Detailed Assessment Report on GLOF Hazard From Thorthormi Glacial Lake and Associated Glaciers

(Field Season: September – October, 2019)

NATIONAL CENTER FOR HYDROLOGY AND METEOROLOGY
ROYAL GOVERNMENT OF BHUTAN
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Executive Summary

On June 20, 2019 there was a small Glacial Lake Outburst Flood (GLOF) from Thorthormi lake which lead to total drainage of the subsidiary lake II. With the financial assistance from Punatshangchu Hydropower Project Authority (PHPA) – I & II, a detailed assessment was conducted by a team from National Center for Hydrology and Meteorology from September to October, 2019. The survey includes aerial survey of Thothormi lake, moraine feature surrounding Thorthormi lake, survey on Luggye glacial lake and bathymetry survey on Baychung glacial lake.

The glacier moraine features of mainly Thorthormi glacial lake was surveyed using Unmanned Aircraft System (UAS) and digital elevation model (DEM) was produced with resolution of 0.05 m. The surrounding moraine features of Thorthormi were topographically surveyed using latest Trimble R10-2 GNSS equipment and mapped the outlet channel. As to verify the causes of recent GLOF event, a physical visit towards upper reach of Thorthormi was conducted and photographs were taken. Our current report focusses mainly on the current situation of Thorthormi glacier and glacial lake.

From the field verifications, the moraine barrier between Thorthormi and Raphstreng glacial lakes was found to be still unstable and the sliding on the slope towards Thorthormi side got reactivated after the recent GLOF from Thorthormi, with minor sliding towards Raphstreng walls. The sliding could have been reactivated by the sudden rise of lake water level and ice dynamics during the recent GLOF event. The narrowest crest on Thorthormi – Raphstreng barrier was measure from DEM and was found to be 33.5 m. With the reactivation of the sliding on Thorthormi – Raphstreng moraine barrier, the criticality of Thorthormi main lake breaching towards Raphstreng lake remains high as reported earlier.

Brief survey on Luggye lake outlet was also conducted and the lake shoreline towards outlet were mapped for future comparisons. Comparing the Bathymetry results on Baychung glacial lake of various years shows that Baychung glacial lake is expanding and annual time series monitoring is required.

Acknowledgement

The National Center for Hydrology and Meteorology (NCHM) and the Cryosphere Services Division (CSD) in particular, would like to thank the management of Punatsangchu Hydropower Project Authority I & II for granting financial support for carrying out detailed assessment on Thorthormi glacial lake without which the current activity would not have happened.

The Center also would like to thank the Dzongkhag Administration of Gasa for arranging the porters for transporting survey equipment from road head to the survey site and back. The Center also would like to acknowledge everyone who were involved in carrying out the task successfully.

Acronyms

2D/3D	: Two/Three Dimensional
AWLS	: Automatic Water Level Station
BCAA	: Bhutan Civil Aviation Authority
CSD	: Cryosphere Services Division
DEM	: Digital Elevation Model
dGPS	: Differential Global Positioning System
GLOF	: Glacial Lake Outburst Flood
GNSS	: Global Navigation Satellite System
GPS	: Global Positioning System
LSS01	: Luggye Soil Sample 1
NCHM	: National Center for Hydrology and Meteorology
PHPA	: Punatsangchu Hydropower Project Authority
PC	: Personal Computer
WGS	: World Geodetic System
RADAR	: Radio Detection and Ranging
RTK	: Real Time Kinematic
SATREPS	: Science and Technology Research Partnership for Sustainable Development
TIN	: Triangulated Irregular Network
TSS01	: Thorthormi Soil Sample 1/2
UAS	: Unmanned Aircraft System
UTM	: Universal Transverse Mercator

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1. Introduction

The global climate change is a known fact and has manifested in rapid melting of polar ice caps, mountain glaciers and global sea level rise. As early as 1900s with the start of industrial revolution, many glaciers around the world started melting giving rise to formation of many supra-glacial lakes which merge to form bigger lakes posing threat to communities downstream. The glaciers located in the high mountain of Asia are not an exception from such phenomena. The melting of Bhutanese mountain glaciers and formation of glacial lakes as early as 1940s were first reported in a report by Leber and team (2002).

In a joint study by the Department of Geology and Mines (DGM) and International Center for Integrated Mountain Development (ICIMOD), 2001 pointed out that there are 24 Potentially Dangerous Glacial Lakes (PDGL) in the headwaters of Bhutan. Later, with the rapid melting of Thorthormi glacier, Leber and team identified Thorthormi glacial lake to be one of the PDGL and recommended for immediate mitigation measures and continuous time series monitoring. Ever since, time serious monitoring on Thorthormi glacial lake was conducted involving geophysical investigation and mitigations such as artificial lowering of Thorthormi main lake from 2009 to 2012. After the mitigation works on Thorthormi, no detailed time series monitoring was carried out but the main glacial ice of Thorthormi continued to melt.

On June 20, 2019, there was a small Glacial Lake Outburst Flood (GLOF) from Thothormi main lake leading to complete drainage of one of the subsidiary lakes (subsidiary lake II) causing panic to policy makers and community downstream in Punakha-Wangdue valley. The GLOF event also damaged one Automatic Water Level Station (AWLS) near the subsidiary lake II. Right after the event, rapid assessment team was formed lead by National Center for Hydrology and Meteorology (NCHM) to assess the cause/s of GLOF and relocate and re-install AWLS. The assessment team found out that the main cause of the GLOF was due to rapid changes/disturbance that took place on Thorthormi glacier ice upstream of which lead to rapid increase of main lake level.

With the financial assistance from Punatsangchu Hydropower Project Authority (PHPA) I and II under the flood control mechanism, a detailed assessment on Thorthormi glacial lake and surrounding moraines were conducted using Unmanned Aircraft System (UAS) by creating high resolution Digital Elevation Models (DEM) of the moraines, lake water level mapping and visual inspection of moraine barriers between Raphstreng and Thorthormi glacial lakes. Alongside, a brief visit to Luggye glacial lake was also conducted and carried out differential Geographical Positioning System (dGPS) survey at the outlet of Luggye glacial lake, river channel and shoreline mapping towards the outlet. In order to track the changes of the fast expanding Baychung glacial lake, the team conducted bathymetry survey mainly to see the longitudinal expansion of the Baychung main lake.

2. Objective

The September-October 2019 field expedition to Lunana under flood control mechanism for PHPA I and PHPA II was carried out with following main objectives.

- **Aerial mapping on Thorthormi lake using Unmanned Aircraft System (UAS)** to create high resolution DEM (cm level) base map of Thorthormi moraine and lake area for mapping high-precision changes on moraines (Thorthormi – Raphstreng barrier) and the lake.
- **Geo-technical study on the moraine dams surrounding the glacial lakes** for dam breach modeling
- **dGPS survey on Thorthormi and Luggye glacial lake and surroundings moraines** for lake outlet and channel mapping
- **Bathymetry survey using Eco-sounder on Baychung glacial lake** to extract lake water volume and expansion

However, due to closely spaced ice masses floating on the Thorthormi main lake, the team could not carry out bathymetry survey.

3. Study Area

3.1. Location and accessibility

Lunana is located in the headwater of Pho Chhu sub basin, at the base of Mount Gangchhen Singye famously known as Table Mountain under Lunana Gewog, Gasa Dzongkhag. It has multiple accessibility following Snowmen Trek. Most of the routes take almost nine to ten days of walk from road head to the site. All the major glacial lakes are located adjacent to each other above Thanza main village requiring a walk of at least an hour from each lake sites. On an average, it takes almost an hour from Thanza village to reach the first glacial lake (Baychung Tsho).

Route 1: Gasa – Laya – Wachey – Lunana (10 days)

Route 2: Goen Shari – Gangju La – Wachey – Lunana (9 days)

Route 3: Sephu (Wangdue) – Metatshota – Gangrinchenzoe – Lunana (8 days)

Route 4: Dhur (Bumthang) – Dhur Tshachu – Zanam – Lunana (9 days)

All the route maps are given in figure 1.

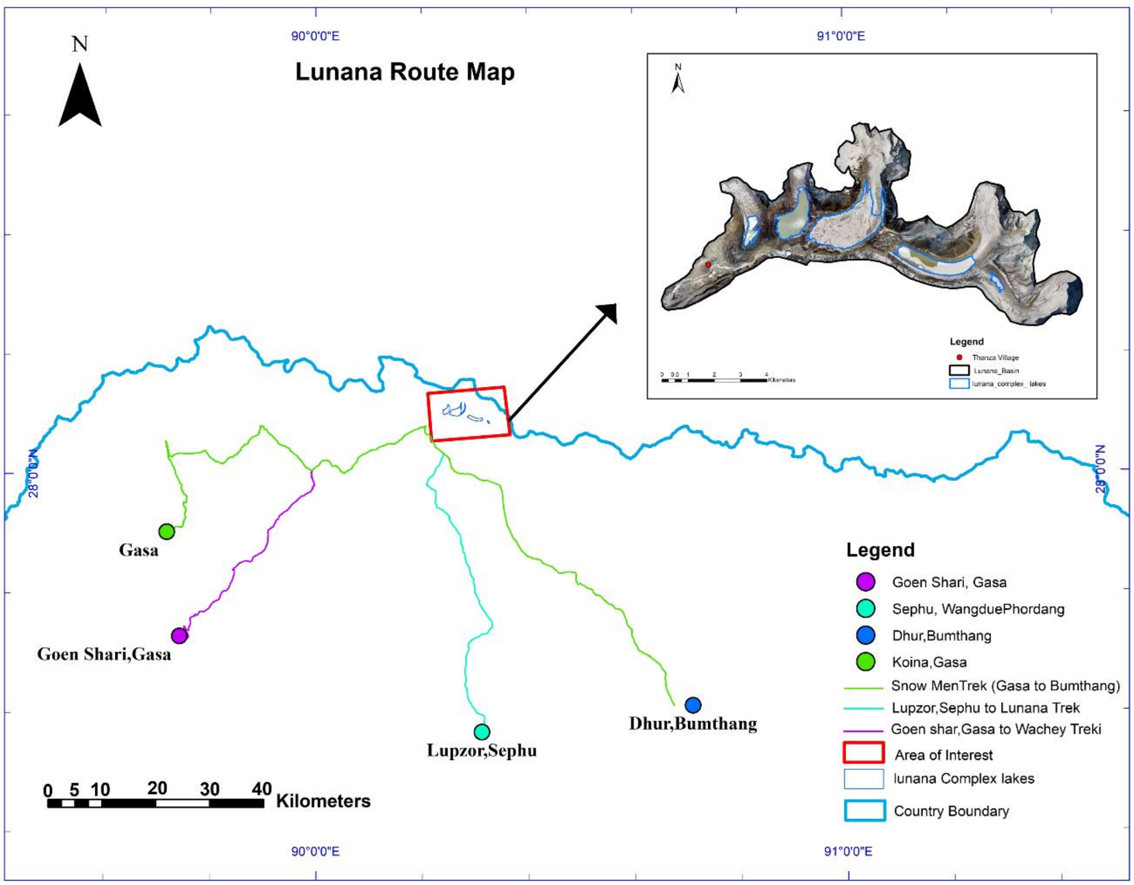

Figure 1: Location map of Lunana glacial lakes and different access routes to Lunana area

4. Methodology

4.1. Aerial Mapping with Unmanned Aircraft System

4.1.1. Equipment and software

The eBee Plus from Sensefly company (Figure 3c) with High-precision; built-in Real Time Kinematic (RTK) functionality was deployed for the aerial mapping of Thorthormi area (partial). The equipment (UAS) is mounted with S.O.D.A. camera for photogrammetric mapping, plus thermal infrared and multispectral options. It also has the wind speed sensors attached. The eBee plus has the advantage of mapping a larger area per flight with lightweight to maximize the efficiency and plan the works. It requires a precise GPS base station linked up with its built-in RTK which saves more time on the ground. The base was set up at 28° 05' 21.85440" N and Longitude 90° 14' 32.39831” E at an elevation of 4676.049 m a.s.l, an aerial distance of about 2 km from the study area (figure 2) and the UAS was launched from the same vicinity. Trimble R10-2 with Global Navigation Satellite System (GNSS) was used for the base station in fast static mode. Details on base station set up are provided under dGPS survey section.

Using the eMotion 3 software, the photos captured during the flight mission were then downloaded and geotagged. As per the requirements, the output products were post-processed and generated in AgiSoft software.

