Reassessment of Potentially Dangerous Glacial Lakes in Bhutan

NATIONAL CENTER FOR HYDROLOGY AND METEOROLOGY

ROYAL GOVERNMENT OF BHUTAN

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Foreword

Bhutan is highly vulnerable to the impacts of climate change. Bhutan is already facing the impacts of climate change such as extreme weather and changing rainfall patterns. The Royal Government of Bhutan (RGoB) recognizes the devastating impacts climate change can cause to the country's natural resources, livelihood of the people and the economy. Bhutan is committed to addressing these challenges in the 12th Five Year Plan (2018-2023) through various commitments, mitigation and adaption plans and actions on climate change at the international, national, regional levels. Bhutan has also pledged to stay permanently carbon neutral at the Conference of Parties (COP) Summit on climate change in Copenhagen.

Accurate, reliable and timely hydro-meteorological information underpins the understanding of weather and climate change. The National Center for Hydrology and Meteorology (NCHM) is the national focal agency responsible for studying, understanding and generating information and providing services on weather, climate, water, water resources and the cryosphere. The service provision of early warning information is one of the core mandates of NCHM that helps the nation to protect lives and properties from the impacts of climate change.

The Strategic Program for Climate Resilience (SPCR) which is being implemented by Gross National Happiness Commission (GNHC) focuses on four main pillars. The pillars are:

- Enhancing information base for hydro-met services and climate resilience
- Preparedness, food and water security
- Sustainable growth and resilient infrastructure
- Strengthening governance, institutional coordination and human resource capacity

NCHM is one of the four technical agencies under the SPCR and it is responsible for undertaking a technical study under the *Pillar I- Enhancing Information Base Hydro-met Services and Climate Resilience*. The fundamental objective of the study is to improve hydro-met base information and identify future investment plans. The list of studies carried out under the Pillar I of SPCR are as follows:

- Analysis of historical climate and climate change projection for Bhutan.
- Re-assessment of potentially dangerous lakes of Bhutan
- Bhutan glacier inventory 2018

Reassessing of the previous list of 25 potentially dangerous glacial lakes are discussed in this report. It has almost been two decades (2001) since the potentially dangerous glacial lakes were identified and some of the lakes listed as PDGL's have burst out. Therefore, this study reassessed the previous list of PDGL's taking into account field reports, physical verification and recent satellite imageries. The current list of PDGL's were updated based on the previous existing list and all glacial lakes were not taken into consideration. It is therefore recommended to compile an inventory of glacial lakes of Bhutan to have a better understanding of the impacts of recent global climate change, melting glaciers which leads to formation of new glacial lakes as well as expansion of existing glacial lakes.

This report is submitted by NCHM to GNHC and the World Bank under the SPCR Project. The findings from this study provide initial assessment of possible future changes of climate over Bhutan. The report is an outcome of Pillar I of the SPCR Project implemented by NCHM. In this regard, I would like to thank all the Divisions, the SPCR Management of NCHM who have worked hard to bring out this report.

(Karma Dupchu)
Director

Acknowledgement

We express our sincere thanks to Dr. Jiro Komori and his team of DGM-JICA/JST GLOF project for providing us with the processed bathymetry data of the PGDL's. We are grateful to Karma, Chief of the Division of CSD, NCHM for his initiative and guidance to come up with updated PGDL of Bhutan and for his valuable comments and suggestions on the draft reports. Our sincere thanks also goes to all the past team members of various projects whose literature were of great reference during the compilation of the report. We would also like to express our thanks to SPCR (Strategic Programme for Climate Resilience) Project for providing support in capacity building of the glacial lake mapping. Thanks to ESA (European Space Agency) for making Sentinel-2 imagery freely available on their webpage. Lastly thanks to CSD colleagues for the help rendered to complete this report

Executive summary

Increase in global temperature have resulted in rapid melting of glaciers globally. Glacial Lake Outburst Flood (GLOF) commonly known as silent/mountain tsunamis are one of the major catastrophes resulting from excessive melting of glaciers. Himalayan countries are mainly affected by global warming, where it has been found that the glaciers are receding at an accelerated rate in the recent decades causing GLOF(s) downstream. Bhutan experienced a massive GLOF in 1994 causing chaos downstream taking life of 20 people and damaging millions worth of infrastructures and properties. After the country's major GLOF event in 1994, the Royal Government of Bhutan undertook various measures to monitor, mitigate and create awareness on risks associated with GLOF hazard leading to identification of potentially dangerous glacial lakes (PDGL).

The first ever inventory on glaciers, glacial lakes and potentially dangerous glacial lakes was published by Department of Geology and Mines (DGM) under the then Ministry of Trade and Industry in collaboration with International Center for Integrated Mountain Development (ICIMOD) ((Mool *et al.*, 2001)) with an objective to identify and segregate potentially dangerous glacial lakes of Bhutan. In the process, the study had identified 24 glacial lakes as potentially dangerous glacial lakes, 5 in Mo Chhu sub basin, 8 in Pho Chhu sub basin, 7 in Mangde Chhu-basin, 3 in Chamkhar Chhu sub basin and 1 in Kuri Chhu sub basin. Later during the Austrian-Bhutan joint project (1999-2002) a new lake (Thorthormi lake) was identified and updated in the list of PGDLs to a total of 25 potentially dangerous glacial lakes in Bhutan. However, the inventory was prepared purely based on remote sensing materials and techniques with no actual field based data and information. Hence this current study was carried out with the objective to verify and update the previous list of PDGL inventory using field verified data sets and latest Sentinel 2 high resolution satellite imageries of 2016.

Under this study bathymetry data compiled by various field works in the past were collected and processed into Bathymetry maps. The data acquired from the maps were collected and compared with the previous inventory and then potentially dangerous lakes were identified using the set of criteria's which was previously defined by Mool et al inventory of 2001. From this current study it was found that out of 25 dangerous glacial lakes, 8 were deemed safe based on lake morphology, it's surrounding features, bathymetry condition and associated feeding glacier, 5 lakes are still not ground verified and 12 were identified as potentially dangerous. The status for those PGDLs which could not be verified on the ground remain unchanged and recommended for ground based verification in the future. From the total of 8 lakes which were deemed safe for GLOF, 3 lakes were from Mo chhu basin, 4 from Mangde chhu basin and one from Chamkhar chhu basin. The remaining 17 lakes are still listed as potentially dangerous and needs constant monitoring because the lakes morphology and its feeding glaciers are changing constantly.

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Abbreviation and Acronyms

CSD	Cryosphere Services Division
DDM	Department of Disaster Management
DGM	Department of Geology and Mines
DHMS	Department of Hydro-Met Services
ESA	European Space Agency
GEF	Global Environment Facility
GIS	Geographical Information System
Gl	Glacial lake
GLOF	Glacial Lake Outburst Flood
GoA	Government of Austria
G**OI**	Government of India
Gr	Glacier
GSB	Geological Survey of Bhutan
GSI	Geological Survey of India
IRS	Indian Remote Sensing
JICA	Japan International Cooperation Agency
LANDSAT	Land Observation Satellite
LDCF	Least Development Countries Fund
LIS	Linear Self Scanning
NCHM	National Center of Hydrology and Meteorology
PDGL	Potentially Dangerous Glacier Lake
RGoB	Royal Government of Bhutan
RS	Remote Sensing
SPCR	Strategic Programme for Climate Resilience
SPOT	Satellite Pour I'Observation de la Terre
TM	Thematic Mapper
WAPCOS	Water and Power Consultancy Services (India) Limited
WWF	World Wide Fund

1. INTRODUCTION

With recent global climate change, glaciers worldwide are retreating resulting in formation of many supra- and pro-glacial lakes. When such smaller glacial lakes start to grow bigger in area, they join to form bigger lakes. In many cases, such glacial lakes are dammed with moraine dams consisting of boulders and ice masses. When the damming part of the lake fails due to hydrostatic pressure from the lake, seismic activities and surge waves created by various mass movements from lateral moraines including avalanches from the accumulation area, large amount of water released causing catastrophic flood in the downstream known as Glacial Lake Outburst Flood (GLOF).

Such phenomenon of both formation of glacial lakes in Bhutan started as early as 1940s (Leber, D. et al, 2003) and several GLOF incidents took place in Bhutan (Komori, J. et al, 2012). Among such incidences in the last few decades, one of the most devastating was from one of the glacial lakes in the Lunana region (Lugge Lake) on October 7, 1994. During that event, the partial outburst released around 18 million cubic meter of water causing severe damages downstream. It washed away pasture lands, agricultural lands, claimed 20 lives and caused partial damage to one of the oldest fortress of the country, the Punakha Dzong (Singh, 2009)

After the 1994 event, the Royal government of Bhutan felt the need to study the lakes in the northern frontiers of the country. Line agencies in collaboration with other national and international agencies, universities and institutes led several expeditions to the glaciated northern frontiers to assess the potential risks and hazards posed by glacial lakes. In 2001, Department of Geology and Mines (DGM) under the then Ministry of Trade and Industry in collaboration with International Center for Integrated Mountain Development (ICIMOD) produced the first ever inventory on glacier, glacial lakes and glacial lake outburst floods of Bhutan categorizing 24 number of glacial lakes as potentially dangerous Glacial Lakes (PGDL). Later, another lake was identified as potentially dangerous increasing the number to 25. (*Hausler, H et al, 2002*).

The 2001 inventory was prepared using aerial photographs, Landsat Thematic Mapper(TM) (1993-1999) Indian Remote Sensing (IRS), ID Linear Self scanning (LIS) S3 (1999) and SPOT (1994) satellite images and topographic maps (1: 50,000) of 1960s and 1950s made by Survey of India (1960). Though the information on potentially dangerous glacial lake (PDGL) was readily available, no updates were made by conducting field verifications. Of recent, many changes have taken place not only at the source but also downstream along the rivers due to modern developmental activities. It is timely that the inventory on potentially dangerous glacial lakes be updated using latest high resolution imageries and field verification. The then Glaciology Division under DGM has started the program of verifying the potentially dangerous glacial lakes by visiting those accessible glacial lakes. Today, about half the number of PDGLs are field verified.
Making use of available data and reports on such glacial lakes, the number of PDGLs are updated with the main aims to provide reliable and realistic figures to public and decision makers.

The following are the main objectives of the present task:

- To update the previous list of PDGLs with the latest available data and information.

- To understand and spread awareness of GLOF phenomenon to public domains and disseminate the results and information to related stakeholders and organizations.

Studies on glaciers and glacial lakes in Bhutan were not carried out until 1960 when Augusto Gansser, a Swiss geologist while doing survey to compile data on the Geology of Bhutan Himalaya took an expedition in Lunana area. He briefly studied the glaciers (1960s to 1970s) and identified numerous dangerous lakes that could cause massive flood in the lower valleys in future. Specifically he mentioned Tarina lake I as the source of flood that destroyed parts of Punakha Dzong (Gansser, 1983). He recommended the Bhutanese officials to come up with identification of valleys which might be affected by future catastrophic floods (Gansser, 1983).

Hence following the recommendations, a preliminary aerial reconnaissance surveys were carried out in Lunana area (Raphstreng Tsho) in September 1974 and August 1981 by an expert team from GSI and the then GSB. A detailed ground survey of Raphstreng Tsho was recommended by the team. Following the earlier recommendations, a joint expedition of GSB and GSI again carried out the study of Raphstreng lake (mentioned as Lunana Tsho in the report) in 1984.The team had further recommended constant monitoring of the lake every two years .Further in 1986 the joint expedition of GSB and GSI carried out a detailed study of the Raphstreng lake taking in detailed bathymetry survey of the lake along with ice flow studies, sediment transport studies, geomorphology of the Thanza valley. With their findings they came to a conclusion that there was no possible danger of a lake outburst in the near future but recommended periodic monitoring every two to three years due to presence of ice cores in the lateral moraine dams of Raphstreng-Thorthomi Tsho (Sharma, A.R. Ghosh, D.K. Norbu, 1986)

1994 was the worst year in the history of Bhutan with the outburst of Lugge lake on 7th October causing massive chaos to the communities downstream. The first Bhutanese expedition in 1994 (Multidisciplinary team) did a preliminary study to identify various lakes that might cause flood. In 1995, a Joint team of GSI and RGoB carried out preliminary studies to identify the source of the flash flood in the headwater of Pho Chhu river. The team consisted of Glaciologist, engineering geologist and surveyors from GOI and Other officials from RGoB. After the study they recommended various short term mitigation and Long term mitigations (GSI *and GSB, Environmental Hazard and Remedial Measurements in lunana (1995),* (Mool et al., 2001))

The Mitigation Project of the Raphstreng lake undertook in 1996 with the funding from Minister of External Affairs, GOI. The WAPCOS was appointed as a consultant for the preparation of designs, estimates and report compilation of the Lunana Project. By the end of the project in 1998, water level in the main lake of Rapstreng tsho was lowered by 4 m thereby achieving the overall target of the project. (*Lunana Project,1998*). The investigations on Lunana lakes was continued by the Austro-Bhutanese joint team from 1999 to 2002 (*Hausler.H et al,2000*) and based on their findings (*Hausler.H et al, 2002*) they introduced a new PDGL (Thorthormi lake) into the earlier list of 24 PDGLs (Pradeep K. Mool *et al.*, 2001) as it was found to bear high risk due to presence of dead ice on its lateral moraine which separates it from Raphstreng lake. Hence they recommended a future mitigation of Thorthormi lake if the subsidiary lakes join together to form a bigger lake.

In 1998 the Japan-Bhutan joint research initiated by Nagoya University, Tokyo Metropolitan University partnered with the then GSB undertook a major research program. The objective of the project was to prepare and update inventory of major glacier lakes located at the head water of major river systems in Bhutan and produce a GLOF risk assessment (Ageta and Iwata 1999). In this research project a total of 18 glacial lakes named by the DGM and 12 other glacier lakes were observed and studied. Using all this data and observations an updated glacial lake inventory and risk assessment of the moraine dam failure of the glacial lakes in Bhutan were presented in the report (Ageta and Iwata 1999).

In the same year the officials of engineering geology and glaciological section, GSB undertook a preliminary study to identify some of the potentially dangerous lakes at the head water of Chamkhar Chhu and found that Chubda Tsho contained dead ice underneath the moraine, active slides and fresh ice cliffs within and around the moraine. So they strongly recommended to constantly monitor the lake and also proposed a detailed technical study of the lake in the future (Karma et al, 1999 (unpublished)).

Another study on the Tsokar Tsho in the head water of Chamkhar Chhu, Bumthang was taken by GSB in April 1999 (Karma et al, 1999 (unpublished)). Out of several lakes in the source of Gomthang chhu, 9 lakes were studied by the team. It was found that Tshokar Tsho was the main lake where all the eight small lakes flow. The team found that Tshokar Tsho flood in 1998 was triggered by the heavy monsoon and excessive discharge from the upper lakes. With steep gradient and active monsoon this outlet area was found to be prone to active sliding. (Karma et al., 1999, GSB (unpublished))

In 2001, DGM in collaboration with International Center for Integrated Mountain Development (ICIMOD) published the inventory of the glacier and glacial lakes of Bhutan (Pradeep K. Mool *et al.*, 2001) mentioning the numbers of potentially dangerous glacial lakes. However, those studies were done completely based on satellite images and topographic maps prepared in the late 1950s and early 1960s. Therefore, it was crucial to validate the severity of the GLOF threats from those glacial lakes through ground verification. In line with these/such objectives, the Glaciology Division under the then DGM has initiated an annual activity called “Time Series Monitoring of Glaciers and Glacial lakes” to ground check the lakes which are categorized as potentially dangerous lakes. This activity is one of the main task of the CSD, NCHM which was formed by merging of the Department of Glaciology Division of DGM with Snow and Glacier division of the then Department of Hydro Met Services following the organizational development exercise carried out by Royal Civil Service Comission. Under this activity many of the potentially dangerous glacial lakes were field verified and monitored.

In 2008 the Thorthomi mitigation project was undertaken by RGOB in partner with UNDP under the GEF project funded by LDCF and co-financed by GoA, WWF Bhutan and RGoB. The target of the project was to reduce the water level of the Thorthomi lake by 5 meter within 3 years with four working seasons per year. (Thorthomi Tsho Mitigation Project). The four-year project could not meet the target of reducing the level by 5m hence the team recommended an extension for this project to meet the goals to lower the water level by 5 m.

With this five-year project coming to an end mitigation of Thorthomi by lowering of water level by 5 m was achieved in main lake as recommended by the Austrian experts. (Project reports on Artificial Lowering of Thorthormi Lake).

