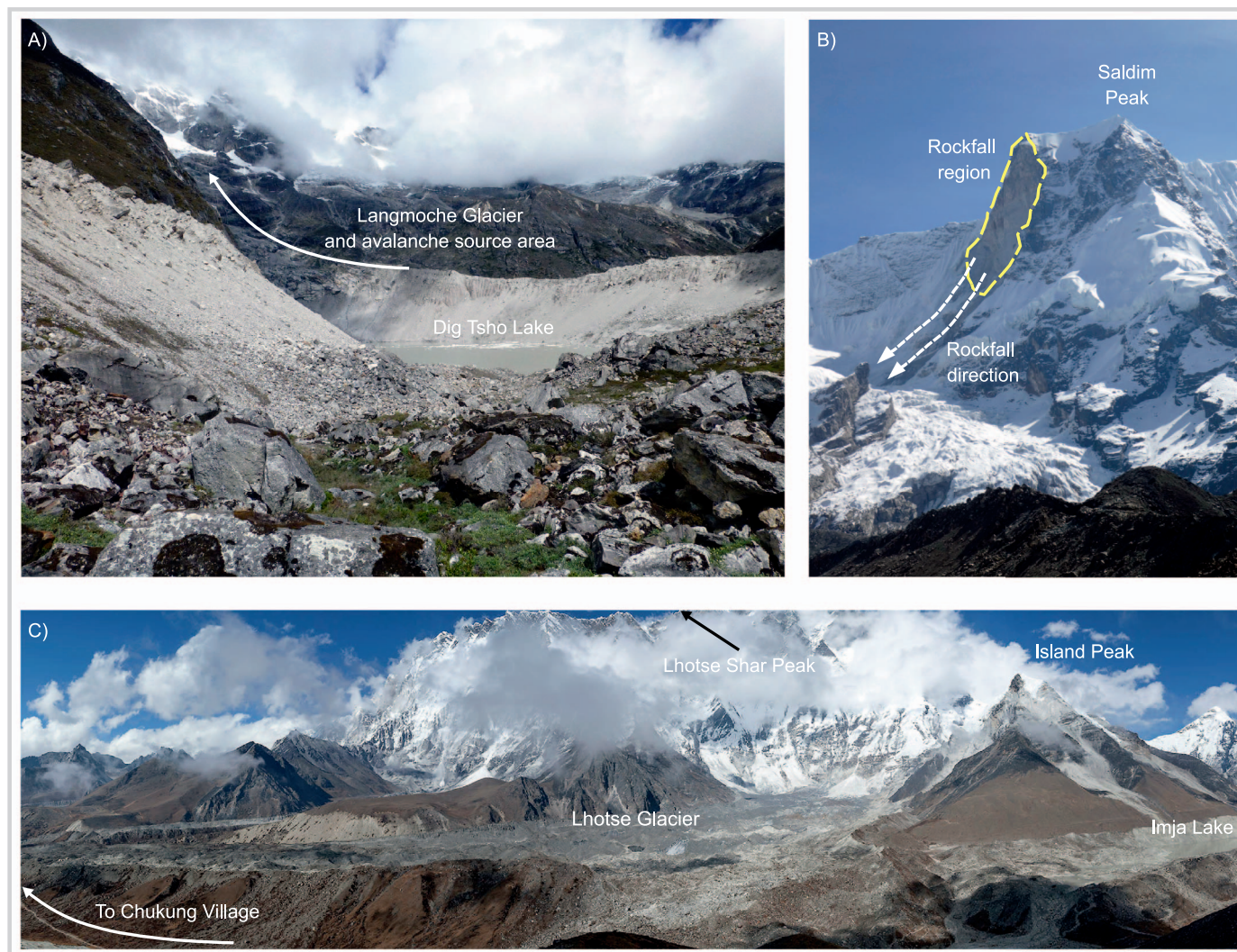
Discussion

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)

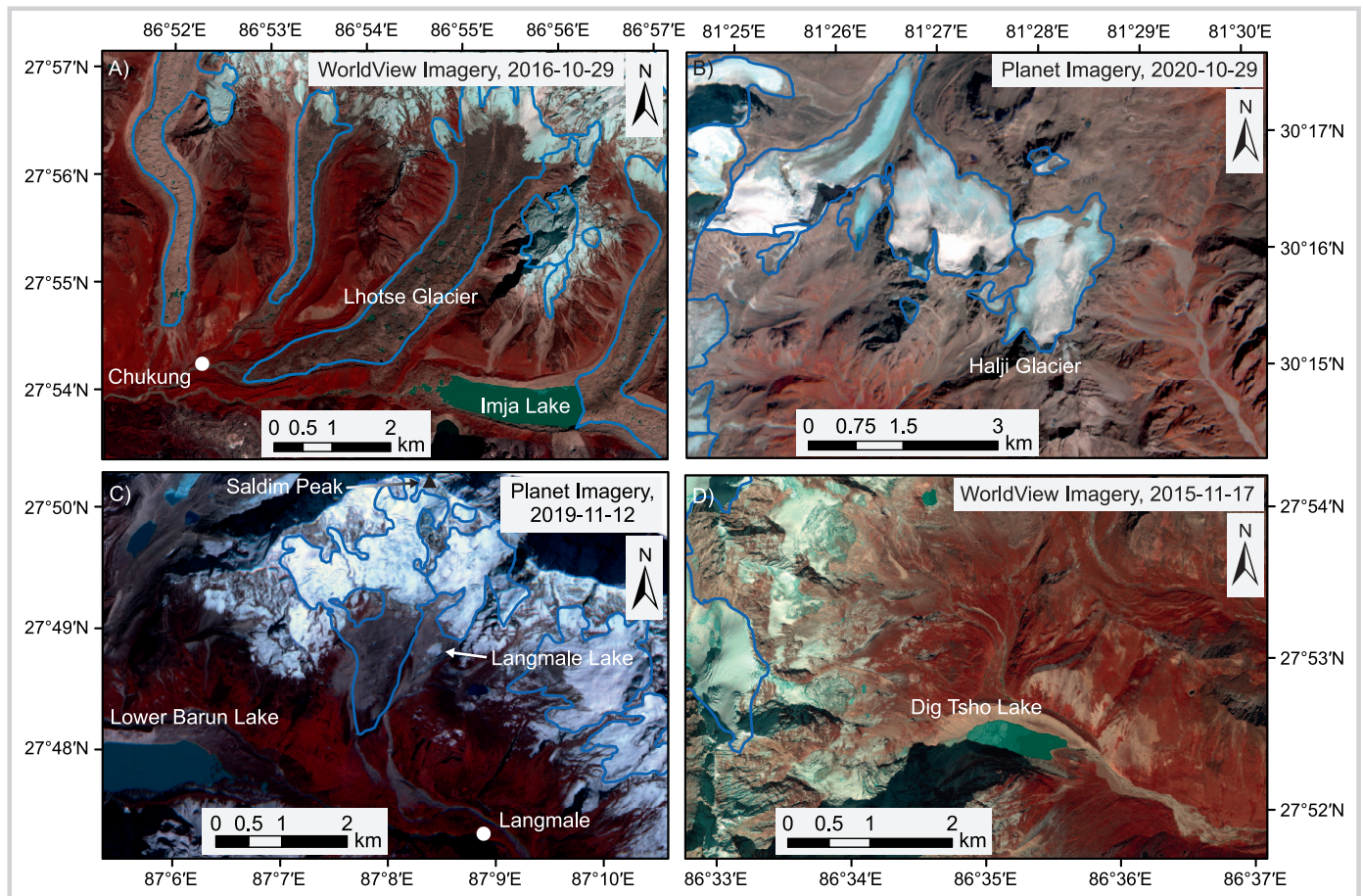


dust clouds and aerial debris, winds capable of leveling entire forests, the generation of additional flood waters through frictional heat and melting processes, the release of water contained in englacial conduits, and the formation of debris flows and/or hyperconcentrated slurry floods. Although small ($<0.1 \text{ km}^2$) 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; Upadhyaya 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 (Portocarrero 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.

ACKNOWLEDGMENTS

The authors acknowledge the support of the National Science Foundation Dynamics of Coupled Natural and Human Systems (NSF-CNH) Program (award no. 1516912) and the National Geographic Society for their partial support of field and travel costs during the field phases of each glacier event covered in the article. Dan Shugar was supported by NSERC 2020-04207, for which he extends his appreciation. Special thanks are extended to the lodge owners and local communities of the Sagarmatha and Makalu-Barun National Park and Buffer Zones, eastern Nepal, for their generous provision of information related to both historic and recent catastrophic events in their home regions.

