TECHNICAL REPORT

POST-EARTHQUAKE ASSESSMENT

IMJA, TSHO ROLPA, AND THULAGI GLACIAL LAKES IN NEPAL

AUGUST 2015

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Cover Photo: Imja Lake, 2015 Alton C. Byers Ph.D.

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ACRONYMS

BGR	Federal Institute for Geosciences and Natural Resources (Hanover, Germany)
CCRD	Climate Change Resilient Development
DEM	digital elevation model
DHM	Department of Hydrology and Meteorology
EWS	early warning system
GDH	Association des Géorisques et Des Hommes (French NGO)
GLOF	glacial lake outburst flood
HiMAP	High Mountains Adaptation Partnership
HRE	Himalayan Research Expeditions
ICIMOD	International Centre for Integrated Mountain Development
INSTAAR	Institute for Arctic and Alpine Research
LAPA	Local Adaptation Plan of Action
NEA	Nepal Electricity Authority
SfM	Structure for Motion
USAID	United States Agency for International Development
WECS	Water and Energy Commission Secretariat

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1. INTRODUCTION

Beginning in the 1960s, glaciers in the Himalayas began to rapidly recede, leaving behind troughs that filled with meltwater as the glacier disappeared to form glacial lakes. Today many of these lakes contain many millions of cubic meters of water, held back by lateral (side) and end moraines that are unlikely to be structurally capable of withstanding the hydrostatic pressures imposed by the growing lakes. A 2011 inventory by the International Centre for Integrated Mountain Development (ICIMOD) identified 1,466 glacial lakes in Nepal, 21 of which were listed as "potentially dangerous" in terms of a sudden and catastrophic discharge of their water, known as a glacial lake outburst flood (GLOF) (ICIMOD, 2011)[1]. Twenty-six (26) separate GLOF events have occurred in Nepal[2], mostly in recent (post-1960) times, and are usually triggered by ice avalanches into the lake that create surge waves that breach the fragile end moraines. When this happens, millions of cubic meters of water and debris are suddenly released that are capable of causing widespread destruction and death below. During the past eight years or so, scientists have become increasingly concerned about accelerations in the formation of glacial lakes in Nepal and the growing prospects for GLOFs, especially with contemporary warming trends that are weakening overhanging ice, melting permafrost, and causing the often ice-cored end moraines to subside.

On 25 April 2015, a magnitude 7.8 earthquake leveled parts of of several cities and villages, including Kathmandu. The result caused more than 8,000 deaths throughout the country, followed by a magnitude 7.3 aftershock on 12 May. Massive landslides wiped out entire villages, rivers were dammed by landslides, and the geologic and geomorphic integrity of high altitude mountains and glaciers was destabilized. Scientists began to worry that the seismic activity could also result in new GLOFs through the weakening of terminal moraines and destabilization of potential GLOF triggers, such as overhanging ice and landslides. The arrival of the monsoon rains could further destabilize mountainsides, hillslopes and moraines through the continuous soaking rains, melting of ice, and saturation of soils.

Miraculously, none of Nepal's 21 potentially dangerous glacial lakes burst out during the earthquake, possibly related to the fact that they were all frozen at the time. But in order to fully understand what the impacts of the earthquake were on lake stability the High Mountains Adaptation Partnership (HiMAP) (www.highmountains.org) fielded a volunteer group of scientists, researchers, and citizens to conduct detailed remote sensing and field-based assessments of three of Nepal's most dangerous glacial lakes—Imja (Everest region), Tsho Rolpa (Rowaling region), and Thulagi (Manaslu region) (Map 1). The goal of the project was to conduct analyses of post-earthquake impacts on the structural integrity of the three glacial lakes that included detecting changes in water volume, discharge, end moraine stability, lateral moraine stability, seepage, glacial terminus, ice-cored moraines, and risk of flooding. Information and data obtained about the lakes was to be shared with all partners at debriefings conducted at the end of each field expedition (roughly 20 days per assessment). In fact, each field study resulted in a set of overall summary conditions and recommendations meant for consideration by the Government of Nepal, donors, researchers, and local communities.

[1] Several of the lakes on the list have since been shown not to be particularly dangerous on the basis of detailed field analyses (see Byers et al. 2013), and one of this report's main recommendations is that a new and updated dangerous lake list be developed.

[2] This new total includes the 24 GLOF events in Nepal as reported by ICIMOD (2011) plus the April 27, 2015 Dig Tsho GLOF and 15 May, 2015 Chukung GLOF in the Khumbu region described in this report.

Map 1. Location of Imja, Tsho Rolpa, and Thulagi glacial lakes.

Imja and Tsho Rolpa glacial lakes were chosen for detailed post-earthquake assessment because they were of immediate concern to the Department of Hydrology and Meteorology (DHM), primarily because of their ranking as high risk lakes susceptible to flooding as a result of earthquakes, dam collapse, or other triggers (e.g., Somos et al. 2013; Reynolds 1999; ICIMOD 2011). Further concern was expressed over the fact that all three contain either significant downstream populations and/or infrastructure (e.g., hydropower plants) that would be severely damaged and/or destroyed in the event of a GLOF. Thirdly, Imja, Tsho Rolpa, and Thulagi are the three most studied glacial lakes in Nepal, offering a solid set of baseline data for comparative analyses; and are also the three most recognized by the popular press, media, and an understandably uneasy public. It was therefore decided to seek clarification of the post-earthquake impacts upon each of these well-known lakes prior to conducting similar assessments at other sites.

Each assessment was conducted in collaboration with Nepal's DHM, International Centre for Integrated Mountain Development (ICIMOD), Nepal Army, and USAID/Nepal, all of whom endorsed the initiative as being of critical importance as well as its selection of Imja, Tsho Rolpa, and Thulagi lakes for further study. Field costs were funded by USAID's Climate Change Resilient Development project (CCRD) with co-financing from the American Society of Civil Engineers, the University of Texas at Austin, Xylem Inc., and US21 Inc. The HiMAP team assembled for this project included Dr. Alton Byers, Team Leader and Mountain Geographer, Institute for Arctic and Alpine Research (INSTAAR), University of Colorado at Boulder and HiMAP Co-Manager; Dr. Daene McKinney, Civil Engineer, Professor at the Center for Research in Water Resources, University of Texas at Austin and HiMAP Co-Manager; Ms. Elizabeth A. Byers, Hydrologist, West Virginia Department of Environmental Protection; and Mr. Daniel A. Byers, Filmmaker and Owner of Skyship Films.; Project affiliates who accompanied the team during the Imja glacial lake assessment included Mr. Ram Kumar Kapair, Hydrologist with the Nepal Department of Hydrology and Meteorology (DHM); and Mr. Prakash Pokhrel and Mr. Pushpa Raj Dahal of the Geosciences Department at Tribhuvan University, Kirtipur, Nepal. Because of the unsafe condition of buildings and lodges the team chose to camp in tents for the entire duration, and expert logistical and field arrangements were provided by Dr. Dhananjay Regmi, Glaciologist and President, Himalayan Research Expeditions (HRE).

The following report presents the results of three separate field expeditions to Imja, Tsho Rolpa, and Thulagi glacial lakes conducted between 3 June, 2015 and 3 August, 2015. The report details, through photographs and descriptive text, the post-earthquake changes in villages, landscapes, and at each lake as measured and/or observed by the team. GLOF risk levels are suggested for each on the basis of field observations and measurements, remote sensing (satellite and repeat landscape photography), literature reviews and assessments, and flood and avalanche modeling. The results of the community consultations held are presented, followed by a summary of conditions found and list of recommendations designed to facilitate the reduction of risks posed by each lake. Detailed bibliographies are provided at the end of each chapter, as is a separate concluding section containing recommendations and next steps applicable to all three of the lakes.

In summary, the report concludes that Nepal has entered an era of accelerated catastrophic events (landslides, floods, avalanches, rockfall) related to climate change, and that increases in the number and frequency of GLOFs can be expected with confidence. The 25 April earthquake and aftershock further destabilized the already deteriorating terminal/lateral moraines of all three lakes through the creation of massive cracks, shifted boulders, and impacts on the outlet channel while further destabilizing existing potential GLOF triggers such as overhanging ice, calving rates of the glacier termini, deterioration of the terminal moraine, and mass wasting of the lateral moraines. Communities downstream of all three lakes are fearful of the likelihood of GLOFs occurring in the near future, and lack adequate information about existing or planned early warning systems (EWSs), lake risk reduction methods, and disaster management planning. Recommended next steps to mitigate these new challenges include detailed surveys of all 21 of Nepal's dangerous lakes; the development of Nepal-specific risk reduction engineering methods; the strengthening of downstream community disaster management planning; and strengthening of the DHM's glacial lake analysis and risk reduction capacities through creation of a Glaciological Unit.

2. IMJA GLACIAL LAKE, KHUMBU REGION

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2.1. EARTHQUAKE DAMAGE IN THE KHUMBU REGION

The team spent 23 days performing post-earthquake glacial lake assessment fieldwork in the Khumbu region of Nepal. Flying into Lukla (2860 m), we made our way up to Imja Lake (5010 m), back to Namche Bazar, and then up to the glacial lake Dig Tsho and finally back to Lukla between 3 and 24 June, 2015. Along the way we observed a great deal of earthquake damage. We estimate that about 90% of the buildings in this area are not habitable and more than 10% have completely collapsed. Patterns relating building materials and construction style (e.g., hewn rock only, hewn rock with mortar, traditional mud and rock, wood) to levels of damage experienced were clearly visible (Figure 1). The most extreme damage (i.e., totally collapsed buildings, etc.) – occurs in the region from Lukla to Monjo, in Thangboche, and in Thame. In these regions, almost all buildings are uninhabitable or collapsed, especially in Thame; in other areas there is extensive structural damage that must be repaired before reoccupying the buildings. Although while entering the Khumbu all that could be seen was the extensive damage to houses, bridges, trails, and other infrastructure, as we were leaving after 3 weeks we observed active reconstruction taking place and major progress achieved in the rebuilding of lodges, homes, and community structures. Villagers and community groups encountered along the way were particularly welcoming and seemingly appreciative of our presence and work there.

a. Mostly rough-hewn rock without mortar (highly susceptible)

b. Mostly rough-hewn rock with mortar (less susceptible)

c. Rough-hewn rock with plaster, but weak gable (highly susceptible)

d. Wood with rock foundation (highly resilient)

Figure 1 (a., b., c., and d., above). Different construction methods used in the Khumbu region and their condition about 1 month after the earthquake.

Figure 2. Example of reconstruction in the Khumbu region approximately 2 months after the earthquake. Note the extensive use of wood. In other buildings a higher usage of rebar, concrete, mortar, and wood-framed paneling was also observed.

Figure 3. Re-activated landslide damaged trail at Phakding with boulders perched above.

During the field work in the Khumbu, we held meetings with several groups and organizations including the main religious leaders in the area, the Sagarmatha National Park leadership, and the Nepalese Army. At Dingboche (4530 m - 14,800 ft, 27° 53.608'N, 86° 49.932'E), we met twice with the Khumbu Alpine Conservation Council (KACC), a local community conservation organization established with assistance from The Mountain Institute in 2004 that is also concerned with flood risk reduction from Imja Lake and other, smaller glacial lakes in the area.