2. DATA AND METHODOLOGY

In the previous inventory of Glaciers and glacial lakes of Bhutan (Mool et al., 2001), the materials used for the study were the topographic maps which were prepared using aerial photos of 1960s by Survey of India (1960), and Landsat Thematic Mapper(TM) (1993-1999) Indian Remote Sensing (IRS), ID Linear Self scanning (LIS) S3 (1999) and SPOT (1994) satellite images. In particular, following criteria were used for identifying the PDGLs of Bhutan:

- Rise in lake water level
- Activity of supraglacial lakes
- Position of lakes
- Dam conditions
- Condition of associated mother glacier
- Physical conditions of the surroundings

The study was purely based on remote sensing analysis and no field based data were incorporated. With such criteria, 24 glacial lakes were pointed out to be potentially dangerous. On the other hand, no detailed explanation on how the criteria are applied on the individual lakes were mentioned. For instance, some of the PDGLs in the headwater of Mo Chhu (Mo_gl 200, Mo_gl 201 and Mo_gl 202) do not qualify to be dangerous in terms of lake surface area but have qualified on the basis of morphology and position of the lake with respect to the associated glaciers. However, a detailed explanation on WHY and HOW the morphology and position of the lake contributed to categorizing these lakes as PGDL is not clear.

Hence, under the current activity all the potentially dangerous glacial lakes will be individually updated based on Mool et al., 2001's criteria backed up with data sets from field work. For few PDGLs, the field data were not available due to various reasons and therefore their status remain unchanged till a detail field verification can be carried out. The depth of the PGDL were measured through Bathymetry survey using echo sounding devices such as Sonar FishElite 500cc. Most of the lakes were surveyed through DGM-JICA/JST GLOFs project (2009-2012) and additional surveys were later carried out through the Time Series Monitoring Program. The data on Lake Bathymetry from DGM-JICA/JST project were in excel format containing latitude, longitude and the depth data. For generating the 3D dimensional map of the lake basin and to extract the lake water volume, the data was imported in ArcGIS and interpolated using the Inverse distance weighted (IDW) tools under 3D analyst limiting to the lake polygon. Hence the new raster file with lake profile is generated and from this the volume of lake is also calculated in million cubic meter. The Bathymetry maps produced were then used to extract lake water volume and surface area. After having listed out information on water volume, the lakes were then updated with the latest information and reviewed upon to determine whether they are dangerous or not with the same criteria by Mool et al., 2001 on lake volume. Except for Lemthang Tsho (Mo_gl 200) all the lake surface area data were extracted by manually digitizing the lakes using Sentinel 2 imagery of 2016. The lake surface area of Lemthang Tsho was collected from the literature review because the lake breached in 2015 and no lake imagery was found in the sentinel 2 imagery of 2016.

In the process of reviewing, all 25 PDGLs were examined individually based on the earlier criteria set by Mool et al., 2001 and complemented with field based data sets and recommendations mentioned in earlier technical reports. Out of 25, only few are not field verified due to various reasons mostly associated with accessibility to the site. For such unvisited glacial lakes, the reviewing criteria and the status of the lake remains same to that of Mool et al., 2001 till further ground based verification could be carried out.

The following criteria were used as basis to reassess and update the list of potentially dangerous glacial lakes:

1. Minimum volume of 10 million m^3
2. Minimum surface area of 100,000 m^2
3. Feeding glacier within a reach of 50 m
4. Relatively high depth near the outlet area
5. Active supra glacial activity on the glacier surface (feeding glacier)
6. Condition of the damming materials
7. Presence of Ice core in the moraine wall.
8. Morphological conditions (mass movement from the lateral moraine and steep rock walls in the accumulation area

3 FINDINGS AND DISCUSSION

3.1 Mo Chu sub-basin

3.1.1 Mo_gl 200 (Kab Tsho/Lemthang Tsho)

The glacial lake Mo_gl 200 (Mool et al., 2001) locally known as Lemthang Tsho (Tsho = Lake) is located at latitude 28^{o}04’05.17” and longitude 89^{o}34’53.42” at 4280 m a.s.l. in the north western part of Gasa Dzongkhag, in the headwaters of Mo Chhu (No 1. in figure 3.1). The lake outlet is oriented southeast direction. The lake is conjoined with the glacier Mo_gr 47 (Debris covered) having an area of 4. 591km^2.The lake was regarded as a fast growing lake until June 2015 when the lake finally breached due to moraine failure (Gurung et al., 2017). The lake was identified as potentially dangerous on the basis of morphology and position of the lake with respect to the associated glacier by Mool et al., 2001.

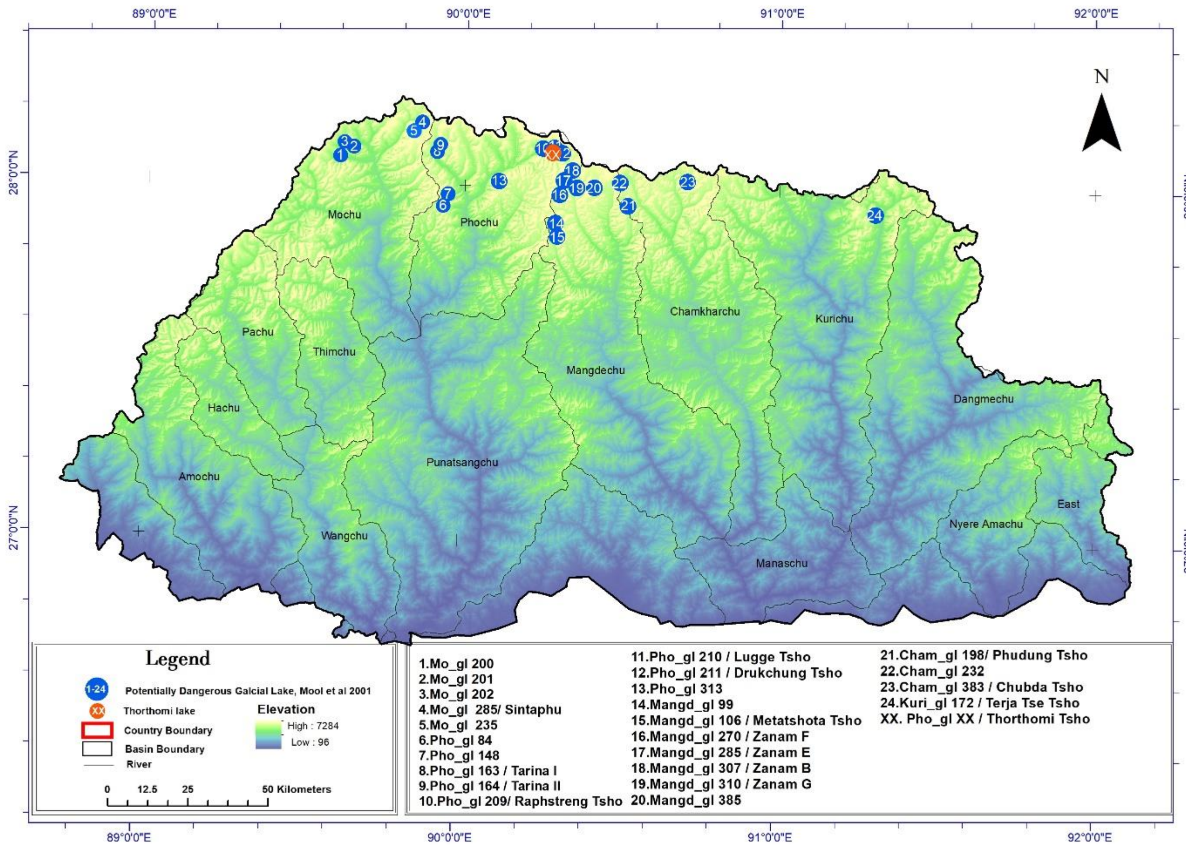

Figure 3.1*: Figure showing the location of potentially dangerous glacial lakes of Bhutan adapted from Mool et al., 2001. The mark xx in orange shows the location of Thorthormi Tsho, which was identified as potentially dangerous through other studies*

A joint team comprising of engineers and glaciologist from ICIMOD, DGM, DHMS, DDM, and Gasa Dzongkhag administration conducted a detailed investigation of the breach. The field investigation revealed that the two interconnected supraglacial pond located upstream of the lake had completely drained into Lemthang Tsho (Gurung et al., 2017).

The lake's surface area was found to be 52100 m^2 in 1960s, 76300 m^2 in 2015 and completely breached on 28th June 2015 with an estimated breach volume of 0.37 million m^3. The GLOF was triggered by the sudden drainage of two interconnected supraglacial ponds at the headwater of the lake (Bajracharya, *investigating Lemthang Tsho outburst in Bhutan*) and the team (Gurung et al., 2017) concluded in detail that the two days of incessant rainfall likely to have destabilized the steep scarp due to relative warmer raindrops melting the glacier. This caused the collapsing of the near vertical wall of the supraglacial lakes resulting in emptying of interconnected supraglacial lakes into Lemthang Tsho which in turn caused the GLOF. The team also found that the damming material of Lemthang Tsho consisted of unconsolidated materials mainly of small boulders with loosely packed clayish sand (figure. 4.1). The investigators suggested that lake basin have now become a river basin as the erosional cut were found to be very deep. This lake is excluded from list of PGDLs of Bhutan due to its low probability in forming into a new glacial lake. (Gurung et al., 2017).

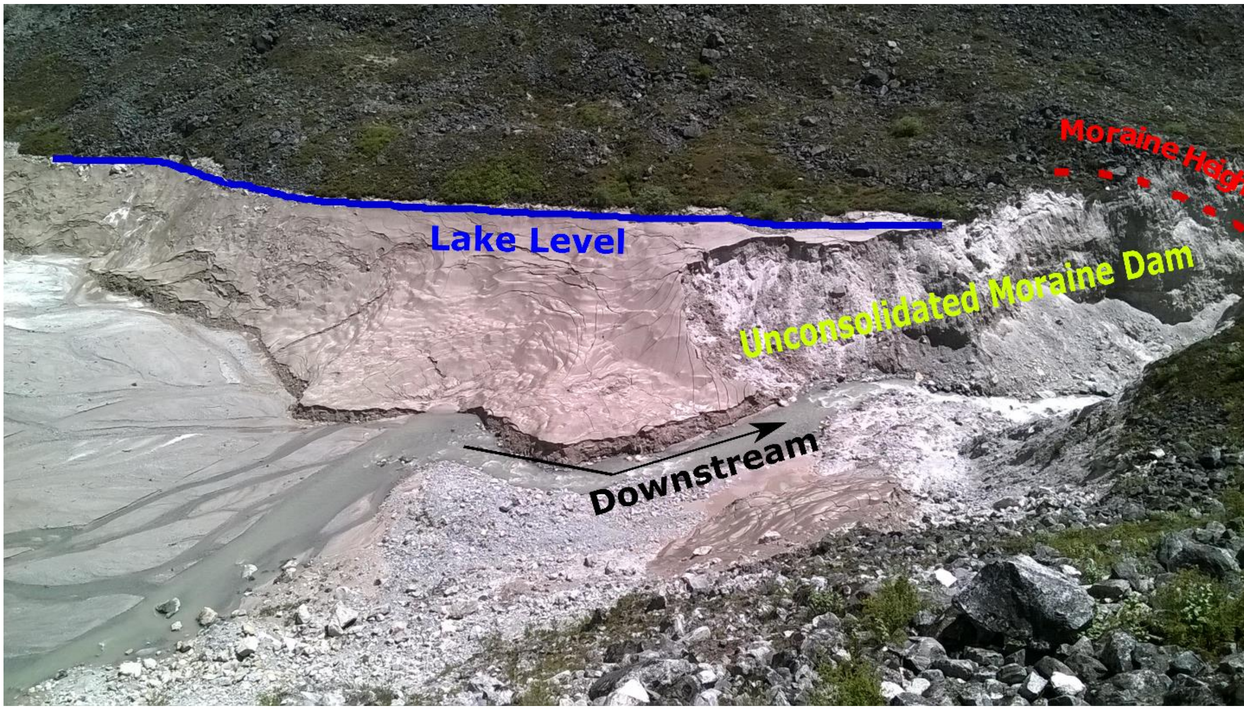

Figure 3.2: *Remnants of Lemthang Lake after the GLOF. Blue line shows the original Lake level and the dotted red line shows the original moraine dam height near the outlet.*

3.1.2 Mo_gl 201

The glacial lake Mo_gl 202 (Mool et al., 2001) is located at latitude 28^{o}07'44.40" and longitude 89^{o}036'31.60" at an altitude of 4380 m a.s.l. in the north western part of Gasa Dzongkhag (No. 2 in Fig.3.1). The cirque glacial lake has ansurface area of 68,138 m^2. The outlet is oriented near East – West and does not have any feeding glaciers. The surrounding topography is steep as revealed from the satellite imageries and this could have been the reason why it was categorized as potentially dangerous lake in the earlier inventory.

The Lemthang lake assessment team also visited this particular lake and scanned the area. On field verification, the lake was found to be stable with all the surroundings vegetated (Fig 3.2) and no sign of any active slides. Though the team did not carry out bathymetry survey, the lake was assumed to be quite shallow especially towards the outlet since the lake bottom was visible. The lake also has a wide and well defined outlet. Later Gurung et al., 2017 suggested that the lake does not pose any immediate threat considering its size, moraine stability, conditions of feeding mother glacier and its surrounding geomorphology. Hence the lake will be removed from the PDGL list.

Figure 3.3: Left: *Photo of Mo_gl 201 showing wide open outlet with stable surrounding conditions;* ***Right:*** *Mo_gl 202 on google earth pro (image date: 17-10-2009)*

3.1.3 Mo_gl 202 (Latshokarp)

The glacial lake Mo_gl 201 (Mool et al., 2001) locally known as Latshokarp is located at latitude 28^{o}06'15.06" and longitude 89^{o}36'55.60" at an altitude of 4434 m a.s.l. in the northwestern side of Gasa Dzongkhag in the headwater of Mo chhu (No. 3 in Fig 3.1). The lake is oriented towards south and is conjoined with the glacier Mo_gr 51 (3.18 km^2). The lake has a surface area of 62,801 m^2. Although this lake did not have sufficient surface area to be deemed potentially dangerous, the presence of feeding glacier within the distance of 50 m upstream and surrounding morphology (from the satellite imageries), the lake was identified as potentially dangerous. In 2015, the technical team who visited Lemthang Tsho also assessed Latshokarp and carried out bathymetry survey along with assessment of surrounding geomorphological settings. Following were the findings by the team:

- The lake water volume was 0.1 million m^3 with surface area of 68,476.5 m^2, maximum depth of 10 m towards the upper reach
- The lake is quite shallow compared to other glacial lakes with relatively flat and wide open outlet (pink rectangular box in Fig.3.4 left).
- The surrounding morphology is fully vegetated and no major changes observed.
- The mother glacier (Mo_gr 51) has rather steep surface and no chances of forming supraglacial ponds.
- Extreme end moraine consists of large boulders with gentle outward sloping.
- Considering such conditions, later Gurung et al., 2017 suggested that the lake does not pose any immediate threat. Hence this lake is also excluded from the PDGL list.

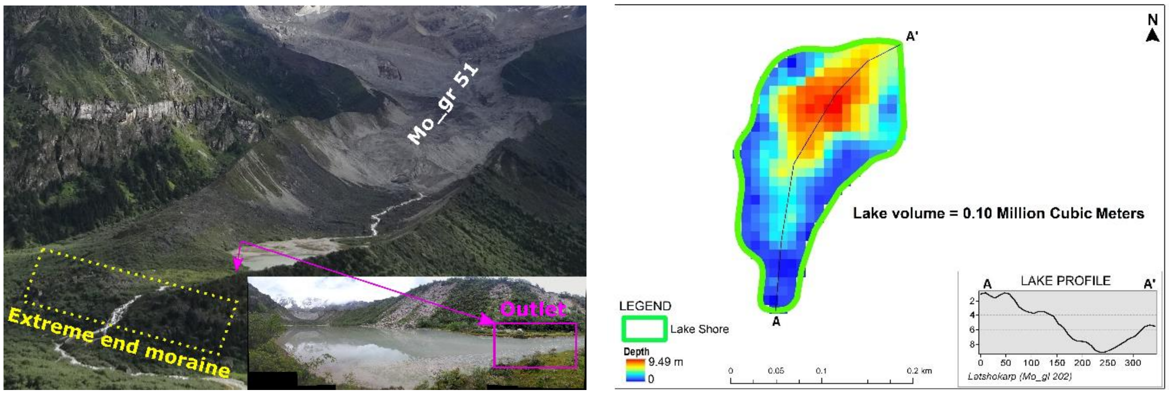

Figure 3.4: Left: *Photo of Latshokarp show the location of Mo_gr 51. The lake has a wide open outlet which is shown in pink rectangular box. Yellow dotted box shows the extreme end moraine.* ***Left:*** *Bathymetry map of the lake with the depth profiles A-A'.*

3.1.4 Mo_gl 234 (Sintaphu tsho)

The glacial lake Mo_gl 234 (Mool et al., 2001) locally known as Sintaphu tsho (named *Setang Burgi Tsho* by Mool et al, 2001) is located at latitude 28^{o}010’6.0” and longitude 89^{o}051’21.1” at an elevation of 4480 m a.s.l. in the north eastern side of Gasa Dzongkhag in the head water of Mo Chhu (No. 4 in Fig. 3.1). It has an average surface area of 238,314 m^2. The Lake outlet is oriented south. This lake was identified based on the criteria of morphology and position of the glacier with respect to the glacial lake. The glacier was found within a distance of 50 m. No subsidiary lake was found during the time of assessing the glacier and glacier lakes of Bhutan in early 2000s. Later in 2011 from the google earth imagery the Supraglacial Lake was observed above the main lake. The Mo_gr 82 glacier having an area of 9.866 km^2 feeds the Supraglacial Lake and the main lakes downstream. In 2016, the lake was assessed in detail under the Time Series Monitoring program for ground verification. The assessment consisted of bathymetry survey, moraine stability study, discharge measurement at the outlet, moraine dam thickness measurement and condition of the dam of subsidiary lake, and checking the conditions on surrounding morphologies. The team (T. Phuntsho and P. Tshering 2016) came out with the following findings

- The total water reserve of the main lake was about 6.2 million m^3, with an average depth of 54 m.
- The supraglacial lake is in the growing stage and attached with the main glacier and feeds the main lake
- The subsidiary lake was found to be 340 m long and 200m wide during the time of carrying out the survey
- The thickness of the moraine which separates the two lakes is 15 m
- No active slides were observed on the lateral moraines/side walls
- Regular monitoring required as rapid growing subsidiary lake may trigger GLOF

Based on the findings and recommendations of the assessment team, the lake will be included in the new list of PDGL.

