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Lemthang Tsho glacial Lake outburst flood (GLOF) in Bhutan: cause and impact

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Abstract

Background: The Hindu Kush Himalayan (HKH) region being seismically active and sensitive to climate change is prone to glacial lake outburst flood (GLOF). The Lemthang Tsho GLOF breached in the evening of 28 July 2015 innorth-western Bhutan is reminds of the looming threat, and stresses the need to have good risk management plan. The need to understand the physical processes in generating GLOF to is therefore imperative in order to effectively manage the associated risk. The paper therefore assesses the cause and impact of the Lemthang Tsho GLOF event using field and remote sensing data.

Results: The collapse of near vertical wall of supraglacial lake triggered by 2 days of incessant rainfall, opened up the englacial conduit resulting in emptying of interconnected supraglacial lakes into Lemthang Tsho. The5.1 magnitude earthquake epicentered 187 km to southeast in the Indian state of Assam in the morning (7:10 am Bhutan Standard Time) of the same day is unlikely to have played any role in triggering the event. The estimated volume of water unleased is 0.37 million m^3, with peak discharge estimated to be ranging from 1253 to 1562 m^3/s, and velocity of 7.14–7.57 m/s. The impact was minimal and confined up to 30 km downstream from the lake. The flood took lives of 4 horses, washed away 4 timber cantilever bridges, 148 pieces of timber, damaged 1 acre of land, and washed away 1 km of trail. The team also monitored 3 out of 25 identified critical glacial lakes and downgraded the risk of all 3 critical glacial lakes based on the finding. This brings the number of critical glacial lakes in Bhutan to 22.

Conclusion: The threat of GLOF still looms large in the Himalaya, particularly in view of impact of climate change and frequent seismic activities. There is a need for good risk management practices which starts fromidentification of critical glacial lakes, to prioritize in-depth investigation. As the present list of critical glacial lakes are largely based on inventory done over a decade based on topographic maps some of which datedback to 1960s, we need to revisit the critical glacial lakes and assess the risk considering recent changes. The new assessment needs to consider supraglacial lakes as one of the criteria in evaluating the GLOF risk, as highlighted by the Lemthang Tsho GLOF.

Keywords: Glacial lake, Glof, Mountain hazard, Climate change, Natural hazard, Bhutan

Background

The glacial lake outburst flood (GLoF), a phenomenon characterized by release of huge volume of water as a result of an outburst of a glacial lake, is one of the important natural hazard (Ives 1986). The outburst happens when the confining moraine wall of unconsolidated material often underlain by dead ice is unable to contain the huge body of water, thus resulting in sudden release of water which can be of the order of several million cubic metres. The volume of water unleased is estimated as 5 million cubic metres in case of Dig Tsho GLOF in 1998 (Vuichard and Zimmermann 1987), 437,000 cubic metres in case of western Zyndan GLOF in 2008 (Narama et al. 2010), 18 million cubic meters in case of Luggye Tsho in 1994 (WWF 2009). Such outbursts in the past resulted of deluge with peak discharge of 10,000 m^3/s in case of Sangwang-Cho (Daoming and Qinghua 1994), 15,920 m^3/s in case of Zhangzangbo

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GLOF (Xu 1988), and 10 m^3/s in case of Lake No. 3 of Gruben area Switzerland (Haeberli et al. 2001), and 2500–3600 m3/s in case of GLOF from glacial lake LC2 in Patagonia, Chile (Jacquet et al. 2017). The GLOF can attain peak discharge of 30,000 m^3/s and travel distance in access of 200 km (Richardson and Reynolds 2000), and traverse with very high velocity. The estimated velocity is 10 m/s in case of Damenhai-Cho GLOF (Ding and Liu 1992), 7–17.9 m/s in case of Zhangzangbo GLOF (Xu 1988), 5–10 m/s in case of Tam Pokhari is (Osti and Egashira 2009; Dwivedi et al. 2000). Therefore, the impact from the high speed deluge extends far beyond the site of origin and often attains catastrophic dimensions resulting in significant loss of lives, and widespread damage to properties, and inflicting long term socio-economic and environmental challenges as experienced in past events (Liu et al. 2014; Khanal et al. 2013; Asraf et al. 2012; Carey et al. 2012; Haeberli 1983; Hewitt 1982). The Luggye Tsho GLOF saw 20 lives being lost apart from damage to 12 houses, 5 watermills, 4 bridges and 816 acre of dry land (WWF 2009). The GLOF from Guangxieco Lake in Tibet, China killed 5 people, swept away 51 houses, and destroyed a ranch and a 6.7 ha farm in Midu Village (Luo and Mao 1995). The Dig Tsho GLOF washed away then

recently completed hydropower. As recent as 5 July 2016 the GLOF originating from Chinese side of the border hit Bhote Koshi (Cook et al. 2017) and swept at least two dozen river side homes and parts of the Araniko Highway (Kathmandupost, dated: 22 January 2017). An outburst event in 1941 in Peru killed almost 4500 people in the city of Huaraz (Lliboutry et al. 1977). Luggye Tsho GLOF generated flood height of over 2 m at distance of 200 km downstream of the source (Richardson and Reynolds 2000). The destruction and damage in monetary valuation ranges in millions of US Dollar. The estimated cost, including the destruction of the hydropower plant, has been estimated at around $500 million in case of Dig Tsho GLOF (Shrestha et al. 2010). With growing urban sprawling in fertile valley and investment on high values infrastructures such as hydropower plants, the damage will escalate further in case of future GLOFs.