2.2. METHODS

Field Assessment Methods

Field assessment methods began with interviews with local communities regarding the timing, impacts, and community response to flood events and perceived hazards. Upon reaching the lake or flood source area on the glacier, we recorded observations of high water marks, entrenchment, channel morphology, lake morphology, landslides, cracks, slumps, thermokarst collapse, and other recent geomorphic features, especially those that could be associated with the recent earthquake activity. We made quantitative measurements of outflow and seepage, noting any changes from pre-earthquake conditions if known. We examined the terminal and lateral moraines for any changes in morphology and seepage. At Imja, we worked with two graduate students from the Geological Sciences Department of Tribhuvan University that conducted electrical resistivity to determine the presence of ice in the terminal moraine (ice being particularly resistant to the flow of electricity) and tracer dye tests to determine the source of water collected at seepage sources at the base of the terminal moraine[3]. We flew a small drone-mounted camera over the terminal moraine to generate a detailed digital elevation model of the outlet area. This will be repeated during future trips to allow detection of changes in the terminal moraine area over time.

Avalanche/Landslide Modeling

Mass movement modeling, i.e., ice avalanches and landslide/rock avalanches, was performed by identifying potentially prone areas and modeling their trajectories using a single flow model. Landsat 8 satellite imagery was used to identify glacierized versus non-glacierized areas using a ratio of the NIR and SWIR 1 bands (Huggel et al., 2004a). Ice avalanche prone areas were considered to be any glacierized area with a slope greater than 45° and landslide prone areas are considered to be any non-glacierized area with a slope greater than 30° based on values reported by Bolch et al. (2011) as shown in Table 1. A single flow model using the flow direction algorithm in ArcGIS in conjunction with a sink-free digital elevation model (ASTER GDEM) was used to model the path of the mass movement.

Table 1. Avalanche and landslide detachment slope and average trajectory slopes used for landslide/avalanche modeling (adapted from Bolch et al., 2011).

	Rock Avalanche	**Ice Avalanche**
Min slope (°) at starting zone	30	45
Avg slope (°) threshold, α	20	17*
* tan(α) = 1.111 - 0.118 log(V)		

The distance of mass movement trajectories was based on average slope thresholds of 20° for rock avalanches. Ice avalanche trajectories had a minimum average slope threshold of 17°; however for ice avalanches with a volume less than 6.67 million cubic meters had a higher average slope threshold based on the log relationship between ice avalanche volume and average trajectory slope reported by Huggel et al. (2004b). The volume of the ice avalanche was determined by assuming various avalanche depths (10 m, 30 m, and 50 m) based off of avalanches previously reported (Huggel et al., 2005) in conjunction with estimates of the avalanche-prone area. The avalanche-prone area was estimated using a variable focal length filter with a 90% threshold.

2.3. SMALL GLOFS AT CHUKUNG

Between Dingboche and Imja Lake, perched between the Lhotse and Lhotse Nup glaciers, is the village of Chukung (4750 m – 15,584 ft., 27° 54.268'N, 86° 52.318'E), formerly a small, seasonal grazing settlement that now contains around 14 tourist lodges complete with wifi, hot showers, and television. At about 9:15 pm (local time) on May 25, 2015, there was a glacial lake outburst flood (GLOF) from a small supra-glacial lake (connected to additional water within the glacier) on the Lhotse glacier above Chukung. This outburst carved an entrenched channel 10 meters deep in the formerly vegetated moraine pasture a few hundred meters upstream of Chukung. The flood was diverted from directly destroying Chukung by a low moraine that shifted the bulk of the flow slightly to the south. At Chukung, the flood surge was 6 meters high, destroying the small bridge leading to Island Peak basecamp, coming within inches of structures, and flooding the courtyard of one lodge to a depth of 10 cm. The estimated peak discharge based on high water marks at four cross-sections adjacent to Chukung was about 1500 m^3/s. At Dingboche, the flood height reached 4 meters where it destroyed the bridge on the upstream end of

[3] Data for both the electrical resistivity and tracer dye tests are currently being analyzed in Nepal.

the village. Importantly, this relatively small flood terrified people from Chukung to Lukla, with everyone running for high ground above the rivers and spending the night there. People downstream thought that it was a GLOF from Imja Lake--in fact, "Imja is coming" was heard in the Khumbu on a daily basis, and continues to be a huge source of local anxiety from Lukla to Dingboche. Such a reaction suggests a need for hazard mapping and disaster awareness building programs for people throughout the valley, particularly since the majority of villages are located well above the potential flood plain with virtually no chance of experiencing any impact from an Imja GLOF. On the other hand, one must understand that at this particular point in time anxiety in general is so high among the local populations that even the smallest suggestion of an oncoming flood, rock fall, or avalanche can send the vast majority of people scurrying for their lives.

Figure 4. Lhotse glacier and Chukung illustrating the numerous supra-glacial lakes on the glacier and the approximate path of the May 25, 2015 Chukung GLOF.

a. Undercutting damage at Chukung resort.

b. Temporary emergency diversion dam.

Figure 5 (a. and b.). GLOF damage and emergency diversion dam at Chukung resort

Figure 6. Drained lake with former volume of about 27,000 m^3 above Chukhung that contributed a portion of the GLOF flow.

Given that most GLOF risk reduction efforts in Nepal have focused on the threat of large, fully formed glacial lakes, the Chukung GLOF is another type of phenomenon[4]. We observed that the entire glacier is melting, top, middle, and bottom, with extensive Swiss cheese-like cave networks, surficial meltwater ponds that may be linked to them, and sub-surface bodies of water that are also interconnected. The caves can become plugged during the winter yet still be filled with water, and with the warmer spring weather the ice plug or lens can burst (possibly the very loud noise people report) and release thousands of cubic meters of water in minutes. Again, this represents a second smaller type of GLOF in addition to the traditional large lake scenario, and one that we need to start taking seriously since it could happen again in the near future with more damaging consequences. Chukung, in particular, is located in a dangerous confluence of the Lhotse and Lhotse-Nup glaciers, and will likely continue to experience smaller but potentially highly damaging floods.

[4] A similar event occurred in 1977 in the Nare Drangka river off the north-facing slopes of Ama Dablam and on the Ngozumpa glacier near Gokyo. Prabhin Maskey of DHM notes that several dozen of these smaller events typically occur each year throughout Nepal.

2.4. IMJA LAKE: OBSERVED AND MEASURED EARTHQUAKE AND CLIMATE CHANGE IMPACTS

Imja Lake is a supraglacial lake formed on top of Imja glacier, and it is bounded on the east by the Lhotse-Shar and Imja glaciers, on the north and south by lateral moraines, and to the west by a 700m wide by 700m long ice-cored terminal moraine complex that has an outlet that drains the lake feeding into the Imja Khola (or Imja River). The lake, which did not exist in 1960, has experienced rapid growth in area and volume since then, increasing to 61.7 million m^3 by 2012. The western, down-valley expansion has stabilized in recent years while the eastern expansion toward the mountains continues unabated mostly through calving from the glacier terminus. Avalanche debris falling from surrounding high mountains and hanging ice is prevented from entering the lake by the high lateral moraines, which are separated from the surrounding mountains by several 10s of meters.

The characterization of the risk of Imja Lake is somewhat controversial, with some researchers declaring it to be relatively dangerous (Hammond, 1988; Kattelmann, 2003; Ives et al., 2010), and others concluding that it may be stable (Fujita et al*.,* 2009; Watanabe et al*.,* 2009; ICIMOD, 2011). ICIMOD (2011) identified Imja Lake as one of six high-priority glacial lakes in Nepal that require detailed investigation, while other studies have stated that Imja Tsho is safe (Fujita et al., 2013) or very low risk (Hambrey et al., 2008). These conflicting classifications are confusing and can be misleading to the general public and communities downstream, who are the stakeholders these studies are meant to assist. The United Nations Development Program (UNDP) is implementing 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 project strategy (UNDP, 2013), the "GLOF risks arising from Imja Tsho will be significantly reduced by reducing the lake volume through an artificial controlled drainage system combined with a community-based early warning system." They recommend lowering the lake level by at least 3 meters to achieve this risk reduction. Risk reduction scenarios have been analyzed through 2-dimensional debris flow modeling and lowering the lake by 3 m was found not to have significant flood reduction benefits. Results indicate that the lake needs to be lowered about 20 meters in order to significantly reduce the impacts that a GLOF could have at Dingboche and further downstream.

The team then traveled from Chukhung to Imja Lake where we spent several days, camped in a new location well above the level of the lake. Following a series of measurements and quantitative/qualitative field assessment methods, we found that lake had been definitely impacted by the earthquake as well as the continuing relentless and accelerating impacts of climate change. Outflow from the lake was unseasonably high, seepage areas present 6 months before were dry while others have increased flow, both indicating shifts in the terminal moraine that is already unstable and changing. Among the impacts of the earthquake and continued rapid changes due to warming that we saw were: abundant new cracks parallel to the lake shore, boulders in the terminal moraine shifted by the earthquake(s), the ponds in the lake outlet merged into a single outlet lake, lateral ponds in the terminal moraine with major extensions merging with the outlet lake, slump benches at the entrance to the outlet lake, thermokarst collapse areas in the terminal moraine, and avalanche prone areas behind the calving front of the glacier. We also did extensive monitoring of the lake and outlet through discharge measurements of the outlet and seepage, and an unmanned aerial vehicle (drone) photographic survey to develop a high-resolution digital elevation model (DEM) of the outlet area where a lake lowering construction project is set to begin within months.

Figure 7. Imja Lake in the Khumbu region of Nepal.

Figure 8. Measuring discharge at the Imja Lake outlet (left) and seepage (right).

a. Setting the targets for the SfM photos

b. Preparing the drone for flight

c. The drone in flight

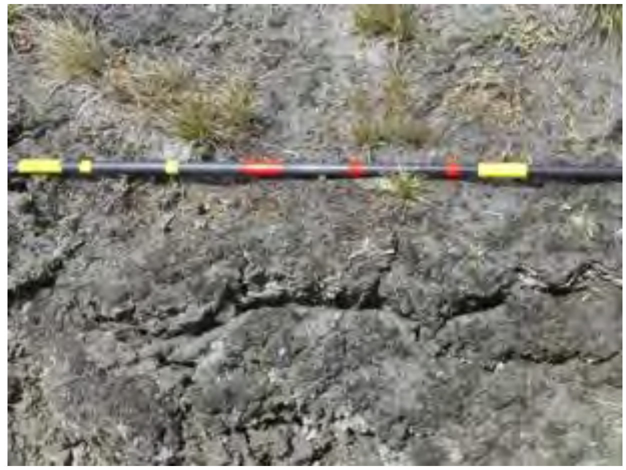
d. Catching the drone for landing

Figure 9 (a., b., c., and d., above). Using a drone at Imja Lake to take Structure for Motion (SfM) images to construct a digital elevation model (DEM) of the preconstruction condition of site.

a. Extensive new braiding of river downstream of outlet

b. Lateral Pond Extensions

c. Boulder in Terminal Moraine Shifted by Earthquake



d. Abundant New Cracks Parallel to Lake Shore

e. Slump Benches at Isthmus

f. Thermokarst Collapse in Terminal Moraine

Figure 10 (a. through f. above). Changes in the terminal moraine and outlet lake complex at Imja Lake.