The UAS survey was executed with prior approval from Bhutan Civil Aviation Authority (BCAA) vide approval number BCCA/OPS/5.01/193 dated September 4, 2019, and on time permissions were sought through calls during the time of launching the UAS

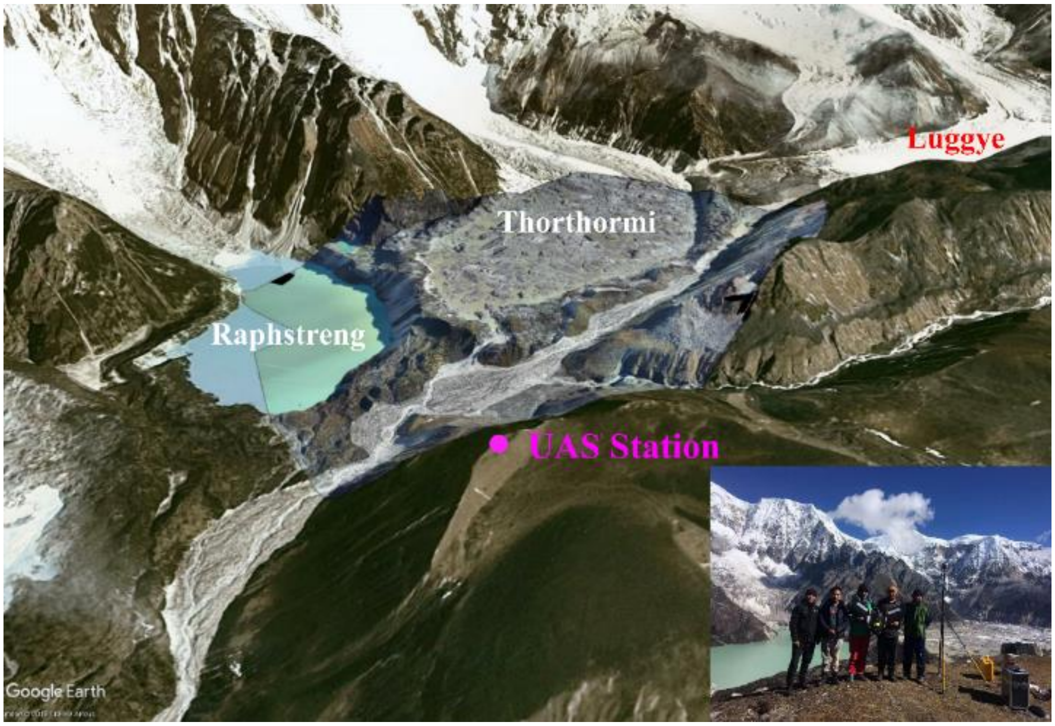

Figure 2: Site map showing Raphstreng, Thorthormi and Luggye glacial lakes with UAS Station

4.1.2. Flight planning in eMotion 3

eMotion 3 is sensefly's drone flight and data management software. It has several options such as mission block flight planning, multi-flight missions, three dimensional (3D) control environment, multiple payload support and cloud connectivity etc. Prior to the launching of UAS for aerial mapping, the flight planning was carried out using eMotion 3 software with following set ups:

- Photo pixel resolution : 8.50 cm/pixel
- Lateral overlap : 76%
- Longitudinal overlap : 60%
- Camera : S.O.D.A
- Area : 3.91 km^2
- Altitude : 361.3 m/ATO
- Number of Photos : 299
- Estimated flight time : 00:59:03
- Estimated flight distance : 41390 m

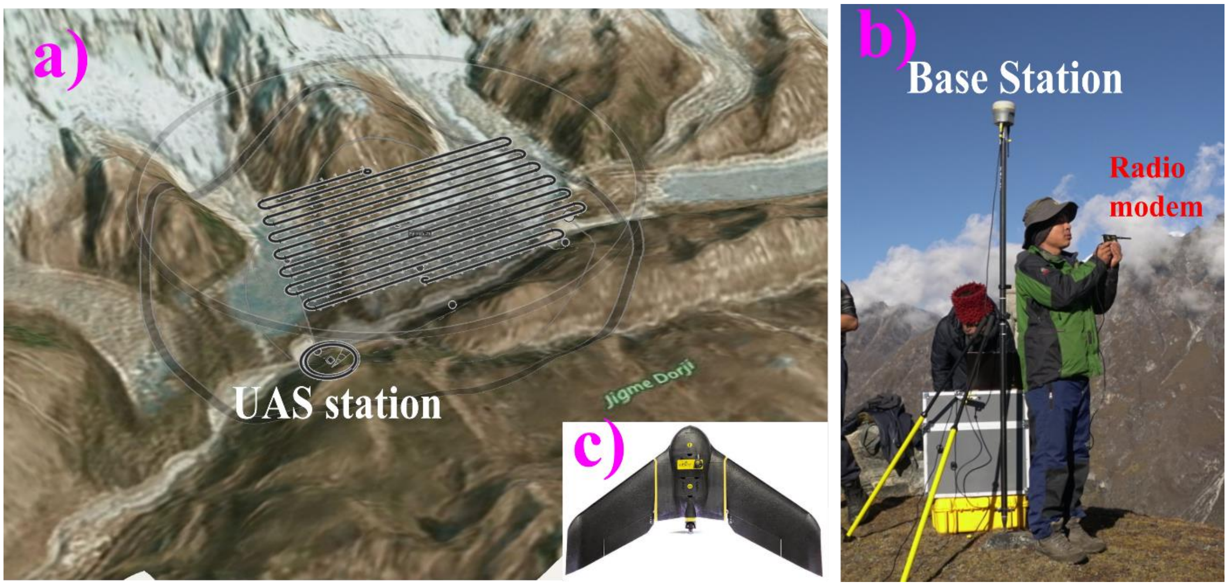

Figure 3 a: Flight mission block showing flight path and mission area prepared in eMotion 3; b: Trimble R10-2 base station and Radio modem which communicates between UAS and base ; c) eBee UAS

The flight plan in eMotion software (in PC) were uploaded to the drone. The continuous logging of base station is connected to the PC and eMotion either through a cable or Bluetooth which communicates with the UAS through a radio modem which is also connected to the PC (Figure 3b). With the base station as reference point, all the photos taken during the mission are then geotagged.

4.1.3. Ariel Photogrammetric processing and DEM Creation

The aerial photo taken using UAV was processed in Agisoft PhotoScan. The alignment of photos and sparse cloud creation were carried out with image quality above 0.7 (70%) in WGS 84/UTM zone 45N. the resulting image is optimized with image count level of 3 and re-projection error close to 1. The dense cloud was created with high image quality and aggressive depth filtering. The outliers were deleted within single chunk dense cloud after manual classification of ground points. The orthophotos were created with the resolution of 0.14 m and the DEM was created at a resolution of 0.05 m.

4.2. Bathymetry Survey on Baychung glacial lake

4.2.1. Equipment and depth sounding

Hummingbird 999SI combo (echo sounder) assembled with the internal Global Positioning System (GPS) was used to map the lake bottom topography. The full set equipment consists of a transmitter, transducer, receiver and a display powered by a 12V external battery. The transducer attached to the rubber boat and immersed few centimeters into the lake surface converts the electrical impulse emitted by the transmitter into sound wave and sends vertically down into the water body. The sound wave strikes the object (bottom surface) and bounces back to the transducer which in turn converts sound waves back to the electrical signal. The returning signal or echo is amplified by the receiver and displayed on the sonar chart showing the depth information. Simultaneously the Sonar log file is then saved to MMC card consisting of its position (Latitude, Longitude) and depth at that particular point (figure 4).

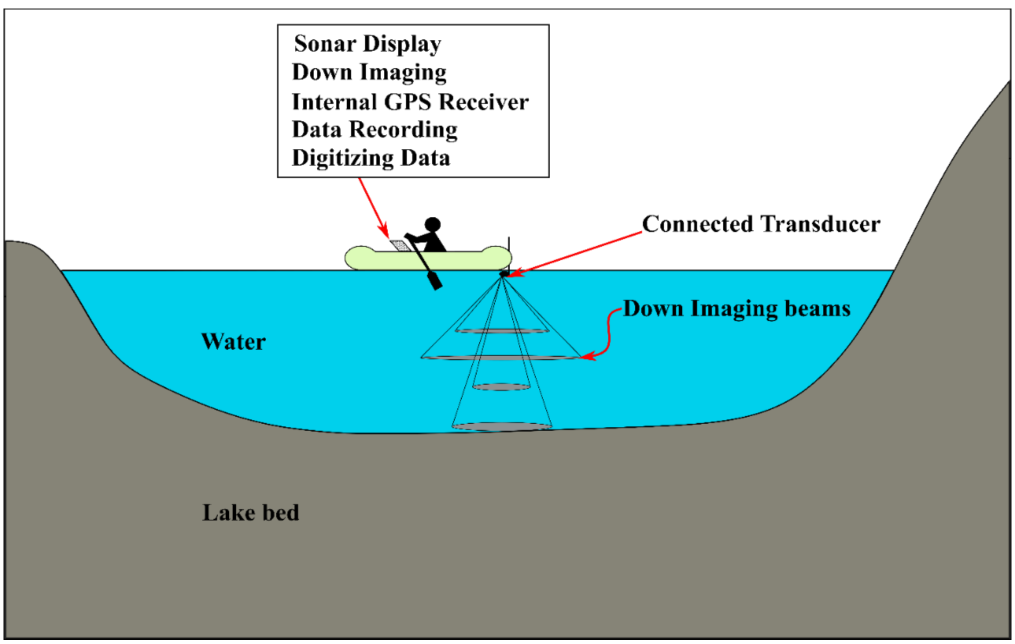

Figure 4: Schematic map of bathymetry survey on lakes

4.2.2. Data post-processing

Hummingbird 999SI combo records the sounding data and generates three folders viz. MATRIX, RECORD and SNAPSHOT. Under the RECORD folder, the data are recorded in two formats (. SON, .IDX). For the current purpose, we use .SON files for further processing and generating lake bathymetry maps. Post-processing is carried out using the Humminbird Autochart Pro software. In Humminbird Autochart Pro, .SON files are imported and converted to .ACD file, which is compatible with Autochart Pro for further analysis. The lake depth map (2D & 3D) was generated with an interpolation limit of 250 m x 250 m. The lake shoreline for Baychung glacial lake (Figure 4, Right) was delineated using Sentinel 2 Imagery (24/06/2019). Incorporating the shoreline data and the bathymetry data, three-dimensional basin map was generated in Autochart Pro to estimate the lake water volume.

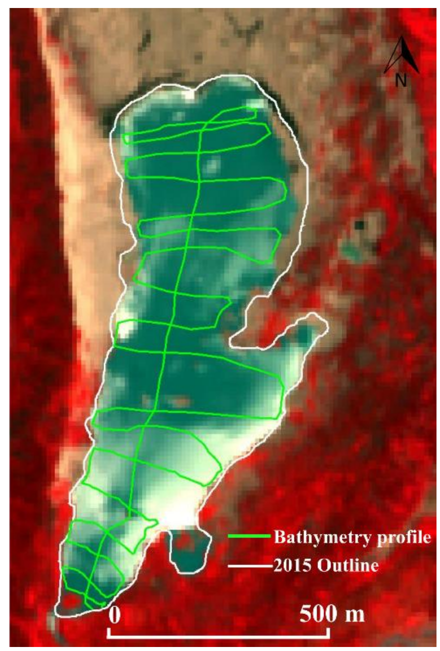

Figure 5: Left: Conducting bathymetry survey on Baychung glacial lake and Right: Survey profile line overlaid on Sentinel 2 MSI (RGB false color composite), imagery date (June 24, 2019)

4.3. Geotechnical Study

4.3.1. Apparatus and sample collection

The geotechnical soil sampling from top of the moraines was carried out on Thorthormi and Luggye glacial lake outlets and one more sample was collected from Thanza village (Figure 4). The following parameters will be used as an input for the GLOF Breach Model (BRCH GUI – BRCH-J)

