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A Field-based Study of Impacts of the 2015 Earthquake on Potentially Dangerous Glacial Lakes in Nepal

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A Field-based Study of Impacts of the 2015 Earthquake on Potentially Dangerous Glacial Lakes in Nepal

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Following the earthquake that occurred on April 25, 2015 in Nepal, and the second major earthquake that occurred on May 12, 2015, we conducted field-based studies of five potentially dangerous glacial lakes in Nepal—Imja Tsho, Tsho Rolpa, Dig Tsho, Panga Dinga, and Thulagi.

This research was undertaken in an effort to better understand what impacts the earthquake may have had on lake stability, flood potential as well as local perceptions of the dangers that post-earthquake outburst floods pose. Although only one relatively small, earthquake-related glacial lake outburst flood (GLOF) was found to have occurred, the presence of new cracks, slumps, shifted or displaced boulders, and landslide activity within the already deteriorating terminal and lateral moraines of the lakes suggests that they may have been further de-stabilized by the earthquake and its aftershock.

Downstream communities feared the increased likelihood of aftershocks and GLOFs, and at least two downstream regions experienced panic when rumors of imminent floods started spreading. In all our visits to these downstream villages, we encountered inadequate awareness of: early flood warning systems, lake risk reduction methods, and disaster management planning.

In order to eliminate the potential impacts of future glacial lake outburst floods to downstream communities, agricultural land, and infrastructure, the authors recommend the development: of standardized glacial lake risk assessment methods, Himalayan-specific lake lowering and risk reduction approaches, user friendly early warning systems, and disaster preparedness training.

Keywords: Nepal, earthquake, glacial lakes.

Introduction

Beginning in the 1960s, hundreds of glacial lakes have formed throughout Nepal and the Himalayan region as a result of climate change and regional warming trends (Benn et al. 2017). Today, many of these lakes contain millions of cubic meters of water, held back by lateral (side) and terminal (end) moraines that, in many cases, are unlikely to be structurally capable of withstanding the hydrostatic pressures imposed by the growing lakes or the erosion of overtopping waves. A 2011 inventory conducted by the International Centre for Integrated Mountain Development (ICIMOD) identified 1,466 glacial lakes in Nepal. Twenty-one of these were listed as ‘potentially dangerous,’ referring to the potential of a sudden and catastrophic discharge of their water, known as a glacial lake outburst flood (GLOF) (ICIMOD 2011). A more recent method for characterizing glacial lake hazards developed by Rounce et al. (2016 2017) suggests that out of Nepal’s 131 lakes greater than 0.1 km² in area, 19 exhibit a very high risk of GLOFs, 26 exhibit a high flood potential, 82 have a moderate flood potential, and four show a low flood potential. Twenty-six GLOFs have occurred in Nepal¹, most of them in recent times (post-1960). They have most commonly been triggered by ice, rock, or debris avalanches that fall into the lake and create a surge wave that spills over, and often breaches, the fragile end moraines (Richardson and Reynolds 2000). When this happens, millions of cubic meters of water and debris can be suddenly released, which frequently causes widespread destruction and death in the river valley below. One example is the 1985 Dig Tsho GLOF that destroyed a \$2 million hydropower plant located adjacent to the Bhothe Kosi River as well as dozens of bridges that were up to 100 km downstream, and killed at least five people (Vuichard and Zimmerman 1986). Other flood triggering mechanisms often include dam failure, debris flows, and earthquakes (Benn et al. 2012; Westoby et al. 2014). During the past decade, scientists have become increasingly concerned about accelerations in the evolution of glacial lakes in Nepal and the growing threat of GLOFs, especially with contemporary warming trends that are weakening overhanging ice, melting permafrost, and causing the common ice-cored end moraines to subside (Haeberli et al. 2016; ICIMOD 2011).

On April 25, 2015, a magnitude 7.8 earthquake leveled parts of Kathmandu and caused more than 8,000 deaths throughout Nepal, followed by a magnitude 7.3 aftershock that occurred on May 12, 2015 (Kargel et al. 2016). The first event was known as the ‘Gorkha earthquake,’ whose massive landslides wiped out entire villages, dammed

ivers, and destabilized the geologic and geomorphic integrity of high altitude mountains and glaciers. Both scientists and the Government of Nepal (GoN) expressed concern that the seismic activity could cause GLOFs through the weakening of terminal moraines and the destabilization of potential GLOF triggers, such as overhanging ice and landslides (Kargel et al. 2016). The coming monsoon rains were an additional concern as they could further de-stabilize mountainsides, hillslopes, and moraines through the continuous soaking rains, melting of ice, and saturation of soils.

Following the earthquake, a volunteer effort by international remote sensing specialists provided regular and valuable data to the GoN regarding earthquake-related phenomena, such as the condition of glacial lakes and the location and size of newly formed landslide dammed rivers (Kargel et al., 2016). Press releases from ICIMOD stated that Tsho Rolpa, considered to be one of Nepal’s most dangerous glacial lakes, “shows no visible disturbance to the moraine dam or to the engineered structures that have been used to lower and control the lake level” based on a helicopter fly over and remote sensing analysis (ICIMOD 2015). A new early warning system² was installed below the lake by the Department of Hydrology and Meteorology (DHM), United Nations Development Programme (UNDP)/Nepal, and Himal Power Limited in the vicinity of Na village in May 2015 (Manandhar 2015). According to press releases at the time, a study by the DHM and Ministry of Science, Technology and Environment (MoSTE) 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), based on evidence derived from helicopter flyovers.

Between June and August 2015, the High Mountains Adaptation Partnership (HiMAP) (<<https://instaar.colorado.edu/research/programs/himap/>>; Byers et al., 2014) fielded a volunteer group of scientists who conducted detailed remote sensing and field-based assessments of three of Nepal’s most potentially dangerous glacial lakes—Imja Tsho, Tsho Rolpa, and Thulagi Tsho (Figure 1)—as per the recommendations of the DHM. The assessments were conducted in partnership with the DHM, ICIMOD, the Nepali Army, and the US Agency for International Development (USAID). These three lakes were of immediate concern to the GoN because of the observed changes in the areas surrounding the end moraines of the lakes (e.g. large cracks near the Tsho Rolpa outlet channel, as seen from helicopter flyovers), and the presence of villages, bridges, agricultural land, and, in the

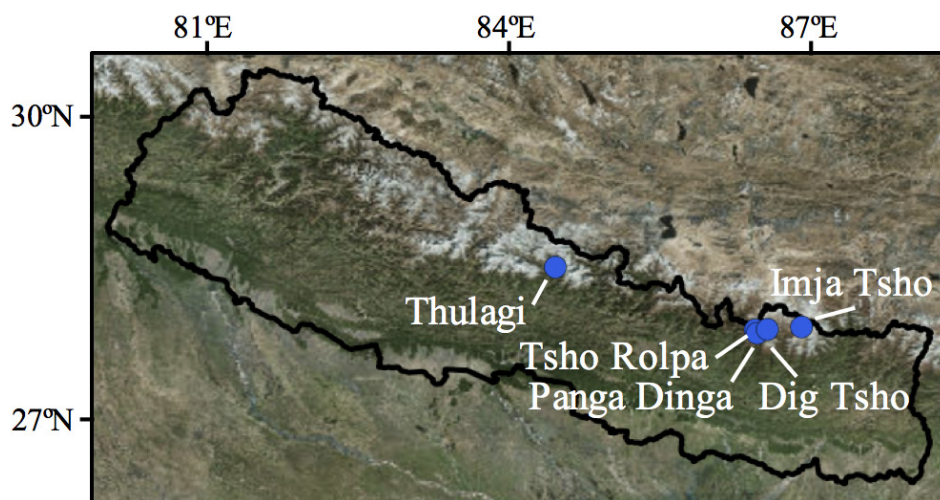


Figure 1. Location of the five glacial lakes in Nepal that were assessed.

(McKinney, 2015, adapted from Google Earth)

case of Tsho Rolpa and Thulagi Tsho, hydropower stations downstream. In the course of the field investigation, two additional glacial lakes—Dig Tsho in the Khumbu region, and Panga Dinga in Rolwaling—were also surveyed for a total of five field-based glacial lake investigations.