Enhanced glacier melting due to rising temperature influences formation and enlargement of glacial lakes, a direct connection between climate change and increased GLOF risk. Although the glacial lake area has been reported to have increased in the Himalayas between 1990 and 2009 (Gardelle et al. 2011), the increase in GLOFs events in recent decades is not certain yet (Komori 2012;
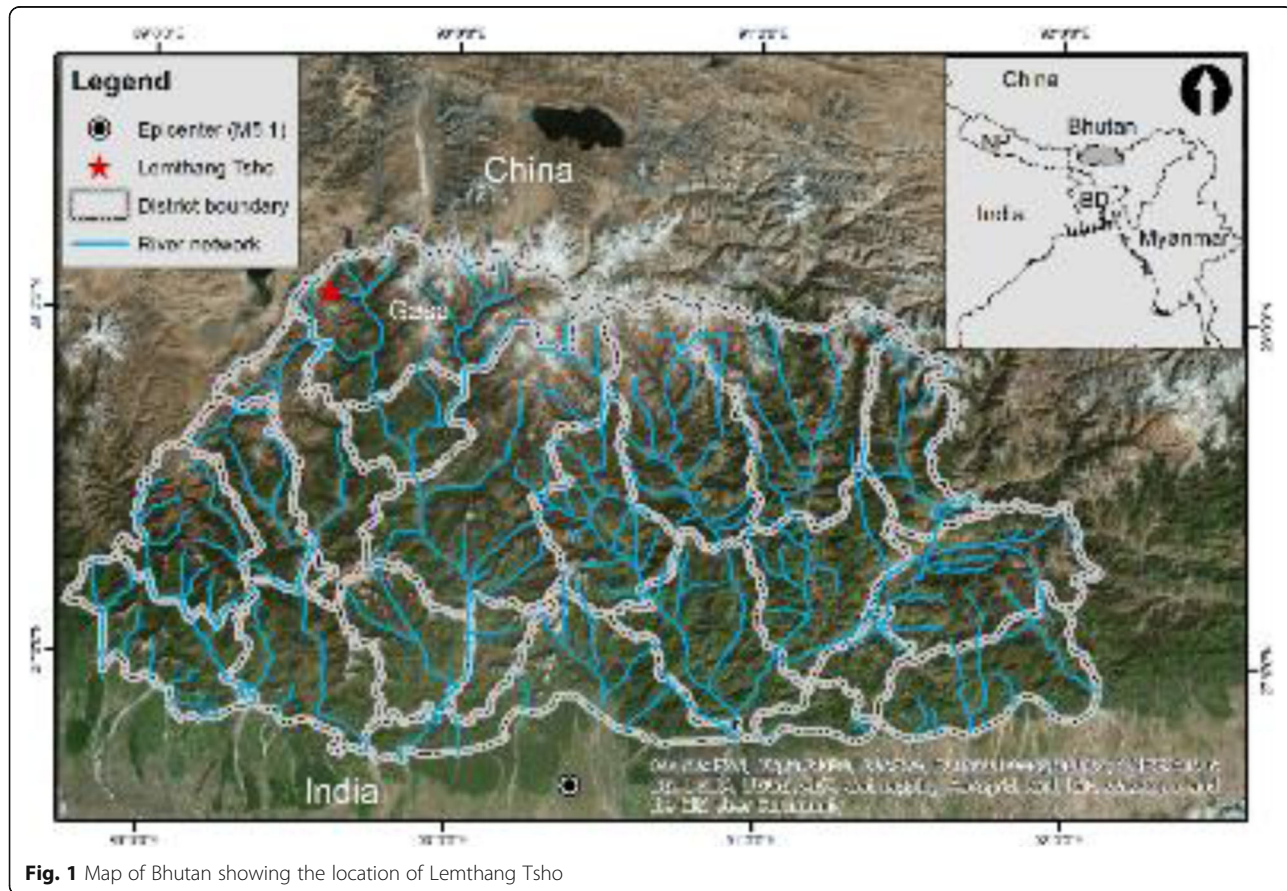

Fig. 1 Map of Bhutan showing the location of Lemthang Tsho

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Richardson and Reynolds 2000). However, enhanced ice melt at the margins of receding glaciers due to observed warming trend and increase in weather extremes: rainfall and temperature (Field 2012) have increased the likelihood of GLOF events (Crammer 2014; Field 2014; Riaz et al. 2014). The HKH region has been witnessing GLOF events from time to time one of which is the Lemthang Tsho GLOF of 28 June 2015 in north-eastern part of Bhutan. Understanding of outburst mechanism of GLOF is critical to our effort to minimize risk, and such real cases provide an excellent opportunity to do so. This paper discusses cause and impact of the GLOF event based on remote sensing analysis and intensive fieldwork.

Study area

The Lemthang Tsho is located in a remote location defined by longitude 89°34′53.42″ and latitude 28°04′05.17″, in north-western part of Bhutan in Gasa district (Fig. 1). It is tugged at an elevation of 4270 m asl, and is 6 h (on foot) away from nearest settlement Laya village and 3 days walk from road head (Gasa town). The lake is positioned in the frontal part of north-west to south-east trending glacier. The lake was mapped as Mo_gl_200 in 2001 inventory (Mool et al. 2001). The lake drains into

Mo Chu (river) which ultimately joint Pho Chu to form Puna-Tsang Chu.

Geologically the study area lies in Greater Himalayan Zone, a crystalline belt mainly consisting of gneiss with occasional intercalation of marble, limestone and leucogranites (Long et al. 2011). The basement lithology in the vicinity of the lake has north-east to south-west trending strike with south-east trending dip with dip angle ranging from 25° to 30°. An east-west trending and north dipping thrust, the Laya Thrust runs close by the lake.

The climate there is temperate type with warm summer and very cold winter. Mean summer temperature ranges from 12 °C to 14 °C while winter temperature ranges from −2 °C to −6 °C (Dorji et al. 2016). Annual precipitation is in the order of 1801 mm to 2600 mm. The area receives heavy snow fall during winter starting from month of November.