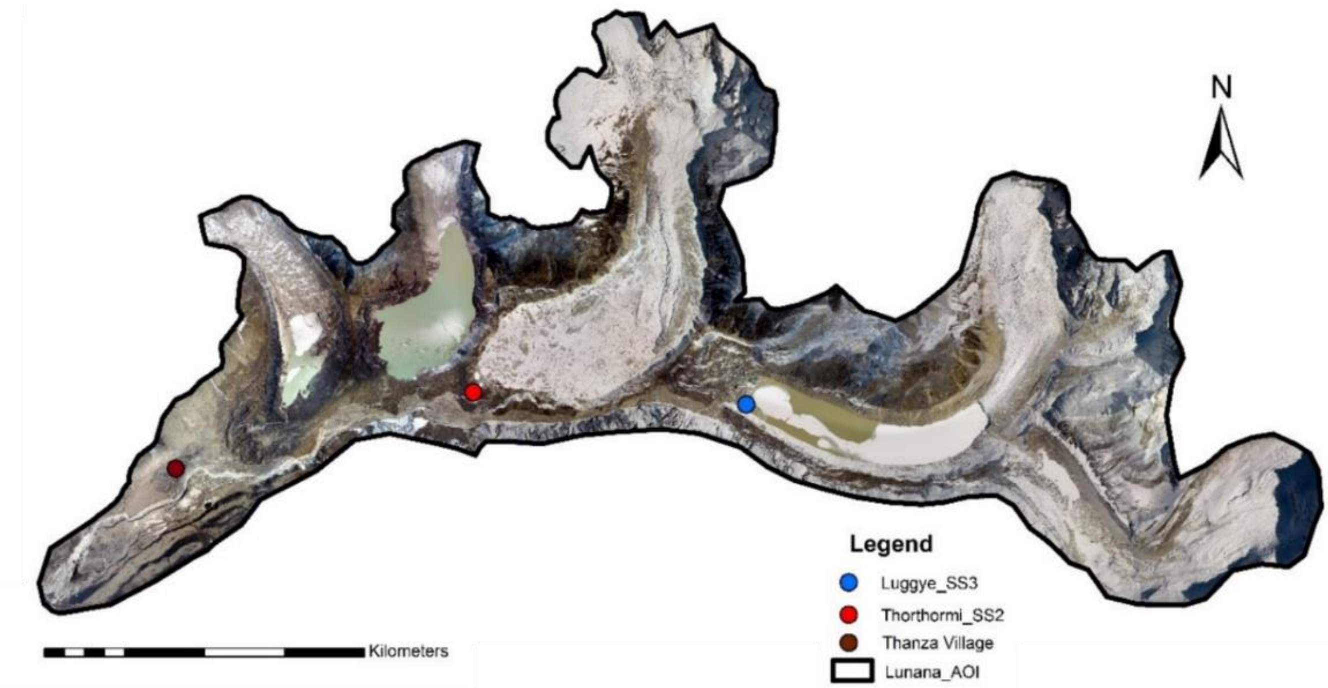

Figure 6: Sampling point location

Grain Size Distribution

A pit of dimension (30 x 30 cm) with a depth of 20 cm were dug at the sampling point ((DIN ISO 18125)). The soils were then collected and sealed in a marked Zip lock bag. The GPS coordinates of the samples were taken by Trimble R-10 2 and the characters of the surrounding morphology were taken note. The soil analysis was done in Geotechnical Laboratory at Department of Geology and Mines since the center did not have the laboratory for the test analysis.

Grain Size Distribution by wet sieve analysis (Gradation test)

The determination of the grain size distribution was carried out by sieving in a British Standard Sieve (BS 410). Since the soil sample contained silt, it was necessary to carried out wet sieving as per the British Standard procedure 1377: Part 2. This was done because the silt particles adhere to sand and gravel sized particles giving the user a wrong soil distribution curve. Therefore, in order to mitigate this error, a wet sieving was done.

This process is done by sieving the soil sample to retain only the soil particles bigger then 0.063 mm for the soil grain analysis. Hence, the soil sample was wet sieved using the 0.063 mm sieve. The retained soil specimen is then dried in the oven at 105-110^{o}c for 12 hours and proceeded to sieving using the British standard sieve. The soil specimen were shaken through a series of woven-wire square-mesh sieves. Each sieve has successively smaller openings so particles larger than the size of each sieve were retained on the sieve. The percentage of each soil size were measured by weighing the amount retained on each sieve and compared the weight to the total weight of the sample. The results of a sieve analysis were plotted as a grain size distribution curve, which were then analyzed to determine the soil gradation of the particular soil.

The following equipment were used for the Grain Size Distribution:

Test Sieves (300mm by half height brass framed sieves, ISO 3310, BS 410)

Sieve size:0.063 mm, 0.150 mm, 0.212 mm, 0.300 mm, 0.425 mm, 0.60 mm, 1.18 mm, 2 mm, 3.35 mm, 6.3 mm, 10 mm, 14 mm, 20 mm), Lid, collecting receptacle, Lab precision weighing scale (0.01 g resolution), drying oven, Sieve Brush.

Density

The Bulk density of the soil was determined by using the liquid substitution method in the Geotechnical Laboratory (DIN 18125). For the displacement method, the zip locked sample was divided into four equal portion (coning). The soil sample was trimmed to produce at least 100 mm dimension mold. The surface void of the specimen was filled insoluble material like putty and weighed to the nearest 1 g (M_f).

The specimen was coated completely by dipping into the molten paraffin wax. The waxed specimen was then cooled and weight to the nearest 1 g (M_w). The waxed sample was then inserted into the known volume cylinder and weighed (M_g).

Calculate the volume of the specimen, Vs (in cm^3) from the given equation:

$$Vs = \left(\frac{M_w - M_g}{\rho_w}\right) - \left(\frac{Mw - M_f}{\rho_p}\right) \qquad \text{---------------------------Eqn-1}$$

where,

M_w is the mass of specimen and wax coating (in g);

M_g is the apparent mass of specimen and wax coating when suspended in water (in g);

M_f is the mass of specimen after making up surface voids in filler (in g);

ρ_p is the density of paraffin wax (in g/cm^3)

$\rho_{w\ is}$ the density of water (in g/cm^3)

Now to calculate the bulk density of the specimen, ρ (in g/cm^3) is calculated using the equation,

$$\rho = \frac{Ms}{Vs} \qquad \text{---------------------------Eqn-2}$$

Where,

M_s is the mass of the soil sample;

V_s is the volume of the specimen;

Hence the density (ρ) of the specimen (in g/cm^3) is calculated.

For displacement method, the following equipment's were used:
Measuring cylinder, paraffin wax, measuring cylinder, precision weighing scale.

4.4. dGPs Survey: Instrument and data collection

Trimble R10-2 GNSS equipment was used for dGPS surveys throughout. Prior to any kind of dGPS surveys, the base station was set and position data were logged for more than 2 – 3 hours to obtain maximum accuracy of the position. After obtaining the point location data, the data set were submitted online (https://trimblertx.com/) for error correction and then used as reference point for other surveys. Such known and corrected geo-locations were marked and will be used in future as Ground Control Points (GCP) for dGPS surveys.

4.4.1. dGPS survey on Thorthormi and Luggye Lake Moraines

For mapping the shorelines of the glacial lakes, moraine surface elevation and outlet channel mapping, we used two sets of Trimble R10-2 GNSS equipment, one as base and the other as rover. The base was set on a known/corrected point in a continuous static mode and the rover in continuous kinematic mode. The rover was connected to the base via Bluetooth in RCMX mode via Trimble assess software. For mapping the outlet channel of Thorthormi and lake water level of post GLOF (June 20, 2019), the points were collected with approximate distance of 1 m and logging duration of 10 seconds. The old water level marks of subsidiary lake II was also mapped with similar method (Figures 7a – b, 8a – b). In case of Luggye outlet channel mapping and surrounding moraine surface elevation mapping, the rover antenna was mounted on backpack with logging interval of 1 m distance and walked continuously (Figures 9a -d)

Figure 7 a: River shoreline mapping using Trimble R10-2 (Rover) at subsidiary lake II remnant and b: logging the survey point

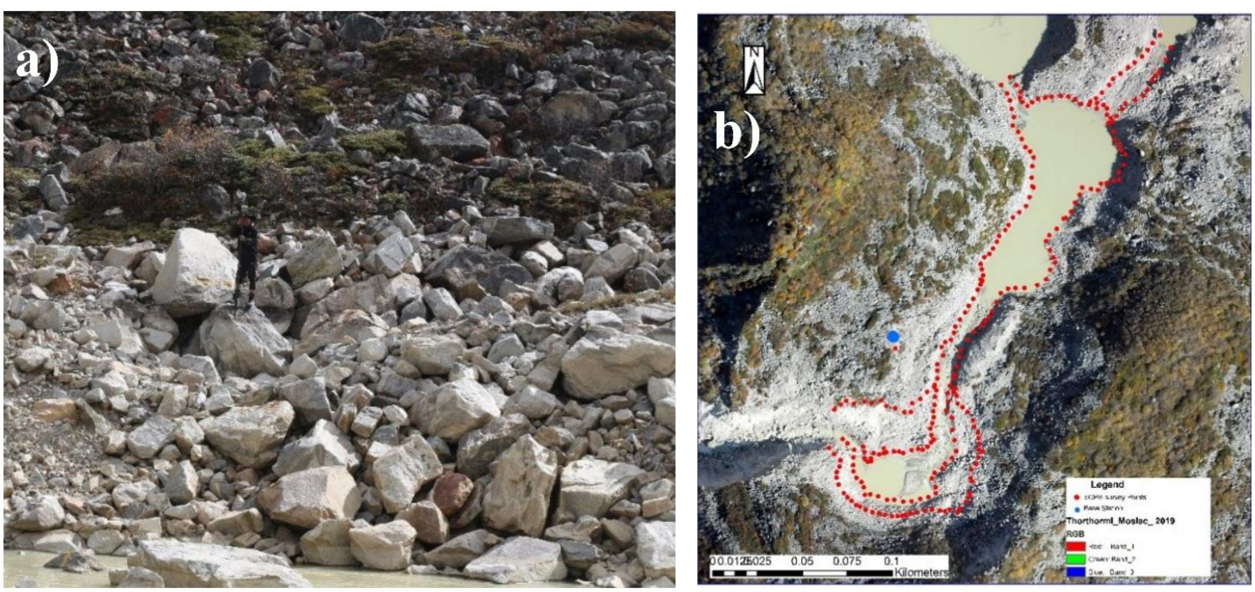

Figure 8 a: Mapping the old lake water level of subsidiary lake II with Trimble R10-2 (Rover) and b: Map showing Thorthormi main lake outlet channel, shoreline of subsidiary lake I, current and old shoreline of subsidiary lake II overlaid on image acquired by UAS

Figure 9: dGPS survey on Luggye outlet channel and end moraine. a: Rover mode (continuous Topo); b: Sentinel 2 MSI image of June 26 2019 (RGB (4,3,2) Composite); c: left side of lake outlet and d: Base Station at Luggye Moraine

4.4.2. Data post-processing

The survey points collected were converted into shapefiles in ArcGIS using the WGS 1984 UTM zone 45 Projection. Using the Create TIN (Triangulated irregular network) feature in the 3D Analyst Toolbox, 3D were created triangulated irregular network (TIN) feature of the lake shoreline to visualize the data.

The Triangulated irregular network model can also be generated in the Trimble access by selecting the feature points and converting it into surface. Using this surface model, the total volume lost from the subsidiary lake 2 (excluding the volume of water that flowed from the main lake.) was computed. First the surface of the old shoreline was created by selecting the old shoreline data, and converting it to a surface. Then the same method is repeated to create the new shoreline surface. From the compute volume in the Cogo tab, we computed the total volume of the water lost (cut volume) from the subsidiary lake II using the surface to surface method, taking the initial surface as the old shoreline surface and final surface as the new shoreline surface.

5. Result and Discussion

5.1. Thorthormi Glacial Lake: June 20, 2019 breach and current situation

5.1.1. June 20, 2019 breach and GLOF

The Rapid Assessment team has carried out not only field assessment at the source but also looked into the air temperature of Lunana area. The team has found out that the summer air temperature (April, May and June) in Lunana area for the year 2019 was warmer compared to other months over the past eight years. Such higher temperature month for 2019 has given rise to rapid melting and collapse of glacier ice on Thorthormi, especially towards upper end of the glacier. Owing to huge mass and disruption of ice mass that occurred around June 20, 2019, displacement of ice occurred ultimately leading to displacement of lake water and movement of floating ice downstream of the lake. Such evidences were backed up by analyzing RADAR images which showed that the Thorthormi glacier was very active in terms of movement and displacement prior to the breaching. The team also found that huge fractured ice masses resting offshore of the Thorthormi main lake indicating sudden rise of lake water level just before the occurrence of the breach.

During the detailed assessment, by referring to the report by rapid assessment team, the physical verifications were carried out on upstream of the Thorthormi glacier and glacial lake. It was found that the sudden and huge fracturing and displacement (both vertical and lateral) of ice have taken place at the upper midpoint of Thorthormi main glacier (Figure 10 a - d) as evidenced from fresh glacier ice surface. Due to mass fracturing of ice, orientation and morphology of Thorthormi, the masses of fractured ice along with water bodies might have led to its movement towards main lake and outlet exerting hydrostatic pressure at the outlet moraines as well as towards Thorthimi – Raphstreng barrier. Such phenomena of ice movement were explained in detail by rapid assessment team after studying the ice velocity using remotely sensed satellite imageries. As the water body moved downstream along with the ice bodies, sudden rise in Thorthormi main lake occurred (Rapid Assessment Report), leading to breach of a moraine near the old outlet leading to sudden discharge of water from Thorthormi main lake which ultimately breached subsidiary lake II and emptied. The team also briefly monitored the condition of the ice from recent satellite imageries and found that the glacier ice is still active towards the upper end.