Methods

We began our assessments by having discussions with local community members along the trail to each lake in order to better determine the timing, impacts, community response to the earthquake, and perceived hazards, such as additional floods and landslides. We then documented our observations of high water marks, entrenchment, channel morphology, lake morphology, landslides, cracks, slumps, and other geomorphic features of each lake, especially those that could be associated with the recent earthquake activity. Additionally, we examined terminal and lateral moraines for any changes in morphology and seepage. The use of bio-indicators, such as the presence or absence of living vegetation upon mass wasting features within the outlet channel or the determination of changes in water level through the observation of the line of permanent woody vegetation on the shore compared to the waterline below, also helped determine new landslide and shoreline slumping activity. We discussed these observations with local people living in, and familiar with, the region, including yak herders, lodge owners, and DHM personnel, to determine if the disturbance feature noted was indeed a result of the earthquake and/or aftershock from April 25 and May 12 2015, respectively. Following each assessment, we held community consultations to share these results with local people, to listen to their concerns, and to answer their questions. Additional debriefings were held in Kathmandu to keep government authorities (e.g. DHM and the Nepali Army) and interested organiza-

tions (e.g. ICIMOD and USAID) informed of our findings and recommendations.

For lake dimensions, we made linear measurements with a laser rangefinder (TruPulse 360B, 1000 m range, distance accuracy: ± 0.3 to 1 m). Channel profiles were measured using a 50 m measuring tape and a laser rangefinder (Forestry Pro 550, 550 m range, distance accuracy: 0.1 m). To detect possible changes in seepage and stream flow from the glacial lake, we used a bucket and stopwatch for very small seeps, or a tape measure and portable velocity meter (Global Water Flow Probe FP111 turboprop positive displacement sensor with a range of 0.1–6.1 m s^{-1} and an accuracy of 0.03048 m s^{-1}) for larger flows.

Study Areas

The authors assessed five glacial lakes: Imja Tsho and Dig Tsho (Khumbu region), Tsho Rolpa and Panga Dinga (Rolwaling region), and Thulagi (Annapurna region). Dig Tsho was added after it was discovered that it had flooded again on the day of the earthquake (Sherpa, L.N. 2015. personal communication, May 10). Panga Dinga was added at the request of the DHM, which was concerned that the lake, perched high above Tsho Rolpa, could trigger a GLOF if it were to suddenly discharge into Tsho Rolpa (Maskey, P. 2015. personal communication, May 30). In the following sections, we describe each study area, the apparent earthquake impacts, and results from our community consultations.

Khumbu Region

Imja Tsho: Located in the Khumbu region of Nepal (Figure 2), Imja Tsho is bounded on the east by the Imja-Lhotse Shar Glacier, on the north and south by lateral moraines, and on the west by a long ice-cored outlet complex



Figure 2. Imja Tsho in June 2015.

(A. Byers, 2015)

through which lake water discharges (Watanabe et al. 2009). The lake has experienced rapid growth in area and volume since the 1960s. A bathymetric survey from September 2012 found that its maximum depth increased from 90.5 m in 2002 to 116.3 ± 5.2 m, and its volume grew from 35.8 ± 0.7 million m^3 to 61.7 ± 3.7 million m^3 (Somos-Valenzuela et al. 2014). Most of the expansion of the lake in recent years has taken place at the glacier terminus-lake interface on the eastern end of the lake, with the glacier receding on average 52.6 m yr^{-1} and the lake expanding in area by $0.032 \pm 0.004 \text{ km}^2 \text{ yr}^{-1}$ (Rounce et al. 2016). A ground penetrating radar survey of the Imja-Lhotse Shar Glacier conducted behind the glacier terminus shows that the ice is over 200 m thick in the center of the glacier (Somos-Valenzuela et al. 2014).

Imja Tsho has been described as one of the most dangerous glacial lakes in the Khumbu region (Hammond 1988; ICIMOD 2011; Kattelmann 2003), while other researchers have concluded that the lake is relatively stable (Fujita et al. 2009; Fujita et al. 2013; Hambrey et al. 2008; Watanabe et al. 2009). These conflicting classifications are misleading to the general public as well as the communities downstream, who are the stakeholders these studies are meant to assist; this confusion, in turn, highlights the need for a standardized, holistic approach to glacial lake risk assessment (Rounce et al. 2016; Rounce et al. 2017). The UNDP has implemented the Community Based Flood and Glacial Lake Outburst Risk Reduction Project in an effort to reduce the possible risk to downstream communities posed by the lake. According to the UNDP/Nepal project

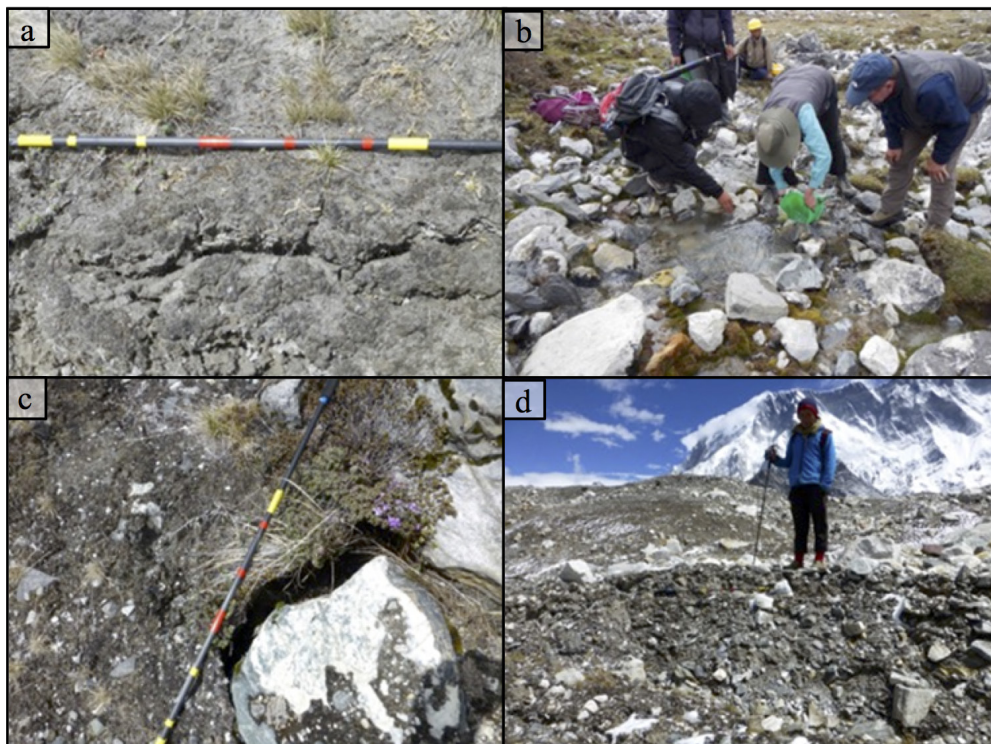


Figure 3. Observations at Imja Tsho: (a) abundant new cracks parallel to lake shore, (b) measuring seepage at the terminal moraine, (c) a boulder in the terminal moraine shifted by the earthquake, and (d) abundant 1 m high slumps parallel to the lake shore.

(E. Byers, 2015 (a, c, and d); McKinney, 2015 (b))

strategy, the “GLOF risks arising from Imja Lake will be significantly reduced by reducing the lake volume through an artificial controlled drainage system combined with a community-based early warning system” (UNDP 2013). This strategy recommended lowering the lake level by at least 3 m to achieve this risk reduction. In 2016, the Nepal Army and Himalayan Research Expeditions, Inc. completed this project to lower Imja Tsho. Although the actual risk reduction benefits of the project still remain uncertain (Inglis 2016; Somos et al. 2013), the UNDP initiative is most certainly building in-country capacity to lower additional lakes in the future (Sharma 2016).

Impacts: Although not necessarily visible from helicopter flyovers or satellite imagery, a range of surficial and sub-surface impacts at Imja Tsho that may have been related to the earthquake were observed and measured within the area of its terminal and lateral moraines. They included the presence of abundant new cracks parallel to the lake shore (2-10 cm wide), the shifting of hundreds of boulders in the terminal moraine (average 10-20 cm gaps), slump benches at the entrance to the outlet (average 3 m deep), and apparently new landslide activity on sections of the inner lateral moraines (Figures 2 and 3). Discharge from Imja Tsho was measured as $2.8 \text{ m}^3 \text{ s}^{-1}$ on June 12, 2015.