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.

REFERENCES

Abdel-Fattah D, Trainor S, Hood E, Hock R, Kienholz C. 2021. User engagement in developing use-inspired glacial lake outburst flood decision support tools in

- Juneau and the Kenai Peninsula, Alaska. *Frontiers in Earth Science* 9:635163. <https://doi.org/10.3389/feart.2021.635163>.
- Adhikari D.** 2011. Power to the people? As winter power shortages shroud Nepal in familiar darkness, Deepak Adhikari unravels the country's hydro debate. *China Dialogue*, 24 January. <https://chinadialogue.net/en/energy/4070-power-to-the-people/>; accessed on 15 October 2021.
- Allen S, Rastner P, Arora M, Huggel C, Stoffel M.** 2016. Lake outburst and debris flow disaster at Kedarnath, June 2013: Hydrometeorological triggering and topographic predisposition. *Landslides* 13:1479–1491. <https://doi.org/10.1007/s10346-015-0584-3>.
- Bajracharya SR.** 2020. Inventory of Glacial Lakes and Identification of Potentially Dangerous Glacial Lakes in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet Autonomous Region of China, and India. Kathmandu, Nepal: ICIMOD [International Centre for Integrated Mountain Development]. <https://lib.icimod.org/record/34905>; accessed on 4 March 2022.
- Bajracharya SR, Mool P.** 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology* 50(53):81–86. <https://doi.org/10.3189/172756410790595895>.
- Benn D, Bolch T, Hands K, Gulley J, Luckman A, Nicholson L, Quincy D, Thompson S, Tourni R, Wiseman S.** 2012. Response of debris-covered glaciers in the Mount Everest region to recent warming and implications for outburst floods. *Earth-Science Reviews* 114(S1–2):156–174. <http://doi:10.1016/j.earscirev.2012.03.008>.
- Bhambri R, Watson CS, Hewitt K, Haritashya UK, Kargel JS, Shahi AP, Chand P, Kumar A, Verma A, Govil H.** 2020. The hazardous 2017–2019 surge and river damming by Shipare Glacier, Karakoram. *Scientific Reports* 10:4685. <https://doi.org/10.1038/s41598-020-61277-8>.
- Bocchiola D, Manara M, Mereu R.** 2020. Hydropower potential of run of the river schemes in the Himalaya under climate change: a case study in the Dudh Kosi basin of Nepal. *Water* 12:2625. <https://doi.org/10.3390/w12092625>.
- Byers AC, Byers E, McKinney D, Rounce D.** 2017. A field-based study of impacts of the 2015 earthquake on potentially dangerous glacial lakes in Nepal. *Himalaya* 37(2):7. <http://digitalcommons.maclester.edu/himalaya/vol37/iss2/7>; accessed on 14 June 2021.
- Byers AC, Chand MB, Lala J, Shrestha M, Byers EA, Watanabe T.** 2020. Reconstructing the history of glacial lake outburst floods (GLOF) in the Kanchenjunga Conservation Area, East Nepal: An interdisciplinary approach. *Sustainability* 12(13):5407. <https://doi.org/10.3390/su12135407>.
- Byers AC, Rounce DR, Shugar DH, Regmi D.** 2019. A rockfall-induced glacial lake outburst flood, upper Barun valley, Nepal. *Landslides* 16:533–549. <https://doi.org/10.1007/s10346-018-1079-9>.
- Carey M.** 2005. Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change* 47(2–4):122–134. <https://doi.org/10.1016/j.gloplacha.2004.10.007>.
- Carey M.** 2010. *In the Shadow of Melting Glaciers: Climate Change and Andean Society*. New York, NY: Oxford University Press.
- Carey M, Huggel C, Bury J, Portocarrero C, Haeblerli W.** 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, Cordillera Blanca, Peru. *Climatic Change* 112:733–767. <https://doi.org/10.1007/s10584-011-0249-8>.
- Chevallier P, Pouyard B, Suarez W, Condom T.** 2011. Climate change threats to environment in the tropical Andes: Glaciers and water resources. *Regional Environmental Change* 11(S1):S179–S197. <https://doi.org/10.1007/s10113-010-0177-6>.