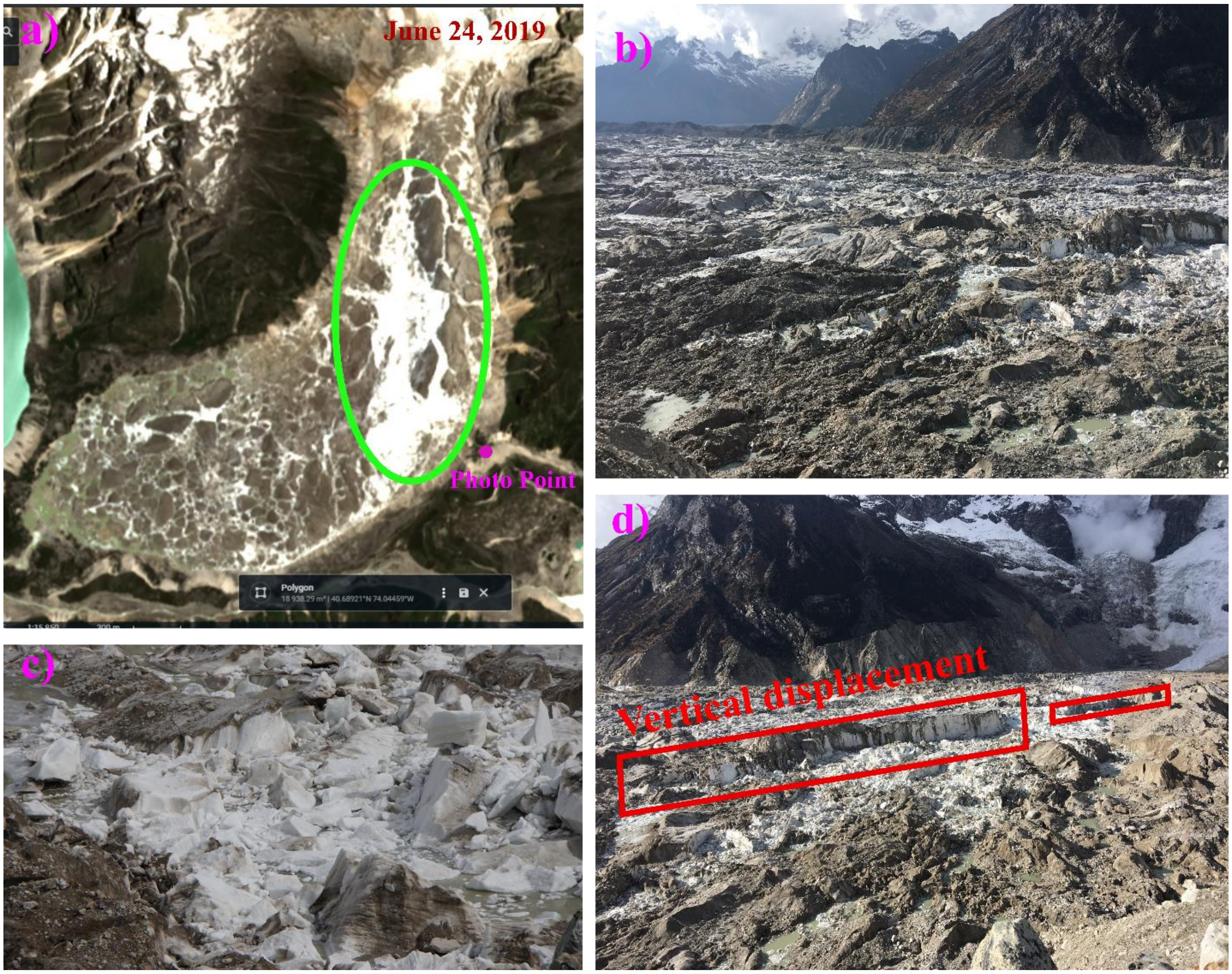

Figure 10: Ice fracturing and displacement on Thorthormi glacier ice towards upper side; a: Thorthormi glacier from Sentinel 2A (June 24, 2019) right after June 20, 2019 GLOF event and the green oval shows the location of maximum ice displacement happened prior to the event. b – d: Photographs showing fresh ice fracturing and red rectangles shows the vertical displacement of ice

5.2. Thorthormi Glacial Lake: UAS survey and surrounding Morphology

5.2.1. DEM and aerial photo mosaic from UAS survey

The three dimensional DEM was generated in Agisoft using the aerial photographs obtained through UAS survey with resolution of 0.05 m. such 3D models will be very useful for future moraine feature changes tracking.

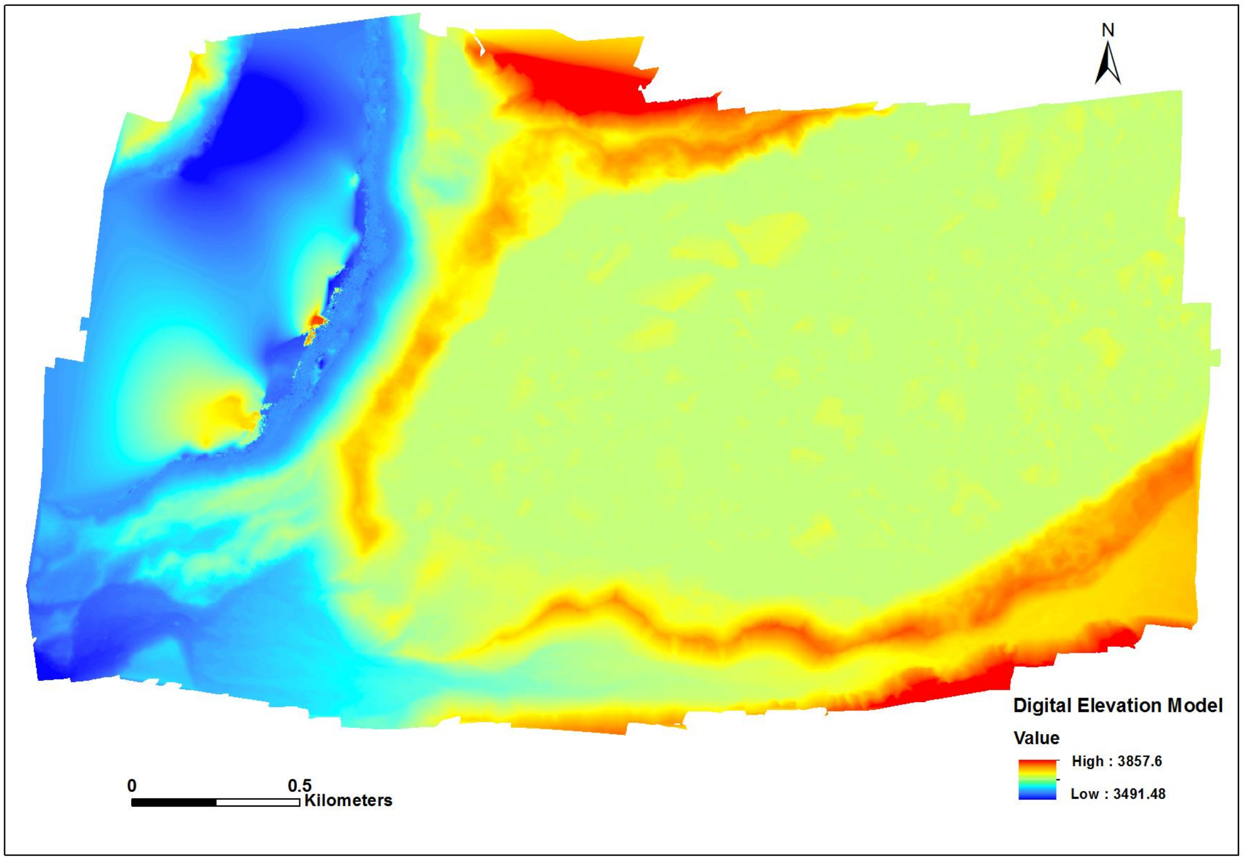

Figure 11: Digital Elevation Model of Thorthormi area created using UAS survey images in Agisoft with a resolution of 0.5 m resolution (50 cm X 50 cm)

5.2.2. Surrounding Morphology

The surrounding morphology of Thorthormi main lake outlet and moraine barrier between Raphstreng and Thorthormi were surveyed through photography and physical inspection. The outlet channel was mapped through dGPS survey. The June 20, 2019 GLOF event has created a new outlet channel and the old channel was found dried up (Figure 12). Subsidiary lake II was completely drained out during the GLOF event. The subsidiary lake II basin was surveyed and through basin volume map, 8036 m^3 of water was released from subsidiary lake II alone, excluding water discharged from Thorthormi main lake. The channel width survey was conducted in 2012 during the last phase of the Thorthormi lake mitigation project and we have compared the data with the current field survey. Few changes were observed with bit of channel deepening and widening at some places (Table 1), the new outlet channel and enlargement of subsidiary lake I by few square meters (Figure 12 a – c). The outlet channel below the subsidiary lake II was deepened by almost 9 – 10 m as reported by the rapid assessment team.

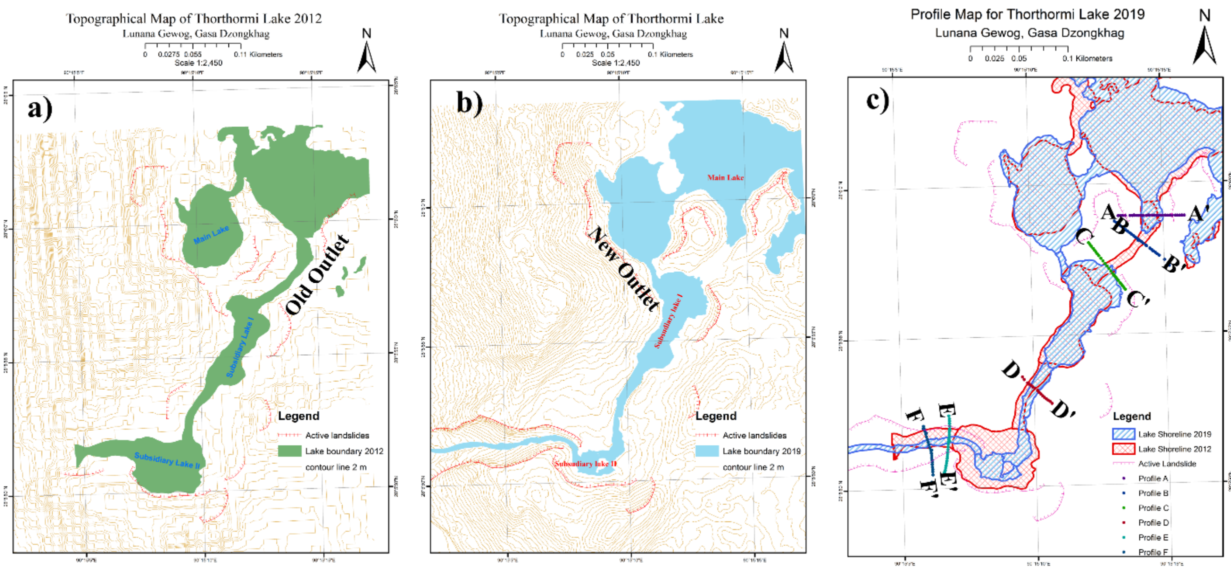

Figure 12: The topographic map at Thorthormi glacial lake outlet. a: The topographic map of 2012 with old outlet channel joining subsidiary lake I. b: Topographic map of 2019 generated from DEM of UAS survey with new outlet channel and; c: topographic map of both 2012 and 2019 overlaid with river channel profile.

Sl No	Profile line	Channel Width (m)	
		2012	2019
1	A – A′	17.30	21.95
2	B – B′	9.30	-
3	C – C′	11.88	13.15
4	D – D′	9.34	10.23
5	E – E′	19.01	5.50
6	F – F′	18.42	5.57

Table 1: The channel width along the profile lines available from 2012 compared to 2019.

