Tsho Glacial Lake Outburst Flood (GLOF) in Bhutan: cause and impact.

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Abstract

Glacial Lake Outburst Flood (GLOF) is an inherent threat in countries in the Hindu Kush Himalayan (HKH) region and is projected to increase in the face of climate change. One of the recent GLOF events in the region was the outburst of Lemthang Tsho (lake) in Bhutan on 28 July 2015. This paper discusses the cause and impact of the event based on the analysis of multi-temporal satellite images and field observation. The event, which was small to medium in volume, was triggered by the emptying of two supraglacial ponds located upstream of Lemthang Tsho. The area had experienced heavy rainfall till the morning of 28 July. On the same day, at 7:10 am local Bhutan time, a 5.1 magnitude earthquake struck about 177 km southeast of the lake. In the absence of firsthand information from the field, it cannot be confirmed that these two events triggered the lake outburst that took place around 3 pm. However, the possibility cannot be ruled out, either. The rainfall and earthquake are likely to have had a role in triggering the outburst.

Keywords: Glacial lake, GLOF, Mountain hazard, Climate change, Natural hazard.

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Introduction

'Jökulhlaup', an Icelandic term for 'glacier run', is characterized by the release of huge volumes of water. This phenomenon is widely referred to as Glacial Lake Outburst Flood (GLOF). Such outburst can have impact of catastrophic dimensions, often resulting in loss of lives and causing damage to properties in the downstream [1-11]. Amid reports that glacial lake area has increased in the eastern Himalayas (Bhutan and Nepal) between 1990 and 2009 [12], the increase in GLOFs events in recent decades is not certain yet [7, 13]. However, enhanced ice melt at the margins of receding glaciers due to observed warming trend and increase in weather extremes (rainfall and temperature) [14] have increased the likelihood of GLOFs [15-17]. The report of the Intergovernmental Panel on Climate Change report (IPCC, 2014a) also corroborates this. The frequency of GLOF in recent years is yet to be assessed, but it is known that GLOF occurs from time to time in the HKH region, the GLOF of Lemthang Tsho being the latest in the series. Based on remote sensing analysis and intensive fieldwork, this paper discusses the cause and impact of the event.

Study Area

Located in a remote area (longitude 89°34'53.42" and latitude 28°04'05.17") in north-western Bhutan, Lemthang Tsho (lake) is tugged at an elevation of 4,270 m asl in Gasa district (Figure 1). The lake drains into the Mo Chu (river), which forms the Puna-Tsang Chu after merging with the Pho Chu in Punakha District. The lake is at a six hours' walking distance from the nearest settlement (Laya village) and a three-day walk from the nearest road head (Gasa town).

Method

Both primary and secondary data were collected and compiled. Information about past GLOF events in the HKH region was compiled through a review of published and unpublished documents and articles. Data on glacial lake (volume, moraine dam) and flood (geomorphological features associated with the event, flood height and width, downstream losses) were collected during fieldwork. Flood height and width were measured based on flood marks on the river bank. The river discharge data was obtained from a station maintained by the Department of Hydro-Met Services (DHMS), Royal Government of Bhutan. Detailed topographic profiles of both the lake and the moraine dam were prepared using Total Station. In addition, river channel survey, water discharge measurement, and measurement of the size of boulders deposited at different points between Lemthang Tsho and Laya were carried out. The information collected was used to develop the channel profile and estimate the peak flood discharge. The diameters of the five largest boulders deposited in the riverbed by the recent flood were measured in order to estimate the velocity using empirical equations recommended by Costa [18]. Information about damage and loss was collected through visual inspection and consultation with local people.