- Clague J, Evans S.** 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews* 19(17–18):1763–1783.
- Coburn B.** 2020. Nepal's road-building spree pushes into the heart of the Himalayas. *Yale Environment* 360, 2 January. <https://e360.yale.edu/features/paving-the-himalayas-a-road-building-sprees-rolls-over-nepal>; accessed on 16 September 2021.
- Coe J, Bessette-Kirton E, Geertsema M.** 2018. Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. *Landslides* 3:393–407. <https://doi.org/10.1007/s10346-017-0879-7>.
- Cook KL, Andermann C, Gimbert F, Adhikari BR, Hovius N.** 2018. Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science* 362(6410):53–57. <https://doi.org/10.1126/science.aat4981>.
- Daiyrov M, Narama C, Kääb A, Tadono T.** 2020. Formation and outburst of the Toguz-Bulak glacial lake in the northern Teskey Range, Tien Shan, Kyrgyzstan. *Geosciences* 10(11):468. <https://doi.org/10.3390/geosciences10110468>.
- DHM [Department of Hydrology and Meteorology].** 2021. मेलम्ची बाढीको सन्दर्भमा [Melamchi Flood Bulletin], 17 June. http://hydrology.gov.np/cm/files/melamchi_flood_bulletin_17_June_2021_1623929718271.pdf; accessed on 14 August 2021.
- Dixit K.** 2021. Disasters in Nepal come in waves: There are crises within crises, layers upon layers of calamities. *Nepali Times*, 17 June. <https://www.nepalitimes.com/banner/disasters-in-nepal-come-in-waves>; accessed on 17 June 2021.
- Dussailant A, Benito G, Buytaert W, Carling P, Meier C, Espinoza F.** 2010. Repeated glacial-lake outburst floods in Patagonia: An increasing hazard? *Natural Hazards* 54:469–481. <https://doi.org/10.1007/s11069-009-9479-8>.
- Emmer A, Harrison S, Mergili M, Allen S, Frey H, Huggel C.** 2020. 70 years of lake evolution and glacial lake outburst floods in the Cordillera Blanca (Peru) and implications for the future. *Geomorphology* 365:107178. <https://doi.org/10.1016/j.geomorph.2020.107178>.

- Etzelmüller B, Guglielmin M, Hauck C, Hilbich C, Hoelzle M, Isaksen K, Noetzli J, Oliva M, Ramos M.** 2020. Twenty years of European mountain permafrost dynamics: The PACE legacy. *Environmental Research Letters* 15:1004070. <https://doi.org/10.1088/1748-9326/abae9d>.
- Fort M, Smadja J, Khanal NR, Shrestha BR.** 2019. Landslide and other damage to building and infrastructures following the April–May 2015 earthquake sequence, Solukhumbu District, Eastern Nepal. *Journal of Nepal Geological Society* 59:95–106. <https://doi.org/10.3126/jngs.v59i0.24995>.
- Gagné K.** 2016. Cultivating ice over time: On the idea of timeless knowledge and places in the Himalayas. *Anthropologica* 58(2):193–210.
- Gruber S, Fleiner R, Guegan E, Panday P, Schmid MO, Stum D, Wester P, Zhang Y, Zhao L.** 2017. Review article: Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. *Cryosphere* 11:81–99. <https://doi.org/10.5194/tc-11-81-2017>.
- Gulley J, Benn D.** 2007. Structural control of englacial drainage systems in Himalayan debris-covered glaciers. *Journal of Glaciology* 53(182):399–412. <https://doi.org/10.3189/002214307783258378>.
- Gulley JD, Benn DI, Sreaton E, Martin J.** 2009. Mechanisms of englacial conduit formation and their implications for subglacial recharge. *Quaternary Science Reviews* 28(19–20):1984–1999. <https://doi.org/10.1016/j.quascirev.2009.04.002>.
- Haeblerli W, Magnin F, Linsbauer A.** 2018. Modeling permafrost occurrence, glacier-bed topography and possible future lakes for assessing changing hazard conditions in cold mountain regions. Paper presented at EUCOP5 [5th European Conference on Permafrost], 23 June–1 July 2018, Chamonix-Mont Blanc. <https://hal.archives-ouvertes.fr/hal-03337508>; accessed on 10 May 2021.