5.2.3. Characteristics of the moraine barrier between Thorthormi and Raphstreng glacial lakes

Post 2009 – 2012 mitigation on Thorthormi glacial lake (Artificial lowering of Thorthormi lake by 5 m), no major slides were observed on the side walls of Raphstreng – Thorthormi moraine barrier. Although no major surveys were carried out on the moraine barrier between the two lakes after the mitigation work, photos of moraine barrier towards Thorthormi lake were taken in 2015 when a team visited Lunana area for lake bathymetry survey. Closely analyzing the photo of 2015, it is observed that the side wall towards Thorthormi was not so active by then (Figure 13). The detailed assessment team found that the sliding has reactivated as evidenced by fresh scarps towards Thorthormi lake (Figure 14). In the absence of photos and data of immediate pre-GLOF event of June 20, 2019 it is difficult to date the reactivations of the sliding. When the rapid fracturing and disturbances on glacier ice occurred towards upstream of Thorthormi (Figure 10), huge and closely spaced floating ice masses have moved (Figure 15) towards main outlet part (Rapid Assessment Report) giving rise to sudden lake water level increase. Due to sudden increase in lake water level as well as huge floating ice masses might have disturbed the moraine side walls towards Thorthormi glacial lake. Therefore, the reactivation of sliding could be attributed to the recent GLOF event.

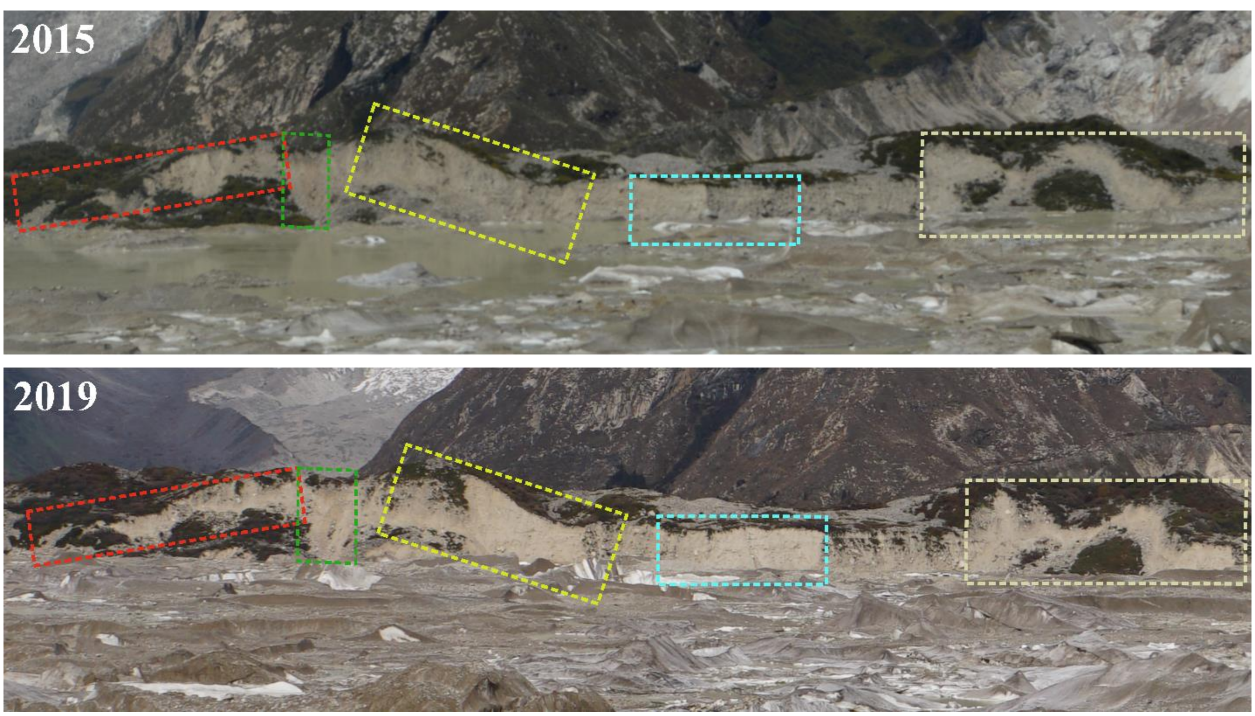

Figure 13: Two photos taken in 2015 and 2019 September showing reactivated sliding by June 20, 2019 GLOF event towards Thorthormi – Raphstreng moraine barrier (Thorthormi side)

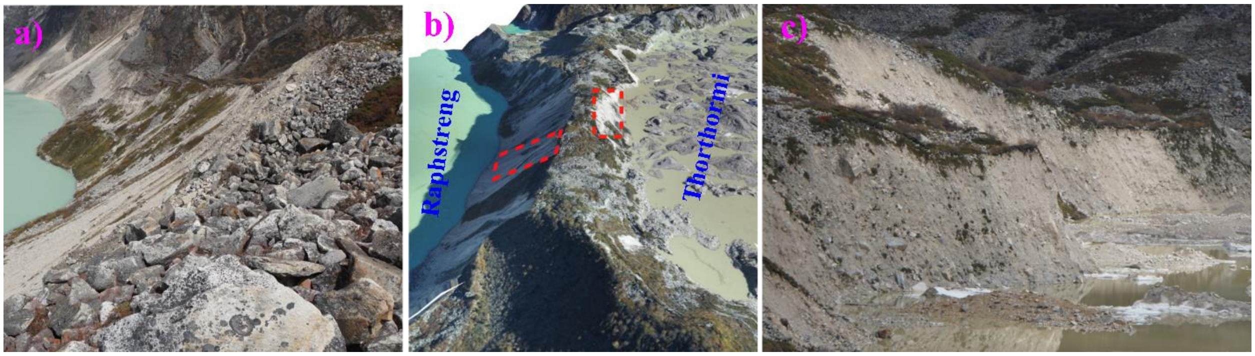

Figure 14: Photos showing new sliding towards a: Raphstreng, c: Thorthormi. b: Red dash-boxes showing the locations of two sliding area and the background image is acquired by UAS survey

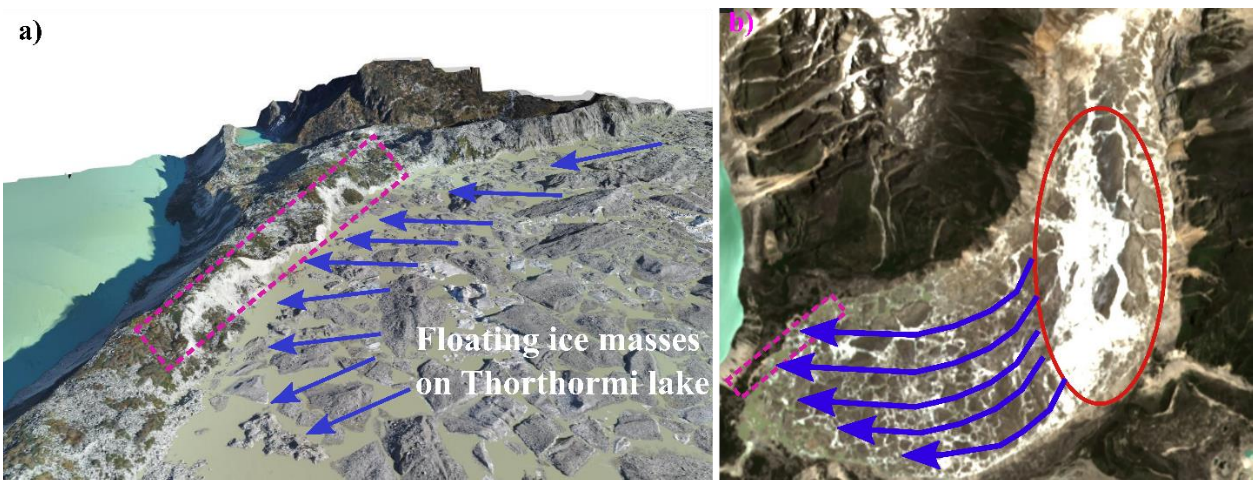

Figure 15: The possible ice movement directions (blue arrow in both a and b) and sliding area on Thorthormi side of the Thorthormi – Raphstreng moraine barrier. The red oval shape in b shows the location of rapid ice disturbance occurred during or prior to the GLOF even on June 20, 2020

After obtaining the 3D DEM from the aerial survey of Thorthormi area, the narrowest crest width of the Thorthormi – Raphstreng barrier was measured in ArcGIS from the DEM. The narrowest point crest width is 33.5 m at the location shown in figure 16. In 2008, a team from Department of Geology and Mines have also measured the crest width and found out to be around 32 m. The measurement locations differ from the current one and the one DGM carried out is bit above the current location. The difference in crest width could be attributed to different location as well as methodology adopted for measurement as earlier was conducted at the field site using measuring tapes. For future monitoring, similar methodology could be adopted.

With such active and unstable findings from the detailed assessment on the moraine barrier, the future breaching of Thorthormi main lake towards Raphstreng remains critical and possess danger if not monitored on time series basis. The fresh scarps on moraine barrier were also verified with Pleiade images obtained before 2015 and recent ortho-images acquired via UAS survey.

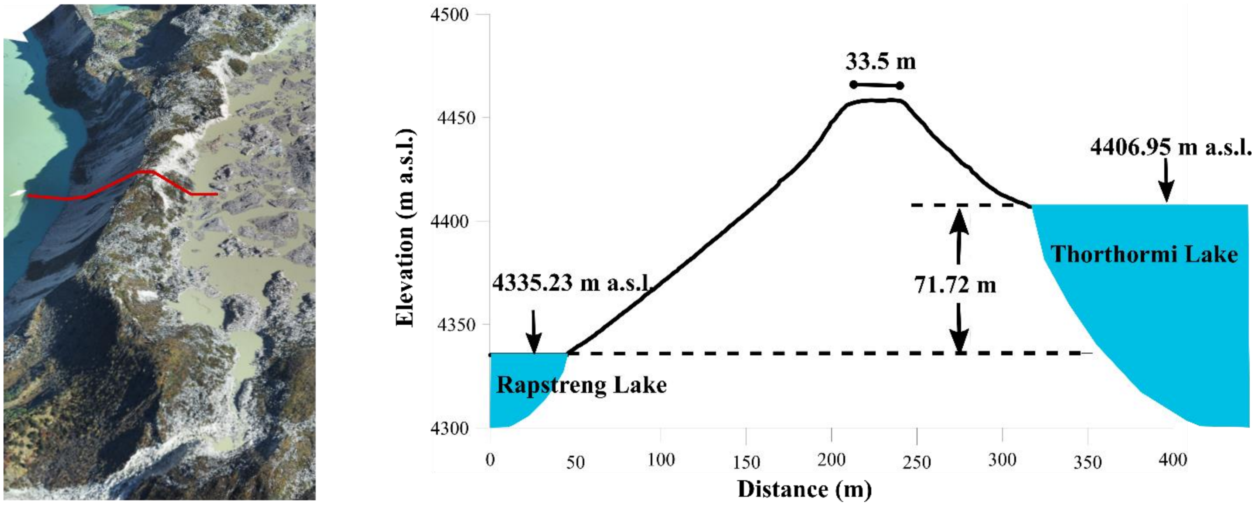

Figure 16: Profile from Raphstreng lake crossing the narrowest crest towards Thorthormi. On the right figure, the lake depths are not to scale. The lake water levels were obtained from DEM generated from UAS survey. The lake level difference between the two lakes are 71.72 m

The slope map for Thorthormi – Raphstreng barrier was also generated from the DEM and is shown in figure 17. From the map, it is observed that the wall towards Thorthormi is near vertical at some locations. Such features indicate that the sliding towards Thorthormi can occur in future as the moraine wall consists of unconsolidated materials and is in contact with active lake surface. Slope angle of as high as 88 degrees were observed (Figure 17)