Methods

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,
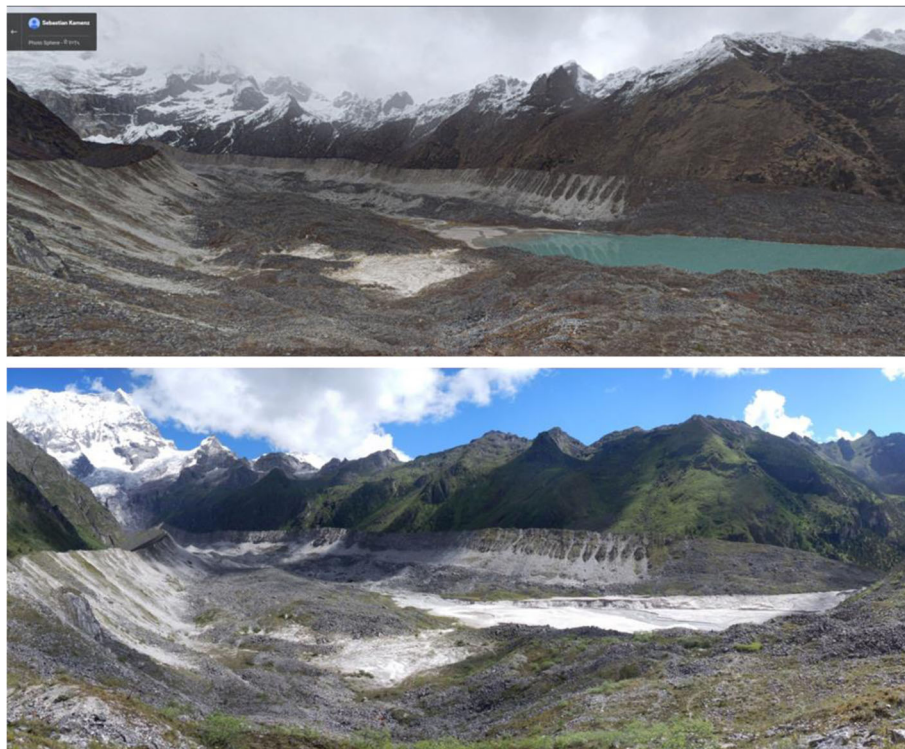

Fig. 2 Repeat photograph of Lemthang Tsho: top (pre event, May 2015) and bottom (post event, July 2015). Photo credit: Sebastian Kammer and Sharad Joshi

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downstream losses) were collected during fieldwork which was conducted after a month from the event. 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 erstwhile Department of Hydro-Met Services (DHMS), Royal Government of Bhutan. The DHMS has been recently renamed as the National Center for Hydrology and Meteorology (NCHM) under restructuring exercise. 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 cross-section 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 (1983). Information about damage and loss was collected through visual inspection and consultation with local people.

Review

Causes of GLOF has been discussed by many researchers (Emmer and Cochachin. 2013; Iwata et al. 2002; Yamada 1998; Vuichard and Zimmermann 1987) and there are comprehensive review on causes of GLOFs in the past (Falátková 2016; Komori et al. 2012). The published work acknowledges the role of external factor as a trigger to unleash the GLOF, thus discussions on the cause of GLOF includes two aspects: triggering mechanism and breach mechanism. The triggering mechanism which directly or indirectly causes the breach has been referred as "dynamic cause" by Emmer and Cochachin (2013). Iwata et al. (2002) in their work on causes of GLOF from moraine dam in Bhutan Himalaya has categorized trigger into in-direct trigger and direct trigger. They imply existence of cause-effect relationship amongst direct trigger, in-direct trigger, and cause of the GLOF, which is also illustrated by Emmer and Cochachin (2013) and Falátková (2016). Two indirect triggers discussed in the review are earthquake and global warming, which evoke secondary process such as ice-calving, glacier surge, failure of outlet, which eventually causes the breach (Iwata et al. 2002). The secondary trigger is termed as direct trigger as it is this that actually directly contribute in failure of the moraine dam. Earthquake can therefore be a direct trigger in an event the breach of moraine dam is caused by seismic tremors (Clauge and Evans 2000). The global warming may not be obvious as indirect trigger like earthquake, but Liu et al. (2014) did find correlation between higher GLOF of frequency and air temperature in Tibet
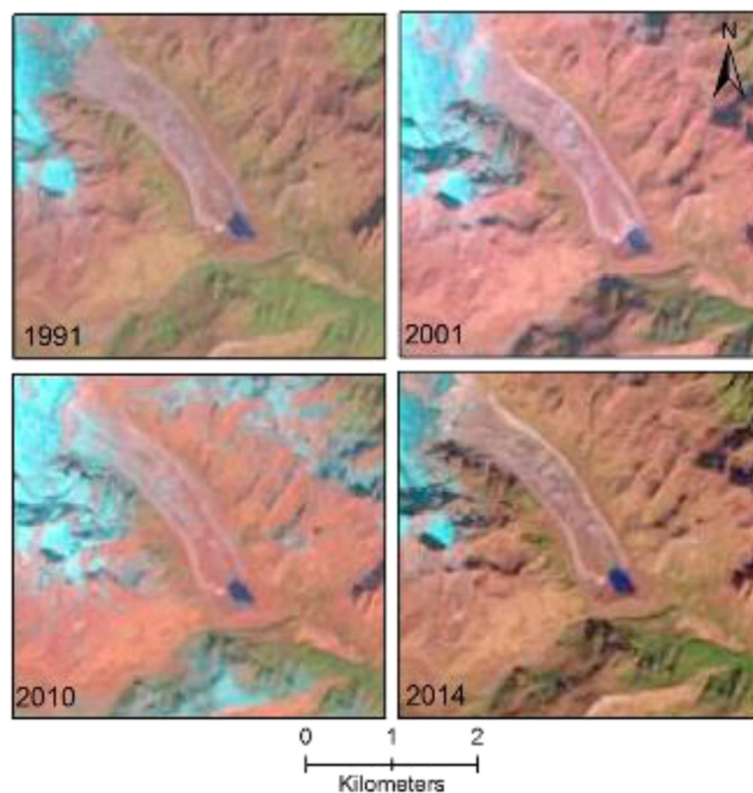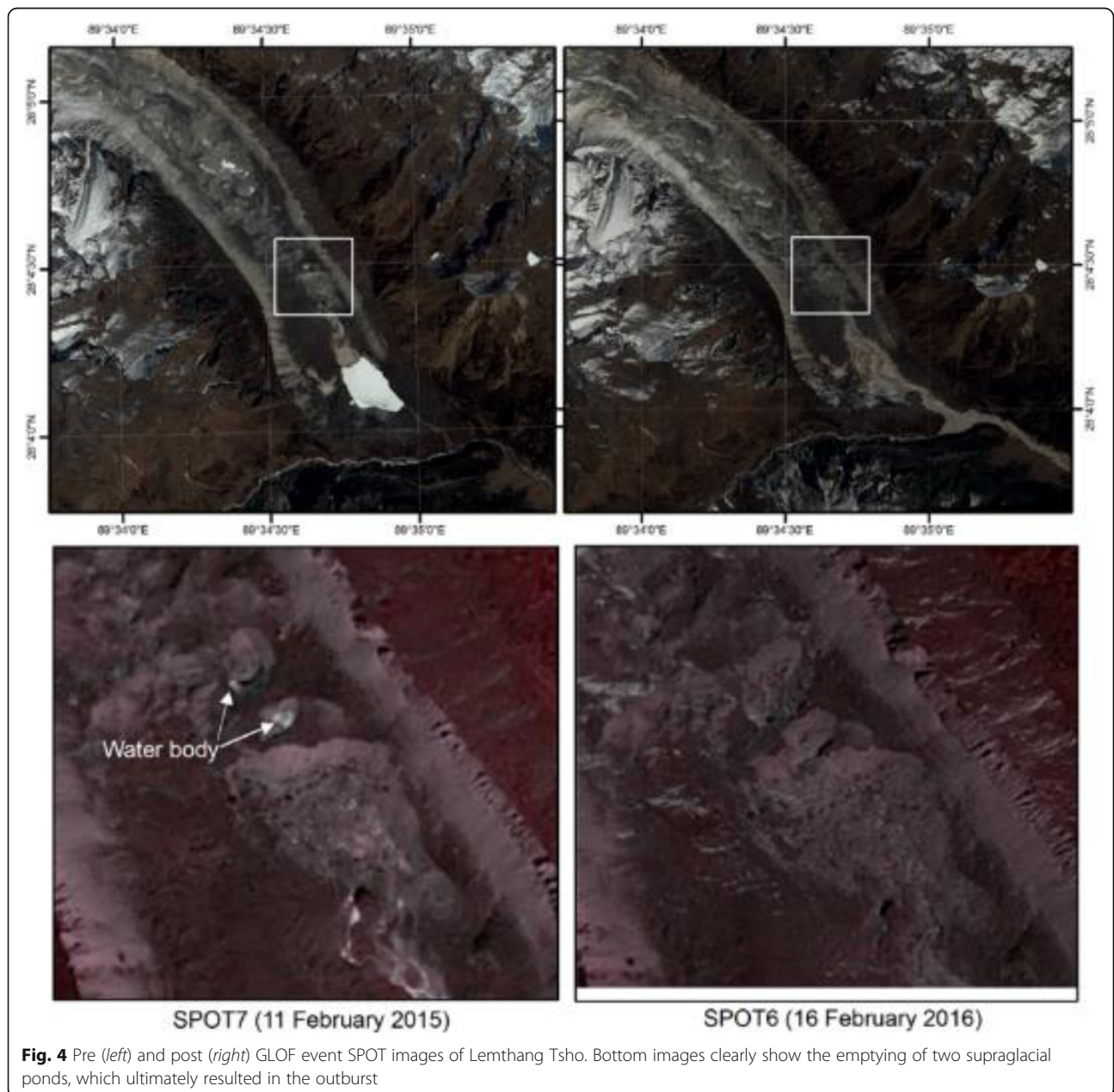