Previous measurements of the outlet flow were $0.98 \text{ m}^3 \text{ s}^{-1}$ in May 2012 (HiMAP 2012) and $2.2 \text{ m}^3 \text{ s}^{-1}$ in September 2013 (Somos-Valenzuela et al. 2015). The seepage at the base of the terminal moraine that had been observed on previous expeditions (Somos-Valenzuela et al. 2015) had ceased. These observations indicate that after the earthquake there may have been internal changes in the terminal moraine structure that could have de-stabilized the already deteriorating moraine conditions that had been a concern of scientists for years (Benn et al. 2012; Watanabe et al. 2009).

Dig Tsho GLOF: Dig Tsho is a glacial lake located at the head of the Langmoche Khola River in the far western region of Sagarmatha (Mount Everest) National Park, and is located northwest of the village of Thame. In 1985, the lake was 300 m wide, 500 m long, and had a surface area of 0.5 km^2 . On August 4, 1985, Dig Tsho experienced a GLOF as a result of an ice avalanche from the Langmoche Glacier entering the lake and creating a surge wave that breached the terminal moraine, which unleashed an estimated 5 million m^3 of water (Vuichard and Zimmermann 1986, 1987).

Although the diminished lake level and water volume that remained following the 1985 GLOF might lead one

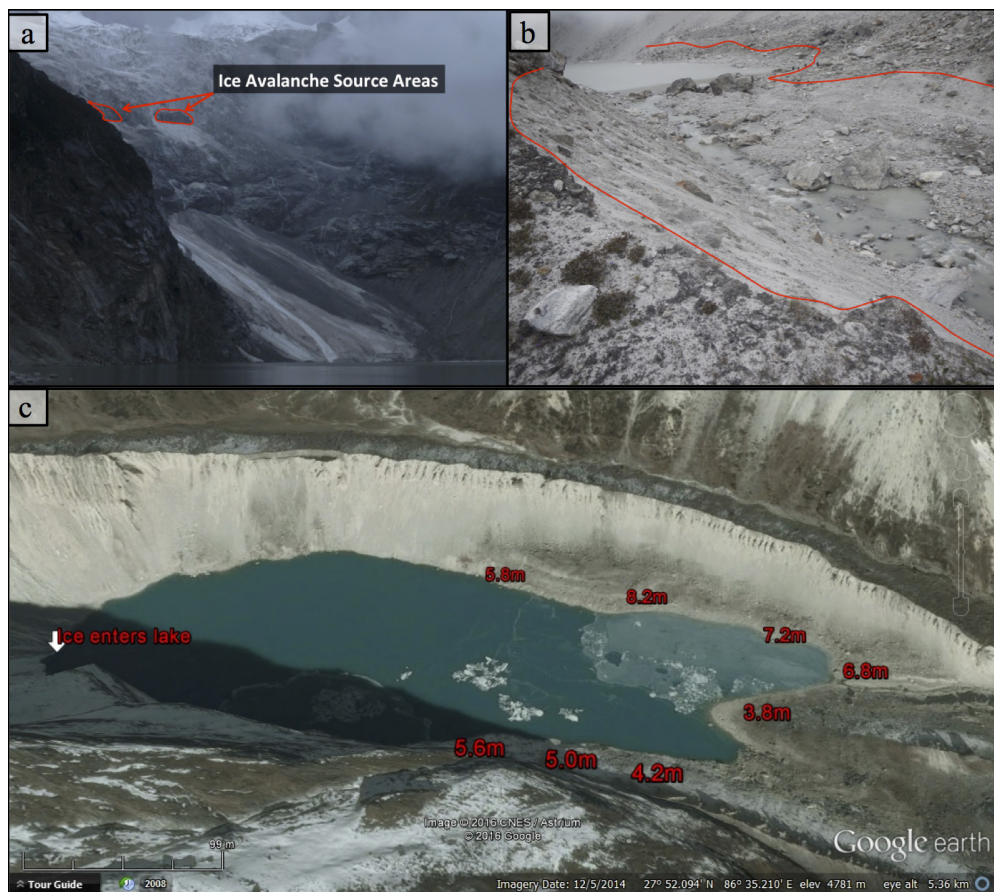


Figure 4. (a) Ice avalanche source areas above Dig Tsho, (b) lake outlet showing approximate path of the surge wave, and (c) measured heights of surge wave along shores of Dig Tsho. There was no significant lowering of the outlet and no subsequent change to future flood hazard.

(A. Byers, 2015 (a and b); E. Byers, 2015 (c), adapted from Google Earth)

to believe that Dig Tsho is no longer dangerous, the 2015 earthquake proved otherwise. On April 25, 2015, the day of the Gorkha earthquake, local villagers reported that an avalanche of ice and rock had dislodged from the Tengi Ragi Tau Mountain (6650 m) and cascaded into Dig Tsho, thus creating a 4.2-8.2 m high surge wave across the lake, as measured by high-water marks, fresh mud and sand deposits on vegetation, and uprooted vegetation (Figure 4). In informal interviews, eyewitnesses, and other informants claimed that, at the time of the flood, villagers in Langmoche, the first village downstream, were terrified, as a massive rock fall caused by the earthquake was taking place on the northern side of the village. The flood destroyed two small bridges downstream and damaged a third, larger bridge at Thametang, where the flood height peaked at about 1.5 m. Downstream, witnesses also reported that half of the Bhote Khosi River was white and half was black, the former being the normal silt-laden water of the Bhote Khosi River and the latter the debris- and mud-laden discharge from the GLOF. By the time of our visit on July 20, 2015, based on bio-indicators (e.g. the line of permanent woody vegetation along the lake shore) and the freshness of the water lines, we could determine the level of the lake had returned to its pre-earthquake level. This is the only known GLOF that was most likely a direct result of the earthquake. The event suggests that even if 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.

Community Consultations: We held a meeting on June 15, 2015 with members of the Khumbu Alpine Conservation Committee (KACC) in Dingboche, which is a community organization that since 2004 has worked to protect and restore alpine ecosystems in the upper Imja Khola (Pheriche to Everest base camp) region (see Byers 2005). A flood that was caused by Lhotse Glacier on May 25,

2015 and narrowly missed the village of Chukung was of primary concern. The flood may have originated from the rapid drainage of a small supraglacial lake, as well as flooded englacial conduits, located upon and within Lhotse Glacier. At Chukung, the flood surge was six meters high as measured from the high-water mark, which destroyed the small bridge leading to Island Peak basecamp and flooded the courtyard of one lodge to a depth of 10 cm. Because the flood occurred at night, people from Chukung to Lukla were terrified and ran for higher ground, believing that it was a massive GLOF from Imja Tsho. The fact that a prophetic “Imja is coming” was heard on a regular basis from that time onward reflects the high levels of stress that local people were feeling. They had already been traumatized by the April 25 and May 12 events.

Rolwaling Region

Tsho Rolpa: Tsho Rolpa is a glacial lake (Figure 5) located in central Nepal at an altitude of 4,546 m, forming the headwaters of the Rolwaling Khola River, which is a tributary of the Tama Kosi Lake in the Dolakha district. The lake is approximately 3.64 km in length, has an area of 1.54 km², a volume of 86 million m³, an average depth of 56.4 m, and a maximum depth of 133.5 m (ICIMOD 2011). Like nearly all of Nepal’s large glacial lakes, Tsho Rolpa began to form in the 1950s when small meltwater ponds at the glacier’s terminus began to coalesce, grow, and form a substantial glacial lake that has continued to grow in length by about 20 m yr⁻¹ for several decades (ICIMOD 2011); however, its growth has plateaued in recent years (Rounce et al. 2016).

Concern about the risk of Tsho Rolpa began in 1991 when Chubung glacial lake (known locally as Dudh Kund), a smaller lake to the immediate north of Tsho Rolpa, experienced a GLOF that damaged a number of homes and properties in the nearby downstream villages of Naagaun and Behding (ICIMOD 2011). In response to the concern



Figure 5. Tsho Rolpa glacial lake from July 2015.