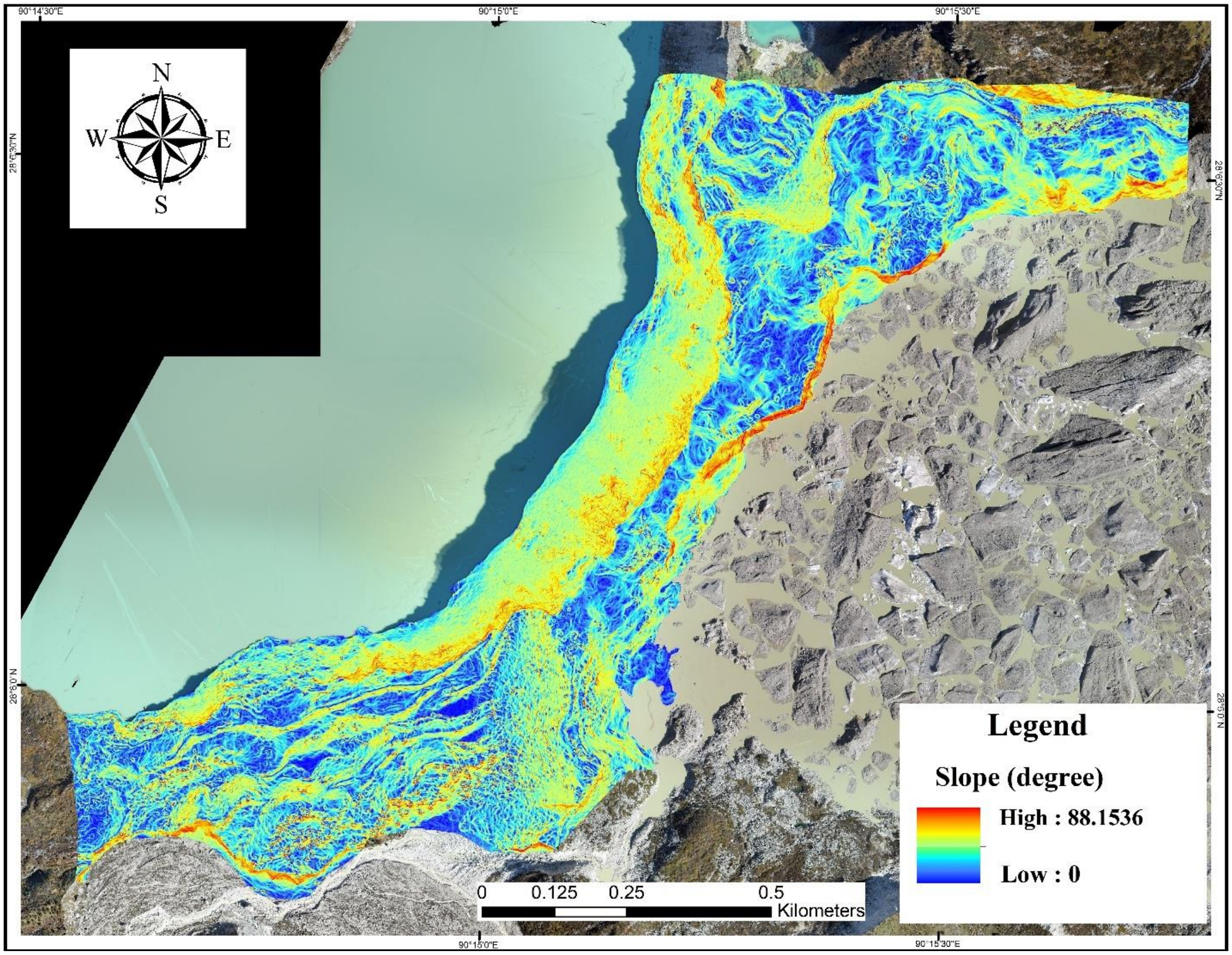

Figure 17: Slope map of Thorthormi – Raphstreng barrier. Slope angle of 0 – 90 degree are represented in blue to red.

After obtaining the high resolution DEM of Thorthormi surrounding morphology the moraine walls surrounding the lake was fully scanned.

5.3. Luggye Outlet and shoreline

The dGPS survey on Luggye lake was conducted with Trimble R10-2 to map the outlet channel and lake shoreline towards the outlet (Figure 18 b). The particular activity was conducted to track the possible changes on outlet channel and lake expansion downstream. The expansion of the lake downstream is possible as the changes and moraine deformation with formation of water bodies on moraine extending towards Thorthormi side was observed (Figure 18 a and c). The fresh water bodies that exists at present indicates the melting of ice occurring beneath the moraine surface.

Such formation of waterbodies might lead to formation of bigger lakes and could join with Luggye main lake. The side walls of the outlet channel (V-shapped) were also mapped and the possible sliding could be monitored in future.

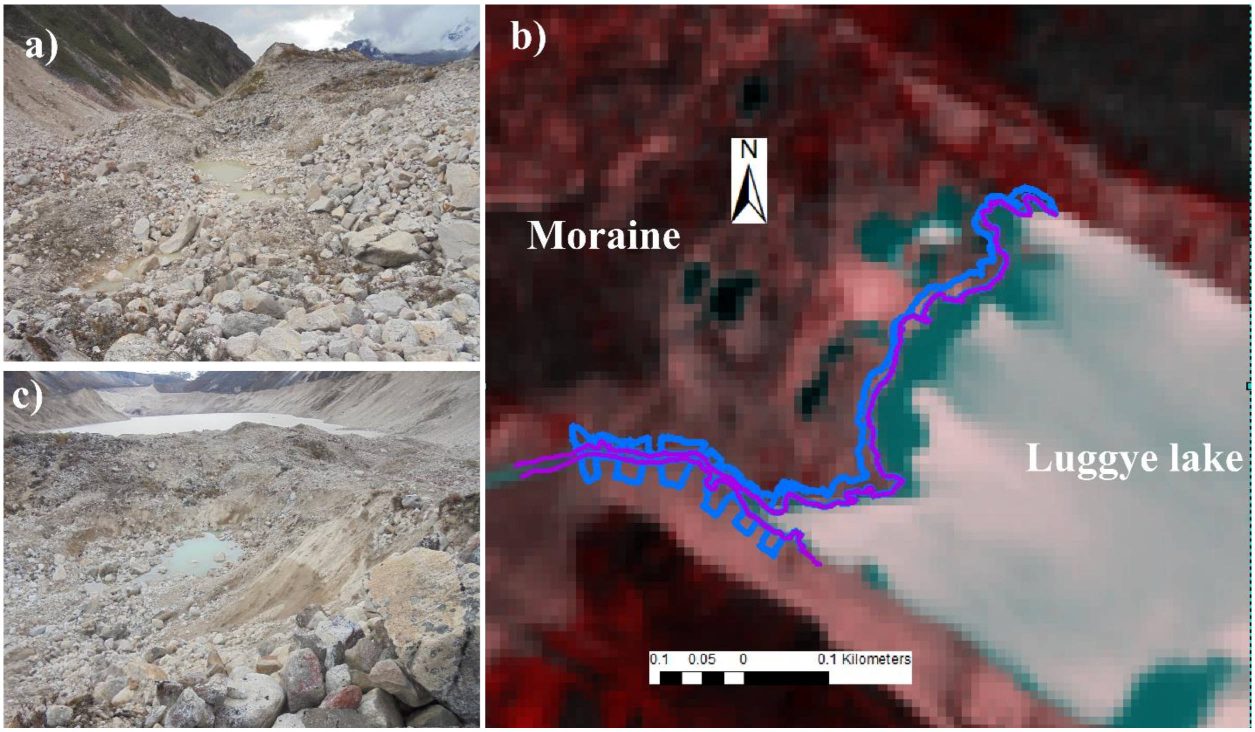

Figure 18: Map showing the dGPS tracks on Luggye outlet in b: the purple line shows the lake shoreline and the outlet channel and the blue line shows the survey tracks on moraines and slopes at the outlet channel. a and c shows the deformation on moraine towards Thorthormi side and water bodies formed

5.4. Bathymetry results on Baychung Lake

Bathymetry survey on Baychung glacial lakes were conducted in 2009 by a team from STREPS Project with DGM and later done in 2015 by a joint team lead by erstwhile Department of Hydromet Services. The bathymetry dataset collected by 2015 team were analyzed during the present activity. Noticing the expansion of the particular lake from satellite imageries, the detailed assessment team also carried out bathymetry survey on Baychung glacial lake to see the changes in expansion in terms of length and volume.

Year / Parameters	2009	2015	2019
Length (m)	743	1099	1199
Area (10^5 m^2)	1.97	3.10	3.80
Max. depth (m)	19.7	31.1	33.1
Volume (mil. m^3)	1.590	2.082	3.449

Table 2: Table showing the length and volume changes from 2015 to 2019 of Baychung glacial lake. The length for 2015 and 2019 were obtained from Landsat and Sentinel 2A respectively.

Baychung glacial lake is still attached with the feeding glacier and is in the expansion process. From 2015 to 2019, the lake has expanded longitudinally by 99 m and increased its water volume by 1.4 million cubic meters in four years (Table 1). Baychung glacier has retreated longitudinally by 99 m in four years which translates to annual retreat rate of approximately 25 m/year. In 2009, the SATREPS project team reported the lake water volume of Baychung to be 1.59 million cubic meters. Comparing the lake water from 2009 to 2019, there is an increase of about 1.9 million cubic meters in 10 years. By then, the maximum depth measured was around 20 m at the middle section of the lake. As the glacier retreated upward giving rise to expansion of the lake, the depth has increased towards upper end (Figure 18)

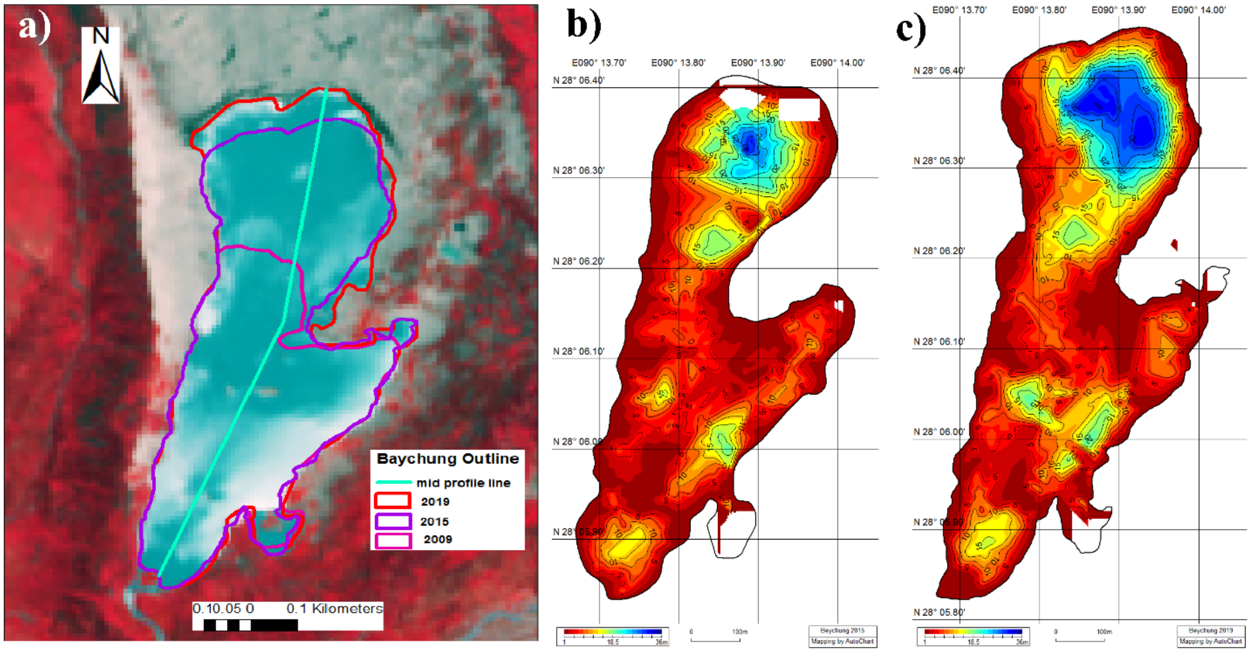

Figure 19: Lake bathymetry map of Baychung glacial lake; a: Lake outline from 2009, 2015 and 2019, b – c: depth map of 2015 and 2019 respectively. From the bathymetry map we can observe the upward expansion of lake and increasing depth upward

5.5. Geotechnical soil parameter results

5.5.1 Thorthormi Subsidiary lake II (TSS1)

The moraine sample TSS1 (figure 6) was collected from the coordinate $28^0$05’53.07093” N and $90^0$15’08.32129” E from the inner dam of the subsidiary lake II moraine. Sandy and gravelly soils with exposed dry glacier silts was found near the sampling pit. The area have minimal patches of vegetated shrubs and more of boulders and gravels. The result of the wet sieve analysis of the sample shows that the grading curve to be a gap graded sandy gravel soil with an internal friction angle of 39 degree. This type of soil is poorly graded soil, with many void spaces in-between the soil particles with high porosity. Therefore, this type of soil shows a low stability characteristic and are more susceptible to soil liquefaction. (Head, K. H, *Manual of soil Laboratory*, 1982 and Mulder. A, *Soil mechanics laboratory manual* 2004)

The geotechnical soil analysis results are given below:

Soil mechanical parameters of TSS-01		
Unit weight (γ) **(δ * g)**	kN/m^3	**22.43**
Density (δ) **(m/V)**	g/cm^3	**2.289**
Angle of internal friction (ϕ)	Degree	**39**
Cohesion c	kN/m^2	**0-10**
Manning’s N		**0.07**
Unconformity coefficient (Cu) (d60/d10)		**14.42**
Coefficient of Curvature (Cc) (($d30^2$)/ (d10 * d60))		**0.889**