- Haeblerli W, Schaub Y, Huggel C.** 2017. Increasing risks related to landslides from degrading permafrost into new lakes in deglaciating mountain ranges. *Geomorphology* 293(B):405–417. <https://doi.org/10.1016/j.geomorph.2016.02.009>.
- Haeblerli W, Weingartner R.** 2020. In full transition: Key impacts of vanishing mountain ice on water-security at local to global scales. *Water Security* 11:100074. <https://doi.org/10.1016/j.wasec.2020.100074>.
- Haeblerli W, Whiteman C, editors.** 2021. *Snow and Ice-Related Hazards, Risks, and Disasters*. 2nd edition (1st edition 2015). Amsterdam, the Netherlands: Elsevier. <https://doi.org/10.1016/B978-0-12-817129-5.10000-9>.
- Harrison S, Kargel J, Huggel C, Reynolds J, Shugar D, Betts R, Emmer A, Glasser N, Haritashya U, Klimes J, et al.** 2017. Climate change and the global pattern of moraine dammed glacial lake outburst floods. *Cryosphere* 12:1195–1209. <https://doi.org/10.5194/tc-12-1195-2018>.
- Higman B, Shugar D, Stark C, Ekström G, Koppes M, Lynett P, Dufresne A, Haessler P, Geertsema M, Gulick S, et al.** 2018. The 2015 landslide and tsunami in Taan Fiord, Alaska. *Scientific Reports* 8:12993. <https://doi.org/10.1038/s41598-018-30475-w>.
- Hovden A.** 2012. Glacial lake outburst flood in Halji, Limi VDC 30 June 2011: An eyewitness account. *Asianart*, 16 July. <https://www.asianart.com/articles/halji2/index.html>; accessed on 26 July 2021.
- How AM, Mätzler E, Santoro M, Wiesmann A, Caduf R, Langley K, Høegh Bojesen M, Paul F, Käähb A, Carrivick J.** 2021. Greenland-wide inventory of ice marginal lakes using a multi-method approach. *Scientific Reports* 11:4481. <https://doi.org/10.1038/s41598-021-83509-1>.
- Hubbard B, Heald A, Reynolds J, Quincey D, Richardson S, Zapata M, Portilla N, Hambrey M.** 2005. Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca. *Earth Surface Processes and Landforms* 30(10):1251–1264. <https://doi.org/10.1002/esp.1198>.
- Huggel C, Kaab A, Haeblerli W, Krummenacher B.** 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: Evaluation and application in the Swiss Alps. *Natural Hazards and Earth System Sciences* 3(6):647–662. <https://doi.org/10.5194/nhess-3-647-2003>.
- ICIMOD [International Centre for Integrated Mountain Development].** 2011. *Glacial Lakes and Glacial Lake Outburst Floods in Nepal*. Kathmandu, Nepal: ICIMOD. <https://doi.org/10.53055/ICIMOD.543>.
- Kargel J.** 2014. One scientist's search for the causes of the deadly Seti River flash flood. *Earth Observatory*, 24 January. <https://earthobservatory.nasa.gov/blogs/fromthefield/2014/01/24/setiriverclues/>; accessed on 15 July 2021.
- Kargel JS, Leonard GJ, Shugar DH, Haritashya UK, Bevington A, Fielding EJ, Fujita K, Geertsema M, Miles ES, Steiner J, et al.** 2016. Geomorphic and geologic controls of geohazards induced by Nepal's 2015 Gorkha earthquake. *Science* 351(6269):aac8353. <https://doi.org/10.1126/science.aac8353>.
- Kargel J, Paudel L, Leonard G, Regmi D, Joshi S, Poudel K, Thapa B, Watanabe T, Fort M.** 2013. *Causes and Human Impacts of the Seti River (Nepal) Disaster of 2012*. Paper prepared for Glacial Flooding and Disaster Risk Management Knowledge Exchange and Field Training Workshop, Huaraz, Peru, July 11–24. Huaraz, Peru: USAID [United States Agency for International Development] and The Mountain Institute.
- Khanal NR, Hu JM, Mool P.** 2015. Glacial lake outburst flood risk in the Poiqu/Bhote Koshi/Sun Koshi river basin in the Central Himalayas. *Mountain Research and Development* 35(4):351–364. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00009>.