Figure 11. Imja glacial lake, June 2015. Careful comparisons with panoramas taken exactly one year ago revealed significant changes in glacier debris cover, new earthquake-induced landslides, and outlet channel form that are related to both climate change as well as the 25 April earthquake. A complete circum-navigation of the lake (excluding the glacier terminus), and thorough examination of the entire terminal moraine, was also conducted.

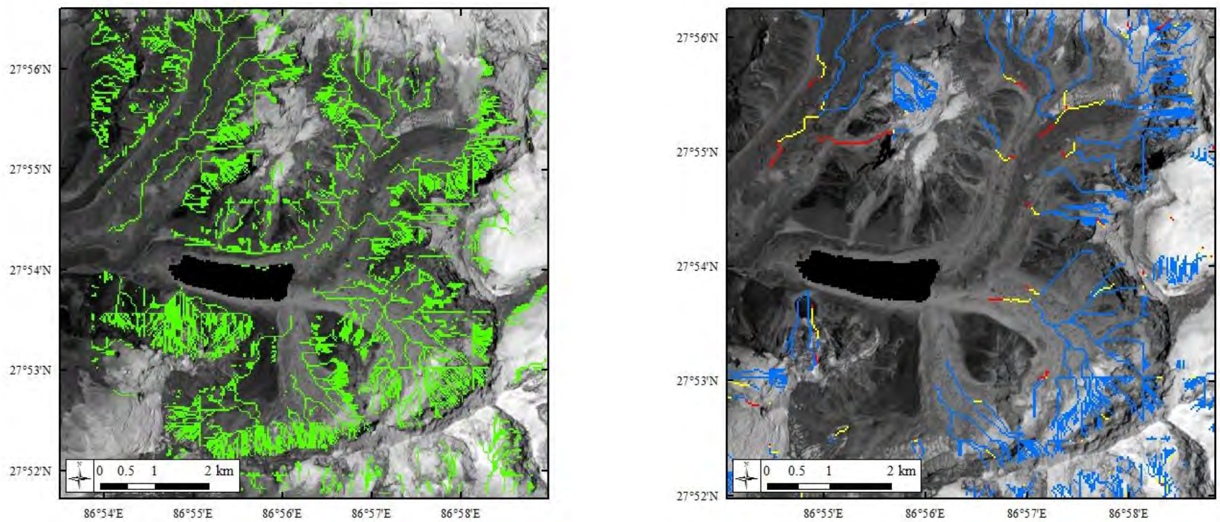


Figure 12. Potential for Landslides/Avalanches at Imja Lake: (a) Landslide/Rockfall, and (b) Ice/rock/snow Avalanches. Source: the Authors.

2.5. DIG TSHO GLOF

Upon completing the assessment at Imja Lake and Chukhung, we returned to Namche Bazar and proceeded up the Bhoti Koshi valley to the village of Thame (27° 49.905'N, 86° 39.039'E) and the glacial lake Dig Tsho. The village of Thame was one of the hardest hit in the Khumbu region by the April and May earthquakes. Every building in Thame and surrounding villages has been severely damaged or destroyed.

Figure 13. Village of Thame, where every building was severely damaged or destroyed by the earthquake.

On April 25, 2015, the day of the earthquake, an avalanche of ice and rock was dislodged from the mountain Tengi Ragi Tau (6650 m) that fell into Dig Tsho, creating an 8 m surge wave that passed through the lake outlet with a very brief peak discharge of about 3000 m^3/s (estimated from high water marks, channel cross-section and slope) and flooded the Bhote Kosi downstream. The flood destroyed 2 small bridges and damaged a third larger bridge at Thametang, where the flood height peaked at about 1.5 meters. Dig Tsho had experienced a major GLOF in 1985 that caused considerable loss of homes, property and infrastructure downstream. Fortunately the flood was contained in the river channel, and downstream witnesses report that half of the Bhote Khosi river was white and half black from the outburst. Villagers in Langmoche, the first downstream village, were terrified, as on one side of the village there was a flood and on the other massive rock falls from the earthquake. This event indicates that even lakes that have already experienced outburst floods are potentially dangerous, and need to be monitored along with the large glacial lakes as part of an effective risk reduction strategy.

Figure 14. Ice avalanche source areas above Dig Tsho.

Figure 15. Eight-meter high surge wave height at Dig Tsho outlet. There was no significant lowering of the outlet and no subsequent reduction in future flood hazard.

2.6. CONCLUSIONS

In spite of ongoing disagreements regarding Imja glacial lake's danger level, the team concluded that the lake poses a significant threat to downstream communities if the terminal moraine were to be compromised resulting in a GLOF, based upon extensively field studies conducted since 2012[5]. The team recommends that the most important first step is to lower the lake level by about 20 m, concurrent with the disaster awareness building, installation of a user friendly early warning system, and development of effective disaster management plans and capacities. This level of risk reduction would provide significant protection of the village of Dingboche and other areas downstream.

Largely because of climate change and the recent impacts of the earthquake and aftershocks, Nepal has entered an era of accelerated catastrophic events (e.g., landslides, GLOFs, floods, small glacial lakes) that will impact the country's population, their lives, and livelihoods for several years to come. Imja glacial lake in particular is a risk to downstream populations and infrastructure and is in need of truly effective risk reduction measures, such as lowering the lake level by 20 m, if a future catastrophe is to be avoided (Somos-Valenzuela et al. 2015). Anxiety among downstream populations is at an all-time high, but understanding of high risk/low risk areas, GLOF processes, and disaster management planning is extremely limited. Nevertheless, Nepal has an opportunity to reduce the risk of Imja and other glacial lakes throughout the country by developing "science-based, community-driven" approaches already

[5] Somos-Valenzuela, M. A., D. C. McKinney, A. C. Byers, D. R. Rounce, C. Portocarrero, and D. Lamsal, Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal. Hydrol. Earth Syst. Sci., 19, 1401-1412, 2015 (http://www.hydrol-earth-syst-sci.net/19/1401/2015/hess-19-1401-2015.pdf)

tested and proven in the course of implementing various climate change adaptation approaches. The HiMAP team looks forward to continued cooperation with the Government of Nepal and other partners to conduct detailed physical/social/engineering surveys of all 20+ of Nepal's potentially dangerous glacial lakes.

2.7. SUMMARY POINTS

- **Nepal has entered an era of accelerated catastrophic events (landslides, GLOFs, floods, small glacial lakes).**
- **Imja glacial lake, the most studied of Nepal's lakes and subject to some controversy regarding its outburst flood potential, is clearly dangerous and a risk to downstream populations and infrastructure as a result of ongoing climate change processes and further destabilizing impacts of the April-May 2015 earthquakes.**
- **Anxiety among downstream populations is at an all-time high; understandings of high risk/low risk areas, GLOF processes, and disaster management planning is limited.**
- **Nepal has an opportunity to reduce the risk of Imja and other glacial lakes while establishing "science-based, community-driven" success stories.**

2.8. RECOMMENDATIONS FOR EFFECTIVE RISK REDUCTION OF IMJA GLACIAL LAKE

- **Lower Imja glacial lake by 20 m, or 17 m lower than the 3 m proposed by UNDP**
- **Develop detailed flood hazard maps as community training tools.**
- **Conduct LAPA-style disaster management planning and training programs (e.g., GLOF/NH sensitization, assets, vulnerabilities, options, planning, implementation, monitoring)[6].**
- **Install a user-friendly EWS for Imja and Chukung.**
- **Build in-country capacity to manage the increasing risks of GLOFs and other natural hazards.**

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[6] (a) Byers, A.C. and Thakali, S. 2015. *Khumbu Local Adaptation Plan of Action (LAPA): Sagarmatha National Park, Solu-Khumbu District*. United States Agency for International Development, Global Climate Change Office, Climate Change Resilient Development Project, Washington, DC, February, 2015.

(b) Byers, A. C., Cuellar, A. D., McKinney, D. C., *HiMAP Local Adaptation Plans of Action: Case Studies and Lessons Learned in Nepal and Peru*, Final Report, United States Agency for International Development, Global Climate Change Office, Climate Change Resilient Development Project, Washington, DC, January 31, 2015.

(c) Byers, A. C., D. C. McKinney, S. Thakali and M. Somos-Valenzuela, *Promoting science-based, community-driven approaches to climate change adaptation in glaciated mountain ranges: HiMAP*, Geography 99(3):143-152, Autumn 2014.

Figure 16. Phase I team at Imja Lake, June 2015. Not shown are Pushpa Raj Dahal and Prakash Pokhrel of Tribhuvan University, who were already on the moraine running ERT transects at 7 am the morning of the photo.

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3. TSHO ROLPA GLACIAL LAKE, ROLWALING REGION

Team members:
Alton C. Byers, Elizabeth A. Byers, Daene C. McKinney

Figure 17. Tsho Rolpa glacial lake in the Rolwaling region of Nepal.

3.1. INTRODUCTION

Tsho Rolpa is located in central Nepal at an altitude of 4546 m, forming the headwaters of the Rolwaling Khola which is a tributary of the Tama Kosi in Dolakha district. The lake is approximately 3.64 km in length, has an area of 1.54 km^2 , volume of 86 million m^3, average depth of 56.4 m, and 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 by about 20 m/yr ever since (ICIMOD 2011: 47).

Interest in Tsho Rolpa began in 1991 when the Chubung[7] glacial lake, a smaller lake to the immediate north of Tsho Rolpa, experienced a glacial lake outburst flood (GLOF) that damaged a number of homes and property in the nearby and downstream villages of Naagaun and Behding. In response to the concern expressed by local residents for the prospective dangers presented by the much larger Tsho Rolpa lake to the south, the Water and Energy Commission Secretariat (WECS) and Japanese International Cooperation Agency (JICA) conducted detailed studies of the lake between 1993 and 1997 that included designs to lower the lake by 4 m. By late 2000, Reynolds Geo-Science LTD, with support from the Government of Nepal and Government of the Netherlands, successfully lowered the lake by 2.8 m. This was considered to be a success in terms of demonstrating that Nepal indeed possessed the capability to perform complicated lake lowering engineering projects, such as those completed by the Peruvians since the 1950s in the Cordillera Blanca region (Portocarrero 2013), but not effective in terms of reducing actual flood risk 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. Following 16 years of changing climate,

[7] Known locally as 'Dudh Kund.'

geomorphology, and deterioration processes, Tsho Rolpa is currently considered to be the most dangerous glacial lake in Nepal in terms of potential GLOF occurrence as well as downstream damage to populations, agricultural land, infrastructure, and hydro power plants.

3.2. LOGISTICS

The team spent 17 days performing post-earthquake glacial lake assessment field work in the Dolakha region of Nepal. After driving from Kathmandu to Singati Bazar, one of the hardest hit communities in the April earthquake and May aftershock, we had to abandon the roads and make our way over high mountain trails due to the landslide hazard on the minor road that follows the river route. After two days, we made our way to the village of Jagat, then back up to the high ridge at Tasinam and traversed across to Simigaon. From there we traveled up the leech-infested river trail to Behding, which had been extensively damaged by landslides that were still active and dangerous in spite of the commendable trail repair work of the Nepal Mountaineering Association. From Behding we proceeded to the Sherpa village of Na, arriving at the glacial lake Tsho Rolpa the following day. The experience of traveling on highly dangerous river trail for two days convinced us to return to the Singati roadhead via a high route across the Daldung La pass, then down the steep ridge trail to Tashinam, then on to the Tama Khosi river town of Jagat. From there we returned to Singati by truck along the heavily damaged and precipitous river road, a journey of less than one hour compared to the two days' walk to Jagat at the expedition's commencement.