(A. Byers, 2015)

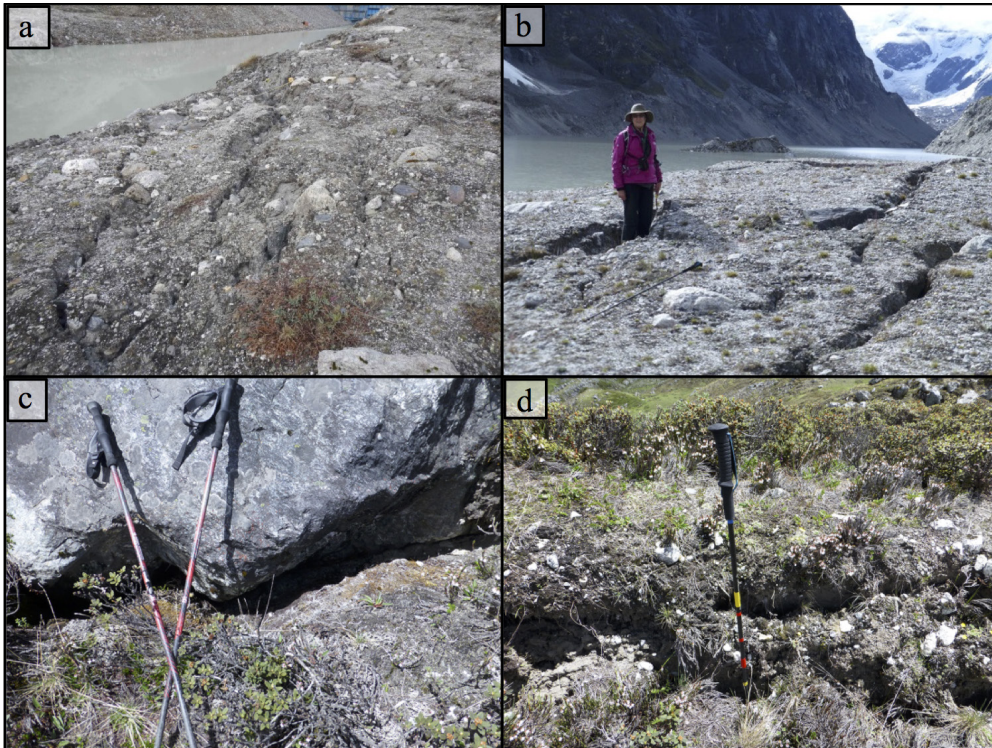


Figure 6. Slumping and cracking at the inlet canal entrance at Tsho Rolpa (a) on the right and (b) left sides of the canal, (c) a displaced boulder, and (d) a major crack at the crest of the terminal moraine.

(A. Byers, 2015 (a, b, and c);

E. Byers, 2015 (d))

of local residents about the risk of the much larger Tsho Rolpa to the south, between 1993 and 1997 the Water and Energy Commission Secretariat (WECS) and Japanese International Cooperation Agency (JICA) conducted detailed studies of the lake that included designs to lower the lake by 4 m. By late 2000, Reynolds Geo-Science LTD, with support from the GoN and the Government of the Netherlands, successfully lowered the lake by 2.8 m (Rana et al. 2000; Reynolds 1999). This endeavor was considered to be a success in terms of demonstrating that Nepal possessed the capability to perform complicated lake lowering engineering projects (Mool et al. 2001), such as the ones the Peruvians in the Cordillera Blanca region had completed since the 1950s (Carey 2010; Portocarrero 2014). However, it was not considered effective in terms of reducing the actual flood risk of Tsho Rolpa, which would require a total lowering of at least 20 m (Rana et al. 2000).

Tsho Rolpa differs somewhat from other glacial lakes in Nepal in that it was considered to be dangerous from the very first field investigation in the early 1990s. Over 20 years later, Tsho Rolpa is still considered to be one of the most dangerous glacial lakes in Nepal based on the potential for a GLOF to occur as well as potential downstream damage to populations, agricultural land, infrastructure, and hydropower plants (ICIMOD 2011).

Impacts: Tsho Rolpa showed considerable evidence of impacts from the earthquake. At the inlet of the canal structure we found distinct slumping and cracking of the

surface in the direction of the lake on both sides of the inlet (Figure 6a, b), damage that was most likely caused by the Gorkha earthquake and aftershock. The cracks measured between 10-15 m in length, 40-60 cm in width and 40-50 cm deep. Their repair is recommended in order to slow and/or stop the deterioration of the inlet to the canal.

Hundreds of boulders (50 cm to 1 m in diameter) in the terminal moraine at Tsho Rolpa were shifted during the earthquake or aftershock, which created gaps in which precipitation and other accumulation could occur that would potentially further destabilize the moraine. The shifting of a massive boulder perched directly on the knife-edged ridge of the right lateral moraine (Figure 6c), which appears to increase the possibility of collapsing into the lake and potentially generating a sizeable surge wave, was of further concern.

A 100 m long, 5-50 cm deep, and 3-40 cm wide crack was found along the ridge of the right lateral moraine with clear earthquake origins (Figure 6d). An older, parallel crack was noted a few feet away, indicating that this joint structure in the moraine has shifted more than once. Smaller cracks, formed through a combination of gravity, weathering, mass wasting, and the earthquake, were noted along the knife edge of the moraine; they may soon lead to the loss of more moraine material into the lake. Several square meters of silt deposits within one of the linear collapses, which appear to have been produced as a result of soil liquefaction, a phenomenon common to earthquakes

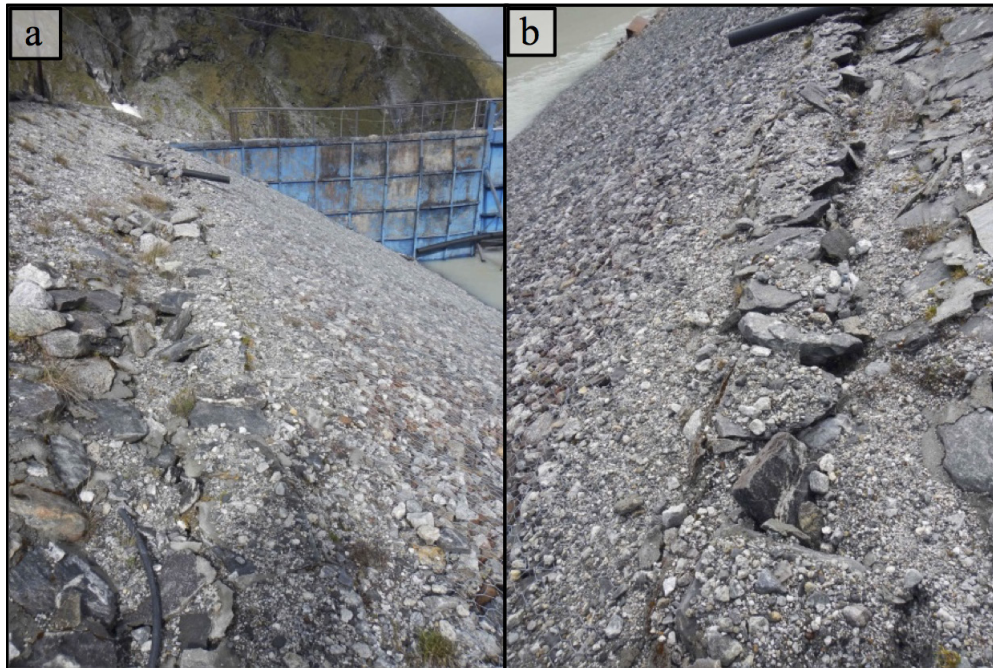


Figure 7. Separations in the sloping gabions on the left side of the inlet leading to the outlet structure: (a) looking west, and (b) looking east.

(McKinney, 2015)

where water-logged sediments near the ground surface lose their strength and behave like a liquid, were also noted; they can cause instability and slip (USGS 2016).

