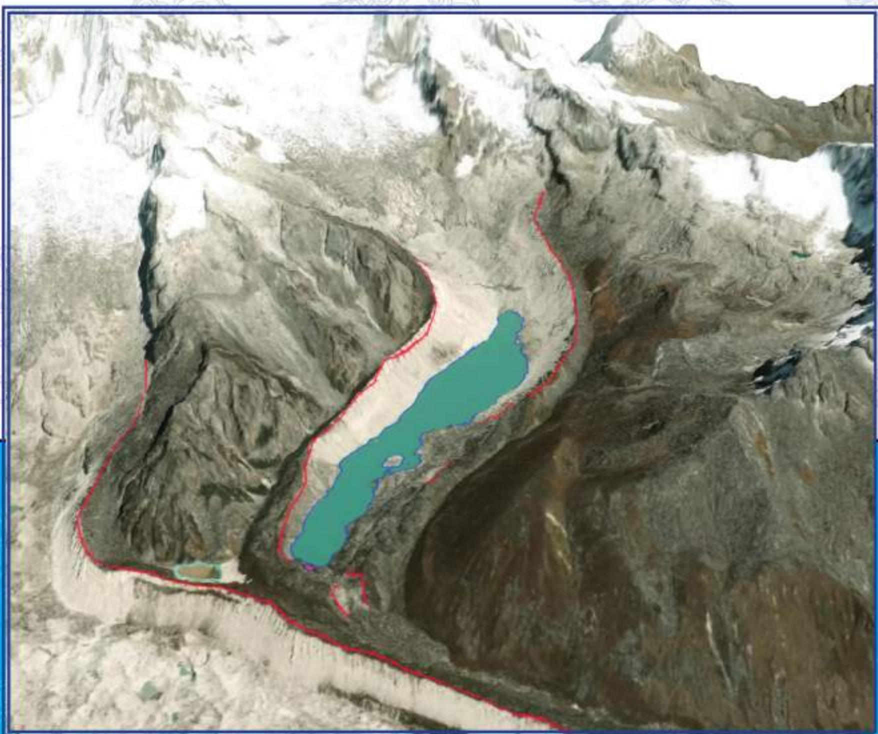
# Time Series Monitoring of Glacial Lake in the Head Water of Pho Chhu subbasin
# ( Wachey Glacial Lake GLP 6.5)
## September-October 2019



Cryosphere Services Division
National Center for Hydrology and Meteorology

The Cryosphere Services Division on behalf of National Centre for Hydrology and Meteorology has produced this work.

Authors:
Wangchuk Namgay,Geologist,CSD,NCHM
Tshering Duba,Engineer,CSD,NCHM
Phuntsho Tshering,Exe.Geologist,CSD,NCHM
Tshering Tashi,Sr.Hydro-met Officer,CSD,NCHM

www.nchm.gov.bt

Figures

# Table of Contents

# 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). With the mandate to study glacial lakes and monitor its associated risk downstream, the cryosphere services division under took Time Series Monitoring of Glacial lakes in the headwater of Pho Chhu (Wachey Glacier lake GLP 6.5) during the FY 2019-20.

The objective of the fieldwork was to conduct bathymetry survey to map bottom topography of the lake and study the geotechnical properties of the moraine wall. With limited previous documents on the lake, the team carried out Remote study using past Landsat 5, 7 and Sentinel 2 Satellite imageries. The team found the lake to be already breached in the past however, the event was not documented. The earliest imagery of 1987 show the lake have already breached by then. The glacial lake had an expansion rate of 39.76 m per year from 1987 until 2008 when the lake fully developed. The bathymetry survey revealed an estimated volume of 7.49 million $m^3$ with a maximum depth of 64 m at the upstream of the lake and shallow depth near the outlet. The feeding glacial was detached from the lake and the moraine was vegetated indicating less activity on the moraine. Therefore, the lake was deemed safe in terms of major GLOF however timely monitoring is needed, as the active sliding on the lateral moraine was found prominent.

# 1. Introduction

Throughout the globe, in most of the glaciered alpine and high-altitude regions, glaciers are retreating at an alarming rate that attributed to the ongoing global climate change (Emmer & Emmer, 2017). Glacier retreat is connected to the various interrelated geomorphological, hydrological processes and changes in hydrological regimes. Formation and evolution of glacial lakes are observed in recently de-glaciated regions.