Figure 18. Singati bazaar.

Figure 19. Landslide along trail.

Along the way we observed a great deal of earthquake damage. We estimate that about 100% of the buildings in Singati Bazaar were damaged beyond repair and most of them were destroyed completely. This commercial village was one of the most heavily damaged by the earthquake with estimates of more than 150 people perishing in nearby landslides and collapsed buildings. Damage reached a similar level in the remote and rural areas traveled through, and when viewed from afar the typical village of some hundred structures or more took on the appearance of candy-colored mosaics against a background of green, from the different tarps covering the roofs donated by different international governments. Life appeared to be continuing as usual in the rural areas because of the need to plant this season's rice and millet, which keep people fully occupied as they began to slowly repair their temporary or permanent residences. People living in bazaar and road head towns such as Singati, however, seemed to be particularly stunned by the loss of their businesses, friends, and trauma of the recent earthquake, and appeared incapable of moving forward, at least for the time being. Several people interviewed in the makeshift structures where our camp was located said that all they did all day was to "eat, sleep, and wait." Little re-building activity of structures was observed in Singati, although from the time between our expedition's beginning and end a new gabion-building project commenced along the Singati river in an effort to protect the shore from further erosion.

Figure 20. Approaching terminal moraine. Figure 21 right. Trakarding Glacier.

3.3. OBSERVED AND MEASURED EARTHQUAKE AND CLIMATE CHANGE IMPACTS

We observed cracks in the fill zone east of the outlet (earthquake). At the inlet of the canal structure there is definite slumping and cracking of the surface in the direction of the lake on both sides of the inlet (see Figure 22). This damage was caused by the April/May 2015 earthquake and aftershock. These cracks are some 10-15 m in length, 40-60 cm in width and 40-50 cm deep. These areas need to be repaired in order to slow and stop the deterioration of the inlet to the canal.

Figure 22. Cracking at the inlet from the lake to the outlet structure.

We observed and documented hanging ice, which now has a distinct avalanche path into the lake based on Swiss models and verified by direct observation of meltwater and debris on the avalanche path entering the lake (climate change, further destabilized by the earthquakes).

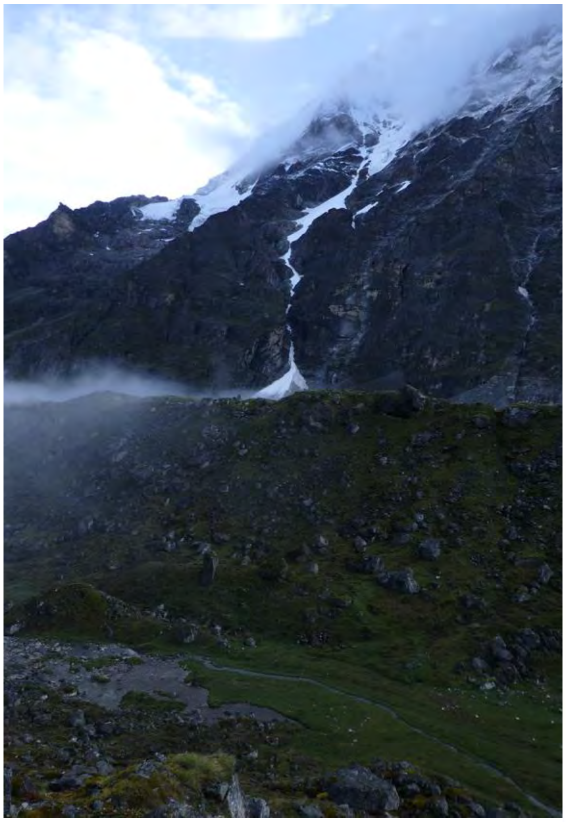

Figure 23. Hanging glacier and avalanche track.

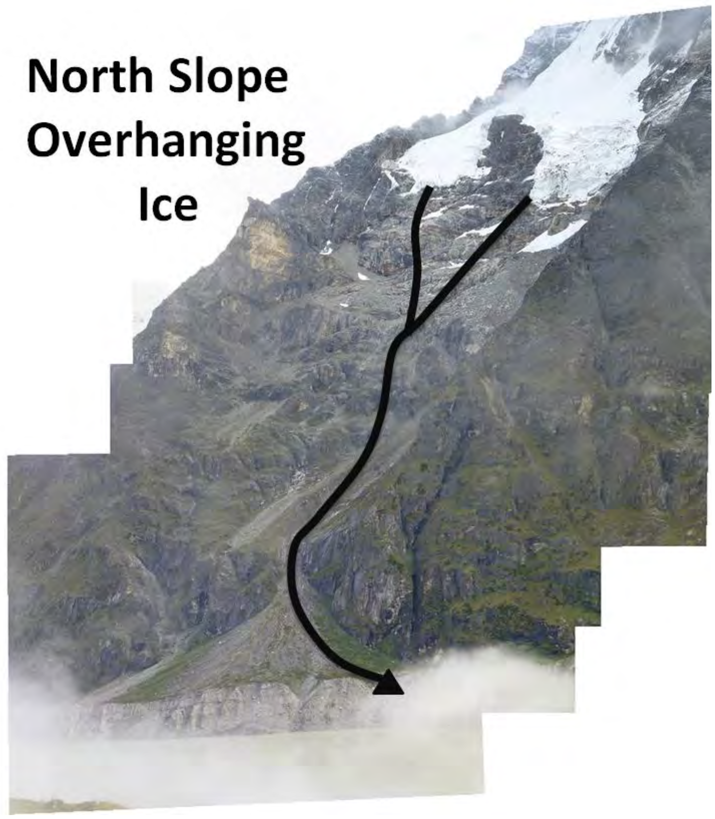

Figure 24. Overhanging ice and avalanche track into lake.

Figure 25. Glacial terminus and overhanging ice.

We performed avalanche and landslide modelling as a result of these observations.

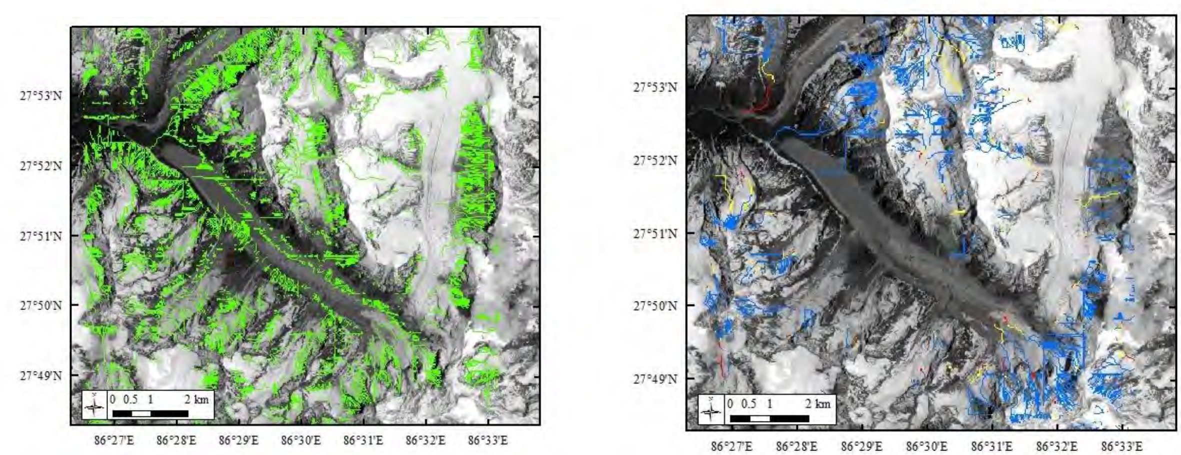

Figure 26. Potential for Landslides/Avalanches at Tsho Rolpa: (a) Landslide/Rockfall, and (b) Ice/rock/snow Avalanches. Source: the Authors.

One of the more serious changes in the geomorphology of Tsho Rolpa over the past 16 years is the continued loss of right lateral moraine material through mass wasting processes that has now opened a direct avalanche channel and path into the lake, increasing the potential for surge wave creation, dam breaching, and catastrophic flood. Previously, the moraine wall was sufficient to buffer the lake against entry by avalanche and rockfall. Mass wasting of the moraine has been so rapid that the original trail to Tashi Lapsa (pass) into the Khumbu region has now been moved to the south side of the lake. Even here, however, a massive landslide about two years ago took out a large section of the trail near the glacial terminus, necessitating a 500 m climb up and around the landslide to reach the first base camp on the glacier some 2 hours beyond. Both are indicative of the relentless deterioration of Tsho Rolpa's lateral moraines, exacerbated by the continued thinning and thermokarst settling of its terminal moraine. **Error! Reference source not found.** shows results of modeling the potential for landslides and avalanches at Tsho Rolpa.

We observed shifted boulders in the terminal and lateral moraines, leaving 20 cm+ cracks vulnerable to monsoon precipitation penetration caused by the earthquake.


Figure 26, left. Shifting of boulders on the terminal moraine.

Figure 27, right. Shifting of massive boulder on the right lateral Moraine (note dark gap to the immediate right of Byers).

Nearly every boulder in Tsho Rolpa's terminal moraine was shifted by the earthquake, creating gaps between the boulder and soil that will now provide easy access and accumulation of monsoon precipitation that may further destabilize the feature. Of further concern was the shifting of a massive boulder perched directly on the knife-edged ridge of the right lateral moraine, increasing the possibility of collapse into the lake and creation of a large surge wave.

We also observed linear collapses, such as troughs and canals in the terminal moraine caused by climate changes.

Figure 28. Six linear collapses were counted and measured on the terminal moraine, and two on the right lateral moraine.

Six linear collapses were counted and measured on the terminal moraine, and two one the right lateral moraine. Believed to be formed by a combination of melting ice and water movement along sub-surface joints, freeboard (the distance between the lake level and top of the moraine dam) was often less than 8 m, providing a discharge path in the event of major surge wave.

Sinkholes were observed and documented in the terminal and lateral moraines likely due to climate change.

Figure 29. Large sinkhole on the terminal moraine.

One large sink hole was found in the northwest section of the terminal moraine that was reported in the literature to have grown rapidly over a period of several years beginning about a decade ago. Two smaller sink holes were found nearby, which suggest that further ice melting and moraine settling have occurred in the interim.

100 m+ long crack in the crest of the right lateral moraine caused by the earthquake.