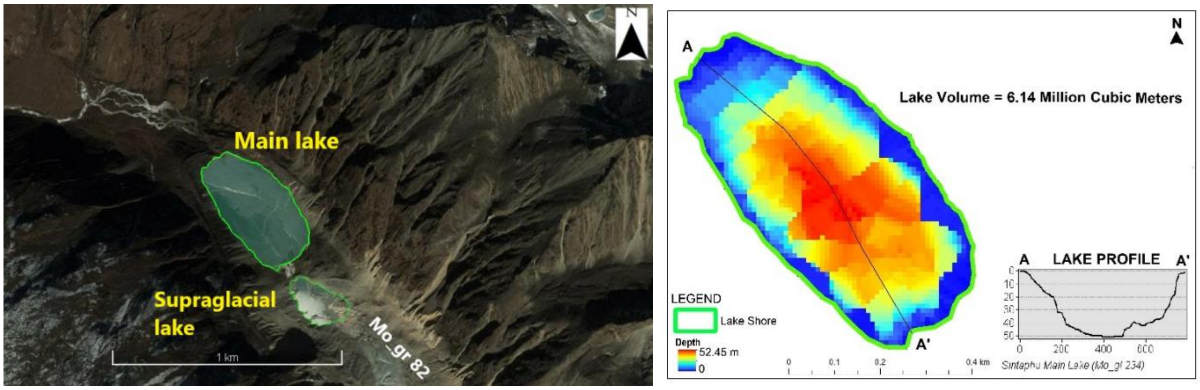

Figure 3.5: Left: *Sintaphu glacial lake and the supraglacial lake on google earth pro image (imagery date: 1-4-2014). The lake boundaries are from the Sentinel 2 image (2016).* ***Right:*** *Bathymetry map of the main lake with depth profile from outlet towards upper reach (A'-A)*

3.1.5 Mo_gl 235

The glacial lake Mo_gl 235 (Mool et al., 1984) is located at latitude 28^{o}08’35.4” and longitude 89^{0}051’21.1” in the north eastern side of Gasa Dzongkhag at the head water of Mo chhu. The lake is situated 4960 m a.s.l. (No. 5 in Fig 3.1), oriented Southwest side and is conjoined with the Mo_gr 84 which feeds the glacial lake. The lake was identified based on the criteria on morphology and condition of the mother glacier. The presence of huge hanging glacier near the glacial lake premises could have been the possible reason for identifying it as potentially dangerous. The surface area of the lake was found to be 128,803 m^{2}.

On May 2016 the team consisting of two officials (T. Phuntsho and P. Tshering) from glaciology division under the DGM’s Time Series Monitoring Activity attempted to visit the lake site but due to the remoteness of the location and the rugged terrain on the way, harsh climatic conditions and time constraints, the team could not reach the glacial lake site during the planned trip. Hence no ground assessment has been carried out till date. However, the team recommended to carry out a detailed field investigation in near future keeping in mind about the rugged terrain and incompatible weather conditions.
As per the latest lake surface area extracted using high resolution Sentinel 2 image, the lake has the surface area exceeding the Mool et al 2001’s threshold area. The glacier is still attached to the lake and hanging glaciers around the lake. Unless, the glacial lake is ground verified, it will be considered to be potentially dangerous based on above criteria.

3.2 Pho Chhu sub-basin

3.2.1 Pho_gl 84

The glacial lake Pho_gl 84 (Mool et al., 2001) is located at latitude 27^{o}56’25.44” and longitude 89^{0}55’48.16” at an elevation of 4997 m a.s.l. in the eastern side of Gasa Dzongkhag, in the head water of Pho Chhu. The outlet of the lake is oriented southwest side and is conjoined with the Pho_gr 8 glacier (0.798 km^{2}) feeding the glacial lake. This lake was identified on the basis of its surface area, presence of hanging glacier above the lake and presence of other lakes in the vicinity (Fig. 3.6, marked with numbers 1-6). The lake had a surface area of 214,078.18 m^{2} in the Mool et al 2001 inventory which used the 1999 IRS 1D imagery. The present sentinel 2 imagery of 2016 reveals the surface area of 742,329 m^{2}. Comparing the surface area obtained using

Sentinel 2 imagery (2016) with IRS 1D (1999), there is a difference of 528,250.82 m^2. Such huge difference could be firstly attributed to the materials (imageries) used for lake outline delineation. Secondly, the lake might have expanded over the years. Taking into account the latter one, the growing lakes over the time are considered as potentially dangerous.

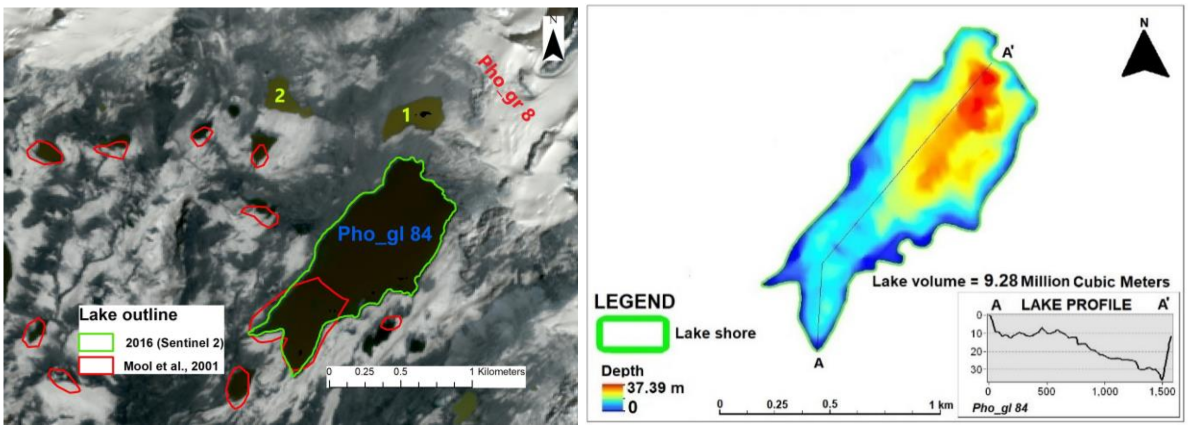

Figure 3.6 :Left: *Pho_gl 84 on Sentinel 2 (2016) with other adjacent lakes and feeding glacier Pho_gr 8. Green and red polygons are the lake outline from Sentinel 2 and by Mool et al., 2001. Number 1 and 2 are the new lakes formed.* ***Right:*** *Bathymetry map of the lake with the depth profile A-A'*

In 2011, a team lead by Dr. Jiro Komori, long term expert for DGM-JICA/JST GLOF project (2009-2012) conducted a bathymetry survey on the lake. It has a maximum depth of 37.39 m with a total volume of 9.3 million m^3. From the lake depth profile, the lake is shallower towards the outlet part and the depth increases gradually towards the upper reach. Over the years, new lakes have formed (marked 1 and 2 in figure 4.5, left) adjacent to the Pho_gl 84.

In the absence of a detailed report addressing its geomorphology, moraine conditions, and its associated glaciers, a detailed study including all the morphological and geotechnical parameter of the lake with field verification is required. Unless the field verifications are conducted, the lake will be included as potentially dangerous due to the following criteria set by Mool et al., 2001:

- Lake surface area exceeds the criteria and have expanded drastically over the years
- Lake volume exceeds the criteria
- Presence and formation of many adjacent lakes
- Presence of hanging glacier above the main lake

3.2.2 Pho_gl 148

The glacial lake Pho_gl 148 (Mool et al 2001) is located at latitude 27°58'11.19" and longitude 89°55'58.57" at an altitude of 5072 m a.s.l. in the eastern side of Gasa Dzongkhag, in the headwater of Pho Chhu (No. 7 in Fig 3.1). It has a surface area of 637,422 m^2. The outlet of the lake is oriented southeast and the lake is conjoined with the Pho_gr 21. This lake was identified based on the morphology, surface area, presence of glacier within 50 m of the lake and adjacent lakes (numbered 1 and 2 in Fig.3.7). Mool et al., 2001 reported the surface area of the lake to be 454,510 m^2, whereas the latest surface area (2016) is estimated at 673,023 m^2. In terms of surface area, there is an increase of 218,513 m^2. As per the criteria by Mool et al., 2001, increase in lake area pose risk. In terms of length, the lake has expanded by 506 m upward.

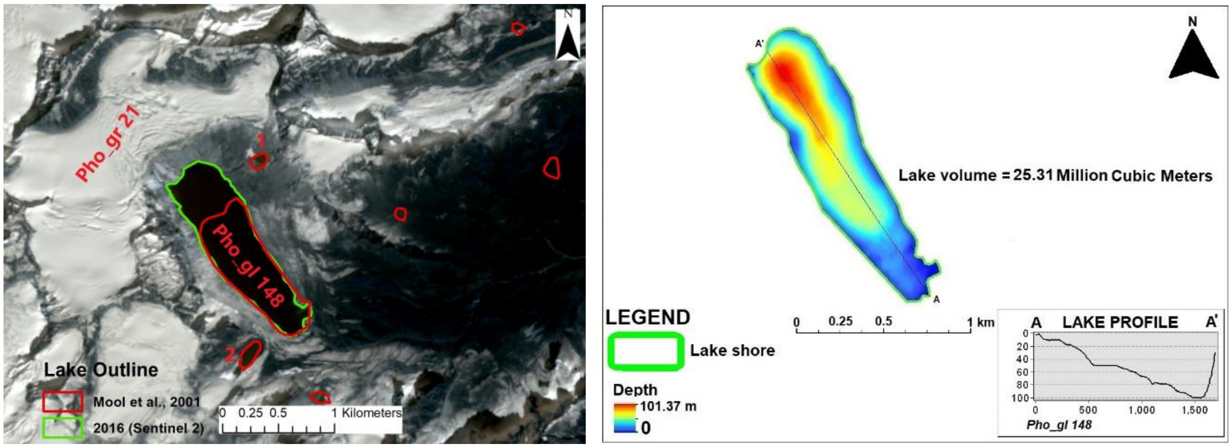

Figure 3.7: Left: *Pho_gl 148 with adjacent lakes lying at higher elevation (1&2) and the feeding glacier Pho_gr 21 which wastes part of it in the form of icefall into the lake. Green and the red polygon shows the lake outline of 2016 (Sentinel 2) and Mool et al., 2001 respectively. Background image is Sentinel 2 (2016).* ***Right:*** *Bathymetry map of the lake with depth profile (A-A'). Lake has shallow depth at the outlet part and deeper towards the upper reach.*

Although no field reports were found, the bathymetry map created from data compiled by Komori and his teams under the DGM-JICA/JST GLOFs project (2009-2012) give us a profile of a lake with a maximum depth of 101 m and a volume of 25.3 million m^3. The lake profile reveals that the lake is shallow towards the outlet. The surrounding morphology consists of high hanging glaciers, and possible active slides.

Since no detailed field study was documented at the site, a detailed study with detail geomorphological parameter of the damming materials is required as the ice calving, avalanche or active slide and outburst of higher lying lakes could possibly be the triggering factor of the GLOF. Until further ground verifications are carried out, the lake will be listed as potentially dangerous.

3.2.3 Pho_gl 163 (Tarina I)

The glacial lake Pho_gl 163 (Mool et al 2001) is located at latitude 28°06'06.43" and longitude 89°54'11.83" at an elevation of 4266 m a.s.l. in the north eastern side of Gasa Dzongkhag in the headwater of Pho Chhu (No. 8 in Fig. 3.1). It has a surface area of 250,813 m^2 (Sentinel 2). The outlet of the lake is oriented south and the lake is in conjoined to Pho_gr 41 (Hanging glacier). Though the lake had a history of breach in 1957 causing GLOF downstream, the lake still has a large surface area and the hanging glacier just above the lake. Such conditions must have let to identification of the lake to be potentially dangerous.

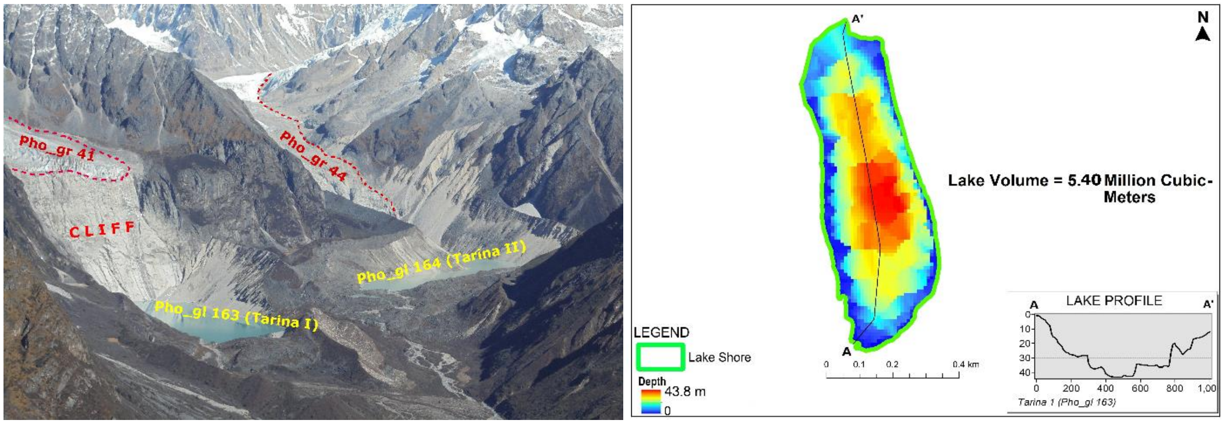

Figure 3.8: Left: *Photo showing Tarina I, Tarina II, Pho_gr 41, Pho_gr 44 and the Cliff along which the Pho_gr 41 feeds Tarina I in the form of ice fall.* ***Right:*** *Bathymetry map of Tarina I along with the depth profile from the outlet towards upper reach of the lake (A-A')*

Tarina Valley lakes were first mentioned by Augusto Gansser in his small assessment reporting the glacier variation and GLOF risk from the lake but no detail studies were done until 1998 when the first reconnaissance survey under the Bhutan-Japan collaboration project took place at Tarina valley. Similarly, during the last phase (Phase IV) of the joint Austria-Bhutan collaborative project undertook a detail study of the lake.

Later, under the Activity of Annual Time Series Monitoring of Glacial lakes, the lake was monitored in 2003 and 2016. The 2016 monitoring team carried out field surveys including bathymetry survey, detailed topographic survey of the moraine dams, geotechnical studies of the damming materials and other geomorphological studies. Through their studies, the team found that:

- The lake has the surface area of 248,200 m^2
- It has a maximum depth of 43 m
- The lake water volume is 5.4 million m^3
- Terminus of the glacier (Pho_gr 41) wastes ice through ice fall to the lake (hanging glacier)
- The end moraine materials are gravelly sandy type with very little or no cohesive strength

Based on above ground verifications such as the lake surface area, lake volume, existence of hanging glaciers and the geotechnical parameters of the end moraines, the glacial lake will be categorized as potentially dangerous.

3.2.4 Pho_gl 164 (Tarina II / Mozum Tsho)

The crescent shaped glacial lake Pho_gl 164 (Mool et al., 2001) locally known as Mozum Tsho (Tarina lake II) is located at latitude 28^{o}06'37.81" and longitude 89^{0}05'37.81" at an elevation of 4338 m a.s.l. in the north eastern side of Gasa Dzongkhag, headwater of Pho Chhu (No. 9 in Fig. 3.1). It has a surface area of 446,325 m^2 (Sentinel 2). The lake outlet is oriented Southwestern side and is conjoined with the Pho_gl 44/67 which feeds the glacial lake. A small subsidiary lake, Pho_gl 165 (Tarina lake III) right above the left lateral moraine also feed the glacier in the form of seepage. This lake seems to have been identified due to its large surface area, presence of adjacent glacial lake (Tarina III) located just above the left lateral moraine and the steep lateral moraines.