Fig. 3 Time series Landsat images showing growth progression of Lemthang Tsho

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during 1960s, 1980s. Similarly Chen et al. (2010) argued that GLOF magnitude and frequency are closely related to positive temperature trend.

There are many direct triggering mechanisms (Iwata et al. 2002) and most common of which is ice avalanche falling into a lake (Falátková 2016; Emmer and Cochachin 2013, Komori et al. 2012; Richardson and Reynolds 2000). Ice avalanche and rock fall into a lake generates a displacement (surge) wave (example Dig Tsho in 1985) which strikes the moraine wall and debilitate the dam, or overflow the dam and initiate the incision which leads to its collapse eventually (Clague and Evans 2000). Other discussed causes are rise in lake level due to enhanced inflow as compared to outflow resulting in hydrostatic pressure and moraine dam yielding to the increased pressure. The enhanced inflow can be from snow and glacier melt or from outburst in the upstream. The discussion on role of supra-glacial lakes in generating GLOF is far and few, and is being recognized lately (Komori et al. 2012), although much is still unknown. Breaching of supra-glacial in itself could result in a GLOF as in case of the Tshojo GLOF of 2009 in Bhutan (Komori et al. 2012), or it could trigger larger GLOF from glacial lake in the downstream. Merging of supra-glacial lakes could result in much larger lakes with potential for outburst as has been considered in case of Thorthormi Tsho in Bhutan. It is important that

Fig. 4 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

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supra-glacial lake as a trigger of GLOF is given due consideration, as it demonstrates a dynamic phenomenon (Qiao et al. 2015). The same research suggested that warmer springs seem related to the draining of some supraglacial lakes during the following seasons, due to the change in glacial drainage from unconnected to connected systems as a result of enhanced ablation during the springs. This paper will therefore deal on one of these many possibilities, and be a step towards our understanding of the role of supra-glacial lakes in generating GLOF.

Falátková 2016 assessed 38 cases of GLOF event due to breach of moraine dam across the Himalaya and reported ice avalanche falling into the lake (34%), hydrostatic pressure as a result of the lake level rise (20%), and melting of dead ice (14%) as three most common causes of GLOF in Asia. Assessment of 60 historical GLOF events witnessed between 1900 and 2009 across Cordillera Blanca of Peru, the North American Cordillera, and Himalaya, found slope movement into the lake constitute 80% of the cause (Emmer and Cochachin 2013). Fifteen percentage of the events were attributed to earthquake. In the Himalaya region over two-fifth of the GLOF events resulted from "dam self-destruction" (Emmer and Cochachin 2013), a term used to describe long-term degradation of the dam without a dynamic initiating event (Yamada 1998). It includes melting of dead ice, impact of hydrostatic pressure, and the effect of time, which contributes in destabilizing the moraine dam. In another assessment of GLOF event across the Himalaya (Richardson and Reynolds 2000) where 26 events were considered, ice avalanches into the lakes constitute over 53%, unknown in case of over

23% of reported events, 12% from moraine collapse due to seepage, 8% from rock avalanche into the lake, and 4% from collapse of moraines due to melting ice-cores. Similar assessment of 21 historical GLOF events in Bhutan (Komori et al. 2012) found plunging of glacier ice down into the lake (44%), glacier calving (33%), and ice deformation around a supraglacial lake (10%) are top three triggering mechanism.