- Kirschbaum D, Watson C, Rounce D, Shugar D, Kargel J, Haritashya U, Anatya P, Shean D, Anderson E, Jo M.** 2019. The state of remote sensing capabilities of cascading hazards over high mountain Asia. *Frontiers in Earth Science* 7:197. <https://doi.org/10.3389/feart.2019.00197>.
- Kochitzky W, Copland L, Painter M, Dow C.** 2019. Draining and filling of ice-dammed lakes at the terminus of surge-type Dañ Zhùr (Donjek) Glacier, Yukon, Canada. *Canadian Journal of Earth Sciences*. 57(11):1337–1348. <https://doi.org/10.1139/cjes-2019-0233>.
- Komatsu T, Watanabe T.** 2013. Glacier-related hazards and their assessment in the Tajik Pamir: A short review. *Geographical Studies* 88(2):117–131. <https://doi.org/10.7886/hgs.88.117>.
- Koukoulos L, Cook S, Edwards L, Clarke L, Symeonakis E, Dortch J, Nesbitt K.** 2018. Modelling glacial lake outburst flood impacts in the Bolivian Andes. *Natural Hazards* 94:1415–1438. <https://doi.org/10.1007/s11069-018-3486-6>.
- Kropáček J, Neckel N, Tyra B, Holzer N, Hovden A, Gourmelen N, Schneider C, Buchroithner M, Hochschild V.** 2015. Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in north-western Nepal. *Natural Hazards and Earth System Sciences* 15:2424–2437. <https://doi.org/10.5194/nhess-15-2425-2015>.
- Mark B, French A, Baraer M, Carey M, Bury J, Young K, Polk M, Wigmore O, Lagos P, Crumley R, et al.** 2017. Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change* 159:61–76. <https://doi.org/10.1016/j.gloplacha.2017.10.003>.
- Mashal M, Kumar H.** 2021. Glacier bursts in India, leaving more than 100 missing in floods. *New York Times*, 7 February. <https://www.nytimes.com/2021/02/07/world/asia/india-glacier-flood-uttarakhand.html>; accessed on 8 February 2021.
- McAdoo B, Quak M, Gnyawali K, Adhikari B, Devkota S, Rajbhandari P, Sudmeier K.** 2018. Brief communication: Roads and landslides in Nepal: How development affects risk. *Natural Hazards and Earth System Sciences Discussions*. <https://doi.org/10.5194/nhess-2017-461>.
- Mergili M, Schneider JF.** 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. *Natural Hazards and Earth System Sciences* 11:1447–1462. <https://doi.org/10.5194/nhess-11-1447-2011>.
- Müller F.** 1958. Eight months of glacier and soil research in the Everest region. In: Barnes M, editor. *The Mountain World 1958/59*. London, United Kingdom: George Allen & Unwin Ltd, pp 191–208.
- Narama C, Daiyrov M, Duishonakunov M, Tadono T, Sato H, Käähb A, Ukita J, Abdrakhmatov K.** 2018. Large drainages from short-lived glacial lakes in the Teskey Range, Tien Shan Mountains, Central Asia. *Natural Hazards and Earth System Sciences* 18:983–995. <https://doi.org/10.5194/nhess-18-983-2018>.
- NASA [National Aeronautics and Space Administration].** 2021. A deadly debris flow in India. *Earth Observatory*, 21 February 2021. <https://earthobservatory.nasa.gov/images/147973/a-deadly-debris-flow-in-india>; accessed on 22 February 2021.
- Nie Y, Sheng Y, Liu Q, Liu L, Liu S, Zhang Y, Song C.** 2017. A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015. *Remote Sensing of Environment* 189:1–13. <https://doi.org/10.1016/j.rse.2016.11.008>.
- Portocarrero C.** 2014. *The Glacial Lake Handbook: Reducing Risks from Dangerous Glacial Lakes in the Cordillera Blanca*. Technical Report, HIMAP [High Mountains Adaptation Program]. Washington, DC: US Agency for International Development. <http://www.ccrdproject.com/high-mountains-adaptation-partnership>; accessed on 18 June 2021.
- Quincey D, Richardson S, Kuckman A, Lucas R, Reynolds J, Hambrey M, Glasser N.** 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change* 56(1–2):137–152. <https://doi.org/10.1016/j.gloplacha.2006.07.013>.