Results

Regional overview of GLOF

Komori [13] reported a total of 21 GLOF events from Bhutan Himalaya; the Lemthang Tsho event raised this number to 22. Among them, 13 events occurred within Bhutan and 9

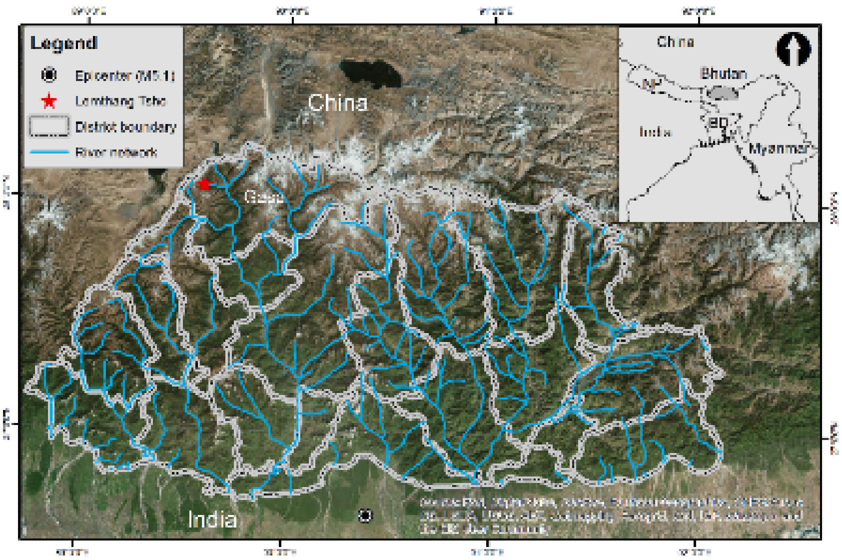


Figure 1. *Map of Bhutan showing the location of Lemthang Tsho.*

occurred in the Tibet Autonomous Region (TAR), China. Out of the 9 GLOF events identified so far in TAR, 4 had impact in Bhutan, along the Kuri Chu, a transboundary river (Figure 1). Out of the 22 events, 18 occurred before the 1970s [13] and 5 occurred after. Similarly, at least 30 GLOFs have occurred in Tibet between 1930 and 2010, resulting in loss of life and properties [10] . In 1988 a GLOF in Guangxieco Lake in China killed 5 people, swept away 51 houses and destroyed a ranch and a farmland. During the event, the debris dammed the Palongzangbu river for half an hour, and the subsequent flash flood washed away 18 bridges, severely destroyed 42 km of the Sichuan-Tibet Highway and caused traffic disruption for 6 months. This shows that there are secondary and tertiary hazards associated with GLOF. Nepal has experienced at least 24 GLOF events in the past, out of which 14 originated in Nepal and the remaining 10 in TAR, China, causing damages in Nepal [19]. The 1981 GLOF event that originated in TAR, China in the Poiqu/Bhotekoshi/Sunkoshi caused a huge loss of life, properties and infrastructure downstream in Nepal [20]. In 2000 a GLOF that originated from a tributary of the Hushe River in Pakistan destroyed 124 houses and a primary school in Kande village [21]. In 2007 and 2008, five GLOF events occurred in the Hunza basin of the Karakoram; these events severely affected the nearby communities and posed a threat for the future [22].

The review shows that the main cause of GLOF is ice avalanche/rock slide; this cause is attributed to over 70% of the reported GLOF events. Only a few (less than 30%) were due to glacier surge. For most of the GLOFs (more than 80%), the failure mechanism was overflow due to moraine dam failure. Less than 20% of GLOF events occurred initially due to piping, followed by overflow due to moraine dam failure (Table 1).

Lemthang tsho

A remote sensing based inventory in 2001 reported 2,674 glacial lakes in Bhutan [23]. Among them 25 have been identified as potentially dangerous glacial lakes [24]. Lemthang Tsho (mo_gl_200 in 2001 inventory), also known as Kab Tso, is one of them. The lake was selected because a large mother glacier is attached to it with a well-defined moraine dam entrapping the water body. The 2001 inventory database was based on a toposheet dating back to the 1960s, which indicates that the lake was present since then. The lake area was 0.0521 km^2 then and 0.0763 km^2 by 2015, while the length increased from 285 m to 445 m. Lemthang Tsho is thus characterized by a slow