Glacial Lake Outburst Flood (GLOF) is a phrase used to describe a sudden release of a significant amount of water from a glacial lake, irrespective of the cause. GLOFs are characterized by extreme peak discharge often several times in excess of maximum discharges of hydro-meteorologically induced floods and with an exceptional erosion and transport potential (GLOF induced debris flow). GLOFs are considered capable of large outspread disasters in the downstream valleys. GLOFs associated with recent glacier retreat are becoming a widely researched topic from the perspective of the hazards and risks they pose to the population and the possibility that they are driven by anthropogenic climate change.

The glacial lake "Pho_gl 196" (Tadono et al., 2012), located in the left lateral moraine of Wachey glacier 'PPhgr16_273' (NCHM, 2018). was referred as GLP 6.5 by Komori and his team (Komori, 2008) and indicated it as dangerous in future via remote sensing study. The lake is not in the list of Potentially Dangerous Glacial Lake of Bhutan. Nevertheless, lake has highest surface area in the vicinity. Since there was no field verification done on the lake, the Cryosphere Services Division proposed a plan to field visit and verify the lake in the FY 2019-20 under the RGoB funding.

# 2. Objective

The September –October 2019 field expedition under time series monitoring of glacial lake was carried out with the following main objectives:

a) Investigate glacial lake changes using remote sensing technologies.
b) Bathymetry survey using Eco-sounder on the glacial lake to map bottom topography and extract water volume of the lake.
c) dGPS survey and geo-technical study on the moraine dams surrounding for future dam breach model.

# 3. Study Area

## 3.1 Location

The Wachey glacial lake GLP 6.5 is located at 28.133ºN and 90.027ºE, at an elevation of 4155.1426 m.a.s.l. The lake has a surface area of 0.379 $km^2$ with a length of 1856.813 m and width of 191.26 m and is fed by PPhgr16_277, which has a surface area of 2.57 $km^2$ (NCHM, 2018). The lake is located just on the base of Jejekhangphu Khang peak (elevation 6965 m,a,s,l). The glacier lake is a moraine-dam breached lake with a small outlet that seeps inside the lateral moraine of the Wachey glacier 'PPhgr16_273'(NCHM, 2018).