Result

Lemthang Tsho GLOF

The Lemthang Tsho GLOF was reported around 6:30 pm Bhutan Standard Time (BST) (GMT 6+) on 28 June 2015 by local people collecting herbs (Kuensel 2015a). The event (GLIDE No. FF-2015-000077-BTN) completely emptied the lake (Fig. 2 and 4), yet the resultant GLOF was relatively small considering the unleased water volume as well as devastation. 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. District authorities of two downstream districts, Punakha and Wangdiphodrong, were duly alerted, as there were concerns about additional hazard from the monsoon rains which had been heavy in the preceding weeks. The siren was manually activated around 8:45 pm (Kuensel 2015a) even before the water level (6.66 m) reached preset alert level (7.5 m) at Taktsemakhang station.

The Lemthang Tsho inventorized as Kab Tso with glacial lake ID of mo_gl_200 in inventory exercise of 2001, using topo sheet prepared using aerial photo taken in 1960s (Mool et al. 2001), indicates the existence of the

Fig. 5 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

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lake over 5 decades. Due to large mother glacier at the foreground and attached to the lake with well-defined moraine dam, the Lemthang Tsho was identified as one of the 24 potentially dangerous glacial lakes (Mool et al. 2001). The lake area was 0.0521 km^2 in 1960s and 0.0763 km^2 by 2015, while the length increased from 285 m to 445 m. With surface area increase of 0.0242 km^2 in over 5 decades, Lemthang Tsho is thus characterized with slow growth rate, which is also obvious from the time series Landsat images (Fig. 3).

Cause of Lemthang Tsho GLOF

A team comprising of engineers and glaciologists were fielded within a month of the outburst to investigate the event and assess residual hazard. Field investigation revealed that two interconnected supraglacial ponds located upstream of the lake had completely drained into Lemthang Tsho which was corroborated by pre- and post-event satellite images (Fig. 4). Based on the field observation and on satellite image, the sudden subglacial draining of the supraglacial ponds is likely to have been triggered by collapse of steep ice scarp of the upper supraglacial pond. The supraglacial ponds being interconnected through a subglacial conduit, the hydrostatic pressure reconfigured the subglacial channel enhancing the flow. It is unlikely that draining of the subglacial ponds was sudden from the eyewitnesses account that breaching of Lemthang Tsho occurred several hours after the draining of supraglacial ponds (Kuensel 2015b). The possibility of a strong surge wave in case of sudden
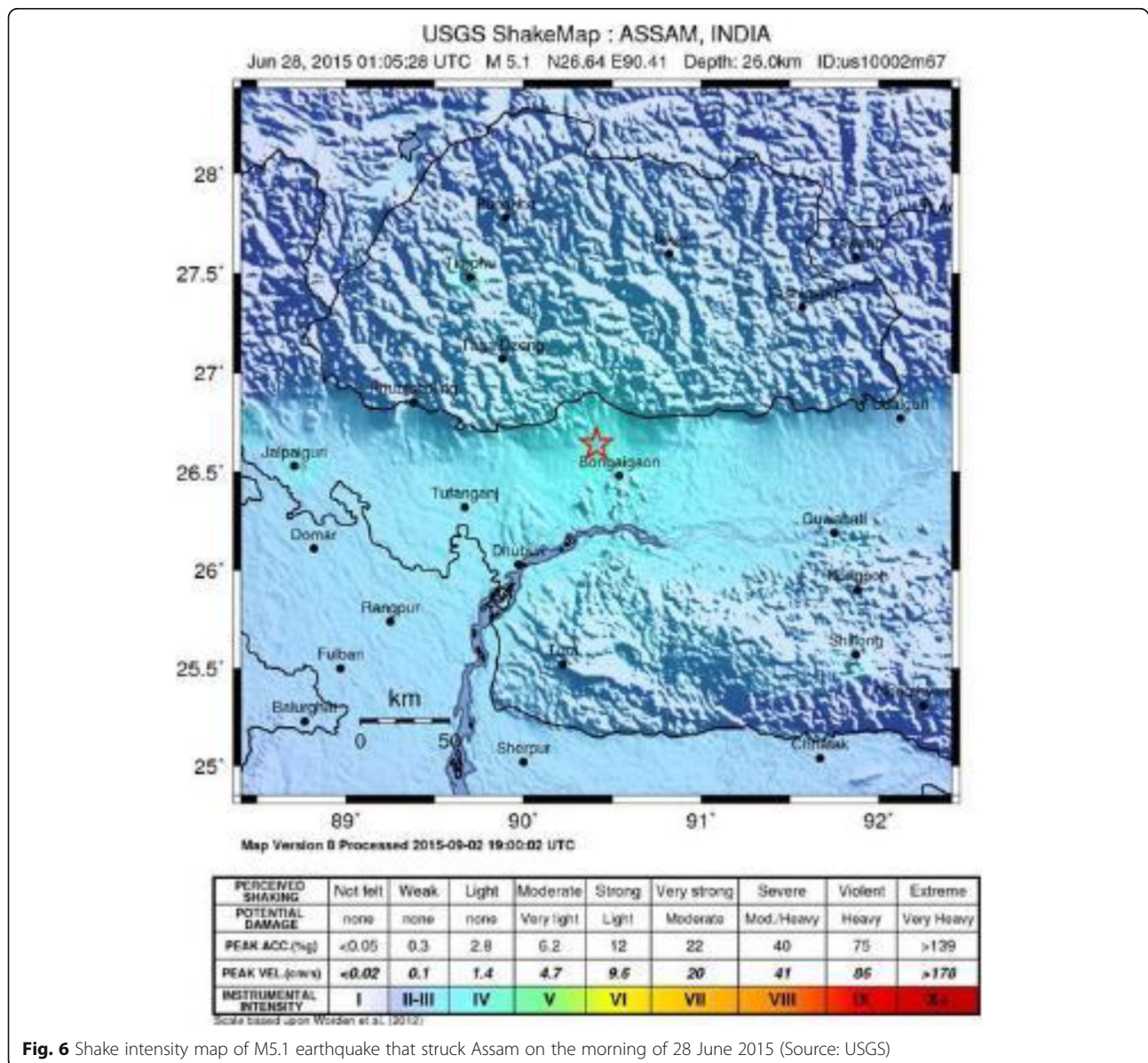

Fig. 6 Shake intensity map of M5.1 earthquake that struck Assam on the morning of 28 June 2015 (Source: USGS)