Table 1. *Estimated peak discharge of GLOF and the distance to downstream sites where the GLOF events caused damages.*

Name of Lake	Country	Date of outburst	Lake volume (million m^3)	Peak discharge (m^3/s)	Velocity (m/s)	Downstream impact (km)	Sources
Qubixiama-Cho	China	10 June 1940		3,690	7.7		LIGG, 1988
Sangwang-Cho	China	16 July 1954	300	10,000		200	Wang et al., 2013
Damenhai-Cho	China	26 September 1964		2,000	10		Wu et al., 2005; Ding and Liu, 1992
Longdaco	China	August 1964		1000			Chen et al., 2013
Gelhaipuco	China	September 1964		4500			Chen et al, 2013
Zhangzangbo	China	11 July 1981	19	15,920	7-17.9	60	Xu, D, 1988
Ganxico (Mitui-Cho)	China	14 July 1988		1,270			Liu et al., 2014
Nare	Nepal	3 September 1977	4.9	830-1,100		90	Buchroter et al., 1982
Dig Tsho	Nepal	4 August 1985	6-10 (8)	1,600-2000		90	Viuchard and Zimmerman, 1987
Tam Pokhari	Nepal	3 September 1988		10,000	5-10	66	OSTI AND Egashira, 2009; Dwivedi et al., 2000
Luggye Tsho	Bhutan	7 October 1994	48	> 2,500		200	Richardson and Reynolds, 2000

growth rate, which is also obvious from the time series Landsat images (Figure 2). The average depth of the lake before the outburst was 6.29 m with a maximum depth of 14.42 m, which would put the estimated water volume prior to the outburst at 0.37 million m^3.

Cause of Lemthang tsho GLOF

The breach of Lemthang Tsho was reported around 5 pm Bhutan local time (GMT 6+) on 28 June 2015 by local people collecting herbs [25]. District authorities of two downstream districts, Punakha and Wangdiphodrong, were duly alerted. There were concerns about additional risks from the monsoon rains, which had been heavy in the preceding weeks. Therefore, the siren was activated around 8:45 pm even before the alert water level was recorded.

The event (GLIDE No. FF-2015-000077-BTN) completely emptied the lake (Photo 1, Figure 3), but the resultant GLOF was relatively small compared to other devastating events in the past. Field investigation revealed that two supraglacial ponds located

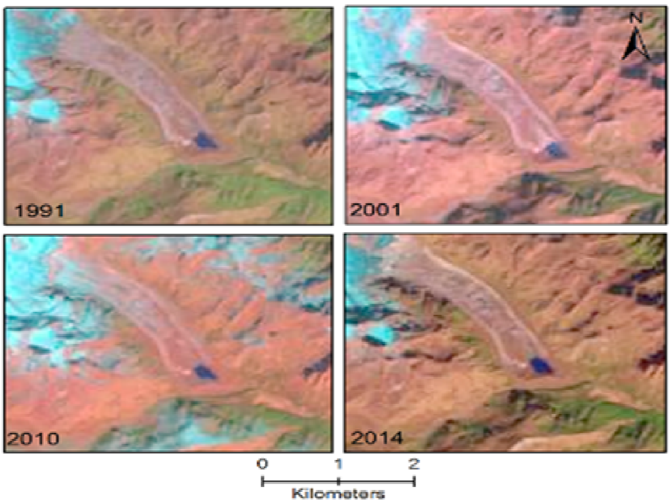


Figure 2. *Time series Landsat images showing growth progression of Lemthang Tsho.*