Tarina Valley lakes was first mentioned by Augusto Gansser where he had written small assessment reporting the glacier variation and GLOF risk from the lake but no detail studies were done until 1998 when the first reconnaissance survey under the Bhutan-Japan collaboration project took place at Tarina valley. Similarly, during the last phase (Phase IV) of the joint Austria-Bhutan collaborative project undertook a detail study of the lake.

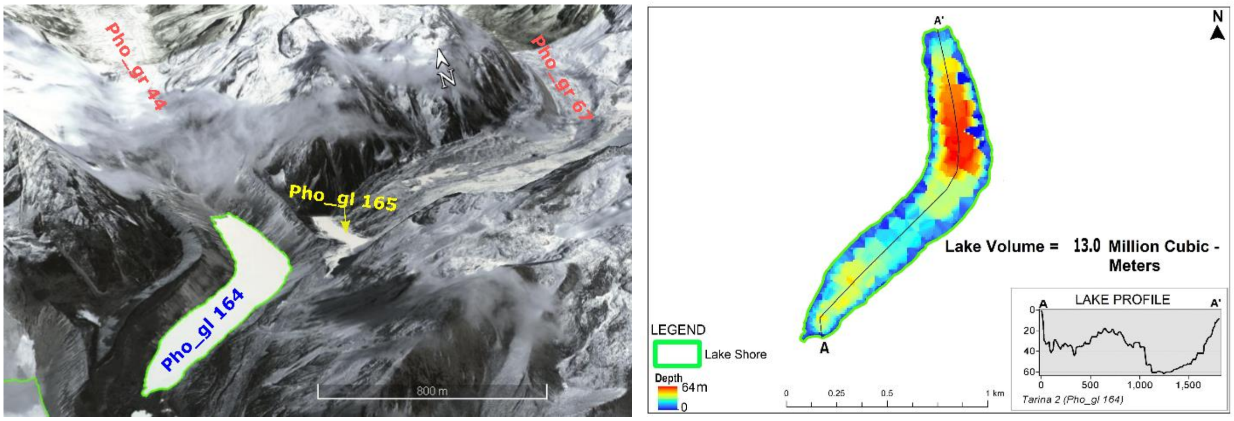

Figure 3.9: Left: *Google image of Pho_gl 164 (Tarina lake II) and Pho_gl 165 (Tarina lake III) along with the feeding glaciers Pho_gr 44 and Pho_gr 67 respectively.* ***Right:*** *Bathymetry map of Tarina lake II along with the depth profile from outlet to the upper reach (A-A')*

Later, under the Activity of Annual Time Series Monitoring of Glacial lakes, the lake was monitored in 2003 and 2016. The 2016 monitoring team carried out field surveys including bathymetry survey, detailed topographic survey of the moraine dams, geotechnical studies of the damming materials and other geomorphological studies.

Through their studies, the team found that:

- The lake has the surface area of 476,300 m^2 but the lake volume has not changed much since 2002
- It has a maximum depth of 67.5 m
- The lake water volume is 13.0 million m^3
- The Pho_gr 67 and Pho_gr 44 has retreated way upstream and doesn't pose direct impact
- The end moraine materials are gravelly sandy type with very little or no cohesive strength
- Tarina lake III have a weak moraine with lots of *seepage points* and has high possibility of destabilizing the moraine dams which contains unconsolidated materials
- Tarina lake III was found to have sessional change of the shorelines due to difference in inflow and outflow of the lake indicating a piping between the main lake and Tarina lake III
- Possibility of dam failure of Tarina III might trigger GLOF of the main lake

Based on the above field findings, Mo_gl 164 (Tarina lake III) will be categorized as potentially dangerous.

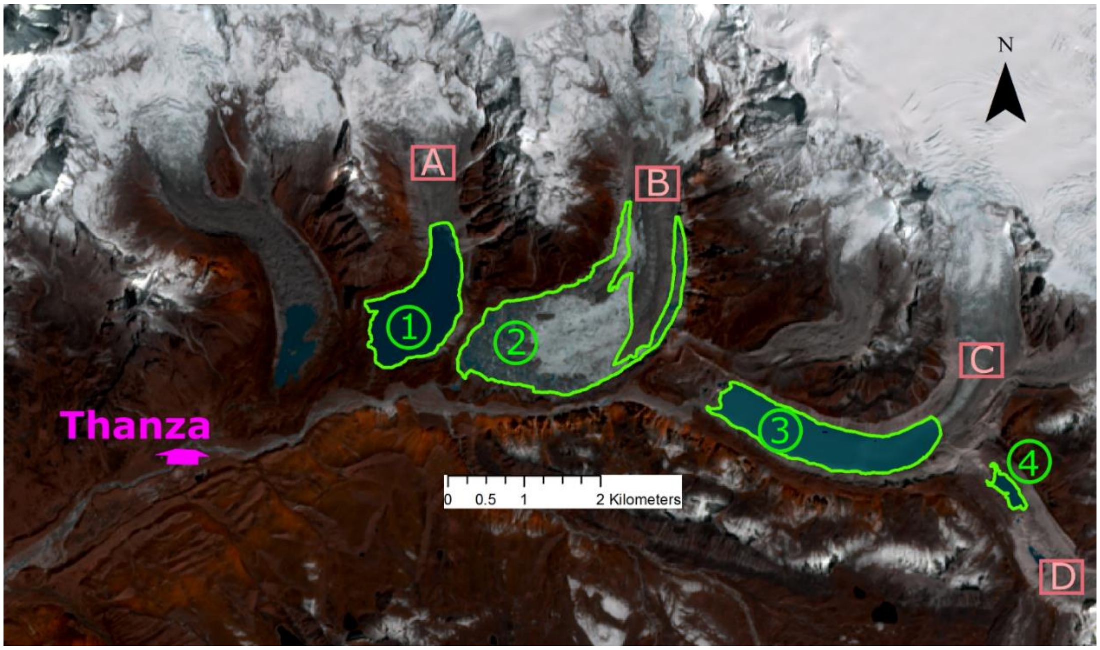

Figure 3.10*: Glacier and glacial lakes in the Lunana region. Circled numbers 1 - 4 are Pho_gl 209 (Raphstreng), Pho_gl xx (Thorthormi), Pho_gl 210 (Lugge) and Pho_gl 2011 (Drukchung) respectively. Letters A – D in the box are the glaciers feeding the main lakes (Pho_gr 83, Pho_gr 84, Pho_gr 86 and Pho_gr 87 respectively).*

3.2.5 Pho_gl 209 (Raphstreng)

The glacial lake Pho_gl 209 (Mool et al., 2001) locally known as Raphstreng Tsho is located at latitude 28^{o}06'43.56" and longitude 90^{0}014'3.65" at an elevation of 4368 m a.s.l. in the north eastern side of Thanza village under Gasa Dzongkhag (No. 10 in Fig. 3.1and circled no. 1 in Fig.3.10). It is oriented Southwest side and is conjoined with the Pho_gl 83 (letter A in Fig. 3.10) which feeds the glacial lake. This lake is one of the largest lake in the Lunana area measuring a surface area of 1,241,970 m^2 (Sentinel 2)**.** This glacial lake could have been identified due to its surface area, feeding glacier and the surrounding morphology.

Numerous field studies were taken up on glacier and glacial lakes of Lunana region by different joint collaboration teams. Under the WAPCOS consultant funded by GOI and RGoB in collaboration with DGM undertook a mitigation project (1995-1998) where the subsidiary lakes below the lake were drained out and the lake level was lowered by 4 m. Later this project was continued by the Austrian - Bhutan joint team where many detailed study of the lake was done by experts. After that several monitoring have already taken place and this lake is constantly monitored by erstwhile Glaciology Division under DGM.

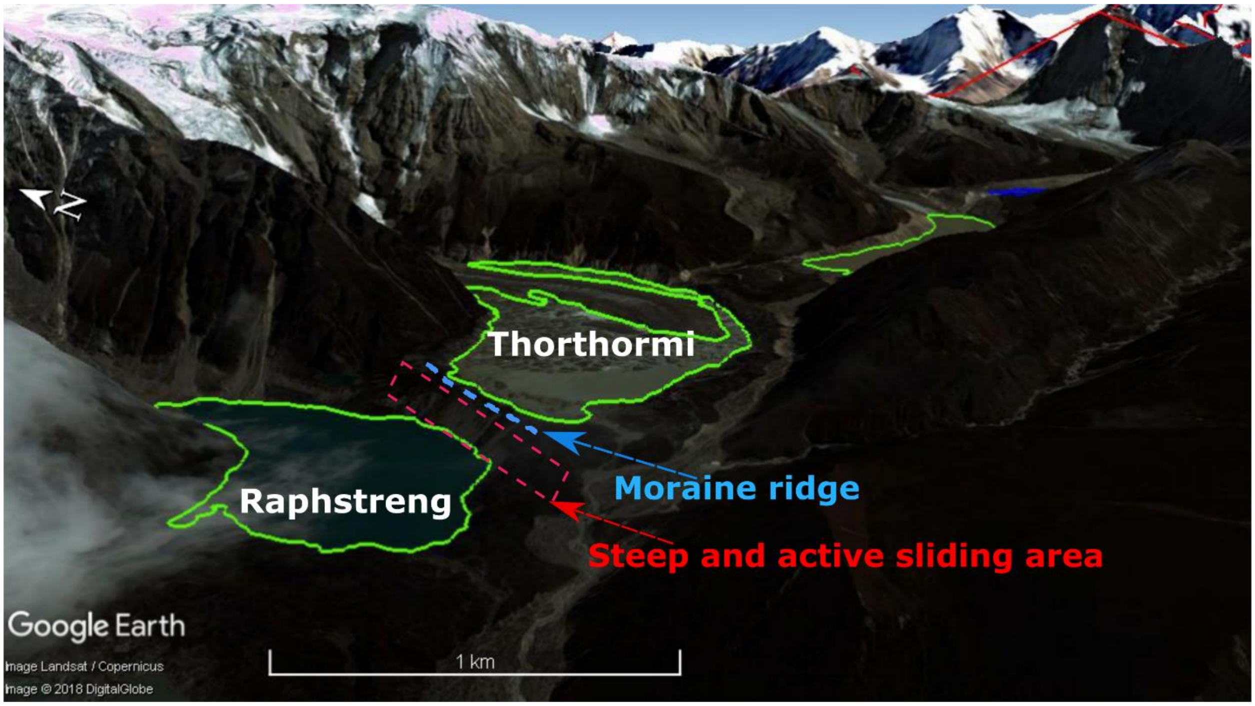

Figure 3.11: *Raphstreng and Thorthormi lakes showing the location of thin and active moraine barrier*

From the latest literature although the glacier feeding the lake have retreated and hit the bed rock, the Raphstreng- Thorthomi moraine which is thinning due to active sliding pose risk. In 2008, the Thorthormi lake mitigation team conducted detailed survey in the vicinity. An electrical resistivity survey to investigate ice core was conducted along the moraine ridge separating Raphstreng and Thorthormi. The result revealed that the moraines were not continuously underlined by dead ice however the presence of ice lenses or highly unconsolidated boulders pose risk. Moreover, the zone of active slides was observed on the Thorthormi side indicating unstable moraine. Under such scenarios, researchers have suggested that the fast developing Thorthormi lake in future might collapse into Raphstreng lake causing huge outburst. If it happens, the worst case estimated flood volume was 53 million m^3 of water. Under the DGM-JICA/JST GLOF project, bathymetry survey was conducted on Raphstreng lake (Fig. 4.11) and the result is presented here with the lake water volume extracted using the same data set. Raphstreng lake has an estimated water volume of 55 million m^3. It has a relatively deep part at the outlet area and deeper towards the upper reach. According to the latest literatures and based on the lake surface area, lake volume and the surrounding morphological characteristics, Raphstreng lake will be categorized as potentially dangerous.

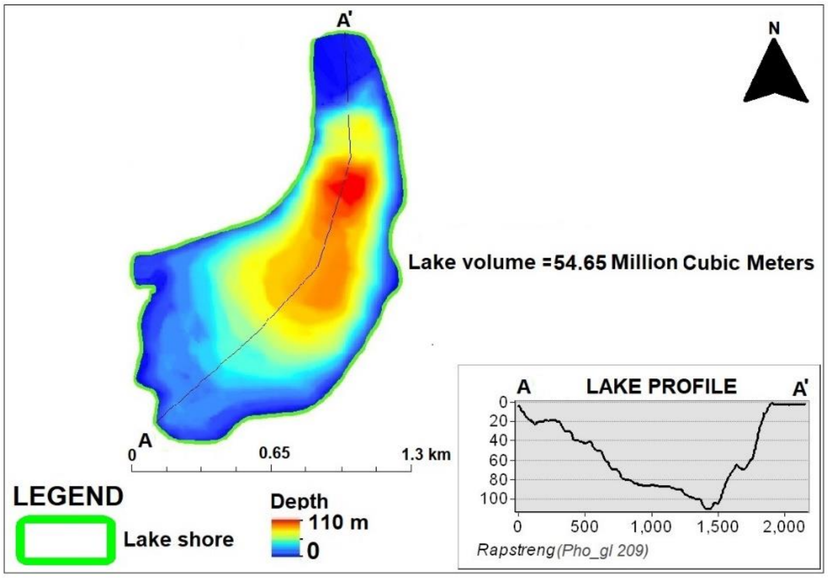

Figure 3.12: *Bathymetry map of Raphstreng lake along with the depth profile (A-A')*

3.2.6 Pho_gl xx (Thorthomi)

The unassigned glacial lake name in the inventory by Mool et al., 2001, locally known as Thorthormi lake is located at latitude 28^{o}06'19.90" and longitude 90^{0}15'48.46" at an elevation of 4446 m a.s.l. in the north eastern side of Lunana under Gasa Dzongkhag (No. xx in Fig. 3.1 and 2 in Fig.3.10). The lake is in the process of developing into a full moraine dammed glacial lake and has no definite surface area due to major and moving ice bodies. Roughly (polygon 2 in Fig. 3.10), the surface area is approximately 2,908,490 m^2. The outlet is oriented South side and is conjoined with the Pho_gl 83 which feeds the glacial lake (Letter B in Fig 3.10). Thorthormi glacial lake is one of the fastest growing lakes in the recent times.

During the Austro-Bhutanese joint project from 1999 to 2002 (*Hausler.H et al, 2000*), a detailed investigation was carried on the retreating Thorthomi Glacier, and found that the glacier was retreating at accelerating pace hence they proposed a detailed study of the proglacial lake. Hence this lake was then added in the PDGL list.

Later in 2005-2007 the detail study of the lake was undertaken under the Time series Monitoring by the erstwhile Glaciology Division, DGM. During the 2005 expedition, the team found that the three proglacial lake were expanding at an accelerated rate and the thinning of the Raphstreng-Thorthormi moraine was noticed. The assessments in the area concluded that the fully developed Thorthormi lake might overtop into Raphstreng causing huge GLOF. So in 2008 the Thorthomi mitigation project was undertaken by RGOB in partner with UNDP under the GEF project funded by LDCF and co-financed by GoA, WWF Bhutan and RGoB. The main objective of the project was to lower the lake level so that the hydrostatic pressure towards the Thorthormi-Raphstreng moraine would be minimized. Through the 5-year long project the lake water level was lowered by 5 m as recommended by the Austrian -Bhutan joint team in 2003.

This lake has now expanded rapidly in the recent decade and is one of the critical lake that might outburst in near future. This lake is currently being monitored under the Time series Monitoring Activity of CSD division under NCHM. As per the recent available literatures on Thorthormi lake and the criteria by Mool et al., 2001 on fast growing lakes, Thorthormi lake will be included in the updated potentially dangerous lakes.

3.2.7 Pho_gl 210 (Lugge Tsho)

The glacial lake Pho_gl 210 (Mool et al 2001) locally known as Lugge Tsho is located at latitude 28^{o}05’00.34” and longitude 90^{0}018’28.58” at an elevation of 4507 m a.s.l. in the north eastern side of Lunana village under Gasa Dzongkhag (No. 11 in fig. 3.1 and 3 in Fig.3.10). It is oriented North West side and is conjoined with the Pho_gl 86 (letter C in Fig.3.10) which feeds the glacial lake. The lake had the surface area of 769,799.72 m^2 in 2001 whereas the current surface area is 1,460,870 m^2.