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draining of supraglacial ponds triggering the breach which often happens in quick succession is ruled out. Alternatively likely scenario involves a gradual rise in the lake level as the supraglacial ponds emptied into Lemthang Tsho and subsequent buildup of hydrostatic pressure which justifies eye witness account of time laps between these two events. As has been discussed in the review section, the increase in outflow as a result of rise in lake water and buildup of hydrostatic pressure increased the outflow discharge and subsequently increased erosion thereby widening the outlet. The dislodgement of the 10 m × 4 m × 3 m boulder (Fig. 5) as a result of increased erosion is considered the moment of breach, which as per eyewitness report happened about 5 pm BST. Sequencing the events based on the eyewitness account and likely scenario, the breach of supraglacial is likely to have happened around 3 pm BST. Two flood

peaks an hour apart at 7:30 pm and 8:30 pm at Laya station indicates breaching to have occurred in two phases, at (Kuensel 2015a). The breach created a 30 m wide V-shaped outlet morphology (Fig. 2), typical of failure of moraine dam. This is not the first time 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, in the headwaters of Pho Chu had resulted in a GLOF (Komori et al. 2012).

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 2015 (Kuensel 2015a). The other suspect is the magnitude 5.1 earthquake with its epi-centre in the Indian state of Assam Fig. 6, 187 km southeast of Lemthang
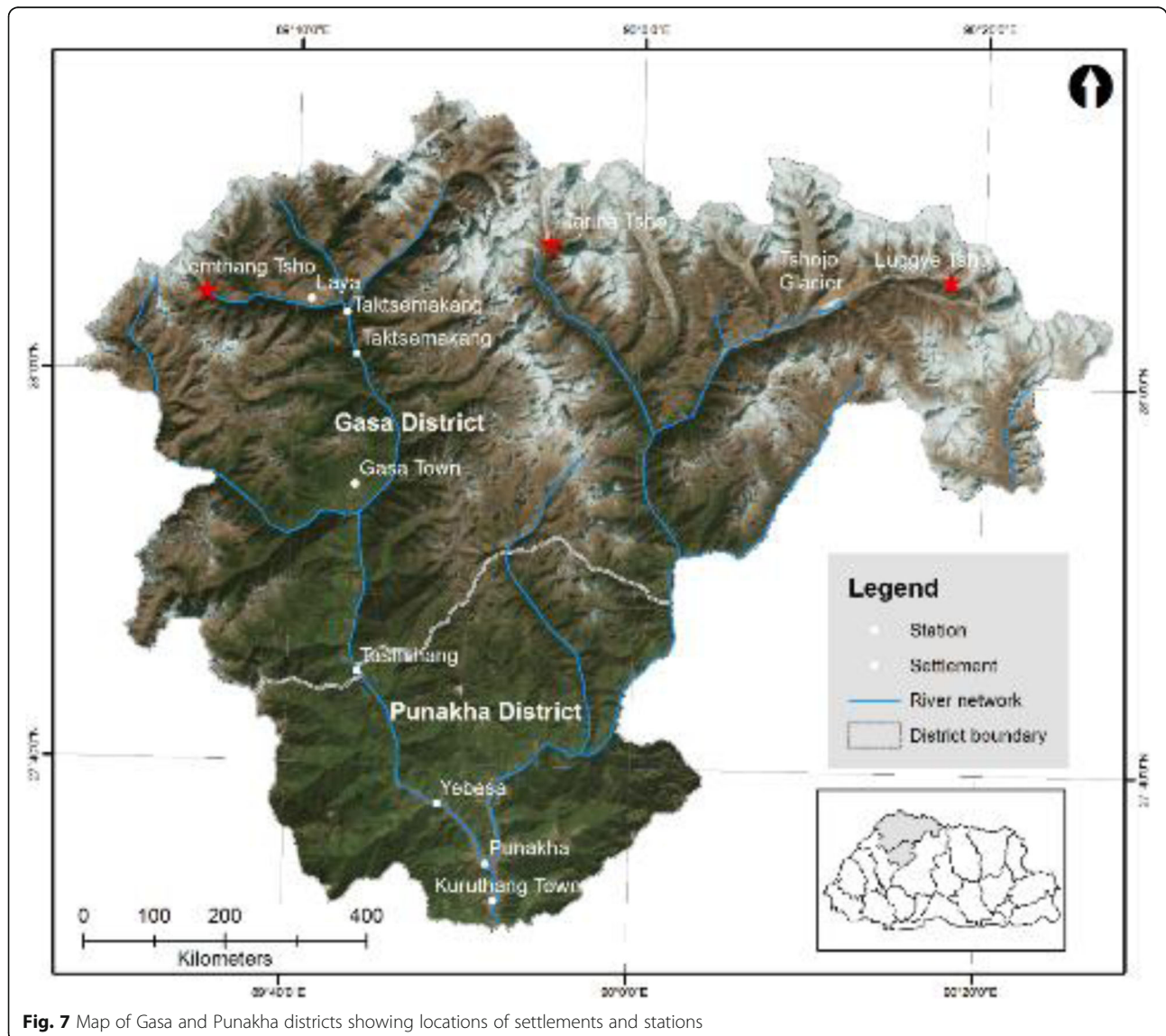

Fig. 7 Map of Gasa and Punakha districts showing locations of settlements and stations

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 m³)	Peak discharge (m³/s)	Velocity (m/s)	Downstream impact (km)	Sources
Qubixiama-Cho	China	10 June 1940		3690	7.7		LIGG, 1988
Sangwang-Cho	China	16 July 1954	300	10,000		200	Xin et al., 2013
Damenhai-Cho	China	26 September 1964		2000	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		1270			Liu et al., 2014
Nare	Nepal	3 September 1977	4.9	830–1100		90	Buchroter et al., 1982
Dig Tsho	Nepal	4 August 1985	6–10 (8)	1600–2000		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	> 2500		200	Richardson and Reynolds, 2000

Tsho (Fig. 1) (https://earthquake.usgs.gov/archive/product/losspager/us10002m67/us/1441220705024/onepager.pdf). The earthquake with hypocenter at depth of 27 km struck at 7:10 am BST on 28 June 2015. Tremor was reported in print media to have felt as far as Thimphu and Bumthang districts but there were no reports from Gasa district (Fig. 1). On the shake intensity map sourced from USGS (Fig. 4), Lemthang Tsho area has been classified under 'weak shaking' (Instrumental Intensity - II). Although it is unlikely that the earthquake to have triggered the slump of the near-vertical wall of the supraglacial ponds, its role in conjunction with heavy rainfall could not be completely ruled out in absence of eyewitness accounts and firsthand data from in-situ stations.