Photo 1. *Repeat photograph of Lemthang Tsho: top (pre event, May 2015) and bottom (post event, July 2015). Photo credit: Sebastian Kammer and Sharad Joshi.*

upstream of the lake had completely drained into Lemthang Tsho; this was corroborated by pre- and post-event satellite images (Figure 3). Eyewitnesses stated that the breaching of Lemthang Tsho occurred several hours after the draining of supraglacial ponds, which rules out the possibility of a strong surge wave triggering the breach. A likely scenario involves a rise in the lake level and subsequent buildup of hydrostatic pressure, which debilitated the moraine wall and finally caused the breach. Eyewitness accounts and the increased discharge at the Lemthang Tsho outlet suggest that the breaching of the supraglacial pond must have occurred around 3 pm. The final breaching of Lemthang Tsho is likely when a boulder (10 m × 4 m × 3 m) was dislodged (Photo 2) from the moraine, followed by enhanced erosion at the outlet channel, finally resulting in the GLOF at 5 pm (BST). The breaching must have occurred in two phases, as indicated by two separate flood peaks an hour apart, 7:30 pm and 8:30 pm, at Taktsemakhang, Laya station (Figure 3). The breach created a 30 m wide typical V-shaped outlet morphology (Photo 1). This was not the first time, and nor will it be the last, that a supraglacial breach induced a GLOF in Bhutan. In the early hours of 29 April 2009, an outburst event at the supraglacial lakes on the Tshojo glacier (Figure 5), in the headwaters of Pho Chu, resulted in a GLOF [13].

The sudden subglacial draining of the supraglacial ponds is likely to have been triggered by the collapse of steep ice scarp of the upper supraglacial pond. As the supraglacial ponds were interconnected through a subglacial conduit, the hydrostatic pressure on one pond resulting from a sudden splash likely debilitated the other pond.

The question of what triggered the slump of the near-vertical wall of the supraglacial ponds has drawn attention to two external events that took place around the same time. Gasa had recorded 3.75 mm of rain on 27 June and received heavy rain that night and on the morning of 28 June [26]. The other event is the magnitude 5.1 earthquake with its epi-centre in the Indian state of Assam, 187 km southeast of Lemthang Tsho (Figure 1) (http://earthquake.usgs.gov/). The earthquake with hypocenter

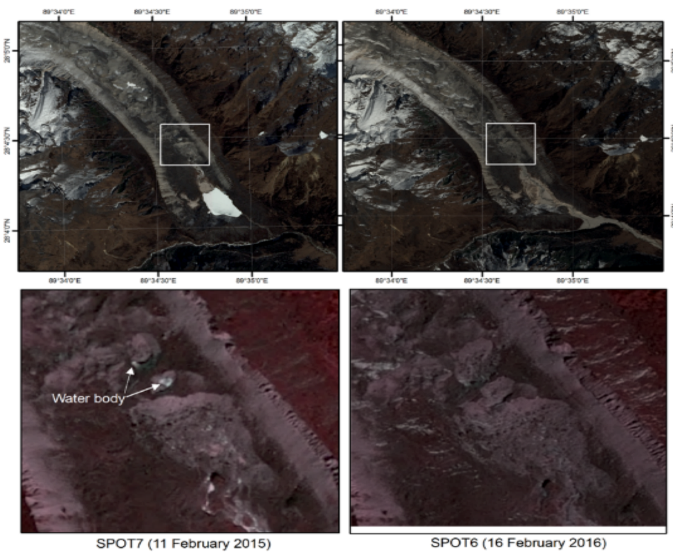


Figure 3. *Pre (left) and post (right) GLOF event SPOT images of Lemthang Tsho. Bottom images clearly show the emptying of two supraglacial ponds, which ultimately resulted in the outburst.*