- Rana B, Shrestha A, Reynolds J, Aryal R, Pokhrel A, Budhathoki K.** 2000. Hazard assessment of the Tsho Rolpa glacier lake and ongoing remediation measures. *Journal of Nepal Geological Society* 22:563–570. <https://doi.org/10.3126/jngs.v22i0.32432>.
- Reynolds JM.** 1999. Glacial hazard assessment at Tsho Rolpa, Rolwaling, Central Nepal. *Quarterly Journal of Engineering Geology* 32:209–214. <https://doi.org/10.1144/QJEG.1999.032.P3.01>.
- Richardson SD, Reynolds JM.** 2000. An overview of glacial hazards in the Himalayas. *Quaternary International* 65–66:31–47. [https://doi.org/10.1016/S1040-6182\(99\)00035-X](https://doi.org/10.1016/S1040-6182(99)00035-X).
- Rick B, McGrath D, Armstrong W, McCoy SW.** 2022. Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019. *Cryosphere* 16:297–314. <https://doi.org/10.5194/tc-16-297-2022>.
- Rounce D, Byers AC, Byers EA, McKinney DC.** 2017. Brief communications: Observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. *Cryosphere Discussions*. <https://doi.org/10.5194/tc-2016-239>.
- Rounce DR, McKinney D, Lala JM, Byers AC, Watson CS.** 2016. A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. *Hydrology and Earth System Sciences* 20:3455–3475. <https://doi.org/10.5194/hess-20-3455-2016>.
- Samiti RS.** 2015. Study rules out immediate outburst of Nepal glacial lakes. *The Himalayan Times*, 21 June. <https://thehimalayantimes.com/environment/study-rules-out-immediate-outburst-of-nepal-glacial-lakes/>; accessed on 1 September 2015.
- SANDRP [South Asian Network on Dams, Rivers, and People].** 2014. Explained: Seti River floods in May 2012, Nepal—A chain of events, starting at 25,000 feet! SANDRP, 26 January. <https://sandrp.in/2014/01/26/explained-seti-river-floods-in-may-2012-nepal-a-chain-of-events-starting-at-25000-feet/>; accessed on 28 June 2021.
- Scherer D, Schneider C.** 2019. *Glacial Lake Outburst Floods in the Halji Region, Nepal*. Proposal to DFG [Deutsche Forschungsgemeinschaft], Bonn, Germany, project SCHN 680/19-1. Available from DFG.

- Schmidt S, Nüsser M, Baghel R, Dame J.** 2020. Cryosphere hazards in Ladakh: The 2014 Gya glacial lake outburst flood and its implications for risk assessment. *Natural Hazards* 104:2071–2095. <https://doi.org/10.1007/s11069-020-04262-8>.
- Shayka D.** 2017. Flood debris block Arun River forming 3-km dam. *Kathmandu Post*, 21 April. <https://kathmandupost.com/national/2017/04/21/flood-debris-block-arun-river-forming-3-km-dam>; accessed on 10 May 2017.
- Shrestha A, Steiner J, Nepal S, Maharjan S, Jackson M, Rasul G, Bajracharya B.** 2021. Understanding the Chamoli flood: Cause, process, impacts, and context of rapid infrastructure development. *ICIMOD Articles*, 3 March. <https://www.icimod.org/article/understanding-the-chamoli-flood-cause-process-impacts-and-context-of-rapid-infrastructure-development>; accessed on 15 June 2021.
- Shugar DH, Jacquemart M, Shean D, Bhushan S, Upadhyay XK, Sattar A, Schwanghart W, McBride S, Van Wyk de Vries M, Mergili M, et al.** 2021. A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science* 373:300–306. <https://doi.org/10.1126/science.abh4455>.
- Singh N.** 2018. *The Kailash Sacred Landscape Conservation Initiative: Assessment and Potential of Cooperation in the Himalayas*. Occasional Paper No. 23. Delhi, India: ICS [Institute of Chinese Studies]. <https://www.icsin.org/uploads/2018/07/02/a2334b01f71ba0699ff01e8d85c71f69.pdf>; accessed on 14 May 2021.