Table 3. The detailed parameter results of the soil sample (TSS-01) obtained from Thorthormi Subsidiary lake II

SIEVING ERROR: 0.8%

SAMPLE STATISTICS

SAMPLE IDENTITY: **Thorthormi SS-01**

ANALYST & DATE: Depratment of Geology and Min

SAMPLE TYPE: Polymodal, Very Poorly Sorted

TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	φ
MODE 1:	2675.0	-1.372
MODE 2:	362.5	1.486
MODE 3:	8150.0	-2.989
D_{10}:	204.7	-3.951
MEDIAN or D_{50}:	2017.1	-1.012
D_{90}:	15460.9	2.289
(D_{90} / D_{10}):	75.54	-0.579
$(D_{90} - D_{10})$:	15256.2	6.239
(D_{75} / D_{25}):	13.60	-0.293
$(D_{75} - D_{25})$:	6976.1	3.766

GRAIN SIZE DISTRIBUTION

GRAVEL:	50.3%	COARSE SAND:	12.6%
SAND:	49.7%	MEDIUM SAND:	12.3%
MUD:	0.0%	FINE SAND:	8.1%
		V FINE SAND:	3.2%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.0%
COARSE GRAVEL:	9.2%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	14.5%	MEDIUM SILT:	0.0%
FINE GRAVEL:	9.4%	FINE SILT:	0.0%
V FINE GRAVEL:	17.1%	V FINE SILT:	0.0%
V COARSE SAND:	13.5%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic φ	Geometric μm	Logarithmic φ	Description
MEAN ($\bar{x}$):	4072.2	1253.5	-0.729	2015.5	-1.011	Very Fine Gravel
SORTING (σ):	5135.6	7.824	2.089	4.979	2.316	Very Poorly Sorted
SKEWNESS (Sk):	1.444	-1.509	0.075	-0.031	0.031	Symmetrical
KURTOSIS (K):	3.856	6.400	2.069	0.754	0.754	Platykurtic

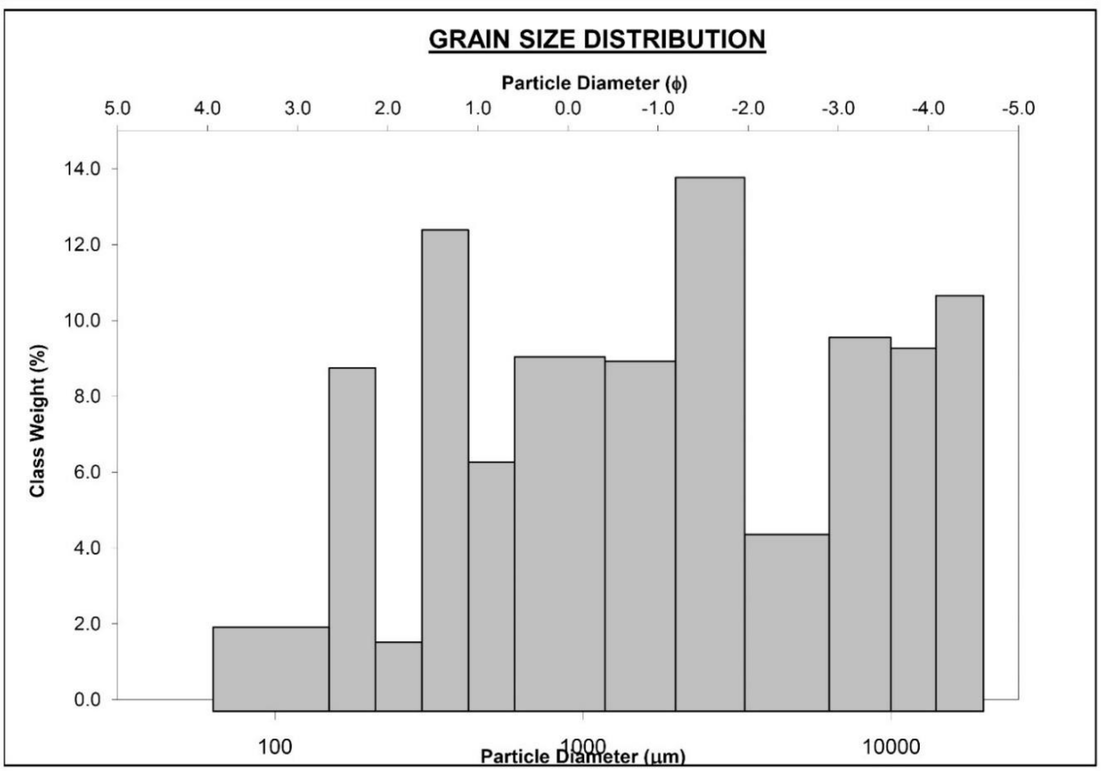

Figure 20: The Soil statics generated using the GRADISTAT version 8 software. The grain size distribution indicating 50.3% Gravel and 49.7% sandy

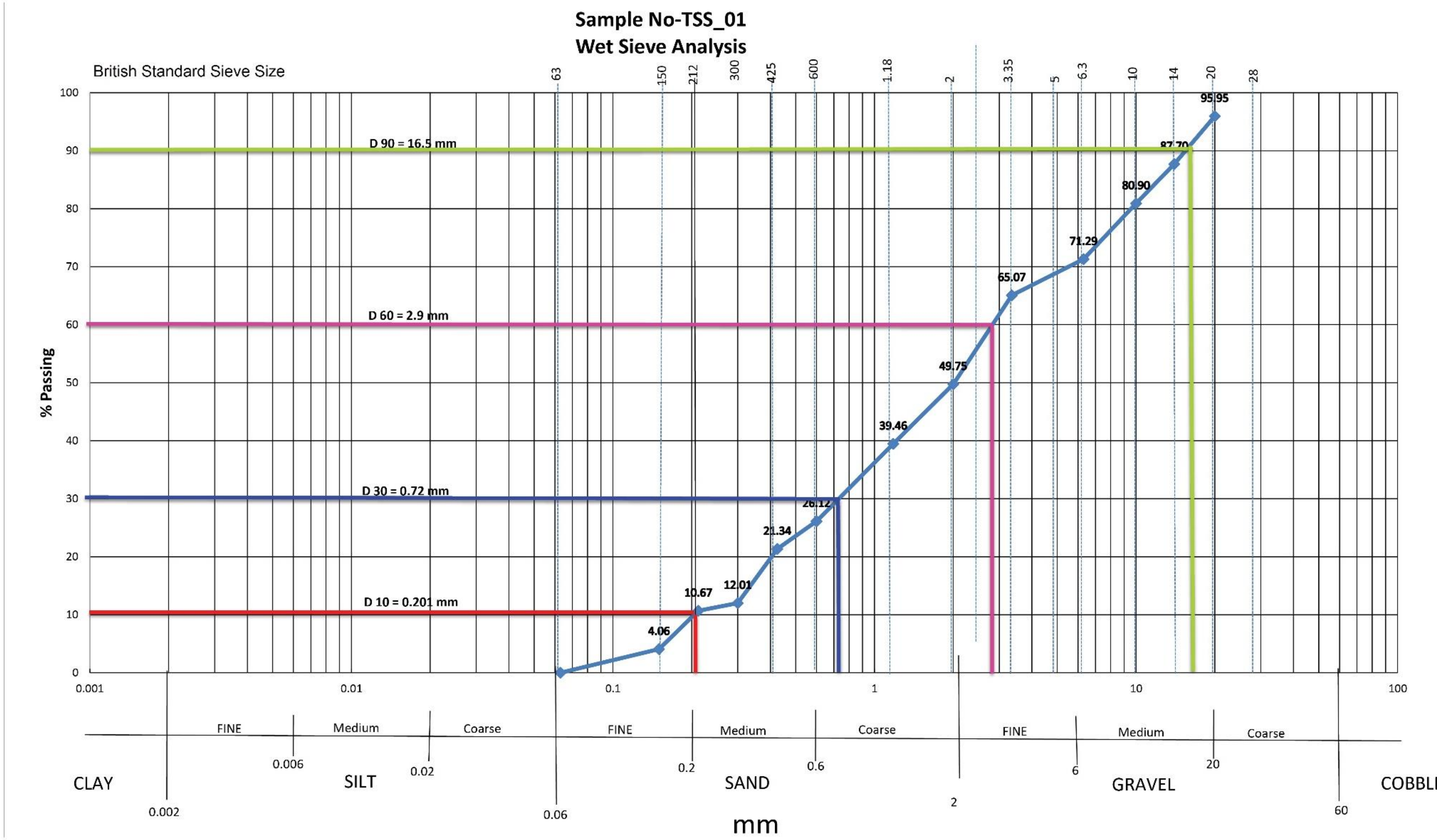

Figure 21: The Soil Grain Analysis chart (log scaled) of Thorthormi Subsidiary Lake II –TSS-01), show a gap-graded curve. The D10, D30, D60 and D90 are indicated as red, blue, pink and green lines respectively.

5.5.2 Luggye lake (LSS-01)

The moraine soil sample LSS1 was collected from the coordinate $28^{0}05'45.22168''$ N and $90^{0}17'12.91379''$ E from the inner dam of the moraine of the Luggye Lake (figure 6). Sandy and gravelly soils with exposed dry glacier silts were found near the sampling pit. Very little vegetation was found in the area of the moraine with fresh exposed boulder and gravels indicating active subsurface activities. The formation of subsidiary lake on the right side of the moraine strongly indicates melting of isotopic ice lenses as suggested by Leber et al. (2002), although no outcrop of ice lenses was found on the moraine during the survey. The wet sieve analysis of the soil sample of that vicinity indicates a gap graded sandy gravel curve with an internal friction of 41 degree. This type of soil are poorly graded soil, with many void spaces in-between the soil particles. Hence shows a low stability characteristic with more porosity and are more susceptible to soil liquefaction (Head, K. H, *Manual of soil Laboratory*, 1982 and Mulder. A, *Soil mechanics laboratory manual* 2004)

The geotechnical soil analysis results are given below:

Soil mechanical parameters of TSS-01		
Unit weight (γ) **(δ * $\boldsymbol{g}$)**	kN/m^3	**22.922**
Density (δ) **(m/V)**	g/cm^3	**2.339**
Angle of internal friction (ϕ)	Degree	**41**
Cohesion c	kN/m^2	**0-10**
Manning's N		**0.07**
Unconformity coefficient (Cu) (d60/d10)		**12.94**
Coefficient of Curvature (Cc) (($d30^2$)/ (d10 * d60))		**0.38**

Table 4. The detailed parameter results of the soil sample (LSS-01) obtained from Luggye Lake right moraine.

SIEVING ERROR: 0.4%

SAMPLE STATISTICS

SAMPLE IDENTITY: **Luggye SS-01**

ANALYST & DATE: Depratment of Geology and Min

SAMPLE TYPE: Polymodal, Very Poorly Sorted

TEXTURAL GROUP: Sandy Gravel

SEDIMENT NAME: Sandy Very Fine Gravel

	μm	ϕ
MODE 1:	362.5	1.486
MODE 2:	2675.0	-1.372
MODE 3:	181.0	2.487
D_{10}:	165.6	-3.598
MEDIAN or D_{50}:	1263.1	-0.337
D_{90}:	12105.7	2.594
(D_{90} / D_{10}):	73.10	-0.721
$(D_{90} - D_{10})$:	11940.1	6.192
(D_{75} / D_{25}):	11.21	-0.843
$(D_{75} - D_{25})$:	3380.8	3.487

GRAIN SIZE DISTRIBUTION

GRAVEL:	43.1%	COARSE SAND:	10.1%
SAND:	56.9%	MEDIUM SAND:	17.1%
MUD:	0.0%	FINE SAND:	13.9%
		V FINE SAND:	5.5%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.0%
COARSE GRAVEL:	4.4%	COARSE SILT:	0.0%
MEDIUM GRAVEL:	12.7%	MEDIUM SILT:	0.0%
FINE GRAVEL:	7.2%	FINE SILT:	0.0%
V FINE GRAVEL:	18.7%	V FINE SILT:	0.0%
V COARSE SAND:	10.3%	CLAY:	0.0%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	3605.2	1227.0	-0.295	1300.8	-0.379	Very Coarse Sand
SORTING (σ):	4949.8	4.777	2.256	5.367	2.424	Very Poorly Sorted
SKEWNESS (Sk):	1.644	0.094	-0.094	0.025	-0.025	Symmetrical
KURTOSIS (K):	4.495	1.846	1.846	0.828	0.828	Platykurtic