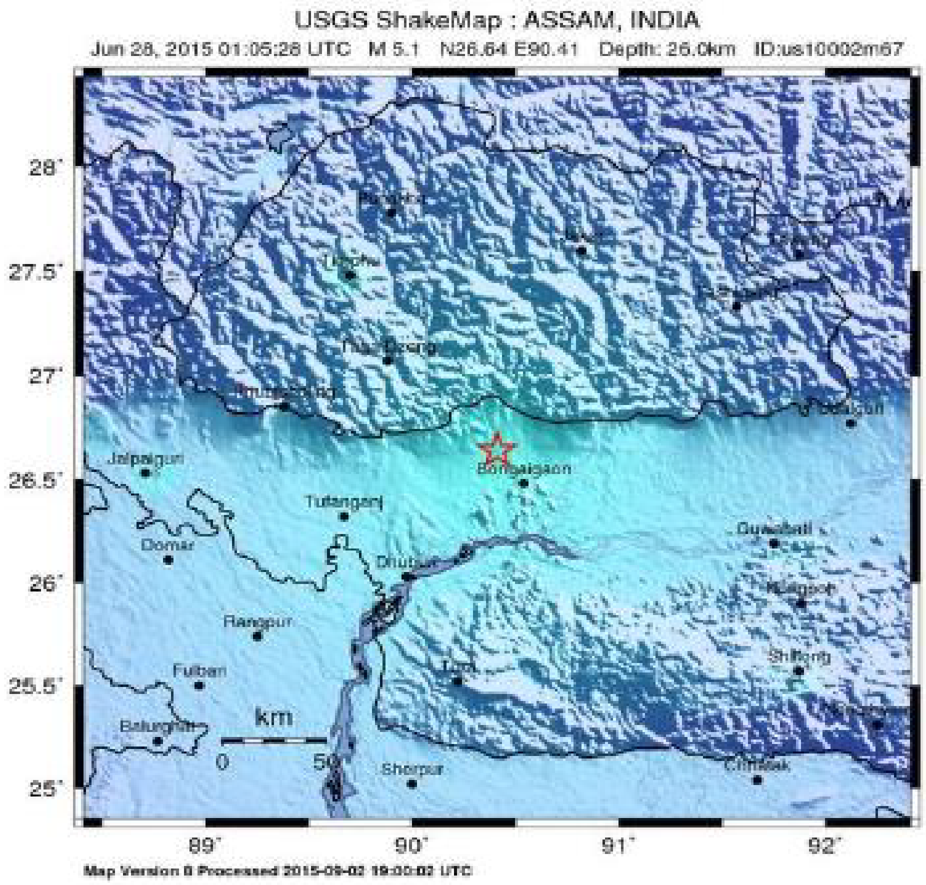
at depth of 27 km struck at 7:10 am Bhutan local time on 28 June. Tremor was reported in print media to have felt as far as Thimphu and Bumthang districts but there were no reports from Gasa district. On the shake intensity map sourced from USGS (Figure 3), Lemthang Tsho area has been classified under 'weak shaking' (Instrumental Intensity -II). Although it is unlikely that the earthquake directly triggered the slump of the near-vertical wall of the supraglacial ponds, the role of the tremor in conjunction with heavy rainfall could not be completely ruled out in the absence of eyewitness accounts and firsthand data from in-situ stations (Figure 4).

Photo 2. *Frontal view of the typical V-shaped channel morphology after the breach. A large dislodged boulder can be seen in front of the breached section.*

Flood characteristic

As mentioned above, the flood propagated in two phases within the span of an hour. The first of the flood peaks recorded at 7:30 pm at Taktsemakhang is 6.660 m; this is well below the set alert level of 7.5 m. Flood wave took 1 hour and 45 minutes to reach the Trashithang station and 2 hours and 45 minutes to reach the Yabesa station; the two stations are 45 km and 75 km downstream from Lemthang Tsho respectively. Average flood velocity based on the travel time and distance is 7.35 m/s, which is higher than Luggye Tsho flood which is estimated to be 3 m/s [5]. Further downstream, maximum discharge of 1,198 m/sec was recorded at Punatsangchu Hydropower project site (Figure 5). Figure 6 is a longitudinal profile of Mo Chu from Lemthang Tsho to Punakha Dzong, a seat of district administration (Figure 1).