To lower the water level of Tsho Rolpa by approximately 3 m, a gated structure of 4.2 m wide by 3 m tall and a 70 m long canal were constructed across the end moraine in 2000 (Figure 7a) (Mool et al. 2001). From our observations over several days, it is clear that weathering and other processes have taken the normal toll on the structure, but that it has held up and performed well since it was built 16 years ago. We observed bulging of the wood facing the upstream (lake side) of the supporting gabions on both sides of the outlet structure gates, as was separation of the sloping gabions from the adjacent material on the left side of the inlet leading to the outlet structure (Figure 7b). We were unable to verify whether these features were new or the result of long-term deterioration of the structure. Regardless, repair we suggest it be repaired before further deterioration sets in.

Panga Dinga: Panga Dinga is a glacial lake located to the south of Tsho Rolpa glacial lake at an altitude of 5,000 m, and is located immediately to the northwest of Panga Dinga Glacier, although it is separated from the glacier by a small drainage divide (Figure 8). Digital Globe imagery from 2009 indicated that the lake was approximately 800 m in length and 200 m in width at that time, which matched the dimensions measured on July 16, 2015. The lake fluctuates in areal extent over time for reasons that are not entirely understood. Evidence of a recent and sudden drainage of nine meters was found based on the freshness of the silt/loam soil between the high-water

mark and current lake level, and a distinct line of woody vegetation at the high-water line (i.e. the presence of other colonizing species between the high-water mark and lake level would have been expected if the lake had drained months, instead of weeks, prior). It is unknown if this sudden drainage was related to the earthquake or to normal seasonal fluctuations. We recommend follow up monitoring of the lake.

Considerable masses of hanging ice are located directly above this small lake, which was the cause of concern for the DHM. Although the lake currently has no surface outlet, a former 20 m wide outflow channel is located 10.4 m above the current lake level. This outflow channel appears to drain into an eroded gully; however, the gully disappears long before reaching the valley floor, which indicates that this past outflow also drained into the subsurface. Any surge wave from Panga Dinga would be impeded by the significant surface roughness and porosity of the outlet channel, moraine, and colluvium between the lake and Tsho Rolpa. At the toe of the moraine, seepage emerges in the form of small springs and seeps, which made up a total flow of $0.36 \text{ m}^3 \text{ s}^{-1}$ on July 8, 2015. This seepage is known as “cave water” by local inhabitants, and also marked as such on trekking maps. It forms a channelized stream between the left lateral moraine and the southern mountainside, and is currently not undercutting or otherwise threatening the thin lateral moraine.

Panga Dinga Glacier, of which the lake is a part, occupies the largest valley on the southern slope adjacent to Tsho Rolpa. Its outlet stream debouches directly into Tsho Rolpa. At this time, the glacier has exposed ice but no



Figure 8. Panga Dinga glacial lake, above Tsho Rolpa.

(A. Byers, 2015)

visible supraglacial ponds. As the glacier melts and englacial/supraglacial water accumulates, however, this area poses a potential risk of small, sudden floods that could discharge into Tsho Rolpa and create a surge wave.

Community Consultations: We held informal community consultations in Naagaun on July 10, 2015 (Figure 9). Project team members explained the objectives of the post-earthquake assessment of Tsho Rolpa to the participants, most of them older men, women, and young girls because the majority of young men had gone to Kathmandu in search of jobs in the trekking and tourism industry. When asking about their perceptions of Tsho Rolpa, the threat of a GLOF, and mitigation efforts to date, community members noted that they were afraid of a GLOF from Tsho Rolpa and shared that, “we can’t sleep at night.” They also shared

that they had little idea of how to reduce their risk to floods and other natural hazards, nor how to protect the valley and their personal assets. They had little understanding of how the newly installed early warning system worked, whether it worked, and what to do in case they received a call from Kathmandu warning them of an impending flood. The warning system sensors are designed to first notify the DHM office in Kathmandu of an oncoming flood, which in turn calls the cell phones of people living in villages below the lake (Maskey, P. 2015. personal communication, August 2); however, cell phone signals are weak or absent in Naagaun much of the time. A glacial lake risk perception study conducted by Dahal (2008) suggested that there was a distance decay factor related to fear of Tsho Rolpa, where villagers in Naagaun and Behding who



Figure 9. Meetings with community members at Naagaun, below Tsho Rolpa.

(McKinney, 2015)

had experienced floods were vastly more concerned about a possible GLOF than those living further downstream in Jagat, Singati, and beyond who had never experienced a flood. However, informal discussions with the Nepal Army, police, lodge owners, and earthquake refugees at Singati suggested that the possibility of a GLOF from Tsho Rolpa is a very real concern. People were clearly traumatized by the earthquakes and were aware that Tsho Rolpa was a large and dangerous lake that could potentially flood. The community was primarily concerned with the following questions: When will a GLOF likely to occur? How high will the flood be? Will their homes be safe?

Annapurna Region

Thulagi: Known locally as Dona Tal, Thulagi is a glacial lake (Figure 10) located in western Nepal (Figure 1), northeast of the Annapurna circuit trek and southwest of the Manaslu Conservation Area. The lake is fed by the debris-covered Thulagi Glacier, which is one of the sources of the Dona Khola. This riverflows into the Marsyandi Khola near the village of Dharapani. The Marsyandi is now the site of major hydropower development projects that include the Lower (Khaireni), Middle (Lamjung), and Upper Marsyandi (Bhulbule and Nadi) construction sites.

Thulagi is one of the three most studied glacial lakes in Nepal, the other two being Imja Tsho and Tsho Rolpa, largely because of its potential threat to the hydropower facilities below, which prompted the Water and Energy Commission Secretariat to launch its first study in 1995 (WECS 1995). Subsequent studies were conducted by the DHM and the Federal Institute for Geosciences and Natural Resources (Hanover, Germany) in 1997 (DHM 1997), by the Nepal Electricity Authority (NEA) and the DHM in 2000 (NEA/DHM/BGR 2001), by ICIMOD in 2009 (ICIMOD 2011), and by the French NGO Association des Géorisques et Des Hommes in 2013 (GDH 2013).

Thulagi began to develop over 50 years ago when a series of small meltwater ponds near the glacier's terminus began to merge and form a small lake. The lake currently

is at an altitude of 4,045 m, is approximately 2 km long, has an area of 0.94 km², a volume of 39 million m³, and a maximum depth of 82 m (GDH 2013). Older terminal and lateral moraines from an earlier glacial advance are present in front of the younger terminal moraine and present-day outlet. Four distinct lateral moraines were counted alongside the present lateral moraines that were formed during different stages of the Thulagi Glacier recession. In addition to the current outlet, several former outlets (low points in the moraine) exist and suggest changing lake levels, glacier movements, and outlets over time.

A second feature of Thulagi worth noting is the terminal complex currently acts as a buffer against possible surge waves and bears the brunt of the lake's hydrostatic pressure. Additionally, the steep right and left lateral moraines erode into the lake.

Impacts: Outflow rates over the past 6 years appear to be relatively constant. ICIMOD measured an outflow rate of 3-4.5 m³ s⁻¹ in July 2009 (ICIMOD 2011), GDH measured 9-10 m³ s⁻¹ in November 2013 (GDH 2013), and we measured 10 m³ s⁻¹ on July 26, 2015.

While the right and left lateral moraines were free of major earthquake-related cracks, the terminal moraine had extensive new cracks along the crest line (based on the observations of our informant, P. B. Gurung, a local yak herder), as well as slumping and mass wasting along the interior slopes (Figure 11a, b). We found that boulders throughout the terminal moraine and terminal complex had shifted considerably. For example, a boulder located near the crest of the terminal moraine, used as a benchmark by previous surveyors, had moved 15 cm toward the lake and 10 cm down the hillslope (Figure 11c). These changes to the terminal complex are of concern because the complex provides an important buffer against the potentially destructive impact of surge waves. As the terminal moraine complex changes and the outlet lakes grow, this buffer may be greatly diminished, which would increase the lake's susceptibility to a GLOF.



Figure 10. Thulagi glacial lake and its outlet complex in July 2015.