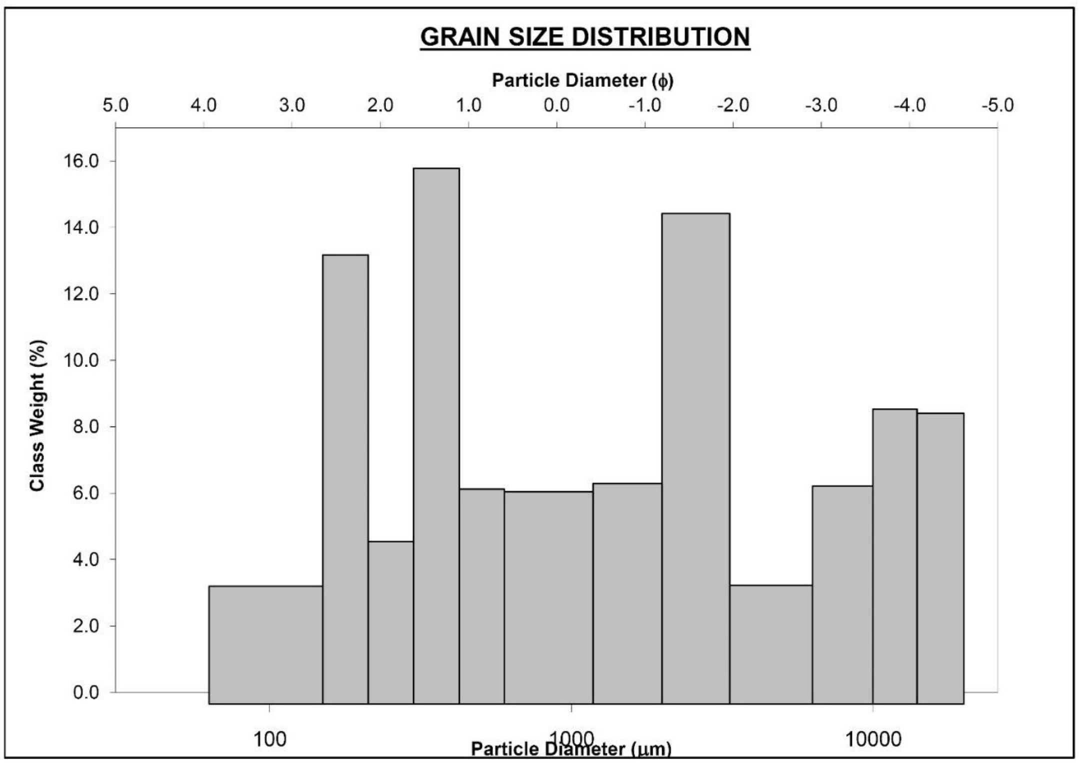

Figure 22: The Soil statics generated using the GRADISTAT version 8 software. The grain size distribution indicating 43.1% Gravel and 56.9% sandy

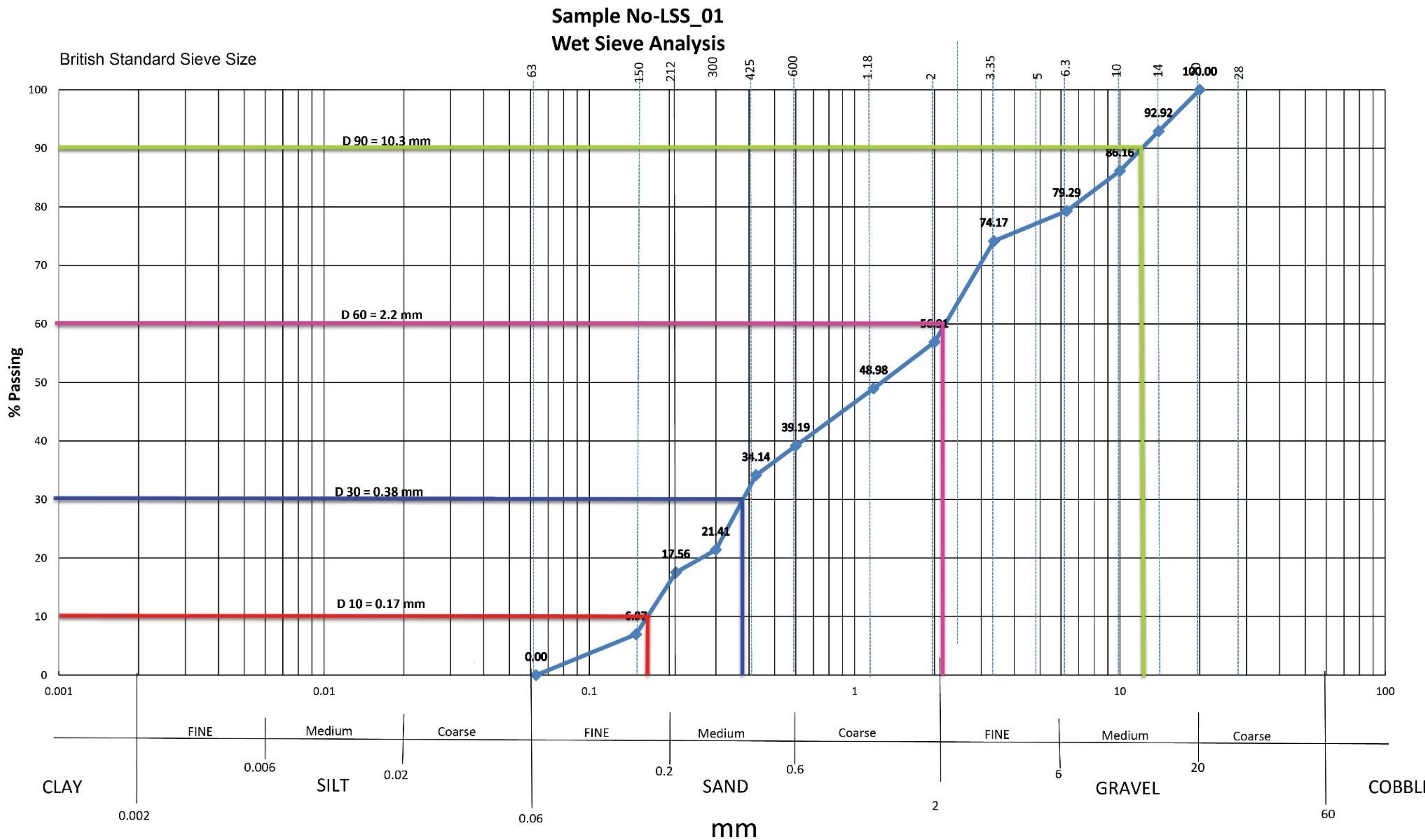

Figure 23: The Soil Grain Analysis chart (log scaled) of Luggye Lake II –LSS-01 show a gap-graded curve. The D10, D30, D60 and D90 are indicated as red, blue, pink and green lines respectively.

6. Conclusion

With the financial assistance from Punatsangchu Hydropower Project Authority I and II under the flood control mechanism, detailed assessment on Thorthormi glacial lake, its surrounding moraines, UAS survey, brief survey on Luggye outlet moraine and bathymetry on Baychung glacial lake was conducted from September to October, 2019.

6.1. Thorthormi Outlet Channel and moraines

Alongside aerial survey of Thorthormi area, the surrounding moraines were physically surveyed using Trimble R10-2, especially the outlet area of Thorthormi main lake. The outlet channel was mapped for future references to see the changes along the channel and also compared with the topographical survey conducted in 2012. From such assessments we conclude the following:

- The outlet channel part of Thorthormi main outlet has deepened and narrowed at some places
- The outlet part is still not stable and changes are taking place which in future might lead to breaching of main lake due to increased hydrostatic pressure in the main lake

6.2. Thorthormi – Raphstreng moraine barrier

Thorthormi – Raphstreng moraine barrier was surveyed in detail using DEM and ortho-images robtained through UAS survey in terms of stability. The changes were also traced by comparing photos of 2015 and 2019 field survey. The narrowest moraine crest width was measured from the DEM. From the current survey on the moraine barrier, we conclude that:

- The narrowest crest width is around 33.5 m
- Sliding on both side of the two main lakes (Thorthormi and Raphstreng) have reactivated in the recent times with major towards Thorthormi glacial lake.
- The sliding could have been triggered by the recent GLOF event of June 20, 2019 as the post 2009 – 2012 mitigation photos (2015) showed no active sliding or fresh scarps.
- Slope maps were also produced from the DEM and found that the slope towards Thorthormi side is much steeper with slope angle of almost 88 degrees at some points. Such steep slopes which are in contact with active lake water surface may trigger more sliding in future

- Such reactivation of sliding on Thorthormi – Raphstreng barrier having high slope angles might erode the moraine walls making it more susceptible to breaching of Thorthormi main lake in to Raphstreng giving rise to a major GLOF event in near future.

6.3. Thorthormi glacier ice towards upstream

The upper section of the glacier ice was physically visited and photographs were taken to see the rapid disruption of ice masses. Recent satellite imageries were also briefly studied to see the current condition of the ice and we conclude the following:

- It was found that the sudden fracturing on ice and sudden displacement has occurred in recent times
- Such ice occurrence of ice dynamics upstream within a short span of time might have led to movement and displacement of lake water body downstream leading to minor breach of Thorthormi outlet moraine and reactivation of sliding on Thorthormi – Raphstreng moraine barrier.
- Recent satellite imageries show that the glacier ice towards upstream are still in active state and ice dynamism taking place. Such active and huge ice masses upstream may lead to instability of the lake and moraine conditions towards outlet like that of June 2019 event.

6.4. Geotechnical parameters

Soil samples from Thorthormi and Luggye outlet moraines were collected and analyzed for geotechnical parameters in Department of Geology and Mines such as density (δ), specific gravity (C_c), coefficient of curvature, unconformity coefficient (C_u), angle of internal friction (ϕ) and unit weight (γ) and we conclude the following:

- The soil parameters were found to be similar to that by Leber and team who conducted the same in early 2000s.
- The soil characteristics of the moraines are poorly graded and has excess or deficiency of certain particle sizes.
- It is filled with many voids spaces in between the soil particles and are highly porous which shows low stability and susceptible to soil liquification (Holtz., R. and Kovacs, W.).
- For future flood modeling, such geotechnical parameters will be very useful.

6.5. Luggye and Baychung glacial lakes

dGPS survey at the outlet of Luggye glacial lake was conducted to map the outlet channel width and to map the lake shoreline towards the outlet for tracking future changes. Bathymetry on Baychung glacial lake was conducted to find the annual expansion rates of the glacial lake as well as the retreat rate of the feeding glacier and we conclude the following:

- Baychung glacial lake is also expanding at a fast rate
- The glacial lake volume of Baychung glacial lake has increased by almost 1.9 million cubic meter from 2009 – 2019 and 1.4 million cubic meters from 2015 – 2019
- With less than 1 km long in 2009 and the lake measured 1199 m in length in 2019. This shows that the lake has expanded longitudinally by 456 m in 10 years with an annual expansion rate of approximately 45.6 m/year.

Recommendations

Based on the field survey findings, the team would like to recommend the following purely for future activities:

a. The team has found in the field that the whole of the Thorthormi glacier ice has almost fractured. It may soon form a complete lake. Due to the ice dynamics towards the upper end, similar event like that of June 19, 2020 may occur and can disturb the moraine barrier between Thorthormi and Raphstreng glacial lakes. Yearly time series monitoring on moraine barrier is recommended
b. The September to October 2019 field team did not have geophysical instruments and could not map subsurface condition of the Thorthormi – Raphstreng moraine barrier. Earlier reports confirmed the presence of ice lenses within the moraine barrier. In order to confirm whether such ice bodies are still present, a detailed geophysical survey is recommended on it.
c. The existing EWS functions completely based on water level sensors and during the winter seasons, it gives false alarm due to freezing of water. As recommended by the rapid assessment team, it is high time that the current EWS be upgraded.

Since the breaching or collapsing of moraine dams are associated with occurrences of disturbances on such moraine dams, the current EWS could be integrated with installation of Seismic sensors on moraine dams

d. In the absence of channel width data of Luggye outlet, no comparison has been made but on visual inspections, the Luggye outlet channel seems narrowing due to sliding from the V-shaped outlet moraine. If a major sliding from the outlet moraine occurs, it may block the outlet giving rise to main lake level rise and increase in hydrostatic pressure. Regular monitoring on the outlet part of Luggye is recommended
e. Though the outlet part of Baychung glacial lake is well vegetated, flat and shallow in terms of lake depth (near the outlet), it is a fast-growing lake. Constant monitoring on Baychung glacial lake is also recommended.

References

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