GLOF characteristic

As mentioned above, the flood propagated in two phases, an hour apart. Flood wave took 1 h 30 min to reach Taktsemakhang station at Laya (Fig. 7). Further down flood took 1 h and 45 min and 2 h and 45 min to travel from Taktsemakhang to Trashithang and Yabesa stations respectively, a distance of 45 km and 75 km (Kuensel 2015a). Therefore flood wave is estimated to have travelled with average velocity ranging from 7.14–7.57 m/s, which is higher than Luggye Tsho GLOF with estimated velocity of 3 m/s (Watanabe and Rothacher 1996) (Table 1). Further downstream, maximum discharge of 1198 m³/s was recorded at Punatsangchu Hydropower project site (Kuensel 2015a) (Fig. 7). Figure

8 is a longitudinal profile of Mo Chu from Lemthang Tsho to Punakha Dzong, a seat of district administration (Fig. 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 equations recommended by Strand (1977) and Costa (1983) to estimate mean velocity (Eqs. 1 & 2). The estimated discharge is found to range from 426 to 558 m³/s near Laya and 1253–1562 m³/s (Table 2) upstream near the confluence of the two rivers, where a debris flow fan was formed (Point No. 2 in Fig. 9). It is likely that the flow was obstructed by the tributary, which resulted in deposition of materials (Strand, 1977; Costa, 1983).
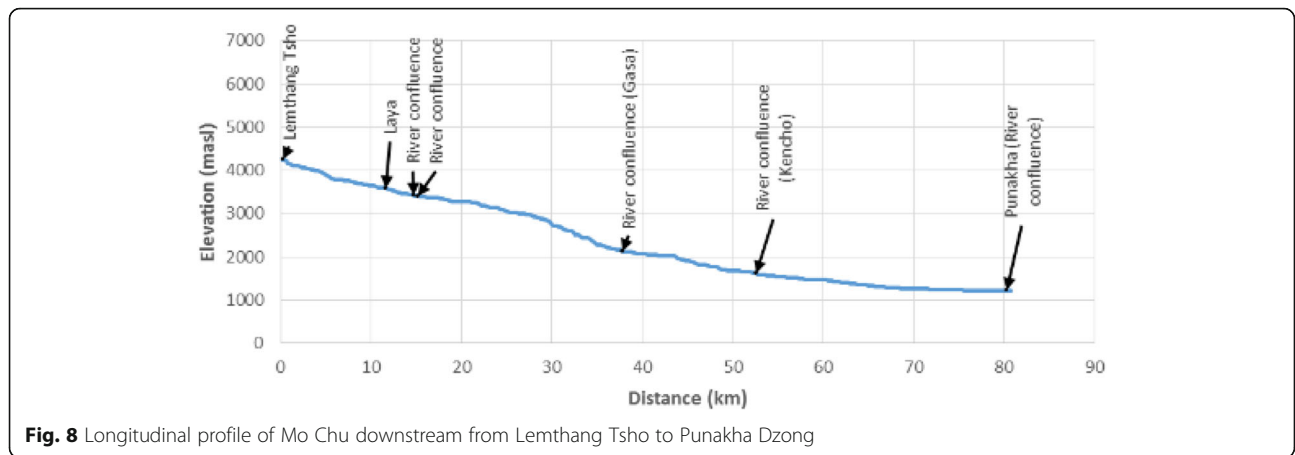
$$\bar{v} = 0.18d^{0.487} \tag{1}$$

$$V_b = 0.51d^{0.5} \tag{2}$$

Impact

Downstream losses from the flood were concentrated in the stretch between the Lemthang Tsho and Kohina village (Fig. 7), a distance of 30 km downstream from the source. As per the Laya Gewog Administration, a total of four bridges were washed and one acre of agricultural land damaged. About 1 km stretch of a trail was damaged due to landslides triggered at several places within

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	2880	8.71–10.85	1253.79–1562.20
2	Laya (9 km downstream)	25	3.2	1190	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

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Fig. 8 Longitudinal profile of Mo Chu downstream from Lemthang Tsho to Punakha Dzong

the stretch as a result of toe cutting by flood on a hilly slope. 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.

Erosion and sedimentation is a major secondary hazard associated with GLOF and can have severe and prolonged socio-ecological impact (Vilímek et al. 2015; Higaki and Sato 2012). The GLOF in the past have converted fertile grazing/agricultural land into a field of sand and boulders, adversely affecting the livelihoods of