The lake is one of the largest lake in the Lunana complex and have already breached on 7th October 1994 killing 20 people and damaging million worth of infrastructure downstream (WWF). There are many theories on why the lake breached. The rapid drainage from Drukchung Tsho (No. 4 in Fig.3.10) has probably caused the sudden rise in Lugge Tsho causing the failure of the left lateral moraine (Leber & Haussler, *Report on Lugge Tsho GLOF project*, 2000). The collapse of the right bank of the moraine into the lake (ice avalanche or landslide) could have possibly triggered the 1994 Lugge GLOF (Fujita et. al,2008).

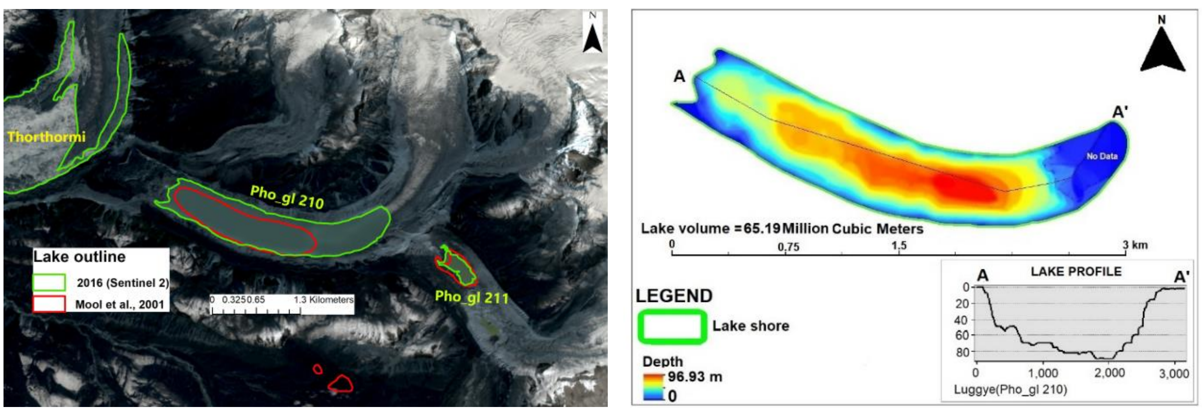

Figure 3.13: Left: *Mo_gl 210 (Lugge Tsho) on Sentinel 2 image. Green and red polygon are the Lake Outline from Sentinel 2 (2016) and Mool et al., 2001. Pho_gl 211 is Drukchung lake.* ***Right:*** *Bathymetry map of Lugge lake (data from 2011). Due to lack of data coverage towards the upper reach, the depth interpolated is lesser.*

Later in 2005 and 2007 the team under the Time series monitoring activity under took a study of the lake. They found that the lake had a narrow outlet having a width of 5 m and active sliding from the left lateral moraine. Hence there is a chance of blockage in the future with changing condition. The glacier, Pho_gr 86 (marked C in Fig.3.10) was also found to be retreating at abnormal rate due to water seeping into the Lugge left glacier causing rapid ablation. The PDGL Pho_gl 211 (Drukchunhg tsho) exists just above the Lugge lake. The bathymetry map was generated from the bathymetry survey data (2011) obtained from DGM-JICA/JST GLOF project and has the water volume of about 65.19 million m^3.

The current scenario of Lugge lake is that:

- It still has relatively deep bottom topography towards the outlet

- It has expanded by 1,050 m longitudinally from 2001 to 2016 where by increasing the surface area by 691070.28 m^2. On the other hand, the feeding glacier is retreating fast
- It has substantially high water volume
- The topography around the lake is changing and narrowing at the outlet region
- An adjacent lake (Drukchung lake) lies above the Lugge lake which might trigger GLOF

Based on such ground verifications, the lake will be categorized as potentially dangerous and recommended for further monitoring of the area.

3.2.8 Pho_gl 211 (Drukchung Tsho)

The glacial lake Pho_gl 211 (Mool et al., 2001) locally known as Drukchung Tsho is located at latitude 28^{o}05'40.45" and longitude 90^{0}018'11.95" at an elevation of 4701 m a.s.l. in the north eastern side of Thanza valley under Gasa Dzongkhag (No. 12 in Fig 3.1 and 4 in Fig. 3.10). The outlet is oriented North West side and is conjoined with the Pho_gl 87 (D in Fig.3.10) which feeds the glacial lake. Another supraglacial lake lies above Drukchung lake (A in figure 4.13) and Lugge lake lies just below this lake. The surface area of the lake was 101,096 m^2(sentential 2)

This lake must have been identified based on its morphology and glacier situated 50 m within the lake by the Mool et al., 2001 inventory.

Leber & Haeusler (*report on Lugge Tsho GLOF project, 2000*), pointed out Drukchung lake to be one of the triggering factor for the 1994 Lugge GLOF. In 1994 when the supraglacial pond above Drukchung emptied leading to increase in lake volume in Drukchung and hence minor GLOF occurred from it. This GLOF might possibly have triggered the 1994 Lugge Tsho outburst as the lake presides right above the Lugge glacier (Leber & Haeusler, *2000*).

Later in 2005 and 2007 the team from the erstwhile Glaciology Division under DGM, monitored all the lakes in lunana area. They located supraglacial ponds above the lake with floating ice bodies due to calving process. No bathymetry survey has been carried out on the lake so far. At present the presence of supraglacial lake just above Drukchung (marked with A in Fig.3.14) might again trigger similar incidences to that of 1994. In particular, Drukchung alone may not be so hazardous but in combination with Lugge lake, the lake is potentially dangerous.

Hence a detailed study consisting of bathymetry survey, geotechnical studies and discharge measurement are need in the future field work. And this lake will be needing a constant monitoring as it will be added in the new PDGL inventory.

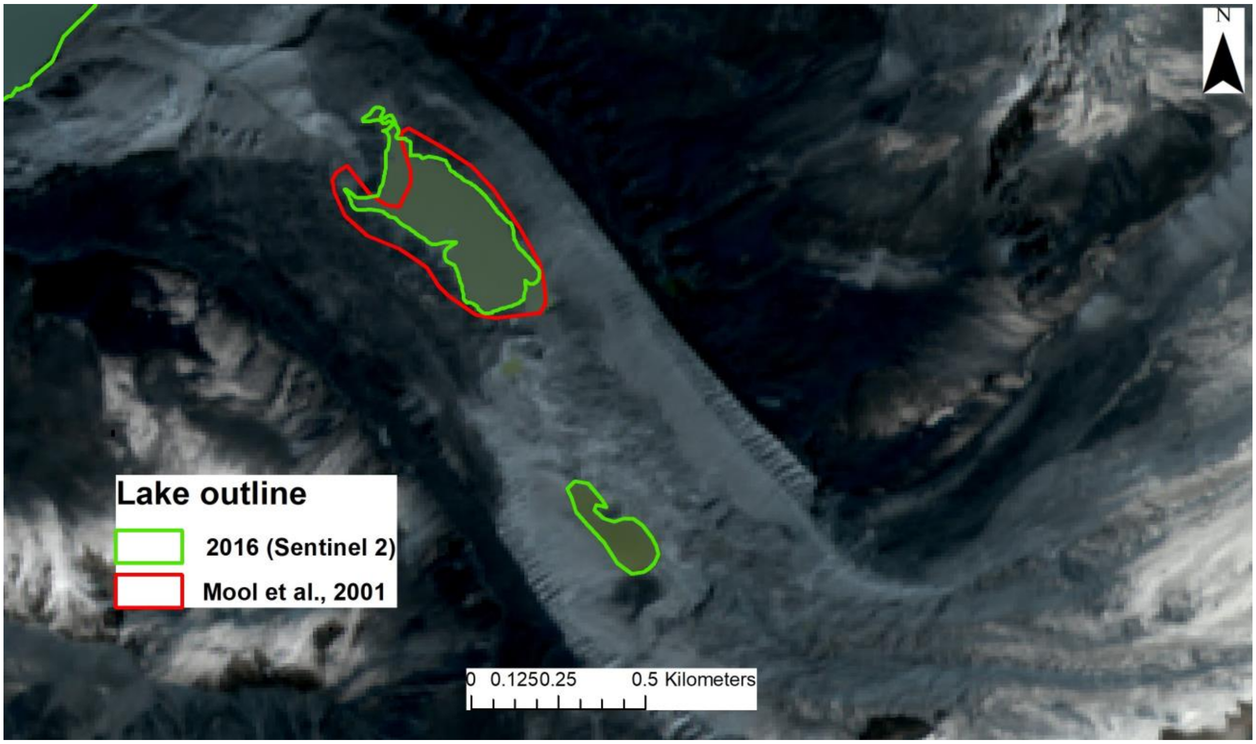

Figure 3.14: *Pho_gl 211 (Drukchung lake). Green and the red polygons are the lake outline from Sentinel 2 (2016) and Mool et al., 2001. Letter A is the suptraglacial lake above Drukchung lake*

3.2.9 Pho_gl 313

The glacial lake Pho_gl 313 (Mool et al., 2001) is located at latitude 27^{o}59’19.03” and longitude 90^{0}07’50.91” at an elevation of 5049 m a.s.l. in the north eastern side of Gasa Dzongkhag (No. 13 in Fig. 3.1). It is oriented South East side. In the inventory, the lake has a surface area of 222,134.80 m^2 and 211,705 m^2 by Sentinel 2 (2016) imagery. This lake might have been identified based on presence of hanging ice just above the lake and the presence of other adjacent lakes lying above the main lake level (marked 1 – 3 in Fig.3.15) and also series of bigger lakes downstream (marked A, B in Fig. 3.15) by Mool et al., 2001.

Due to lack of access to the site, no field study has been carried out so far. However, by comparing the surface area by Mool et al., 2001 and the surface area delineated from Sentinel 2 (2016) imagery, there is not much of changes (2001 – 2016). The present scenario of the lake is:

- It has the surface area exceeding more than 100,000 m^2
- There are many adjacent lakes including series of other lakes downstream
- Big glacier mass lying above the glacial lake

Based on such findings, the lake will be included in the updated potentially dangerous glacial lakes.

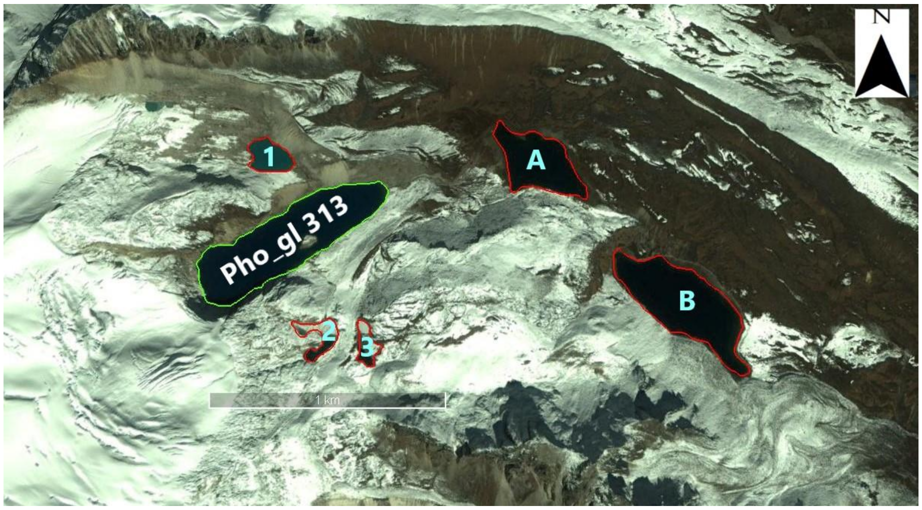

Figure 3.15: *Pho_gl 313 on google earth pro image (2002) along with series of lakes downstream (A, B) and other adjacent lakes lying above the lake level (1, 2, 3)*

3.3 Mangde Chhu sub-basin

3.3.1 Mang_gl 99 (GLT 9)

The glacial lake Mang_gl 99 (Mool et al 2001) coded as GLT 9 (*Ageta, Y. and Iwata, S., 1999*) is located at latitude 28^{o}06'43.56" and longitude 90^{0}014'3.65" at an elevation of 5155 m a.s.l. in the north western side of Trongsa Dzongkhag on Gangrinchezoe plateau (No. 14 in Fig. 3.1). It is oriented Southwest side and is conjoined with the Mang_gr 7 which feeds the glacial lake. Mool et al., 2001 reported the surface area of 192,607.3 m^2 and the recent Sentinel 2 (2016) image reveals the surface area of 228,905 m^2.The Japan-Bhutan joint research team (*Ageta, Y. and Iwata, S., 1999*) did a detailed study on the glacial lakes on the Gangrinchenzoe plateau. The Mang_gl 99 (GLT 9), like many other lakes in the Gangrinchenzoe plateau were found to have:

- Relatively little water volume in shallow lake basin
- The glaciers feeding the lake was found to have no risk for avalanche or rock fall because of gentle glacier basin,
- The relative height between the lake levels and the local basin levels were small
- Wide and flat valley bottoms, extending downstream the lake serves as retention basins

Hence with all the above findings they concluded that the lake does not pose any risk of outburst flood in future.

Later under the DGM-JICA/JST GLOF project (2009 – 2012), lake bathymetry survey was conducted on Mang_gl 99 and showed a maximum depth of 51.72 m with a total volume of 4.70 million m^3 (Fig.3.16 right). The present scenarios is that:

- The lake did not change its surface area much (36,297.4 m^2) (refer Fig.3.16 left)
- The feeding glacier (Mang_gr 7) has retreated further upward and has a gentle glacier morphology
- The surrounding morphology is rather flat and no possibility of sliding

Based on the findings by *Ageta, Y. and Iwata, S., 1999* and from the current analysis, the Mang_gl 99 will be deemed safe and removed from the list of potentially dangerous glacial lakes.

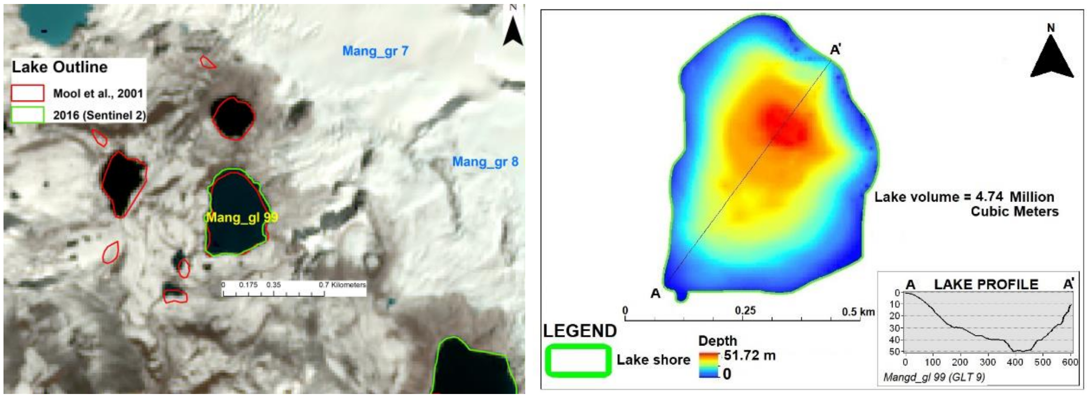

Figure 3.16: Left: *Mang_gl 99 with feeding glacier Mang_gr 7. Green and red polygons are the lake outline from Sentinel 2 (2016) and Mool et al., 2001.* ***Right:*** *Lake bathymetry map of Mang_gl 99 along with the lake depth profile from outlet to upper reach (A-A’)*

3.3.2 Mang_gl 106 (Metatshota)

The glacial lake Mangd_gl 106 (Mool et al., 2001) locally known as Metatshota is located at latitude 28^{o}053’06.43” and longitude 90^{0} 017’33.94” at an elevation of 5065 m a.s.l. in the north western side of Trongsa Dzongkhag in the headwater of Mangde Chhu (No. 15 in Fig. 3.1). Its outlet oriented southwest and is conjoined with the Mang_gr 5 which feeds the glacial lake. The Mang_gl 5 has numerous ice cliffs which wastes its mass in the form of ice fall into the lake. Due to the presence of such hanging glaciers, surface area and surrounding steep morphology might have attributed for the identification of the lake as potentially dangerous in the inventory by Mool et al., 2001. The inventory reported the surface area of 868,294 m^2 whereas the Sentinel 2 (2016) imagery reveals the surface area of 1,203,880 m^2 showing the difference of about 335,586 m^2. The material used by Mool et al., 2001 was IRS 1D of 1999.

Under the DGM-JICA/JST GLOF project (2009 – 2012), lake bathymetry was conducted in 2009. Later, within the same project, the lake was covered for the risk assessment of GLOF on the Mangde Chhu river basin. They concluded that:

- The total water volume to be 41 million m^3 with maximum depth of 120 m
- The frontal basin near the outlet is less than 40 m deep
- The moraine dam near the outlet has been deeply eroded so the actual height of the dam crest from the frontal plain is only 25 m
- Downstream slope of the moraine dam is gentle with crest width of 110 m
- No dam breach event could be generated for any amount of inflow up to 5,000 m^3/sec
- The breach potential of Mang_gl 106 (Metatshota) lake is definitely low at the moment but considering the large amount of water stored in the lake basin, and the changes that might take place on the outlet moraine dams, probable large scale scenario of a GLOF in the Mangde Chhu river basin.