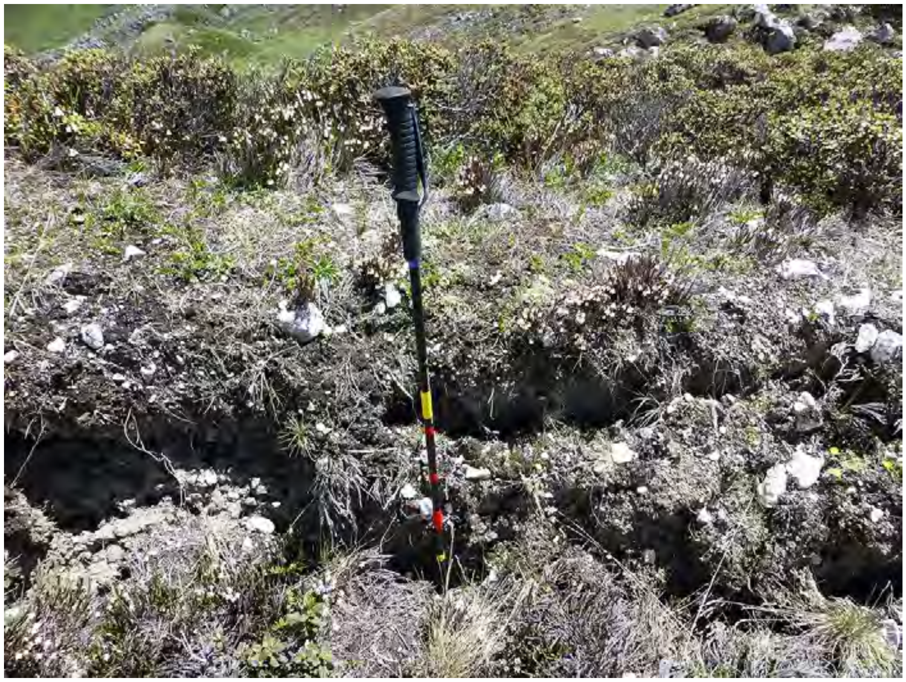

Figure 30. 100 m+ long crack in the right lateral moraine.

A 100 m+ long, 5-50 cm deep, and 3-40 cm wide deep crack was found along the ridge of the right lateral moraine with clear earthquake origins. 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 along the knife edge of the moraine, formed through a combination of gravity, weathering, mass wasting, and the earthquake were noted that will soon lead to the loss of more morainal material into the lake.

Soil liquefaction in the top of the terminal moraine at Tsho Rolpa from the earthquake.

Figure 31. Soil liquefaction in the top of the terminal moraine at Tsho Rolpa.

Several square meters of silt deposits within one of the linear collapses were noted which appear to have been produced as a result of soil liquefaction, a phenomenon common to earthquakes where soil losses its stiffness and strength and behaves like a liquid.

3.4. IMPACTS TO OUTLET CHANNEL

Figure 32. Tsho Rolpa outlet structure.

a. Outlet structure

To lower the water level of Tsho Rolpa by approximately 3 m, a gated structure (Figure 32. Tsho Rolpa outlet structure.) of 4.2m wide, 3m deep and a 70m long canal were constructed across the end moraine in 2000 (Mool et al., 2001). It was recognized at that time that to fully reduce the risk of a GLOF from Tsho Rolpa the lake needed to be lowered a full 20 m to reduce the volume of the lake by 35 million m3.

Figure 33. The gated outlet structure at Tsho Rolpa (top left); structure from lake side, (top right); structure from downstream side (bottom left); and spillway on downstream side (bottom right) with cables holding spillway boulders in place.

From 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. The 2015 April/May earthquake and aftershock appear to have done little damage to the structure, but there are definite minor issues that need to be dealt with. These are discussed in the following sections.

b. Outlet gates and gabions

The main outlet gates and gabion support structures, shown on the downstream side in Figure 33 right hand side (a), and left hand side (b), appear to be in good operating condition with the wires of the gabion cages remaining properly stacked and aligned. Some damage to the lower gabion on the lower left outlet wall (photo c above) was observed that is in need of repair.

(a) (b)

Figure 34. Outlet gates and gabions from downstream side (a) right hand side, and (b) left hand side.

c. Bulging at outlet structure

One of the things that is very noticeable at the outlet structure gates is the bulging of the wood facing on the upstream (lake side) of the supporting gabions on both sides of the gates (see Figure 35). Our team was unable to verify if this has developed over the 15 years since construction was complete or if it is a result of the earthquake and aftershock. However, the blue paint covering the wood has obviously deteriorated over time and the bulging might be an accompanying warping of the wood due to weathering. However, there could also be a failure of the gabion cage wire next to the wood. In any case, this needs to be investigated and proper repair and maintenance performed on these structures.

Figure 35. Bulges in the supports to the gates at the outlet structure.

d. Separation of gabions

Another slight damage to the outlet structure is separation of the sloping gabions from the adjacent material on the left side of the inlet leading to the outlet structure. Figure 35 shows this looking west toward the gates (a), and east toward the lake (b), respectively. We were unable to verify if this is a new development or if it is long-term deterioration of the structure. In any case, it needs to be repaired before it deteriorates further.

Figure 36. Separations in the sloping gabions on the left side of the inlet leading to the outlet structure: (left photo) looking west, and (right photo) looking east.

e. **Lake lowering**

One way to lower Tsho Rolpa by 20 m would be to use the old outlet of the lake (pre-2000) as a channel, build a coffer dam to isolate the lake form this channel, and begin excavating that channel. Once a depth of 20 m below the original water level of the lake had been reached, then a drainage tunnel could be placed in the cut in the moraine. After that, the cut would be refilled with sturdy material and covered with a facing of stone and concrete in the manner of the Peruvian lake safety dams (Portocarrero, 2014). Figure 37 shows the old outlet (before 2000 construction of outlet structure) at Tsho Rolpa, and Figure 38 shows the concept of the excavation process to lower the water level of glacial lakes held by moraine dams or other loose sediments (a), and (b) a cross-section showing the characteristics of the spillway (left) and a lateral view of the canal showing the restored security dam that will contain surges resulting from falling ice (right).

Figure 37. Old outlet (before 2000 construction of outlet structure) at Tsho Rolpa.

f. **Excavation process**

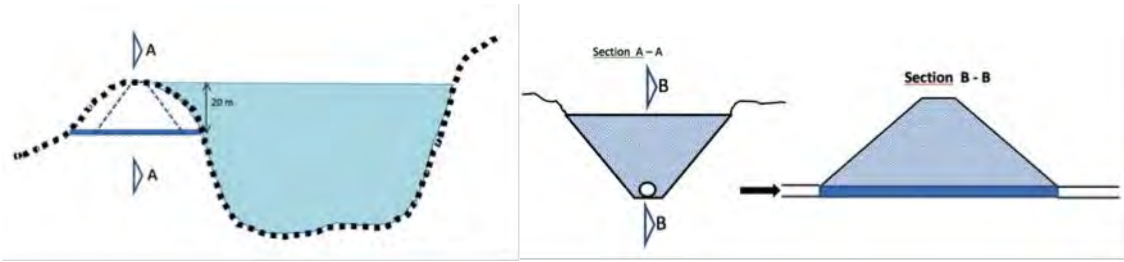

Figure 38. (a) Excavation process to lower the water level of glacial lakes held by moraine dams or other loose sediments, and (b) Cross-section showing the characteristics of the spillway (left) and a lateral view of the canal showing the restored security dam that will contain surges resulting from falling ice (right). Source: Portocarrero (2014)

g. Peru examples

Several examples of Peruvian lake safety dams are shown in Figure 39. These dams were built in the 1970s and 1980s in the Cordillera Blanca where Peruvian engineers constructed more than 30 of these dams between 1960 and 1990.

(a) Lake Palcacocha safety dam

(b) Lake Huallcacocha safety dam

(c) Llaca Lake safety dam

Figure 39. Examples of constructed glacial lake safety dams in the Peruvian Cordillera Blanca. Source: Portocarrero (2014)

3.5. POTENTIAL TRIGGERS ON THE SOUTHERN SLOPE

a. Panga Dinga Glacial Lake

Panga Dinga glacial lake is located to the south of Tsho Rolpa at an altitude of 5,000 m, and immediately northwest of Panga Dinga glacier. The team was asked by the DHM to assess the lake's potential for flooding during the Tsho Rolpa survey because of its concerns that the flood waters from the newly formed lake could potentially spill over into Tsho Rolpa, thereby creating a massive surge wave and triggering a GLOF.

Figure 40. Small lake northwest of Panga Dinga Glacier.

GoogleEarth analyses suggested that the lake was 800 m in length, 200 in width, and that it fluctuates in areal extent over time for reasons that are not entirely understood. When the survey team visited the lake on 8 July they found these dimensions to be essentially correct. Evidence of a recent and sudden drainage of 9 meters depth was found based on the freshness of the silt/loam soil between the high water mark and current lake level, and 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, previous). It is unknown if this sudden drainage was related to the earthquake, or to normal seasonal fluctuations, and follow up monitoring is suggested.

Considerable masses of hanging ice are located directly above this small lake and formed the basis of concern from the DHM. The lake currently has no surface outlet. A former 20-meter-wide outflow channel rises 10.4 meters above the current lake level. Any surge wave from the lake would be further impeded by the significant surface roughness and porosity of the outlet channel, moraine and colluvium between it and Tsho Rolpa. There is some evidence of a past overflow of the small lake, in the presence of a 20-m wide outflow channel that drains to an eroded gully. However, the gully disappears long before it reaches the valley floor, indicating that this past overflow also drained into the subsurface. At the toeslope, seepage emerges in the form small springs and seeps, making up a total flow of 0.36 m^3/s on July 8. 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 mountain slope, and is currently not undercutting or otherwise threatening the thin lateral moraine.

b. Panga Dinga Glacier

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

3.6. COMMUNITY CONSULTATIONS AND LIST OF CONCERNS

Figure 41, left. Community consultation at Naagaun.

Figure 42, right. Riverside chats at Singati Bazar.

Informal community consultations were held in Naagaun on 10 July, 2015 (Figure 41). Project team members explained the objectives of their post-earthquake assessment of Tsho Rolpa to about 20 village participants, most of them older men, women, and young girls because of the outmigration of young men to Kathmandu in search of jobs in the trekking and tourism industry. When asked for their perceptions of Tsho Rolpa, the threat of a GLOF, and mitigation efforts to date, the following comments were recorded:

a. **Community members were afraid of a GLOF—"we can't sleep at night"—but had little idea how to reduce their risk to floods and other natural hazards, nor how to protect the valley and their personal assets.**
b. **There was little understanding about the newly installed early warning system (EWS) in terms of how it worked, whether it worked, and what to do in case they received a call from Kathmandu warning them of an impending flood (sensors are designed to first notify the Kathmandu DHM office of an oncoming flood, which in turn calls the cell phones of people living in villages below the lake). We noted that cell phone signals were weak to absent in Naagaon much of the time.**
c. **Villagers requested information re: how glacial lakes have been lowered in other parts of the world, such as Peru.**

The team promised to send copies of HiMAP's Glacial Lake Handbook by Cesar Portocarrero (2013) to the Everest Summiter's Club, a local organization attending the meeting that also serves as director/facilitator of development and recovery projects.

A glacial lake risk perception study by Dahal (2008) suggested that there was a distance decay factor related to fear of Tsho Rolpa, i.e., that villagers in Naa and Behding were vastly more concerned about a possible GLOF than were those living further downstream in Jagat, Singati, and beyond who had never experienced a flood. Other factors mentioned that might have influenced downstream nonchalance included the large influx of new immigrants; widespread poverty precluding any concern over a distant threat; a feeling that "it can't happen to me" or that "God won't let a flood happen;" the position that engineers had already "fixed" the lake so why bother about a flood; and low priority of GLOFs on the agendas of politicians who focus more on roads, schools, hospitals, and development.