(A. Byers, 2015)

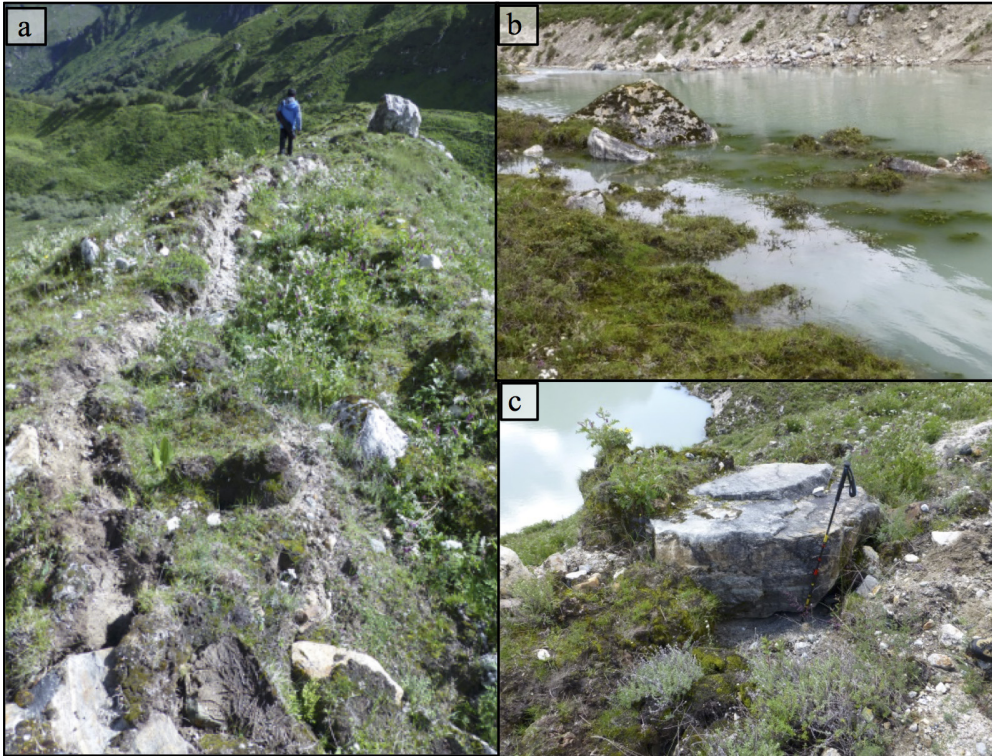


Figure 11. (a) Large crack and slump at the crest of the terminal moraine, (b) recent slumping of outlet channel sides as evidenced by submerged upland vegetation below slump scars, and (c) shifted benchmark boulder #2 located near the edge of the lake.

(A. Byers, 2015)

Observations from informant P. B. Gurung, as well as a range of bio-indicators, suggest recent changes in the shoreline and indicate that the outlet pond widened as a result of the slumping activity along the shoreline that was induced by the earthquake. The size of the lowest outlet pond had increased from 7,850 m² on November 26, 2013 to 9,230 m² on October 27, 2015, and its width has increased from 70 to 85 m, respectively. As the outlet pond continues to widen and deepen, and the terminal complex subsides and deteriorates, the hydrostatic pressure against the thinning terminal moraine will continue to increase, thereby making the moraine more susceptible to failure. We recommend that detailed studies be conducted to more thoroughly investigate the moraine stability.

In general, the terminal complex at Thulagi slopes from south to north and is pockmarked with thermokarst depressions and slope failures resulting from a melting ice core. These slumps occur toward and into the outlet pond and channel, which also contributes to the increasing the size of the outlet ponds. Other disturbances we found included an approximately 2 m wide, 20 m long swath of shoreline along the southern bank of the outlet pond that had slumped into the lake as a result of the earthquake (P. B. Gurung, 2016, personal communication, July 28). The slumps were covered by large masses of fresh vegetation and are now located within the outlet pond and channel.

A finger-like extension of the lake located at the junction of the left lateral moraine and terminal complex increased in length from 35 m to 75 m as a result of the earthquake, based on the before and after observations of informant P. B. Gurung. It is unlikely that any further and significant growth of this extension will occur within the near future, unless there is significant movement along the junction of the lateral moraine with the terminal complex.

Some grazing land located above the left lateral moraine was lost as a result of the earthquake. The loss of land was triggered by the earthquake and aftershocks (Gurung, P. B. 2015, personal communication, July 30). A large, house-sized boulder was also displaced approximately 20 m downslope due west of the landslide area. Although previous studies suggested that rockfall from the mountains adjacent to the lake were buffered by the lateral moraines, we found that this was no longer the case. The continued loss of morainic material has made it possible for rockfall and landslides to enter the upstream half of the lake, which could potentially trigger a GLOF if the volume and velocity were of sufficient size (Rounce et al. 2016). Snow and ice avalanches, however, are limited to the Thulagi Glacier region and are unable to cascade into the lake (Rounce et al. 2016).

The changes that resulted from the de-stabilizing effects of the April and May 2015 earthquake and aftershocks

include shifted boulders in the terminal moraine and silt boils in the terminal complex. The continued deterioration of the terminal moraine was evidenced by the widening of the last outlet pond, the increasing length of the left lateral moraine lake finger, and observed slumping into the outlet channel. The earthquake and aftershocks further destabilized an already deteriorating terminal/lateral moraine complex through the creation of new cracks, shifted boulders, slumps, and other impacts on the outlet channel.

Community Consultations: We held a community consultation in the village of Karte, on the banks of the Marsyandi Khola Lake, on July 31, 2015. Approximately 20 representatives from local development, mothers', and youth groups from the villages of Naache and Karte attended this event. Concern about the possibility of a GLOF was high, as people were aware of the deteriorating nature of the terminal moraine complex, continued expansion of the outlet lakes, and the earthquake impacts, which all could increase the likelihood of a GLOF in the future. On April 25, 2015, the date of the earthquake, a rumor spread throughout the valley that Telicho Lake to the north had burst and that the flooding of downstream villages was imminent. As a result, in the village of Tal, residents carried the old and sick up the mountainside, while lodge owners ran to the tourist campgrounds, woke the trekkers up, and ran with them to higher ground. Linked to the trauma associated with the April and May seismic events, this panic appears to be very similar to the rumor that Imja Tsho had burst on May 25, 2015 in the Khumbu region.

Discussion and Recommendations

Following the Gorkha earthquake, three types of investigations were carried out by various researchers to determine the impacts of the earthquake on various glacial lakes. The first consisted of the remote sensing efforts led by Kargel et al. (2016), which correctly determined that no major GLOFs had occurred as a result of the earthquake. The second involved helicopter flyovers by the DHM, which identified worrisome cracks near the Tsho Rolpa outlet channel, but otherwise suggested that none of Nepal's glacial lakes were in immediate danger of flooding. The third type involved rapid field reconnaissance, oral testimony, and remote sensing, i.e., the current study, which was able to determine that the cracks at Tsho Rolpa were most likely the result of settling processes, but that the widespread nature of shifted boulders, landslides, slumps, and large cracks in the terminal moraines of three of the five lakes surveyed had most likely destabilized the moraines to some extent. These investigations highlight the importance of installing long-term instrumentation and early warning systems in addition to using remote

sensing, oral testimony, and other means to continually assess the growth, stability and flood hazard associated with Nepal's glacial lakes, which pose a sizeable threat to downstream communities and infrastructure.

Kargel et al. (2016), using remote sensing, found that nine glacial lakes in Nepal had been impacted by landslide and avalanche events as a result of the Gorkha earthquake, but that no GLOFs or other floods with glacier origins could be detected. Since earthquakes have long been cited as one of several potential GLOF triggers, it is curious that more outbreaks did not occur, and this could be related to the fact that many of the higher altitude lakes were frozen at the time (Kargel, J. 2015. personal communication, May 1). Additionally, Kargel et al. (2016) hypothesize that the location of the glacial lakes at the valley floor may have dampened the ground accelerations, and that the surrounding mountain ranges may have shielded the glacial lakes by scattering the shockwaves.

Additionally, the field-based assessment that we conducted discovered that Dig Tsho in the Khumbu region, which experienced a GLOF in 1985, experienced another GLOF on the day of the Gorkha earthquake. The fact that this second GLOF was much smaller than the first may explain why it was undetected by the remote sensing and helicopter surveys mentioned previously. Other flood events that may or may not have been related to the earthquake and aftershock include the sudden discharge of water from Lhotse Glacier on May 25, 2015 and another large discharge reportedly from the Hongu Khola, Makalu-Barun National Park and Buffer Zone, in late June 2015 whose origins remain unknown. The assessment also revealed that the moraines of Imja Tsho, Tsho Rolpa, and Thulagi displayed a range of earthquake-related impacts, which included cracks, displaced boulders, slumps, landslides, soil liquefaction, and the expansion of the outlet channel. It is likely that the Gorkha earthquake further destabilized their already deteriorating moraines, which are vital for containing the stored lake water. Regular monitoring of the lakes, both satellite- and ground-based, is recommended.