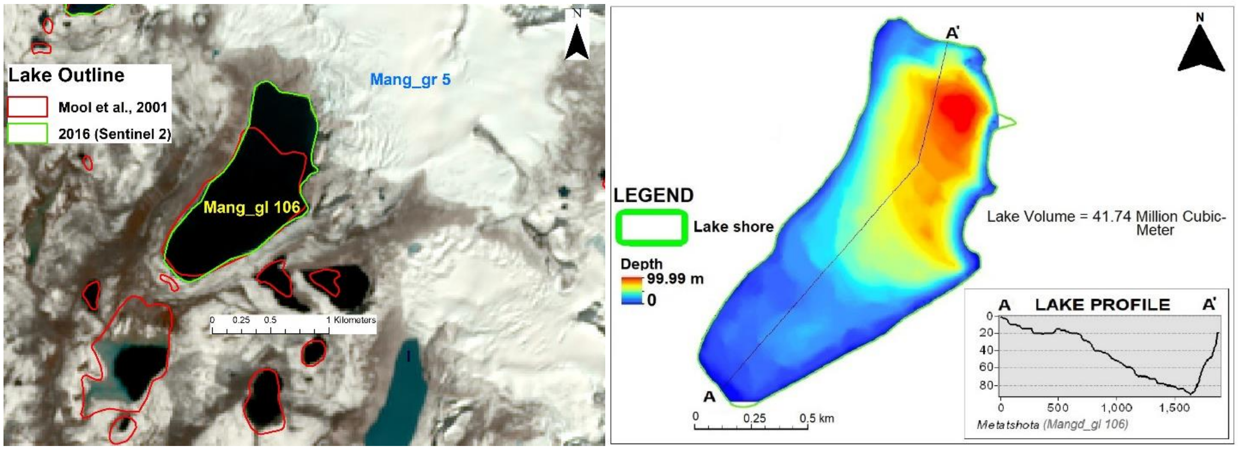

Figure 3.17: Left: *Mang_gl 106 (Metatshota) delineated using Sentinel 2 of 2016 (Green) IRS 1D of 1999 (Mool et al., 2001).* ***Right:*** *Lake bathymetry map prepared using the data set of 2009 (DGM-JICA/JST GLOF Project) along with depth profile A-A'*

At present, the scenario in and around Metatshota Lake is that:

- It has the large surface area
- It has large amount of water stored
- Large area of hanging glacier which wastes the mass in the form of ice fall into the lake (Fig.3.18)

Figure 3.18: *Metatshota lake with hanging glacier above (Mo_gr 5)*

Taking into consideration the large amount of water stored and surrounding morphology (hanging glacier), the glacial lake will be included in the list of potentially dangerous glacial lakes.

3.3.3 Mang_gl 270 (Zanam F)

The glacial lake Mang_gl 270 (Mool et al., 2001) coded as Zanam F by DGM-JICA/JST GLOF project team (2009 – 2012) is located at latitude 27^{o} 58'9.32" and longitude 90^{0}20'6.89" at an altitude of 5311 m a.s.l. in the north eastern side of Trongsa Dzongkhag, headwater of Mangde Chhu (No. 16 in Fig. 3.1). It is oriented east-west and is conjoined with the Mang_gr 51 which feeds the glacial lake. Its surface area reported by Mool et al., 2001 is 239,778.31 m^2. The lake could have been identified as potentially dangerous based on its surface area, existence of glacier within the distance of 50 m and the outlet moraine features.

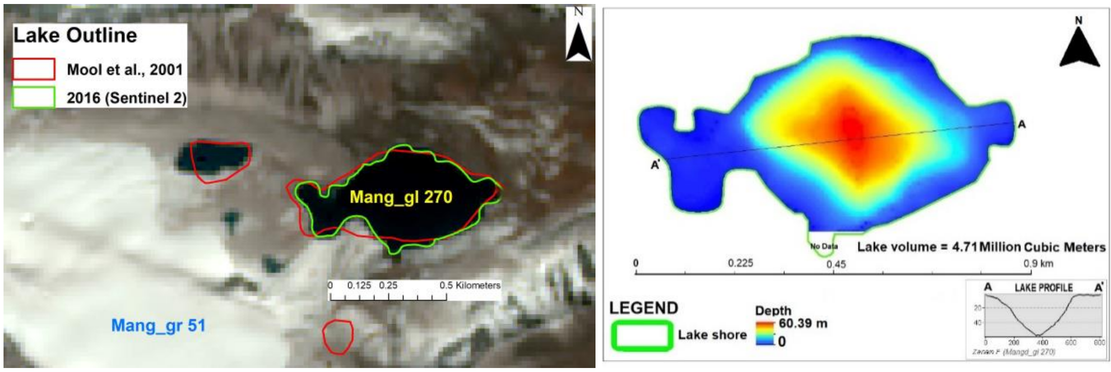

***Figure 3.19: Left:** Mang_gl 207 (lake Zanam F) on Sentinel 2 (2016) image with lake polygons of Mool et al., 2016 (red) and Sentinel 2 (2016). **Right:** Lake bathymetry map with depth profile (A-A').*

First ever field survey of the lake was conducted in 2009 by DGM-JICA/JST GLOFs project. Lake bathymetry was carried out and the lake water was calculated to be 4.7 million m^3 with a maximum depth of 60.4 m. No detailed report was documented. Current scenario of the lake is that:

- The surface area is 223,163 m^2 and no surface area difference observed from 2001 to 2016 (Fig.3.19, left)
- The feeding glacier (Mang_gr 51) has retreated further upstream and has a gentle glacier morphology
- Wide and gentle surrounding topography with no active slides
- Shallow depth towards outlet (Fig.3.19, right)
- Moraine dam conditions are firm and no changes observed

Though the surface area exceeds 100,000 m^2, based on other surrounding conditions the lake will be deemed safe and will be removed from the list of potentially dangerous glacial lakes.

3.3.4 Mang_gl 285 (Zanam E)

The glacial lake Mang_gl 285 (Mool et al., 2001) coded as Zanam E by DGM-JICA/JST GLOF project team (2009 – 2012) is located at latitude $28^{o}0'20.90"$ and longitude $90^{0}19'50.77"$ at an elevation of 5370 m a.s.l. in the northern east of Trongsa Dzongkhag, in the headwater of Mangde Chhu (No. 17 in fig. 3.1). It is oriented South and is fed by Mang_gr 57 glacier having a surface area of 1.579 km^2. Mool et al., 2001 reported the lake surface area of 341,412 m^2 whereas lake surface area delineated from Sentinel 2 (2016) reveals 342,874 m^2. The lake must have been identified as potentially dangerous on the basis of hanging glacier (Mang_gr 57 in Fig.3.20) found within 50 m upstream and the lake surface area (341,412 m^2).

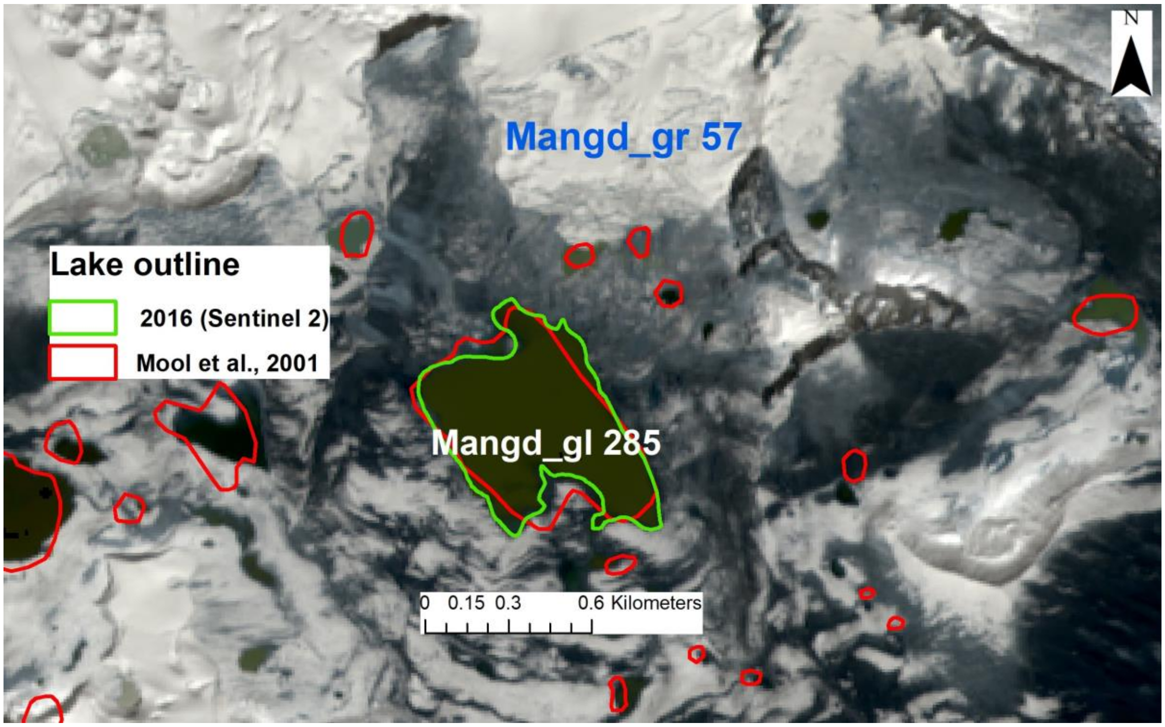

Figure 3.20: *Mang_gl 285 (Zanam E) with feeding glacier Mang_gr 57. The red and green polygons are the lake outline by Mool et al., 2001 and delineated from Sentinel 2 (2016) respectively.*

No field studies have been done so far at this site by any officials. But as per the desktop studies it was found that the lake has:

- Large feeding glacier area with gentle glacier morphology
- The surface area of 342,874 m^2
- Surface area has not changed from 2001 to 2016 which indicates the lake is stable
- Flat and wide surrounding topography with no triggering factors such as active sliding

Based on such conditions, the lake will be deemed safe and will be removed from the list of potentially dangerous glacial lakes.

3.3.5 Mang_gl 307 (Zanam B)

The glacial lake Mang_gl 307 (Mool et al., 2001) coded as Zanam B by DGM-JICA/JST GLOF project team (2009 – 2012) is located at latitude 28^o1’40.51” and longitude $90^0$21’58.87” at an elevation of 5208 m a.s.l., in the north eastern side of Trongsa Dzongkhag in the headwater of Mangde Chhu (No. 18 in Fig.3.1). It is oriented Southwest side and is conjoined with the Mang_gr 65 which feeds the glacial lake. The surface area of the lake was reported to be 767,429.09 m^2 (Mool et al., 2001). Another glacial lake (Mang_gl 303, coded as Zanam A) having the surface area of 477,649 m^2 lies just above the lake at the crest width of 20 m and at the vertical height difference of 55 – 60 m (google earth pro). From the Sentinel 2 (2016) imagery, the lake surface area is about 862,181 m^2. The lake might have been included in the inventory (Mool et al., 2001) on the basis of feeding glacier partly attached to the lake and party feeds in the form of icefall, presence of glacial lake (Zanam A) just above the main lake which is also fed by another glacier within the vicinity of 50 m.

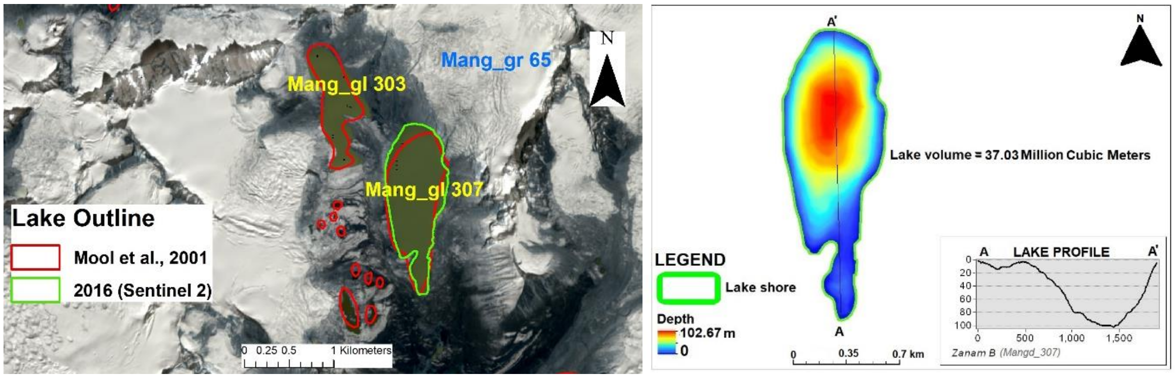

Figure 3.21: Left: *Mang_gl 307 (Zanam B) and Mang_gl 303 (Zanam A) on Sentinel 2 (2016) imagery. The red polygon is the lake outlines by Mool et al., 2001 and green is from Sentinel 2 (2016).* ***Right:*** *Bathymetry map of Mang_gl 307 along with depth profile from outlet to upper reach (A-A').*

The first field work was carried out by the DGM-JICA/JST GLOF project in 2010 during which the lake bathymetry was conducted. The deepest part of the lake was around 103 m with shallow depth towards the outlet of 15 – 20 m. From the bathymetry survey, the volume of the lake was calculated to be 37 million m^3. Lake bathymetry was also conducted on Zanam A and found the water volume of approximately 7 million m^3 with maximum depth of 46.8 m. The project covered the lake for risk assessment in terms of GLOF in the Mangde Chhu river basin. T. koike and S.Takenaka, 2012 concluded that:

- The upslope and downslope of the lake moraine has low slope angle
- The constant discharge of more than 5.0 m^3/s or temporal discharge of 40 m^3/s could have a GLOF scenario of the lake but may not have much affect downstream
- The triggering factor could be ice avalanche or mass slope failure
- Constant monitoring required to check whether the volume of the lake is increasing

Based on the findings and recommendations by T. koike and S. Takenaka, 2012, the lake will be included in the list of potentially dangerous glacial lakes.

3.3.6 Mang_gl 310 (Zanam G)

The glacial lake Mang_gl 307 (Mool et al., 2001) coded as Zanam G by DGM-JICA/JST GLOF project team (2009 – 2012) is located at latitude 27°58'51.47" N and longitude $90^0$22'53.97" E at an elevation of 5224 m a.s.l. in the north western side of Trongsa Dzongkhag in the headwater of Mangde Chhu (No. 19 in Fig.3.1). It is oriented Southwest and is conjoined with the Mang_gr 65 which feeds the glacial lake. As per the record by the earlier inventory (Mool et al., 2001) the lake has the surface area of 200,746.34 m^2 whereas the newly mapped surface area using Sentinel 2 (2016) is 206,234 m^2. The lake could have been identified as potentially dangerous based on its surface area, presence of adjacent glacial lake and the mother glacier found within the distance of 50 m (Fig. 3.22, left).

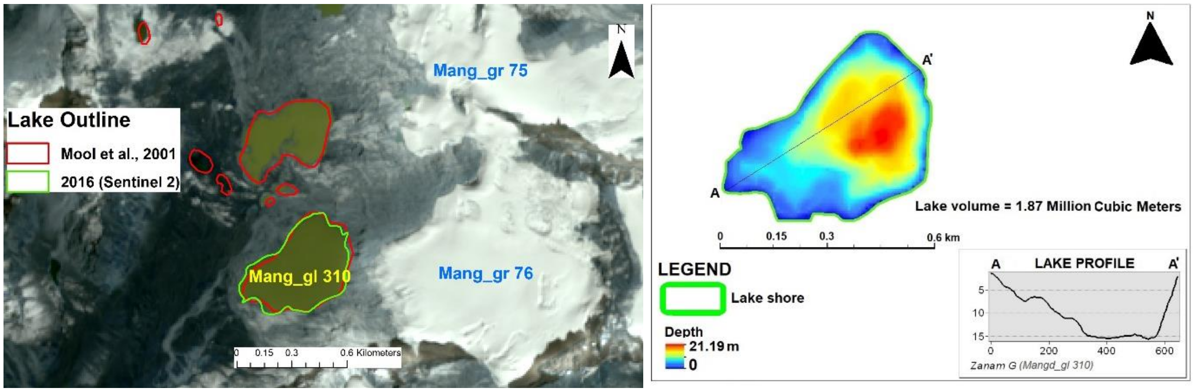

Figure 3.22: Left: *Mang_gl 310 (Zanam G) on Sentinel 2 (2016) imagery. The red polygon is the lake outline by Mool et al., 2001 and green is from Sentinel 2 (2016).* ***Right:*** *Bathymetry map of Mang_gl 310 along with depth profile from outlet to upper reach (A-A').*

The field work on the site was first carried out by the DGM-JICA/JST GLOF project (2009 – 2012). The project team has conducted the lake bathymetry survey (Fig. 3.22, right) but no detailed report is documented. From their survey, the lake volume was mapped to be 1.84 million m^3 with the maximum depth of 21 m which lies towards the upper reach. The current scenario of the lake is that:

- The lake surface area did not change much from 2001 to 2016
- The feeding glacier (Mang_gr 76 in Fig.3.22, left) has a gentle topography and may not trigger GLOF
- The lake has shallower depth towards the outlet exhibiting safe condition
- It has a wide and flat surrounding topography and does not pose any danger from active sliding

Based on the above conditions, the lake will be deemed safe and will be removed from the list of potentially dangerous glacial lakes.