However, informal discussions with the Army, police, lodge owners, and refugees at Singati suggested that concern over a GLOF from Tsho Rolpa was in fact very high. People were clearly traumatized by the earthquakes, and on top of that were aware that Tsho Rolpa was a large and dangerous lake that could burst at any time. Primary concerns were (a) when an outburst was likely to happen, (b) how high the flood would be, and (c) whether or not their homes would be safe. Follow up studies focused specifically on highland/lowland perceptions of Tsho Rolpa and its GLOF potential are clearly indicated.

3.7. SUMMARY

The processes of lake instability and terminal/lateral moraine deterioration identified by experts some 16 years have continued, and in most cases accelerated as a result of climate change and the May-June 2015 earthquakes. Tsho Rolpa remains a highly dangerous lake, clearly one of the most dangerous in Nepal, and is urgently in need of risk reduction measures. Nepal's Little Ice Age (ca. 1500-1850) glaciers, such as Imja, Tsho Rolpa, and Lower Barun, have clearly entered into an era experienced by its larger glaciers at the end of the Pleistocene some 20,000 years ago, when all of the glacial lakes created by warming trends eventually drained through their temporary moraine dams (Figure 43). This suggests that, as cited by numerous other experts, increases in the number and frequency of GLOFs in Nepal can be expected with confidence (Figure 44).

Figure 43. Glacial lakes throughout Nepal are following a natural flood cycle already demonstrated by Pleistocene glaciers some 20,000 years ago, all of which eventually drained through their temporary moraine dams following the commencement of warming trends. Increases in the number and frequency of GLOFs in Nepal can be expected with confidence.

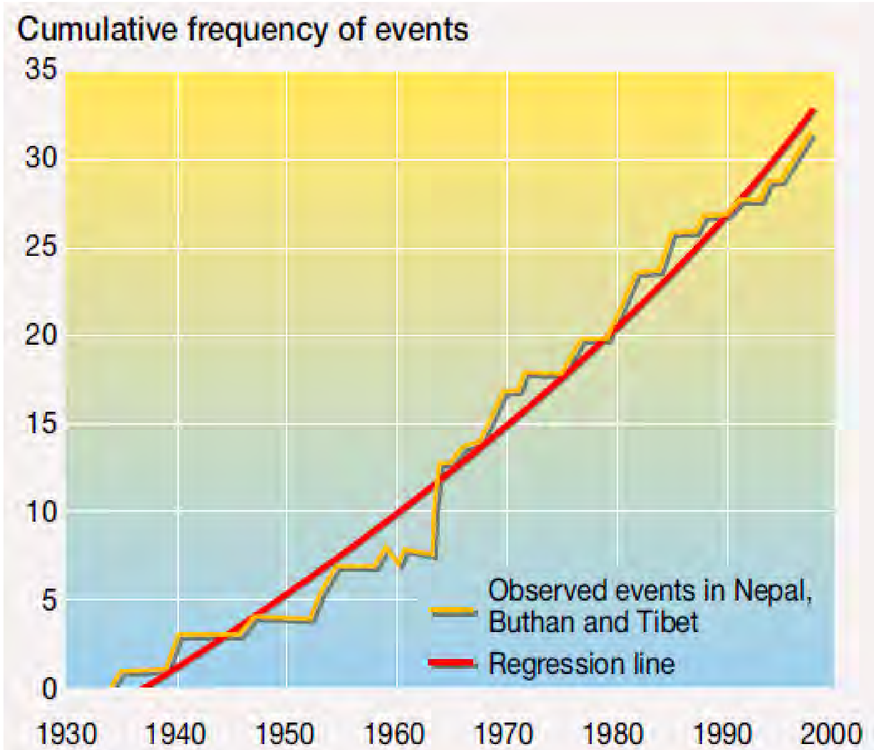

Figure 44. Cumulative frequency of GLOFs in Nepal, Bhutan and Tibet. Source: Richardson and Reynolds, 2000

- There is a large body of excellent research surrounding Tsho Rolpa, which from the beginning was considered to be a highly dangerous lake in need of lowering by at least 20 m (the origins of the 20 m estimate, however, remain unknown).
- Outlet construction, which successfully lowered the lake by 2.7 m, was of the highest quality and remains intact after 16 years and two large earthquakes. The outlet was considered to be a successful demonstration of Nepal's capacity to lower glacial lakes but insufficient to realistically reduce risk.
- Tsho Rolpa remains a highly dangerous lake in need of serious risk reduction planning and action, particularly given the destabilizing impacts of the recent earthquake and ongoing deterioration caused by climate change.
- The 25 April earthquake and aftershock further destabilized an already deteriorating terminal/lateral moraine through the creation of massive cracks, shifted boulders, and impacts on the outlet channel while further destabilizing existing potential GLOF triggers such as overhanging ice, calving rates of the glacier terminus, deterioration of the terminal moraine, and mass wasting of the lateral moraines.
- Processes of terminal and lateral moraine deterioration identified 16 years ago have visibly accelerated.
- Glacial lakes throughout Nepal are following a natural flood cycle already demonstrated by Pleistocene glaciers some 20,000 years ago, all of which drained through their temporary moraine dams following the commencement of warming trends. Increases in the number and frequency of GLOFs in Nepal can be expected with confidence.
- Downstream communities are fearful of a potential GLOF and lack adequate information about the EWS, lake risk reduction methods, and disaster management planning.

- Field-based reconnaissance methods, combined with remote sensing, modeling, and information sharing, are essential to the most accurate understanding of post-earthquake and climate change impacts on dangerous high altitude glacial lakes.

3.8. RECOMMENDATIONS

- Determine the effective lowering depth for Tsho Rolpa through bathymetry and flood modeling to remove the uncertainty surrounding the recommended 20 m depth.
- Develop new approaches to lowering glacial lakes in the context of Nepal's high mountain geography, remoteness, and lack of roads.
- Lower Tsho Rolpa to a safe level ("safe" is defined as not causing damage to human life and livelihoods even in the event of an ice avalanche or other potential flood triggers).
- Develop detailed flood hazard maps as community training tools.
- Conduct concurrent LAPA-style and training programs based on GLOFs and other natural hazards (e.g., GLOF/NH sensitization, assets, vulnerabilities, options, planning, EWS, implementation, monitoring) for downstream communities that increase their capacity for disaster management planning and implementation.
- Develop an effective and user-friendly early warning system protocol from the existing, installed EWS for Tsho Rolpa.
- In-country capacity should be built to manage the increasing risks of GLOFs and other natural hazards. It is recommended to establish an Office or Institute of Glaciology covering the following tasks:
    - Regularly update the inventory of glaciers and glacial lakes.
    - Regularly update the hazard level posed by each lake based on the probability of a catastrophic flood and its estimated downstream impacts.
    - Develop community-based disaster response plans based on probable downstream impacts.
    - Develop new methodologies appropriate to the Nepal context to lower the dangerous lakes to a safe level.
    - Install early warning systems where lakes have not yet been rendered safe.
    - Follow-up studies, projects, and works on dangerous glacial lakes in Nepal, including undertaking monitoring and maintenance of those lakes with existing works of risk reduction.
- Conduct detailed physical/social/economic surveys and risk reduction action plans for all 20+ of Nepal's dangerous glacial lakes

Figure 45. Phase II team at Tsho Rolpa Lake, July 2015.

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4. THULAGI (DONA TAL) GLACIAL LAKE, MANASLU REGION

Team members:
Alton C. Byers and Elizabeth A. Byers

Figure 46. Thulagi glacial lake (4045 m), central Nepal.

4.1. INTRODUCTION

Thulagi (Dona Tal) glacial lake (Figure 46) is located in central Nepal, northeast of the famous Annapurna circuit trek and southwest of the Manaslu Conservation Area (Figure 47). The lake, known locally as Dona Tal, is fed by the debris-covered Thulagi glacier, which is one of the sources of the Dona Khola. The Dona Khola flows into the Marsyandi Khola near the village of Dharapani. The Marsyandi, formerly the easternmost leg of the world-famous Annapura circuit that for decades was Nepal's most popular trekking destination, is now the site of major hydropower development projects that include the Lower (Khaireni), Middle (Lamjung), and Upper Marsyandi (Bhulbule and Nadi) construction sites. Road construction, vehicle traffic, industrial/commercial development, and associated pollution have largely contributed to a dramatic reduction in tourist numbers along the Annapurna circuit. Likewise an all-weather road now connects Dumre (located on the Kahtmandu-Pokhara road and formerly the starting point of the Annapurna circuit) with the town of Besisahar to the north, where a precipitous and dangerous seasonal road continues to the village of Manang[8].

[8] Beyond Manang is the Thorong La pass (5416 m), site of many of the fatalities resulting from the 14 October, 2014 snowstorm that dropped nearly 1.8 m of snow in the region within a 12 hour period. The Manang to Muktinath section is the only part of the Annapurna circuit that is not located either on or within sight of a road, which has reportedly resulted in a dramatic loss of tourism to the region as well as changes in transportation patterns.

Figure 47. Location map.

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

Figure 48, left. Upper Marsyandi power plant.

Figure 49, right. Marsyandi river and new road.

4.2. LOGISTICS

The team left Kathmandu on 20 July, 2015 by car, arriving at Besisahar some six hours later. From here, two jeeps were hired for the six hour drive to Chamje on a seasonal road built eight years ago, a one lane and precipitous route often thousands of meters above the Marsyandi River that can only be characterized as normally dangerous, more so during the monsoon, and extremely dangerous following an earthquake. We encountered a fresh landslide about halfway to Chamje that blocked the road, but the indefatigable Himalayan Research Expedition staff were able to remove enough rocks to permit a cautious crossing (Figure 50). The leg from Chamje to Karte was even more precipitous and dangerous, with the team and staff electing to walk the four hours rather than endure another jeep ride.

From Karte the team ascended 1200 m the morning of 23 July, 2015, arriving at Alubari[9] (3000 m) in the early afternoon. The next day involved a descent of some 300 m to the Dona Khola, through beautiful fir/birch/rhododendron forests that were unusually infested with leeches, then a climb to 3600 m to the Dharmsala *kharkas* (high altitude pastures). Structural damage related to the earthquake was surprisingly absent in all villages encountered, as the region is due west of the earthquake and aftershock epicenters. However, the earthquakes triggered substantial new landslide activity along the right hand slopes of the Dona Khola, where the trail is located, which slowed down the expedition considerably (i.e., what is normally a 5 hour walk took the team more than 8 hours to complete)(Figure 51). On 25 July, 2015 the team ascended the remaining 400 m to Thulagi lake (4045 m), camping high on a knoll well above the flood plain and outlet channel. As at Imja and Tsho Rolpa, the weather was mostly clear in the mornings with excellent views of the Annapurnas, Kangaru, Phungi, Lamdung, and Manaslu.

Figure 50. Crossing a landslide enroute to Chamje.

Figure 51. Landslides in the Dona valley.

[9] "Alu" = potato, "bari" = field, actually a combination of potato/mustard/medicinal plant fields and summer grazing lands carved out of the fir/birch/rhododendron forest.