Reconstruction of peak discharge was carried out using average intermediate diameters of the five largest boulders measured at different downstream points, using river width and depth information obtained from the field. For this we used empirical



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Figure 4. *Shake intensity map of M5.1 earthquake that struck Assam on the morning of 28 June 2015 (Source: USGS).*

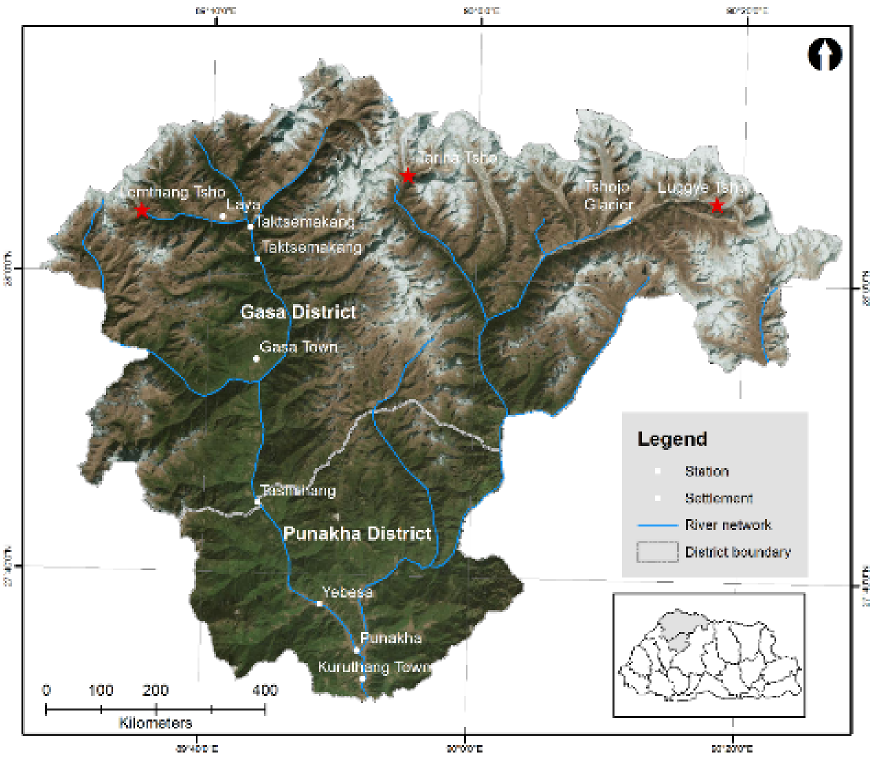


Figure 5. *Map of Gasa and Punakha districts showing locations of settlements and stations.*

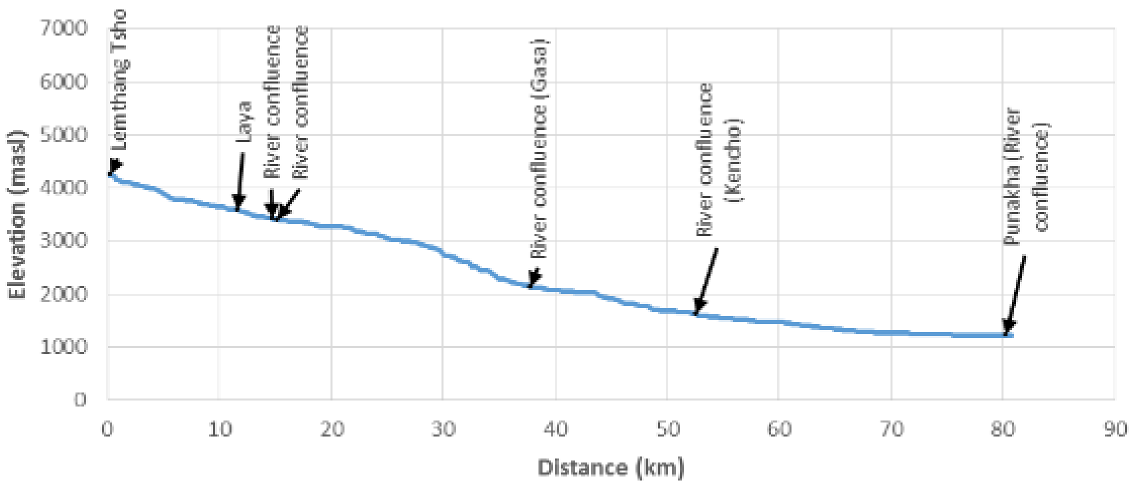


Figure 6. *Longitudinal profile of Mo Chu downstream from Lemthang Tsho to Punakha Dzong.*