3.3.7 Mang_gl 385

The glacial lake Mang_gl 385 (Mool et al., 2001) is located at latitude 27^{o}58'58.53" and longitude 90^{0}26'21.90" at an elevation of 5089 m a.s.l., in the north eastern side of Trongsa Dzongkhag and in the headwater of Mange Chhu (No. 20 in Fig.3.1). The ice dammed lake is oriented north conjoined with glacier Mang_gr 44. Mool et al., 2001 reported the surface of the lake to be 466,125.34 m^2 but the recent Sentinel 2 (2016) image reveals the surface area of 248,574 m^2. The lake is dammed by ice (Mang_gr 177). The major difference observed is that the lake polygon by Mool et al., 2001 has included the upstream that feeds the lake (Fig.3.23) whereas in Sentinel 2 (2016) imagery it is omitted. This has led to the surface area change of (-) 217,551.36 m^2 from 2001 to 2016. Since the lake is dammed by ice, it could have been the reason for identifying it as potentially dangerous.

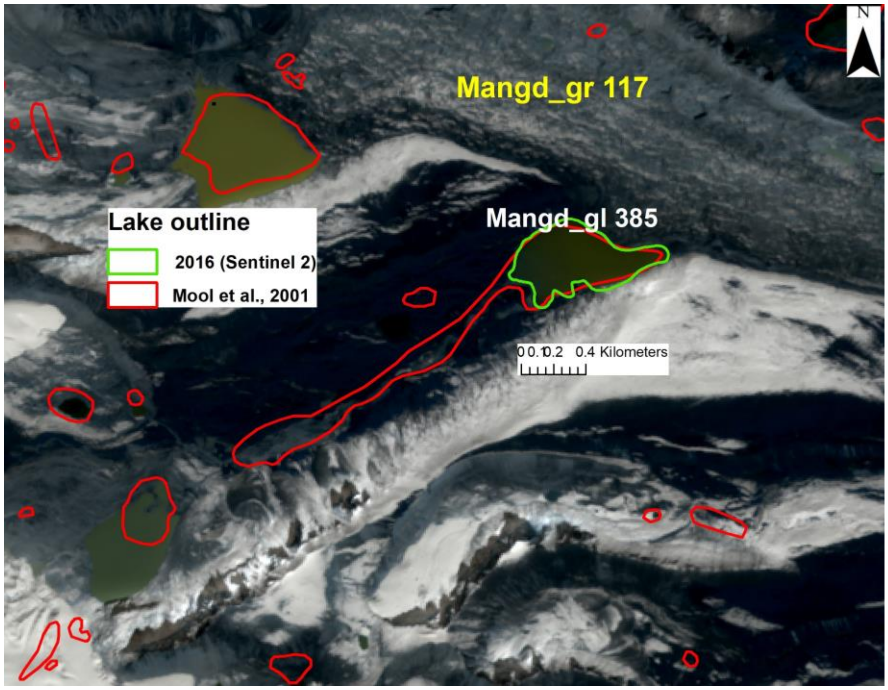

Figure 3.23: *Mang_gl 385 with damming glacier (Mang_gr 117) on Sentinel 2 (2016) imagery. The red polygon is the lake outline by Mool et al., 2001 and green is from Sentinel 2 (2016)*

So far, no field survey has been conducted on the glacial lake as it is located at a very remote area and it is inaccessible. However, from the desktop studies, still the lake is dammed by glacier ice (Mang_gr 177) and is intact. Ice dams are subtle to change (Huggel et al 2002) and a detailed field observation is recommended. Hence, the lake will be considered potentially dangerous as no detailed field records are available.

3.4 Chamkhar Chu Sub-basin

3.4.1 Cham_gl 198 (Phudung lake)

The glacial lake Cham_gl 198 (Mool et al., 2001) locally known as Phudung Tsho is located at latitude 27^{o}58’58.53” and longitude 90^{0}26’21.90” at an elevation of 5062 m a.s.l. in the northern side of Bumthang Dzongkhag in the headwater of Chamkhar Chhu (No. 21 in Fig.3.1). The outlet is oriented north east. The surface area was reported to be 624,669.81 m^2 by Mool et al., 2001. Using the Sentinel 2 (2016) imagery the lake outline was delineated and reveals the surface area of 582,729 m^2. The surface area difference is negligible which can be attributed to type of imagery used for delineation and methodology (red and green polygons in Fig.3.24, left). It is a fully developed lake.

This lake could have been identified based on the surface area, steep outlet morphology and the steep glacier feeding the lake as observed from the Remote Sensing data. From the google earth and other remote sensing data, steep morphology can be observed.

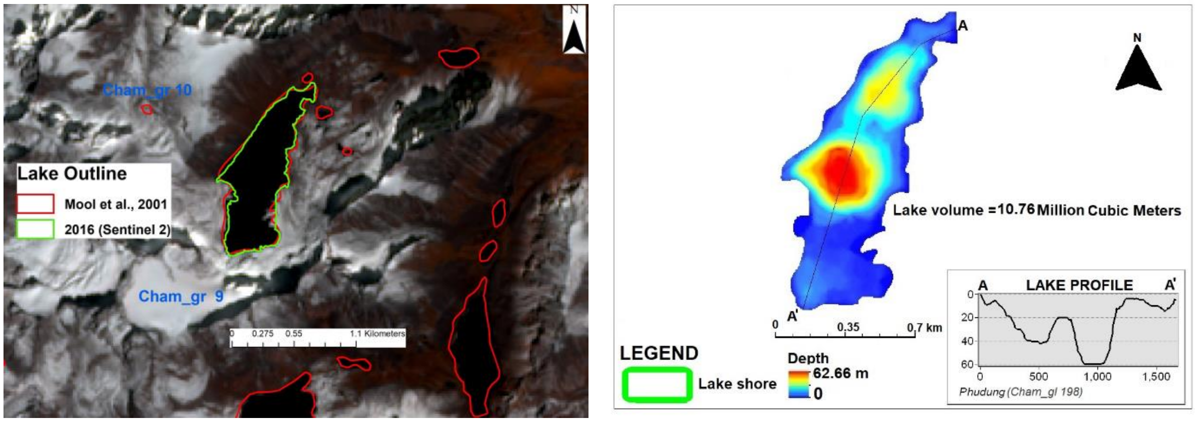

Figure 3.24: Left: *Cham_gl 198 (Phudung Tsho) on Sentinel 2 (2016) imagery. The red polygon is the lake outline by Mool et al., 2001 and green is from Sentinel 2 (2016).* ***Right:*** *Bathymetry map of Cham_gl 198 along with depth profile from outlet to upper reach (A-A')*

Figure 3.25: *Panoramic view of Cham_gl 198 (Phudung Tsho) lying completely in a bedrock topography. Dotted red box show the location of the lake outlet*

The first field work was conducted under the DGM-JICA/JST GLOF project (2009-2012) and initiated the lake bathymetry survey. From their survey, the lake volume was extracted to be 10.7 million m^3 with the maximum depth of 63 m. The team found that the feeding glacier has retreated further upstream posing no threat of ice avalanche. The damming material of the lake consists of bed rock and in the events of overtopping of lake water, no erosion of damming material could occur. Ultimately, no GLOF scenario can happen downstream. Based on the above observations and findings, the lake is considered as safe.

3.4.2 Cham_gl 232

The glacial lake Cham_gl 232 (Mool et al., 2001) is located at latitude 27^{o}59'11.33" and longitude 90^{0}30'31.42" at an elevation of 5205 m a.s.l., in the northern side of Bumthang Dzongkhag and in the headwater of Chamkhar Chhu (No. 22 in Fig.3.1). It is oriented south and conjoined with glacier chamkr_gr 15 which feeds the glacial lake. Mool et al., 2001 reported the lake surface area of 205,146.23 m^2 whereas the latest satellite imagery (Sentinel 2) of 2016 reveals the lake surface area to be 188,550 m^2. The lake could have been identified to be dangerous based on its surface area exceeding 100,000 m^2, presence of few adjacent lakes and the presence of feeding glacier in the vicinity. An interesting feature observed at present is the development of another lake just above the Cham_gl 232 (marked no. 1 in Fig.3.26) which was not mapped in earlier inventory by Mool et al., 2001.

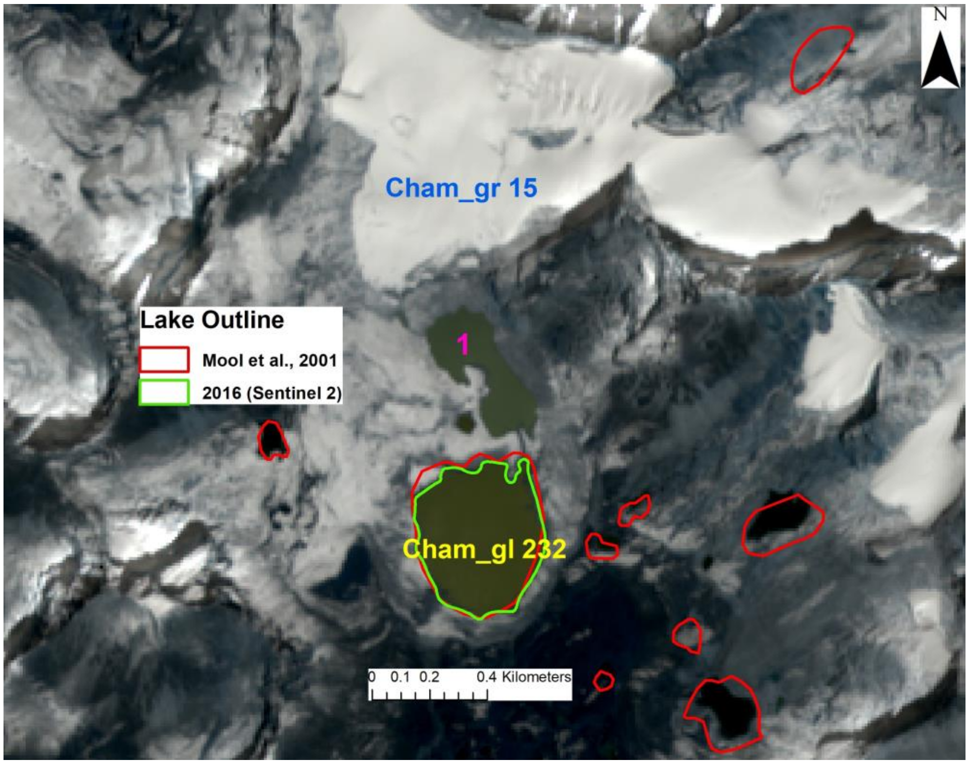

Figure 3.26: *Cham_gl 232 on Sentinel 2 (2016) imagery. The red polygon is the lake outline by Mool et al., 2001 and green is from Sentinel 2 (2016). No. 1 marked in pink shows the presence of a lake which was not mapped in earlier inventory by Mool et al., 2001*

No field work was done on the side at the moment but from the desktop studies (satellite imageries and google earth pro) it was found that:

- The surface area has not increased from 2001 to 2016
- The feeding glacier (Cham_gr 15) has retreated further upstream and has a gentle glacier morphology indicating no direct thread
- A new lake is visible using latest satellite imageries (Sentinel 2)
- It has a wide and gentle topography indicating no threads from active slidings

Based on above points the lake seems safe from GLOF. However, a new lake is observed using latest satellite imageries, which is missing in the inventory by Mool et al., 2001. In this regard, until further field verifications are made, the lake will be included in the list of potentially dangerous glacial lakes.

3.4.3 Cham_gl 383 (Chubda Tsho)

The Glacial Lake Cham_gl 383 (Mool et al, 2001) locally known as Chubda Tsho is located at latitude 28^{o}01’25.91” and longitude 90^{0}041’31.77” at an elevation of 4868 m a.s.l. in the northern part of Bumthang Dzongkhag in the headwater of Chamkhar Chhu(No. 23 in Fig.3.1). The lake measuring the surface area of 1,388,320 m^{2} (Sentinel 2) is one of the biggest lake in the Chamkhar Chhu headwater. The lake outlet is oriented southwest and is directly fed by Cham_gr 71. The lake is one of the biggest lake in the headwater of Chamkhar Chhu. The surface area reported by Mool et al., 2001 is 1,035,131.51 m^2 and is expanding at a rate of 0.027 km^2 per year i.e. an increase of about three fold in the last 3 decades. (*Komori, J. et al., 2004*)

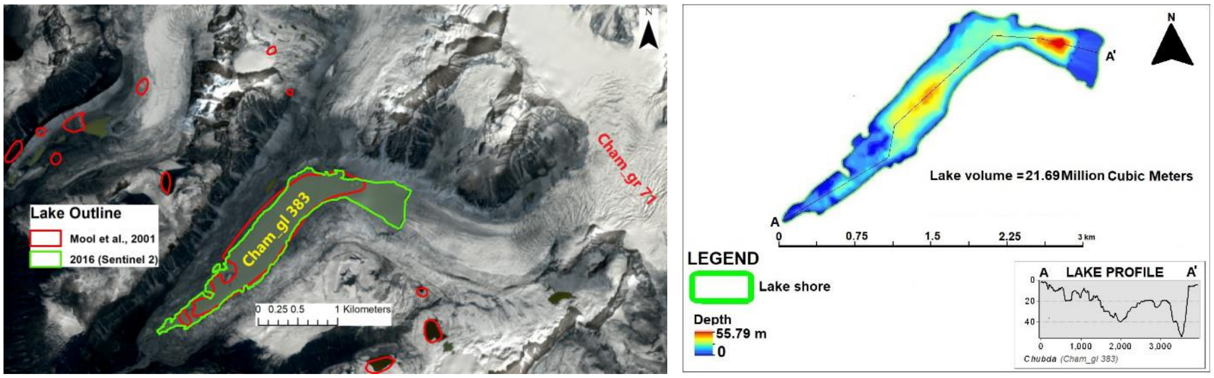

Figure 3.27: Left: *Cham_gl 383 (Chubda Tsho) on Sentinel 2 (2016) imagery. The red polygon is the lake outline by Mool et al., 2001 and green is from Sentinel 2 (2016).* ***Right:*** *Bathymetry map of Cham_gl 383 along with depth profile from outlet to upper reach (A-A')*

Numerous studies have been carried out in the headwater of Bumthang (karma et al., 1999; Karma et al., 2000; Iwata et al., 2003; Komori et al., 2004). They found that the lake has an ice cored moraine dam. Besides, it was also noticed that the expansion rate of the lake and rate of glacier retreat was taking placing at an accelerated rate. This lake is not a moraine dammed but a supraglacial lake with flat threshold existing at the end moraine (*Karma et al.,1999*). Komori et al., 2003 concluded that the position of the terminus of Chubda Tsho has not changed but the existence of the threshold might possess a greater risk in near future.

The lake bathymetry survey was carried out in 2010 by the DGM-JICA/JST GLOF project (2009-2012) and the lake water volume was extracted to be 21.7 million m^3 approximately with maximum depth of 56 m towards the upper reach. Most of the earlier studies recommended for a detailed studies especially the damming part. Comparing the lake polygons by Mool et al., 2001 and the from the Sentinel 2 (2016) imagery (Fig.3.27, left), the lake has expanded upward by approximately 564 m in 17 years accounting to 33 m per year. This rate of glacier retreat (debris cover glaciers) still falls well within the estimated rate by the earlier researchers in Lunana region where the rate of glacier retreat was mentioned as 30 to 35 m per year.

Based on recommendations from earlier studies and current situation, the lake Cham_gl 383 (Chubda Tsho) will be included in the list of potentially dangerous glacial lakes.

3.5 Kuri Chu Sub-basin

3.5.1 Kuri_gl 172 (Terjatse Tsho)

The glacial lake Kuri_gl 172 (Mool et al., 2001) locally known as Terjatse Tsho is located at latitude 27^{o}55’49.76” and longitude 91^{0} 17’59.53” at an elevation of 4373 m a.s.l., in the north eastern side of Lhuntse Dzongkhag in the headwater of Kuri Chhu (No. 24 in Fig.3.1). The lake is oriented north east and is conjoined with the Kuri_gr 10 which feeds the glacial lake. In the earlier inventory by Mool et al., 2001, the lake’s surface area was reported to be 161,706.43 m^2 whereas the latest imageries reveal the surface area to be 167,540 m^2. There is another lake above the kuri_gl 172 which would be a potential triggering factor for a GLOF case and could be the reason why the lake was categorized to be potentially dangerous in the 2001 inventory.