As with most other glacial lakes in Nepal, Thulagi began to form about 50 years when a series of small meltwater ponds near the glacier's terminus began to merge and form a small lake. Today it is approximately 2 km long; has a surface area of 0.94 km^2; contain 39 million m^{3}of water; has a maximum depth of 82 m; and lake level at 4045 m above sea level (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 (Figure 52), and four distinct lateral moraines were counted alongside of the present lateral moraines that were formed during different stages of Thulagi glacier's recession (Figure 53). In addition to the current outlet, several former outlets (low points in the moraine) exist that suggest changing lake levels and outlets over time. Although the GDH report suggests that the current outlet was probably formed as a result of a glacial lake outburst flood (GDH 2013) that reduced the lake by some 18 m in depth, a more plausible scenario would be its formation as a normally eroding outlet stream, or possibly a result of a series of small outburst floods from Thulagi glacier, as with the May 15, 2015 flood near Chukung in the Mt. Everest region (see Imja glacial lake report). A large outburst flood would have assuredly been noticed and reported by local people.

Figure 52. Older lateral and terminal moraines in front of the present day outlet.

A second feature of note is the terminal complex (red line, Figure 53) which acts as a buffer to surge waves as well as bearing the brunt of most of the lake's hydrostatic pressure which otherwise would be directly against the thin, unconsolidated, and increasingly fragile terminal moraine (blue arrow, Figure 54). A third feature of note are the steep right and left lateral moraines, which continue to erode slowly into the lake (Figure 54).

Figure 53. Terminal complex.


Figure 54. Steep lateral moraines. The glacier terminus is to the far right.

4.3. OBSERVED AND MEASURED EARTHQUAKE AND CLIMATE CHANGE IMPACTS

a. Uncertain trend in outlet flow

We were not able to detect any changes in outlet flow rates, as was done at Imja lake, because of the disparity of figures given by the limited number of past studies. We measured a rate of 10 m^3/s on July 26, 2015; GDH measured 9-10 m^3/s in November of 2013 (GDH 2013); and ICIMOD measured 3-4.5 m^3/s in July 2009 (ICIMOD 2015). The DHM believes that the GDH measurement is most likely in error. While it is tempting to suggest that the HiMAP and ICIMOD measurements are correct, and thus indicative of a possible increase in outflowsimilar to that observed at Imja Lake, the lack of additional data preclude such assumptions and suggest a need for further measurements.

Figure 55. Outlet channel, looking downstream.

b. Seepage (earthquake)

Figure 56. Seepage below the outlet channel.

No new seepage was detected at the base of either the lateral or terminal moraines. Seepage in the valley below the base of the terminal moraine was measured at 2.3 liter/second, but this is most likely from the outlet channel as it infiltrates into valley floor sediments, and not from the lake or dead ice within the terminal moraine.

c. New cracks and slumps in the thin terminal moraine and lateral moraines (earthquake)

Figure 57. Massive cracks along the crest of the terminal moraine as a result of the earthquake.

While the right and left lateral moraines were surprisingly free of major earthquake-related cracks, the terminal moraine had extensive new cracks along the crest line, as well as slumping and mass wasting along the interior slopes. This was of particular concern because of the razor-thin nature of the terminal moraine, which although currently buffered by the terminal complex could someday be all that remains between the lake body and valley below.

d. Shifted boulders (earthquake)

Figure 58. Displaced benchmark boulder on the terminal moraine.

Boulders throughout the terminal moraine and terminal complex were found to have shifted and moved considerably. Benchmark #2, a boulder located near the crest of the terminal moraine, moved 15 cm toward the lake and 10 cm down the hillslope.

e. Widening of the outlet pond (earthquake)

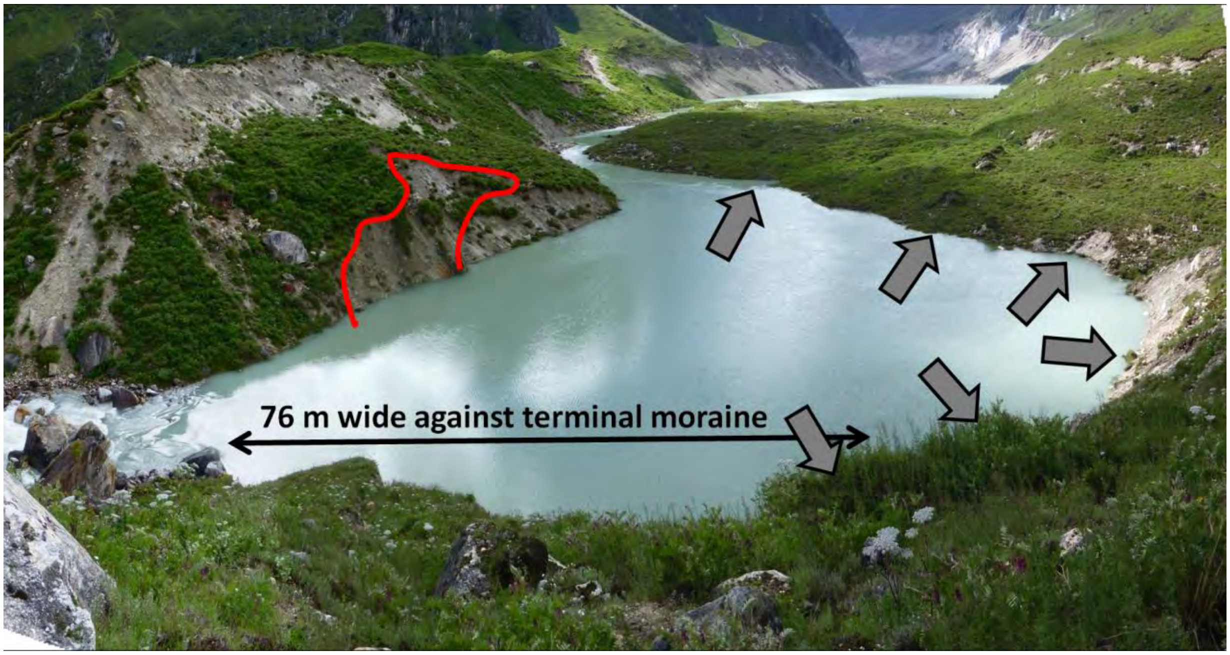

Figure 59. The outlet pond increase in width by several meters.

The outlet pond widened as a result of accelerated slumping activity along the shore that was induced by the earthquake. Width of the outlet pond along the face of the terminal moraine is now 76 m and growing. The concern is that as the outlet pond continues to widen and deepen, and the terminal complex subsides and deteriorates, the hydrostatic pressure against the fragile terminal moraine will continue to increase, at some point releasing a possibly catastrophic flood.

f. Fresh slumping and vegetation calving into the outlet pond and channel (earthquake)

Figure 60. Fresh slumping along the shoreline of the outlet pond.

Approximately 2 m of shoreline along the southern bank of the outlet pond was lost as a result of the earthquake, as indicated by the large masses of vegetation-covered earth now floating in the outlet pond and channel. This is the third time that "bio-indicators" have proven useful to the current study, the first being at Dig Tsho, where the absence of significant lake lowering after a small outburst was confirmed by the line of woody/perennial vegetation at 30 cm above the current lake level. The second was at

Pangadinga lake above Tsho Rolpa, where the lake's recent and sudden drainage was confirmed by the presence of a line of woody vegetation at the old lake level line and the absence of all but a handful of newly sprouted pioneer species in the drained area. In general, the terminal complex at Thulagi slopes from south to north; is pockmarked with thermokarst depressions and slope failures resulting from the melting ice core; and is clearly slumping toward and into the outlet pond and channel, increasing the size of the outlet pond with every passing year.

g. Soil liquifaction (earthquake)

Figure 61. Silt boils on the terminal complex.

Several square meters of silt deposits were found on the terminal complex beach which appear to have been produced as a result of soil liquefaction, a phenomenon common to earthquakes where soil loses its stiffness and strength and behaves like a liquid. Since the silt boils were small and few in number they do not appear to be a cause for concern, but merely reflect another geomorphic impact of the earthquake.

h. Lake finger extension (earthquake)

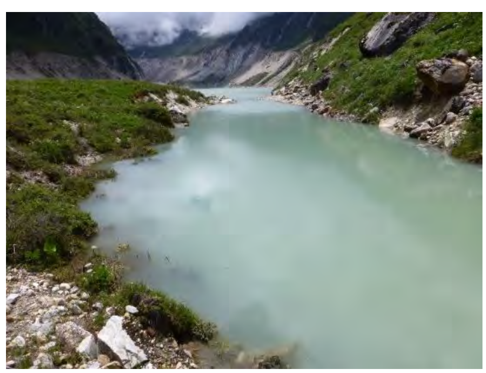

Figure 62. A recently formed finger lake on the south side of the terminal complex grew by 35 m as a result of the earthquake.

An approximately 35 m long lake finger extension located at the junction of the left lateral moraine and terminal complex increased in length to 75 m as a result of the earthquake. It is unlikely that any further and significant growth of the extension will occur within the near future, unless there is significant movement along the junction of the lateral moraine with the terminal complex.

i. Loss of grazing land (earthquake)

Figure 63. Grazing land was lost (upper right) and the huge boulder to the lower left displaced on the day of the earthquake.

Valuable grazing land located above the left lateral moraine was lost as a result of the earthquake. The entire lateral moraine is undergoing constant undercutting from the lake and glacier, but the loss of land was definitely triggered by the earthquake and aftershocks, as verified by Purna Bahadur Gurung, who owns the grazing rights to this area. Similar lateral erosion processes are found in the Gokyo valley of Sagarmatha National Park, where land masses the size of the Lukla airstrip routinely collapse into the debris below. A large (house-sized) boulder was also displaced due east of the photopoint (Figure 63).

j. Rockfall and avalanches (climate change and earthquake)

Although previous studies suggested that rockfall from the mountains adjacent to the lake were buffered by the lateral moraines, we found that this is no longer the case because of the continued loss of morainal material. There are now direct rockfall and landslide channels into the upstream half of the lake, which could possibly trigger an outburst flood if the volume and velocity were of sufficient size (DHM 2013). Snow and ice avalanches, however, are limited to the Thulagi glacier region and are unable to cascade into the lake. No overhanging ice exists above the lake.

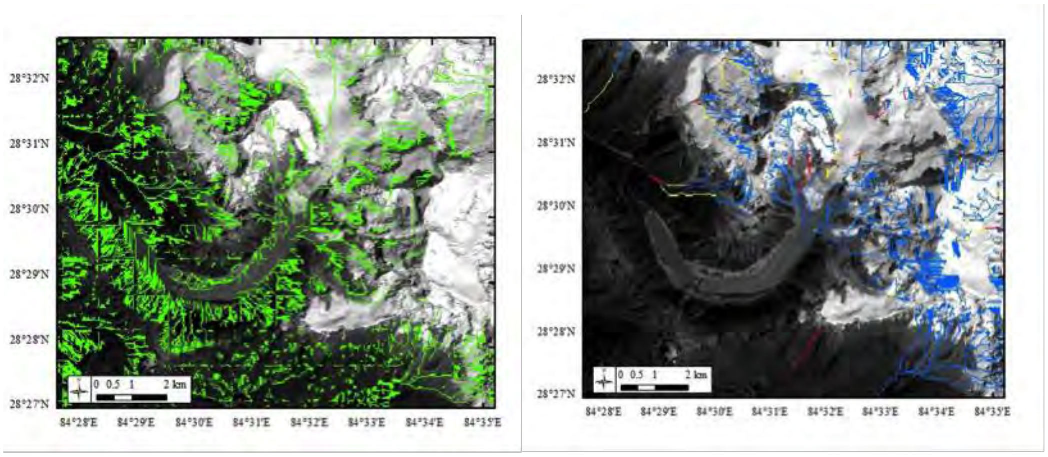

Figure 64. Potential rockfall (left) and avalanche tracks (right).

k. Calving front (glacier terminus) (climate change)

Figure 65. The glacier terminus.