Concern regarding the likelihood of future GLOFs was expressed by all of the local people we interviewed and during all of the community consultations we held. Information about glacial lakes, early warning systems, and risk reduction methods was not generally available, nor does there appear to be adequate disaster preparedness capacity building and training in Nepal, as evidenced by these conversations and the 2015 earthquake its aftershocks. Consultations with local people living near Imja Tsho, Tsho Rolpa, and Thulagi proved to be an invaluable tool in determining the sequence of earthquake-re-

lated impacts, especially given the fact that so little pre-earthquake data exists.

The Department of Hydrology and Meteorology recently announced that “six glacial lakes in the high Himalayas are at serious risk of an outburst,” including Imja Tsho, West Chamlang, Lumding, Thulagi, and Lower Barun glacial lakes, and that “early warning system, draining the lakes and building capacity of locals and other stakeholders are some of the ways to reduce risks” (Acharya 2016). This new policy represents a significant opportunity for scientists, governments, donors, and local communities to engage in the active study and reduction of these hazards. Furthermore, the recent 3 m lowering of Imja Tsho, using an all-Nepali workforce, represents an invaluable initiative that has directly increased the capacity of Nepal to develop Himalayan-specific methods to lower its potentially dangerous glacial lakes.

Several recommendations that could help to facilitate the ways to increase GLOF preparedness and mitigate potential dangers caused by a GLOF outlined above that are based upon our 2015 field assessments, as well as our experience gained in the Andes and Himalayas in the course of implementing the High Mountain Adaptation Partnership, include the following:

Build consensus on a standard protocol for assessing glacial lake risk in Nepal based on parameters generated by remote sensing, flood and avalanche modelling, rapid field assessments, and intensive field assessment methods (e.g. see Rounce et al. 2016; 2017). This would be a holistic approach to glacial lake risk evaluation and mitigation that includes physical, social, socio-economic, environmental, and conservation aspects to develop risk reduction action plans for all of Nepal’s dangerous glacial lakes.

Based on the glacial lake risk assessment protocol, update and revise the current list of potentially dangerous glacial lakes in Nepal to incorporate the results of recent field studies and include a separate list of lakes that may not be dangerous now but may be in the near future. For the lakes deemed to be dangerous, determine the required depth that the lake needs to be lowered to reduce the risk to a safe level, where ‘safe’ is defined as not causing significant damage to human life and livelihoods in the event of a GLOF. Glacial lake lowering methods should take into account the heterogeneity of Himalayan glacial lakes, i.e. each is different and requires site specific analyses, as well as the lack of roads, the difficulty of construction at high altitudes, and other factors.

Develop and install effective and user-friendly early warning systems for dangerous glacial lakes and disseminate effective protocols for existing systems (e.g. Tsho Rolpa) and planned systems (e.g. Imja Tsho).

Develop flood hazard maps for dangerous glacial lakes as part of a natural hazard community training tool kit and improve existing maps by incorporating 2-D models and better topographic data.

Develop climate change adaptation planning and training programs targeted at GLOFs and other natural hazards for communities to increase their capacity for disaster management planning and implementation.

Conclusion

Nepal has entered an era of increasingly dangerous events (landslides, floods, avalanches, and rockfalls) related to climate change that may have been exacerbated by the major seismic events of spring 2015. The earthquakes most likely further destabilized already deteriorating conditions in three of the five glacial lakes surveyed through the creation of new cracks in the terminal moraines, shifted boulders, loss of land through landslides, and outlet channel slumping. Some pre-existing potential GLOF triggers, such as the deterioration of terminal moraines, mass wasting of lateral moraines, and unconsolidated nature of the terminal moraines, were likely also further destabilized. Communities downstream of all surveyed areas are fearful of the likelihood of GLOFs occurring in the near future, but continue to lack adequate information about early warning systems, lake risk reduction methods, and disaster management planning. Recently announced Government of Nepal policies may signal the advent of a glacial lake risk reduction program to lower Nepal’s dangerous lakes. Concurrent attention to the needs of downstream communities, such as disaster management and disaster preparedness training, will need to be incorporated to minimize future loss of life and livelihoods.

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Endnotes

1. This new total includes the 24 GLOF events in Nepal as reported by ICIMOD (2011), plus the April 27, 2015 Dig Tsho GLOF described in this report and April 20, 2017 Langmale glacier flood in the Barun valley (see <<http://glacierhub.org/2017/05/17/a-visit-to-the-source-of-a-recent-glacier-flood-in-nepal/>>).

2. The first EWS at Tsho Rolpa was installed in 2000 as part of a project designed to lower the lake by 3 m (Rana et al. 2000). It was dysfunctional within a year, reportedly as a result of lack of maintenance, vandalism, and/or its destruction by Maoist insurgents. The lack of participation by local people has also been cited as a possible cause of the system's failure (Bajracharya 2010).

References

- Acharya, S. 2016. Six Glacial Lakes in High Risk of Outburst. *myRepublica*, July 27, 2016. <<http://www.myrepublica.com/news/2778>> (Accessed June 22, 2017).
- Bajracharya, S. R. 2010. Glacial Lake Outburst Flood Disaster Risk Reduction Activities in Nepal. *International Journal of Erosion Control Engineering* 3(1): 92-101.
- Benn, D. I., T. Bolch, K. Hands, J. Gulley, A. Luckman, L. I. Nicholson, D. Quincey, S. Thompson, R. Toumi and S. Wiseman. 2012. Response of Debris-Covered Glaciers in the Mount Everest Region to Recent Warming, and Implications for Outburst Flood Hazards. *Earth-Science Reviews* 114: 156-174.
- Byers, A.C. 2005. Contemporary Human Impacts on Alpine Landscapes in the Sagarmatha (Mt. Everest) National Park, Khumbu, Nepal. *Annals of the Association of American Geographers* 95(1): 112-140.
- Byers, A. C., D. C. McKinney, S. Thakali and M. Somos-Valenzuela. 2014. Promoting Science-Based, Community-Driven Approaches to Climate Change Adaptation in Glaciated Mountain Ranges: HiMAP. *Geography* 99(3): 143-152.
- Carey, M. 2010. *In the Shadow of Melting Glaciers: Climate Change and Andean Society*. New York: Oxford University Press.
- Dahal, K. R. 2008. Hazard and Risk: Perception of Glacial Lake Outburst Flooding from Tsho Rolpa Lake, Nepal. M.S. thesis, Michigan Technological University.