Another factor could be due to its steep morphology at the outlet of the lake. The lake feeds the Khoma chhu and finally flows into Kuri Chhu downstream.

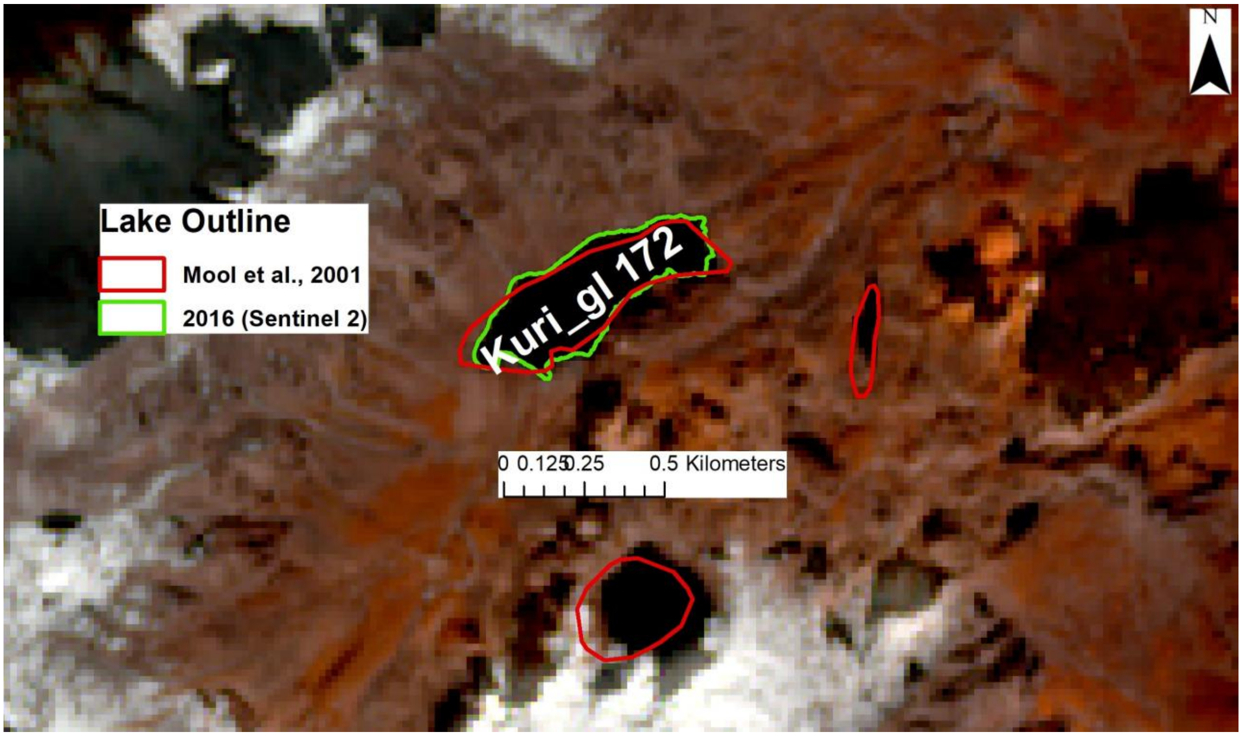

Figure 3.28: *Kuri_gl 172 on Sentinel 2 (2016) image. The red polygon is the lake outline by Mool et al., 2001 and green is from Sentinel 2 (2016)*

Komori et al (2013) mentioned that the lake is not a glacial lake as the glacier associated with it has retreated way above. In April 2018 a group of officials consisting of Geologists and Engineers went for a detail study of the lake. Due to excessive avalanche from the route site, and steep hill from the other alternating route the study could not be carried out. From the recent satellite imageries (Sentinel 2 (2016)), the lake surface area has not changed.

However, since no ground verifications are made the lake will be included in the list of potentially dangerous glacial lakes until further detailed field studies are conducted.

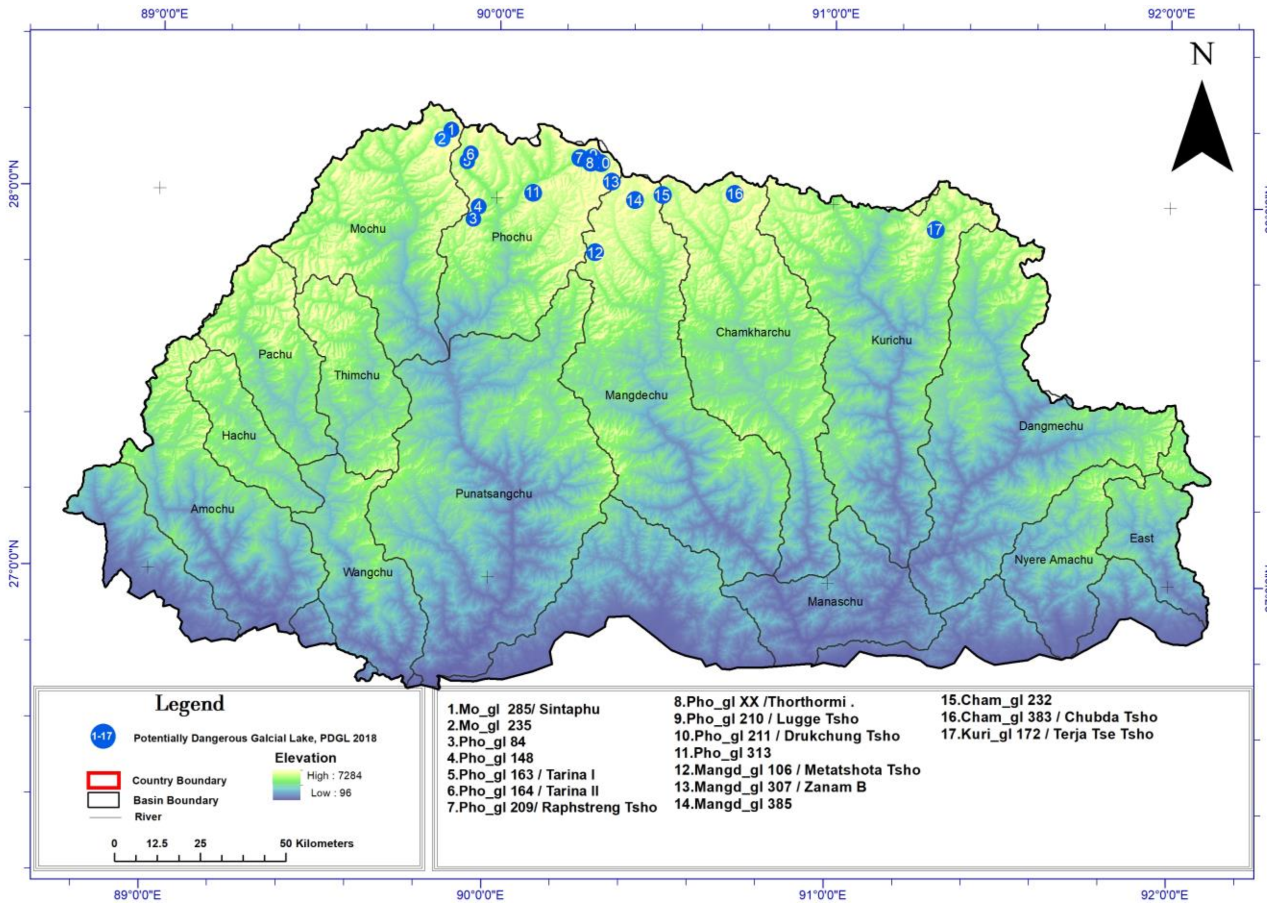

Figure 3.29 *Locations of updated list of PDGLs*

Table 1: New status of Potentially Dangerous Glacial Lakes of Bhutan

SNo.	Lake	Local Name	Latitude	Longitude	Altitude	Area (m^2)	Volume (m^3)	Remarks
Mo Chu Sub-basin								
1	Mo_gl	Lemthang	28° 04' 00.00	89° 35' 05.50	4280	0	0	Safe
2	Mo_gl		28° 06 15.60	89° 36' 55.60	4380	68,138	NA	Safe
3	Mo_gl	Latshokarp	28° 07' 44.40	89° 36' 31.60	4434	62,801	NA	Safe
4	Mo_gl	Sintaphu	28° 10' 06.00	89° 51' 21.10	4480	238,314	6,410,000	PD
l	Mo_gl		28° 08' 35.40	89° 51' 21.10	4960	128,803	NA	PD
Pho Chhu Sub-basin								
6	Pho_gl		27° 56' 48.53	89° 55' 14.03	4997	742,329	9,280,000	PD
7	Pho_gl		27° 58' 09.42	89° 56' 16.69	5072	637,422	26,310,000	PD
8	Pho_gl	Tarina I	28° 06' 06.43	89° 54' 11.83	4266	250,813	5,400,000	PD
9	Pho_gl	Tarina II	28° 06' 37.22	89° 54' 37.81	4338	446,325	13,000,000	PD
10	Pho_gl	Raphstreng	28° 06' 43.56	90° 14' 03.65	4368	1,241,970	54,650,000	PD
11	Pho_gl	Lugge	28° 05' 00.34	90° 18' 28.58	4570	1,460,870	65,190,000	PD
12	Pho_gl	Drukchung	28° 05' 40.45	90° 19' 11.95	4701	101,096	NA	PD
13	Pho_gl		27° 59' 58.72	90° 07' 18.86	5049	211,705	NA	PD
14	Pho_gl	Thorthormi	28° 06' 19.90	90° 15' 48.46	4446	2,908,490	NA	PD
Mangdechhu Sub-basin								
15	Mang_gl	GLT 9	27° 54' 22.13	90° 16' 45.88	5155	228,905	4,740,000	Safe
16	Mang_gl	Metatshota	27° 53' 19.45	90° 17' 33.94	5065	1,203,880	41,740,000	PD
17	Mang_gl	Zanam F	27° 58' 09.32	90° 20' 06.98	5311	233,163	4,710,000	Safe
18	Mang_gl	Zanam E	28° 00' 20.90	90° 19' 50.77	5370	341,412	NA	Safe
19	Mang_gl	Zanam B	28° 02' 21.01	90° 21' 58.87	5208	862,181	37,030,000	PD
20	Mang_gl	Zanam G	27° 58' 49.87	90° 23' 05.53	5224	206,234	1,870,000	Safe
21	Mang_gl		27° 58' 58.53	90° 26' 21.90	5089	248,574	NA	PD

Chamkhar Chhu Sub-basin								
22	Cham_gl 198	Phudung	27° 56' 22.27	90° 32' 15.91	5062	582,729	10,760,000	Safe
23	Cham_gl 232		27° 59' 11.33	90° 30' 31.42	5205	188,550	NA	PD
24	Cham_gl 383	Chubda Tsho	28° 01' 25.91	90° 42' 31.77	4868	1,388,320	21,690,000	PD
Kurichhu Sub-basin								
25	Kuri_gl 172	Terja tse Tsho	27° 55' 47.56	91° 18' 08.77	4373	167,540	NA	PD

Note: *PD - Potentially Dangerous*

NA- Not Available

CONCLUSION

In this current work, the list of potentially dangerous glacial lakes of the Bhutan Himalayas (Mool et al., 2001) are updated by carefully reviewing the previously identified 25 PGDL's. The work is executed based on recommendations from earlier literature including technical reports, field reports, scientific reports and findings from recent satellite imageries (Sentinel 2 (2016)) and google earth pro. Of the 25 potentially dangerous glacial lakes, so far 19 had been field verified. Of the 19 field verified potentially dangerous glacial lakes, data from previous studies have concluded that 7 are safe. Of the 6 lakes which were not field verified 5 are still considered to be potentially dangerous glacial lakes until further ground verifications are conducted and one in the headwater of Mangde Chhu (Mang_gl 285/Zanam E) was deemed safe as it lies on a gentle and flat topography with no possible triggering factors. For the lakes which were not field verified surface area change from 2001(Mool et al., 2001) to 2016(Sentinel 2) were observed and compared using satellite imageries. With the removal of 8 lakes from the previous list of PDGLs, the new updated list of PGDL's consist of 17 Potentially dangerous glacial lakes, with a major of 9 lakes in the Pho Chhu sub basin ,3 in Mangde Chhu sub basin, 2 in Mo Chhu sub basin, 2 in Chamkhar Chhu sub basin and one in Kuri Chhu sub basin(Fig.3.29 and Table 1).The updated inventory on PDGL aims to provide more accurate information and awareness of GLOF phenomenon to public domains so that concerned agencies can act accordingly for prevention and mitigation.

Recommendation

The current work on assessing and updating of potentially dangerous glacial lakes were based on existing 25 potentially dangerous glacial lakes of Bhutan Himalayas and did not take into account other glacial lakes. Due to recent global climate change, melting glaciers lead to formation of new glacial lakes as well as expansion of existing glacial lakes. In this line, the center would like to recommend the following:

- Conduct field assessment on those glacial lakes listed as potentially dangerous glacial lakes which are not yet field verified.
- Update the inventory of glacial lakes covering northern frontiers of Bhutan
- Develop an appropriate list of criteria's for assessing and categorizing potentially dangerous glacial lakes
- All other glacial lakes must be assessed so as to come up with a comprehensive inventory of glacial lakes and identify them in terms of the safety from GLOF.

References

Dorji. Y., (?????) *Glaciers and Glacial Lakes Feeding Pho Chhu and The Risk Associated with these Lakes. GSB(unpublished).*

Gansser, A. (1983). *Geology of the Bhutan Himalaya*. *Birkhaüser Verlag* (Vol. 8). https://doi.org/10.1016/0160-9327(84)90075-9

Iwata.S.,Gurung.D.R and Komori.J.(2002) *Preliminary Report on Chubda Tsho in the Headwater of Chamkhar Chhu,Bumthang.DGM(unpublished)*

Iwata, S., Ageta, Y., Naito,N., Sakai,A., Narma,C and Karma.(2002)*Glacial Lakes and their Outburst Flood Assessment in the Bhutan Himalaya.*

Karma. and Tamang.K.B (1999) *Preliminary Report on TsokarTsho in the Headwater of Chamkhar Chhu,Bumthang. Engineering Geology and Glaciology Wing GSB(Unpublished)*

Karma.,Thapa.T. and Ghalley.K.S.,(1999) *Preliminary Report on Chubda Tsho in the Headwater of Chamkhar Chhu,Bumthang.Engineering Geology and Glaciology Wing GSB(Unpublished)*

Karma., Tshering,P and Penjor,T.,(2016) *Time Series Monitoring of Glacier and Glacial Lakes of Tarina Glacier and Glacial Lakes (Pho Chhu Western Branch) under Gasa Dzongkhag. DGM(unpublished)*

Komori, J., T. Koije, T. Yamanokuchi and P. Tshering (2012) Glacial Lake Outburst events in the Bhutan Himalayas. *Global Environmental Research, 16:59-70.*

Koike,T and Takenaka,S.(2012) *Scenario Analysis on Risk of Glacial Lake Outburst Floods on the Mangde Chhu River,Bhutan.Global Environment Research,16/41-49.*

Komori.J., Iwata.S.,Gurung.D.R and Yabuki.H.(2003) *Variation and Lake Expansion of Chubda Glacier,Bhutan Himalayas, during the last 35 years.*

Leber,D., Haeusler, H., Brauner,M. & Skuk, S.(2000*) Lugge Tsho outburst Flood Mitigation Project , Lunana, Bhutan.Institute of Geology University of Vienna.*

Mool, P. K., Wangda, D., Bajracharya, S. R., Kunzang, K., Gurung, D. R., & Joshi, S. P. (2001). *Inventory of Glacier, Glacial Lakes and Glacial Lake Outburst Floods: Monitoring and Early Warniing Systems in the Hindu Kush-Himalayan Region, Bhutan. Quality*. https://doi.org/10.1017/CBO9781107415324.004

Penjor.T., Galley.S. And Gyeltshen.J.(2012) *Time Series Monitoring of Glacier and Glacial Lakes of Mo-Chu Basin under Gasa Dzongkhag. DGM (unpublished).*

Singh, S. M. (2009). The Cost of Climate Change: The Story of Thorthormi Glacial Lake in Bhutan.

Tshering,P, and Penjor,T.(2016) *Time Series Monitoring of Glacier and Glacial Lakes of Mo-*

Chu Basin (Singtaphu and Rodophu Area) under Gasa Dzongkhag. DGM (unpublished)

Tshering, T., Gyenden, L., Ghalley, K.S.Chettri, L.K., Dorji,P. and Tamang,T.(2007) *Report on annual Monitoring of Glaciers and Glacial Lakes in Lunana. DGM. (unpublished)*

"The costs of natural disasters can set back a community or nation by decades – not to speak of the lasting emotional damage inflicted on the people affected."

His Majesty Jigme Khesar Namgyel Wangchuck, King of Bhutan,
Convocations address to the students of Calcutta University, 5th October 2010

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