the local people. The extent of erosion and sedimentation in this event was limited and was confined up to 25 km downstream from the lake (Fig. 7). As the outburst dislodges and washes away moraine materials a debris in the form of a fan in front of the end moraine is clearly visible in the satellite image (Fig. 4 and 5). Similarly, sand and boulder debris were found deposited further downstream (Point No. 2 in Fig. 9) where loss of gradient has decreased carrying capacity of the flood. As usual there were scouring at places along the river bank
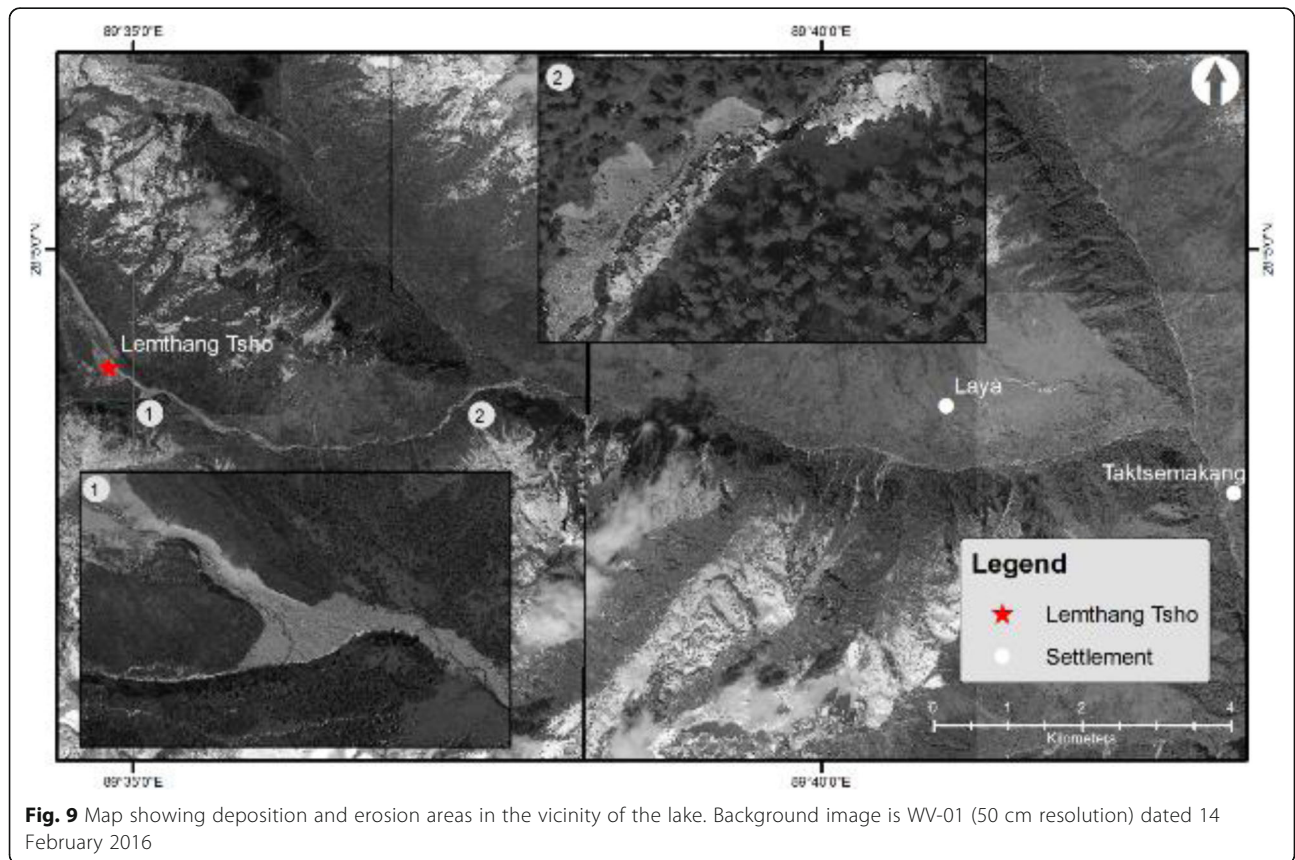

Fig. 9 Map showing deposition and erosion areas in the vicinity of the lake. Background image is WV-01 (50 cm resolution) dated 14 February 2016

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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		

Source: Laya Gewog Administration and Observation

up to 25 km downstream. Since the river runs through a deep gorge beyond 25 km between Kohina and Gasa (25 km–39 km), the 14 km stretch is inaccessible. There was no impact noticed further down at Tashithang (about 50 km downstream). Given the terrain is steep and barren, and climatic condition harsh, it will be a while before the erosion process ceases and stability regained. This will have prolonged impact in the downstream due to increased sediment transport sourced from such erosional sites. Thus the impact could be long drawn out process.

Discussion and conclusion

The threat of GLOF still looms large in the Himalaya due to climate change and regular seismic activities, and risk management interventions should be based on sound understanding of the processes involved, including the cause. Among many different causes discussed earlier, the avalanche (ice and rock) triggering the surge wave and causing breach seems to be the most common cause of GLOF in the Himalaya. The role of supraglacial lakes in triggering GLOF has been largely left from the discussion, and is not considered a criteria to identify critical glacial lakes. The Lemthang Tsho GLOF and Tshojo GLOF (Komori et al. 2012) cases highlights that supraglacial ponds can trigger GLOF, and needs to be considered while doing hazard/risk assessment. The role of earthquake in triggering Lemthang Tsho GLOF event is difficult to confirm or discount in absence of firsthand information, but seems unlikely due to weak intensity of shaking. Strasser et al. (2008) expressed that role earthquake in triggering GLOF in general is difficult due to vary many ways it can manifests, some of which are sub-glacial phenomenon. As in case of lake Parón, inhibited outflow due to an earthquake resulted in rise in lake level which ultimately caused GLOF, but well past the earthquake event (Lliboutry et al. 1977). The two days of incessant rainfall is likely to have destabilized the steep scarp due to relatively warmer raindrops melts the glacier, and is more likely have played a role in creating Lemthang Tsho GLOF. However, the region being seismically very active zone, the role of earthquake as a trigger of GLOF cannot be overlooked.

The Lemthang Tsho GLOF event by all measure was a small event accounting for relatively minimum impact in terms of direct damage. However, indirect damage such as impact on livelihood due to loss of grazing land to debris, and prolonged hillslope erosion is far reaching. The event despite its' small size reminds us of the GLOF risk that HKH countries faces, and to take the threat seriously.

There is a need to relook into existing list of critical glacial lakes and update it, as the existing list was prepared over a decade ago using topo maps some of which prepared based on aerial photo of 1960s'(Mool et al. 2001; Ives et al. 2010). Since then glaciers and glacial lakes must have undergone lot of changes thus warranting a revision. Total of 24 glacial lakes were identified as the critical glacial lakes based on the condition of lakes, dams, associated mother glaciers, and topographic features around the lakes and glaciers. Addition of Thorthormi glacial lakes had brought the figure to 25 (WWF 2009). The Thorthormi Tsho was categorized as dangerous lake based on unstable moraine condition, seepage, and likelihood of developing into a large lake by Iwata et al., 2002 also. Two other critical glacial lakes: Latshokarp (Mo_gl_201) and Langdo Latshokarp (Mo_gl_202) among 25 are located in adjacent valley to Lemthang Tsho, which the team verified in the field. Having found that that they do not pose immediate GLOF threat considering the size, moraine stability, mother glacier, and surrounding geomorphology, risk level is downgraded (Kuensel 2015b). The updated figure of critical glacial lakes in Bhutan, having downgraded the risk level of 3 glacial lakes (including Lemthang Tsho) is 22. The Lemthang Tsho GLOF highlights the role of supraglacial lake in triggering GLOF event and its' importance as a criteria for updating the list of critical glacial lakes. Finally, the issue of GLOF being a trans-boundary concern, cross learning across countries in the region and beyond needs to be promoted. There is benefit in addressing the common threat collectively.

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