equations recommended by Costa [18] to estimate mean velocity (Equation 1 & 2). The estimated discharge is found to range from 426-558 m^3/s near the Laya and 1253-1562 m^3/s upstream near the confluence of the two rivers, where a debris flow fan was formed (Point No. 2 in Figure 7). It is likely that the flow was obstructed by the tributary, which resulted in deposition of materials.

$$\bar{v} = 0.18d^{0.487} \quad \text{……………..Equation 1}$$

$$V_b = 0.51\, d^{0.5} \quad \text{……………...Equation 2 [18]}$$

Damage and loss

Downstream losses from the flood were concentrated in the area between the lake and Kohina village (Figure 5), 30 km downstream from the lake (Table 2). As per the Laya Gewog Administration, a total of four bridges and one acre of agricultural land were damaged. About 1 km stretch of a trail was damaged due to landslides triggered as a result of toe cutting on a hill slope by flood. Four horses and timber piled along the riverbed were swept away by the GLOF. The summary of direct loss due to the flood event is provided in Table 3.

Source: Laya Gewog Administration and Observation.

Erosion and sedimentation

Erosion and sedimentation is a major secondary hazard associated with GLOF and can have severe and prolonged socio-ecological impact [27]. During a GLOF, fertile grazing/agricultural land, which is often limited in high mountain terrain, gets completely converted into a field of sand and boulders, adversely affecting the livelihoods of local people. The extent of erosion and sedimentation in this event was limited and was observed up to 25 km downstream of the lake (Figure 5). Fan of debris

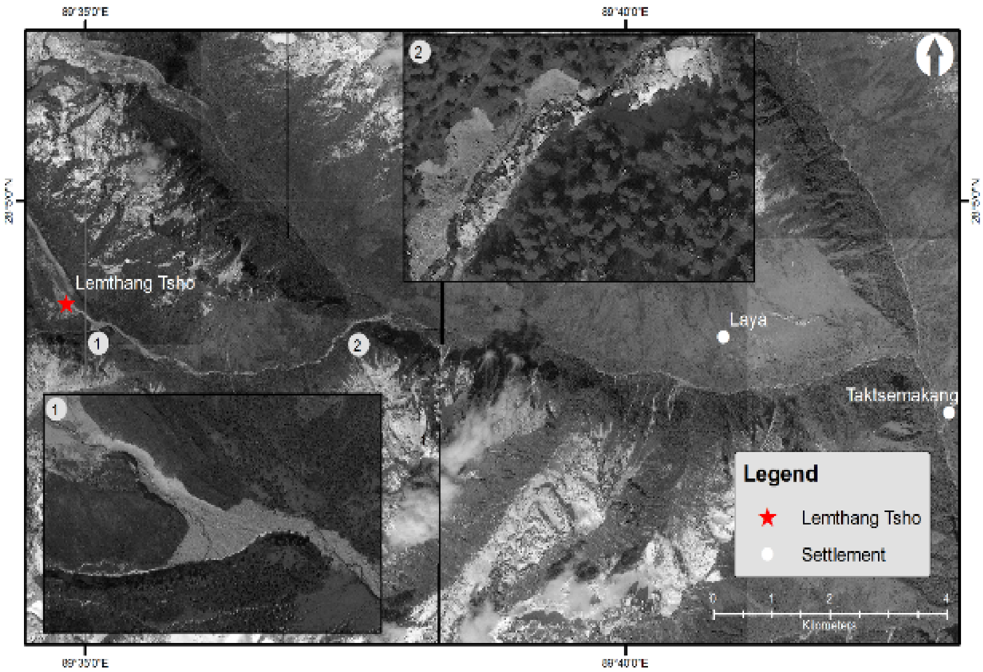


Figure 7. *Map showing deposition and erosion areas in the vicinity of the lake. Background image is WV-01 (50 cm resolution) dated 14 February 2016.*