- Somos-Valenzuela MA, Chisolm R, Rivas D, Portocarrero C, McKinney D.** 2016. Modeling a glacial lake outburst flood process chain: The case of Lake Palcacocha and Huaraz, Peru. *Hydrology and Earth System Sciences* 20:2519–2543. <https://doi.org/10.5194/hess-20-2519-2016>.
- Theule J, Crema S, Marchi L, Caval, M, Comiti F.** 2018. Exploiting LSPIV to assess debris-flow velocities in the field. *Natural Hazards and Earth System Sciences* 18:1–13. <https://doi.org/10.5194/nhess-18-1-2018>.
- TMI [The Mountain Institute].** 2011. *Preservation of the 11th Century Halji Monastery: Mitigating the impact of RECURRENT Glacial Lake Floods on a Priceless Cultural Heritage Site in Nepal*. Proposal to the US Ambassadors Fund for Cultural Preservation, 9 December. Kathmandu, Nepal: TMI.
- Upadhyay M.** 2021. After the Melamchi disaster: Planners need to realise and accept that the era of megaprojects in Nepal is over. *Kathmandu Post*, 12 August. <https://kathmandupost.com/columns/2021/08/12/after-the-melamchi-disaster?fbclid=IwAR3XGlwARJA6JWYswCA-Dhy7PCDo164kxx1F7ZiGbap9HmhanVJLI9fZ7ng>; accessed on 15 August 2021.
- USAID [US Agency for International Development].** 2014. *Affirmative Investigations for Hydropower Projects in Nepal: Upper Marsyandi 2, Upper Trisuli 1, and Upper Arun*. Washington, DC: USAID/E3 [USAID's Bureau for Economic Growth, Education and Environment].
- Vallangi N.** 2019. Climate change threatens 1,000-year-old monastery in remote Nepal. *Aljazeera*, 24 January. <https://www.aljazeera.com/features/2019/1/24/climate-change-threatens-1000-year-old-monastery-in-remote-nepal>; accessed on 10 June 2021.
- Veh G, Korup O, von Specht S, Roessner S, Walz A.** 2019. Unchanged frequency of moraine-dammed glacial lake outburst floods in the Himalaya. *Nature Climate Change* 9:379–383. <https://doi.org/10.1038/s41558-019-0437-5>.
- Vilca O, Mergili M, Emmer A, Frey H, Huggel C.** 2021. The 2020 glacial lake outburst flood process chain at Lake Salkantaycocha (Cordillera Vilcabamba, Peru). *Landslides* 18:2211–2223. <https://doi.org/10.1007/s10346-021-01670-0>.
- Vuichard D, Zimmermann M.** 1986. The Langmoche flash-flood, Khumbu Himal, Nepal. *Mountain Research and Development* 6:90–94. <https://www.jstor.org/stable/3673345>; accessed on 5 July 2021.
- Watanabe T, Byers AC, Somos-Valenzuela MA, McKinney DC.** 2016. The need for community involvement in glacial lake field research: The case of Imja Glacial Lake, Khumbu, Nepal Himalaya. In: Singh RB, Schickhoff U, Mal S. editors. *Climate Change, Glacier Response, and Vegetation Dynamics in the Himalaya: Contributions Toward Future Earth Initiatives*. Cham, Switzerland: Springer International Publishing, pp. 235–250. https://doi.org/10.1007/978-3-319-28977-9_13.
- Watanabe T, Khanal N, Gautam M.** 1998. The Nangama glacial lake outburst flood occurred on 23 June 1980 in the Kanchenjunga area, eastern Nepal. *Annals of the Hokkaido Geographical Society* 72:13–20.
- Watanabe T, Lamsal D, Ives JD.** 2009. Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja glacier, Khumbu Himal, Nepal. *Norsk Geografisk Tidsskrift* 63:255–267. <https://doi.org/10.1080/00291950903368367>.
- Zhang G, Yao T, Xie Hongjie Wang W, Yang W.** 2015. An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change* 131:148–157. <https://doi.org/10.1016/j.gloplacha.2015.05.013>.
- Zheng G, Allen SK, Bao A, Ballesteros-Cánovas JA, Huss M, Zhang G, Li J, Yuan Y, Jiang L, Yu T, et al.** 2021. Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change* 11(5):411–417. <https://doi.org/10.1038/s41558-021-01028-3>.