- Department of Hydrology and Meteorology. 1997. Thulagi Glacier Lake Study. Final Report Prepared for the Department of Hydrology and Meteorology, HMG/N, Kathmandu, Nepal, in Cooperation with Federal Institute for Geo-Science and Natural Resources (BGR), Hannover, Germany.
- Evans, S. G., N. F. Bishop, L. F. Smoll, P. Valderrama-Murillo, K. B. Delaney and A. Oliver-Smith. 2009. A Re-Examination of the Mechanism and Human Impact of Catastrophic Mass Flows Originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970. *Engineering Geology* 108: 96–118.
- Fujita K., A. Sakai, T. Nuimura, S. Yamaguchi and R. R. Sharma. 2013. Recent Changes in Imja Glacial Lake and Its Damming Moraine in the Nepal Himalaya Revealed by In-Situ Surveys and Multi-Temporal ASTER Imagery. *Environmental Research Letters* 4(4): 1-7.
- Fujita, K., A. Sakai, S. Takenaka, T. Nuimura, A. B. Surazakov, T. Sawagaki and T. Yamanokuchi. 2013. Potential Flood Volume of Himalayan Glacial Lakes. *Natural Hazards and Earth System Sciences* 13: 1827–1839.
- GDH (Association des Georisques et des Hommes). 2013. Risk Assessment of Glacial Lakes Outburst Floods (G.L.O.F.), Phase 2: Thulagi Lake. Petzl Foundation, Crolles, France.
- Haeberli, W., Y. Schaub and C. Huggel. 2016. Increasing Risks Related to Landslides from Degrading Permafrost into New Lakes in De-Glaciating Mountain Ranges. *Geomorphology* 1-13, doi:10.1016/j.geomorph.2016.02.009.
- Hambrey, M. J., D. J. Quincey, N. F. Glasser, J. M. Reynolds, S. J. Richardson and S. Clemmens. 2008. Sedimentological, Geomorphological and Dynamic Context of Debris-Mantled Glaciers, Mountain Everest (Sagarmatha) Region, Nepal. *Quaternary Science Reviews* 27: 2361–2389.
- Hammond, J. E. 1988. Glacial Lakes in the Khumbu Region, Nepal: An Assessment of the Hazards. M.A. Thesis, University of Colorado.
- International Centre for Integrated Mountain Development (ICIMOD). 2015. Little Additional Risk of Earthquake-Induced Outburst Floods Found for Many Himalayan Lakes. *ICIMOD*, Kathmandu, Nepal <<http://www.icimod.org/?q=18316>>.
- International Centre for Integrated Mountain Development (ICIMOD). 2011. Glacial Lakes and Glacial Lake Outburst Floods in Nepal. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal.
- Inglis, S. 2016. Military Intervention at Nepal's Fastest Growing Glacial Lake. *GlacierHub*, June 22, 2016. <<http://glacierhub.org/2016/06/22/military-intervention-at-nepals-fastest-growing-glacial-lake/>> (Accessed on August 22, 2016).
- Ives, J. D., R. B. Shrestha and P. K. Mool. 2010. Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal.
- Kargel, J. S., G.J. Leonard, D. H. Shugar, U. K. Haritashya, A. Bevington, E. J. Fielding, K. Fujita, M. Geertsema, E. S. Miles, J. Steiner, E. Anderson, S. Bajracharya, G. W. Bawden, D. F. Breashears, A. Byers, B. Collins, M. R. Dhital, , A. Donnellan, T. L. Evans, M. L. Geai, M. T. Glasscoe, D. Green, D. R. Gurung, R. Heijnen, A. Hilborn, K. Hudnut, C. Huyck, W. W. Immerzeel, J. Liming, R. Jibson, A. Kääh, N. R. Khanal, D. Kirschbaum, P. D. A. Kraaijenbrink, D. Lamsal, L. Shiyin, L. Mingyang, D. McKinney, N. K. Nahirnick, N. Zhuotong, S. Ojha, J. Olsenholler, T. H. Painter, M. Pleasants, K. C. Pratima, Q. Yuan, B. Raup, D. Regmi, D. R. Rounce, A. Sakai, S. Donghui, J. M. Shea, A. B. Shrestha, A. Shukla, , D. Stumm, M. van der Kooij, K.Voss, W. Xin, B. Weihs, D. Wolfe, W. Lizong, Y. Xiaojun, M. R. Yoder and N. Young. 2015. Geomorphic and Tectonic Controls of Geohazards Induced by Nepal's 2015 Gorkha Earthquake, *Science* 351(6269): 140-150.
- Kattelman, R. 2003. Glacial Lake Outburst Floods in the Nepal Himalaya: A Manageable Hazard?. *Natural Hazards* 28: 145-154.
- Manandhar, R. 2015. Early Warning System Installed at Tsho Rolpa. *Kathmandu Post*, May 21, 2015. <<http://kathmandupost.ekantipur.com/printedition/news/2015-05-20/early-warning-system-installed-in-tsho-rolpa.html>> (Accessed on August 5, 2015).
- Mool, P. K., S. R. Bajracharya and S. P. Joshi. 2001. Risk Assessment of Lake Rolpa Glacial Lake along the Rolwaling and Tama Kosi Valleys Dolakha District, Nepal, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal.
- NEA/ Department of Hydrology and Meteorology /BGR. 2001. Thulagi Glacial Lake Monitoring Report 2000. Internal Report Prepared by Nepal Electricity Authority (NEA) and Department of Hydrology and Meteorology (Department of Hydrology and Meteorology), Kathmandu, Nepal, and Federal Institute for Geo-science and Natural Resources (BGR), Hannover, Germany.

- Portocarrero, C. 2014. The Glacial Lake Handbook: Reducing Risk from Dangerous Glacial Lakes in the Cordillera Blanca, Peru. High Mountains Adaptation Partnership (HiMAP). United States Agency for International Development, Washington, DC.
- Rana, B., A. Shrestha, J. Reynolds, R. Aryal, A. Pokhrel and K. Budhathoki. 2000. Hazard Assessment of the Tsho Rolpa Glacier Lake and Ongoing Remediation Measures. *Journal of Nepal Geological Society* 22: 563-570.
- Reynolds, J. M. 1999. Glacial Hazard Assessment at Tsho Rolpa, Rolwaling, Central Nepal. *Quarterly Journal of Engineering Geology* 3(2): 209-214.
- Richardson, S.D. and J.M. Reynolds. 2000. An Overview of Glacial Hazards in the Himalayas. *Quaternary International* 65/66: 31-47.
- Rounce, D. R., D. C. McKinney, J. M. Lala, A. C. Byers and C. S. Watson. 2016. A New Remote Hazard and Risk Assessment Framework for Glacial Lakes in the Nepal Himalaya. *Hydrology and Earth Systems Sciences* 20: 3455-3475.
- Rounce, D. R., C. S. Watson and D. C. McKinney. 2017. Identification of Hazard and Risk for Glacial Lakes in the Nepal Himalaya Using Satellite Imagery from 2000 – 2015. *Remote Sensing* 9(7): 654-673.
- Samiti, R. S. 2015. Study Rules out Immediate Outburst of Nepal Glacial Lakes. *The Himalayan Times*, June 21, 2015. <<http://thehimalayantimes.com/environment/himalayan-glacier/study-rules-out-immediate-outburst-of-nepal-glacial-lakes/>> (Accessed on July 15, 2015).
- Sharma, B. 2016. Himalayan Hazards. *Kathmandu Post*, August 9, 2016. <<http://kathmandupost.ekantipur.com/news/2016-08-09/himalayan-hazards.html>> (Accessed on August 10, 2016).
- Somos-Valenzuela, M., D. C. McKinney, D. R. Rounce and A. C. Byers. 2014. Changes in Imja Tsho in the Mt. Everest Region of Nepal. *The Cryosphere* 8: 1661-1671.
- Somos-Valenzuela, M., D. C. McKinney, A. C. Byers, D. R. Rounce, C. Portocarrero and D. Lamsal. 2015. Assessing Downstream Flood Impacts Due to a Potential GLOF from Imja Lake in Nepal. *Hydrology and Earth Systems Sciences* 19: 1401-1412.
- UNDP-United Nations Development Programme. 2013. Community Based Glacier Lake Outburst and Flood Risk Reduction in Nepal. Project Document, UNDP Environmental Finance Services, Kathmandu, Nepal.
- USGS-United States Geological Survey 2016. USGS Earthquake Glossary: Liquefaction. USGS Earthquake Hazards Program. Reston, VA. <<http://earthquake.usgs.gov/>>.
- Vuichard, D. and M. Zimmermann. 1986. The Langmoche Flash-Flood, Khumbu Himal, Nepal. *Mountain Research and Development* 6: 90-94.
- Watanabe T., D. Lamsal and J. D. Ives. 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.
- WECS. 1995. Preliminary Report on the Thulagi Glacial Lake, Dhana Khola, Marsyandi Basin. WECS Report No. 473, Seq. No. 2/3/170795/1/1. Kathmandu: WECS.
- Wegner, S. 2014. Lo Que el Agua se Llevó: Consecuencias y Lecciones del Aluvión de Huaraz de 1941. Technical Note 7 of the series “Technical Notes on Climate Change,” Ministry of Environment, Lima, Peru: 88.
- Westoby, M. J., N. F. Glasser, J. Brasington, M. J. Hambrey, D. J. Quincey and J. M. Reynolds. 2014. Modelling Outburst Floods from Moraine-Dammed Glacial Lakes. *Earth Science Reviews* 134: 137-159.