We were unable to reach the Thulagi glacier terminus because of landslides that obliterated the usual trail, but we observed it from a distance of about 600 m. The calving front has slumped somewhat into the lake, but the distinctive snow stratigraphy lines are still visible. The height of the calving front is now about 30 meters, reduced from the approximately 40 m height noted by GDH (2013) and ICIMOD (2009). It is doubtful that calving activity could result in a surge wave large enough to overtop the terminal complex, and the steepness of the glacier suggests that contact between the glacier and lake could cease in the foreseeable future as the glacier recedes further upslope. An increase in the number and frequency of small floods from sub-glacial lakes and water-filled caves, however, is to be expected.

4.4. COMMUNITY CONSULTATIONS

Figure 66. Community consultation at Kharte.

A community consultation was held in the village of Karte on 31 July, 2015 that was attended by about 20 representatives from local development, mothers, and youth groups from the villages of Naache and Karte. Concern about the possibility of a glacial lake outburst flood was not as high as the team found at both Imja and Tsho Rolpa glacial lakes, although people were aware of the deteriorating nature of the terminal moraine at Thulagi and that within 10 years the lake will most likely be far more dangerous than today. It is also of note that on 27 April, 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. In the village of Tal, residents carried the old and sick up the mountainside, while lodge owners ran to the tourist camp grounds, woke the trekkers up and ran with them to higher ground. When it was clear that no flood was forthcoming, all returned to their homes, lodges, or campgrounds. Linked to the trauma associated with the 27 April and 12 May earthquakes, this panic appears much the same as that caused in the Everest region with the rumor that Imja glacial lake had burst on 15 May, 2015.

4.5. SUMMARY

Of the three glacial lakes assessed, Thulagi is at present the least dangerous and most stable because of (a) its terminal complex that acts as a buffer against the hydrostatic pressure of the lake; (b) lack of flood triggers such as overhanging ice; and (c) lack of excessive glacial terminus calving and 2 km length, which together would most likely buffer any surge wave created. Cliff failure and rockfall into the lake, however, are potential triggers, and conditions are deteriorating so that the lake will most likely represent a significant danger to downstream populations and infrastructure within 5-10 years. Sections of extremely narrow gorges in the Dona river channel suggest that even small floods could bottleneck at these locations, damming and backing up the water to form new lakes that would eventually burst with even greater downstream impacts.

The changes that resulted from the destabilizing effects of the April and May 2015 earthquake and aftershock, include the following:

- Deterioration of the thin terminal moraine accelerated
- Last outlet pond widened as indicated by slumping and submerged vegetation, increasing hydrostatic pressure against the terminal moraine
- Rockfall and landslides entering the lake in its upstream half

- Lake finger along the left lateral moraine doubled in length
- Silt boils in terminal complex similar to Tsho Rolpa
- Terminal complex slumping into the outlet channel/ ponds
- Boulders shifted in terminal moraine, including benchmark #2

In brief, the 25 April earthquake and aftershock further destabilized an already deteriorating terminal/lateral moraine complex through the creation of massive cracks, shifted boulders, slumps, and impacts on the outlet channel. The team therefore felt that Thulagi should be classified as a dangerous lake; that it should be lowered to a level that eliminates the possibility of an outburst flood; and that detailed hazard maps and LAPA-style disaster management planning should be made available to downstream populations[10]. The team recommends that lowering be done as soon as possible, while the risk of inadvertently triggering a flood is still relatively low and costs can be kept to a minimum. With each year that passes, the process of lake lowering will become riskier and more expensive, as hydrostatic pressure continues to build against the thin terminal moraine dam and existing buffers deteriorate.

4.6. RECOMMENDATIONS

- **Determine effective lowering depth of Thulagi lake (no flood modelling has been completed to date, as was done by HiMAP at Imja lake, to determine the depth required for maximum risk reduction.**
- **Develop new approaches to lowering Thulagi in the context of Nepal. While the Peruvian excavation and pipe method at the existing outlet may be an appropriate method for some lakes, other lakes may be suited to trying less expensive construction approaches, including breaching of lateral moraines to take advantage of the low hydraulic gradient and natural dam that is sometimes present on the valley floor behind the lateral moraine. Likewise, the development of methods to lower glacial lakes in Nepal must take into account the heterogeneity of Himalayan glacial lakes (i.e., each is different, and in need of site specific analyses), as well as the lack of roads, inexperience in lowering glacial lakes, difficulty of doing construction work at high altitudes, and other factors).**
- **Lower Thulagi to a safe level.**
- **Develop detailed flood hazard maps as community training tools (also recommended by the GDH report).**
- **Conduct concurrent LAPA-style disaster management planning and EWS training programs for downstream communities**
- **Train local people in repeat photography methods to encourage regular lake monitoring and communication with DHM**

[10] Following the 5 August, 2015 debriefing at ICIMOD, representatives of the GON Office of the Investment Board approached the team and requested additional information on Thulagi and Lower Barun glacial lakes, lake lowering methods, and any flood modeling that was available. They are in the process of finalizing the financial commitments for the Arun III (Lower Barun glacial lake) and Marsyandi (Thulagi glacial lake) hydropower projects, and noted that the EIS's for both projects mention potential flooding from GLOFs as a significant risk, but that little concern or follow up activity had commenced to address the issue. Materials were forwarded to the Office of the Investment Board on 10 August, 2015 and included the HiMAP glacial lake handbook, Imja and Thulagi reports, ICIMOD 2011 glacial lake report, and various other documents.

Figure 67. Phase III team returning from Thulagi glacial lake, Manaslu region, August 2015.

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5. OVERALL SUMMARY

- Nepal has entered an era of accelerated catastrophic events (landslides, floods, avalanches, rockfall) related to climate change. Increases in the number and frequency of GLOFs can be expected with confidence.
- The 25 April earthquake and aftershock further destabilized the already deteriorating terminal/lateral moraines of all three lakes through the creation of massive cracks, shifted boulders, and impacts on the outlet channel while further destabilizing existing potential GLOF triggers such as overhanging ice, calving rates of the glacier termini, deterioration of the terminal moraine, and mass wasting of the lateral moraines. All three lakes should be re-classified as being dangerous, not "potentially" dangerous.
- Communities downstream of all three lakes are fearful of the likelihood of GLOFs occurring in the near future, and lack adequate information about early warning systems (EWSs), lake risk reduction methods, and disaster management planning.

6. CONCLUDING REMARKS AND RECOMMENDATIONS

Nepal has clearly entered an era of accelerated catastrophic events that has been exacerbated by the recent earthquake and aftershocks. The continuation of glacial lake outburst floods can be predicted with confidence, both in frequency as well as magnitude.

This is not the first time a developing country has faced the hazard of growing and unstable glacial lakes. Peru, with glaciers at lower elevations and closer to the equator, was in a similar predicament 60 years ago. In 1951 the Government of Peru established a Glaciological Unit based in the city of Huaraz, at the foot of the Cordillera Blanca or "white mountain range." The reason for the establishment of the unit was that, between 1941 and 1950, three GLOFs had occurred that killed an estimated 10,000 people while also destroying the hydropower plant that furnished the region with most of its electricity. A survey of all glacial lakes was first conducted that concluded that 35 were potentially dangerous and in need of risk reduction measures. Engineers then set about studying each lake and designing methods to lower them to safe levels, ranging in sophistication from mere ditches, to large drainage pipes with reinforced terminal moraines, to drilling through 1000 m of solid rock and installing a system of valves and canals that enabled the regulation of lake depth. By the 1990s, all 35 lakes had been lowered, and although potential GLOF triggers continued (e.g., massive ice avalanches), not one was sufficient to actually cause an outburst flood, and no one in Peru has died as a result of a GLOF since the 1950s (Portocarerro 2013; Byers et al. 2013).

We argue that there is no need to wait until GLOFs kill people, and destroy hydropower installations, in Nepal before taking action. Building upon the lessons learned from Peru, the team felt strongly that the time is now to begin conducting detailed scientific surveys of all lakes, designing Himalayan-specific methods to reduce their risks, and to finding the funding to accomplish all tasks. Furthermore, the evidence suggests that future risk reduction work in Nepal and elsewhere in the high mountain world should take more of an interdisciplinary and participatory approach than in the past, considering the human, economic, environmental, and development aspects of glacial lake mitigation in addition to the standard physical and engineering surveys (see: Byers et al. 2013 2014, 2015; Byers and Thakali 2014).

Several key recommendations could help to facilitate these processes include the following:

1. Determine the effective lowering depth for each of the three lakes.
2. Develop new approaches to lowering the lakes appropriate to the context of Nepal. While the Peruvian methods may be appropriate for some lakes, other lakes may be suited to trying less expensive construction approaches, including breaching of lateral moraines to take advantage of the low hydraulic gradient and natural dam that is sometimes present on the valley floor behind the lateral moraine. Likewise, the development of methods to lower glacial lakes in Nepal must take into account the heterogeneity of Himalayan glacial lakes (i.e., each is different, and in need of site specific analyses), as well as the lack of roads, inexperience in lowering glacial lakes, difficulty of doing construction work at high altitudes, and other factors.

3. Lower each lake to a safe level, where "safe" is defined as not causing significant damage to human life and livelihoods even in the event of an ice avalanche or other potential GLOF triggers.
4. Develop detailed flood hazard maps for each of the three lakes as community training and planning tools.
5. Conduct concurrent local adaptation plan of action (LAPA) style and training programs targeted at GLOFs and other natural hazards (e.g., sensitization, assets identification, vulnerabilities determination, options development, planning, early warning system, implementation, monitoring) for downstream communities that will increase their capacity for disaster management planning and implementation.
6. Develop and install effective and user-friendly early warning systems and disseminate effective protocols for existing systems (e.g., Tsho Rolpa) and planned systems (e.g., Imja Lake).
7. Build in-country capacity to manage the increasing risks of GLOFs and other natural hazards. It is recommended to establish an Office or Institute of Glaciology covering the following tasks:

    - Regularly update the inventory of glaciers and glacial lakes
    - Regularly update the hazard level posed by each lake based on the probability of a catastrophic flood and its estimated downstream impacts.
    - Develop community-based disaster response plans based on probable downstream impacts.
    - Develop new methodologies appropriate to the Nepal context to lower the dangerous lakes to a safe level.
    - Install early warning systems where lakes have not yet been rendered safe.
    - Follow-up studies, projects, and works on dangerous glacial lakes in Nepal, including undertaking monitoring and maintenance of those lakes with existing works of risk reduction.

8. Conduct detailed physical/social/economic surveys and develop risk reduction action plans for all of Nepal's dangerous glacial lakes.
9. Update and revise the current list of potentially dangerous glacial lakes in Nepal to incorporate the results of recent field studies, also including a separate list of lakes that may not be dangerous now but will be so within 10-15 years. Build concensus on the development of a standard protocol for assessing risk parameters based on remote sensing, flood and avalanche modeling, rapid field assessments, and intensive field assessment methods.

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