Table 2. *Summary of estimated discharge at three downstream sites.*

Site	Name	Width (m)	Average depth (m)	Average boulder diameter (mm)	Velocity (m/s)	Discharge (m³/s
1	Near confluence (5.5 km downstream)	45.7	3.15	2,880	8.71-10.85	1253.79-1562.20
2	Laya (9 km downstream)	25	3.2	1,190	5.66-6.98	453.06-558.05
3	Laya (9.5 km downstream)	25	3.8	730	4.46-5.45	424.07-519.04

Table 3. *Direct loss due to the GLOF.*

Damages	Quantity	Estimated loss (Nu. Million)	Remarks
Bridges washed away	4	0.976	Timber cantilever
Land affected	1 acre		
Horses lost	4 (3 phochen and 1 dreng)		
Timber washed away	148 pieces		
Trail damaged	1 km		

has been deposited right in front of the end moraine, which is clearly visible in the satellite image (Photo 1). Similarly, sand and boulder debris were found deposited further downstream (Point No. 2 in Figure 7) where Lemthang Tsho runoff meets stream from adjacent lake. As usual there were scouring along the river bank up to 25 km. River runs through a deep gorge between Kohina and Gasa (25-39 km downstream from the lake) and 14 km of this stretch is inaccessible. Further down at Tashithang (about 50 km downstream), no impact of the flood was observed. Given the steep and barren terrain and harsh climate, it will take a long time for the hill slope to stabilize.

Critical glacial lakes

In the 2001 glacial lakes inventory [28], 24 glacial lakes have been identified as potentially dangerous. Ives [1] have argued that the term 'critical' is more appropriate, as 'potential' can mean different things in different sources. The Department of Geology and Mines (DGM), Royal Government of Bhutan (RGOB) added Thorthormi Tsho as 25th critical glacial lake as the water body has assumed a significant size. Iwata [29] also categorized it as dangerous lake based on unstable moraine condition, seepage, and likelihood of developing into a large lake. While in the field, the team investigated three more critical glacial lakes namely, Latshokarp, Langdo Latshokarp, and Tshojokha, and found that they do not pose immediate GLOF threat [30] based on size, moraine stability, and surrounding glacier. The team downgraded the risk level of the four glacial lakes (including Lemthang Tsho), bringing the number of critical glacial lakes in Bhutan down to 21.

Conclusion

The Lemthang Tsho GLOF event demonstrates the role of supraglacial ponds in triggering a GLOF event, and underscores the fact that assessments of critical glacial lakes, which often tend to prioritize capital-intensive, site-specific investigations, should take the role of supraglacial ponds into account. Although the role of the earthquake could not be confirmed or discounted in this case, risk of earthquake triggering a GLOF is a real possibility in a seismically active region like the HKH. As the event was relatively small compared to the Luggye Tsho GLOF, the impact (damage and loss) was minimum [31-41].

This outburst event reminds us that the HKH region, which has several thousand glacial lakes, faces a persistent GLOF threat, particularly in light of climate change and the seismic activity of the region. The countries in the HKH region need to take the GLOF threat seriously and invest in risk mitigation measures, such as undertaking hazard/risk mapping, mitigation, and establishing a GLOF early warning system. A mechanism should be in place for regularly monitoring glacial lakes using the remote sensing approach, and if needed, through field visits. As countries in the region have different levels of experience in GLOF risk management, sharing best practices and learning from each other's experience would be the best way forward. Regional cooperation in GLOF risk management is imperative given that GLOF is a transboundary threat [42-50].

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