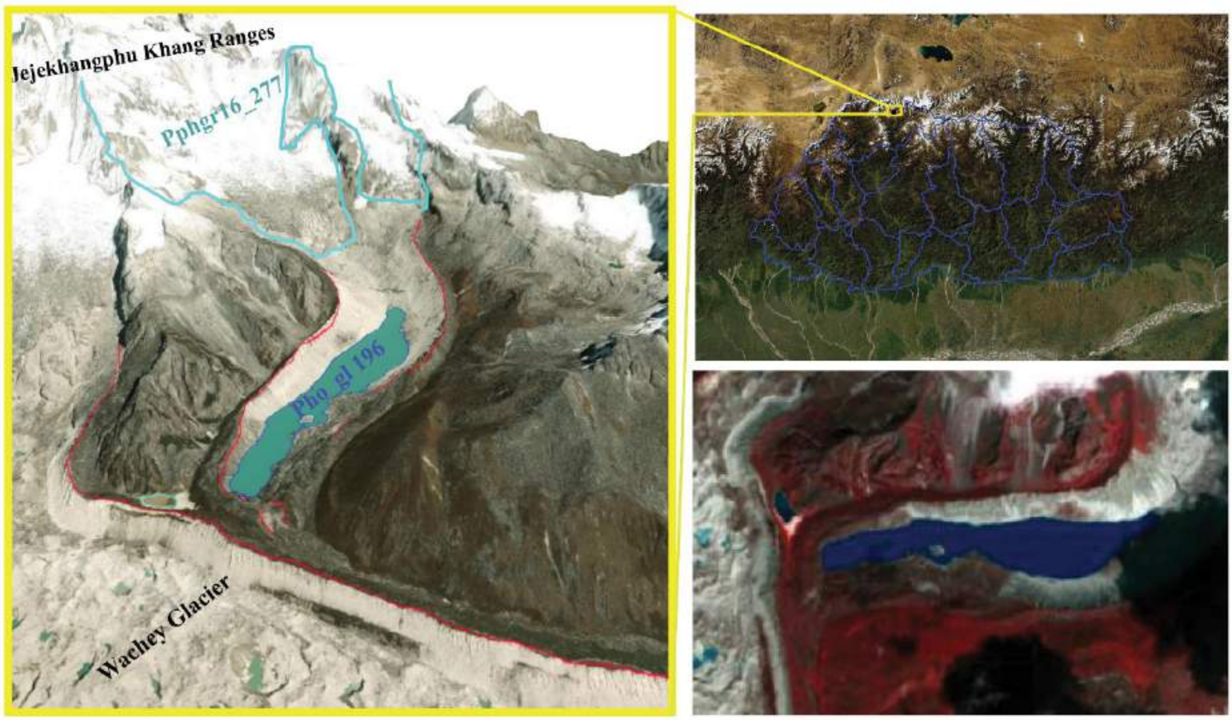



*Figure 1 Location map of Glacial lake GLP 6.5)*

## 3.2 Accessibility

The glacier lake can be accessed via two routes. The first route is via Gasa –Laya- Tarina – Wachey – Lake site, which takes eight days on foot. While the other route is via Tshorimzam – Goenshari – Gangju La- Wachey Tsachhu – Domchuthang and takes five days to reach the Domchuthang base camp. The lake site can be reached following the yak trail from the left lateral moraine of the Wachey glacier "PPhgr16_273" from Domchuthang base camp. The team has visited during the month of September-October, when snow and weather conditions at are better than any of the seasons in a year.

# 4. Methodology and Data Processing

## 4.1 Remote Study

### 4.1.1 Equipment and Data Acquisition

With Regard to space-borne remote sensing data, there has been a growing use of multispectral data for hazard assessment (Yang et al., 2019). The Landsat TM 5, 7, and Sentinel 2 MS were used for mapping the surface area of the lake.

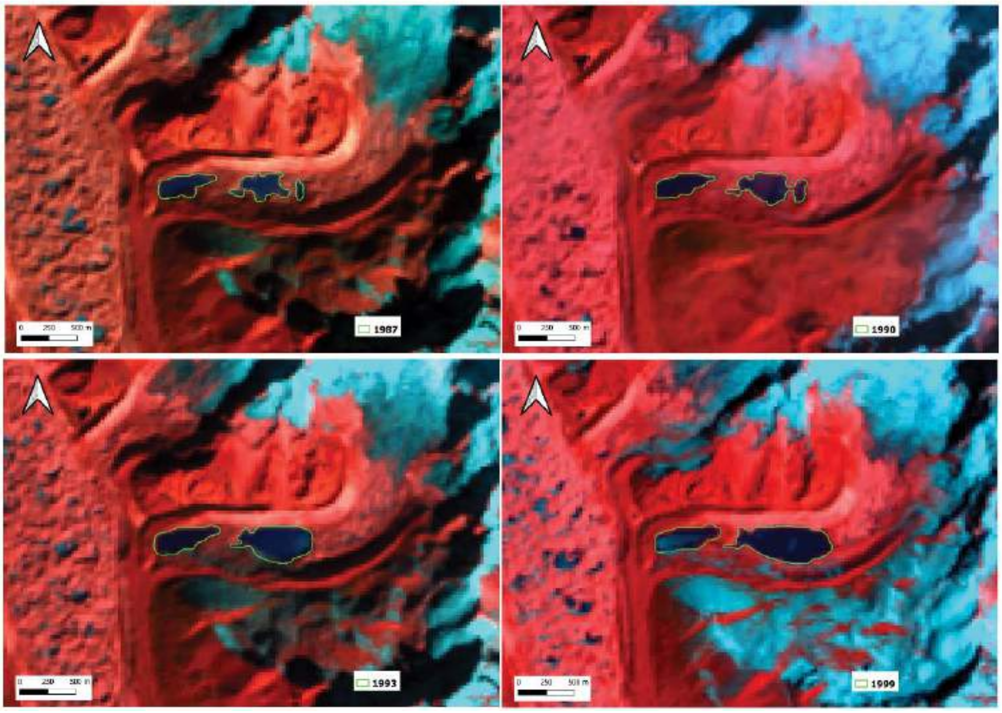
The images were collected and analyzed in the cloud-based platform 'Google Earth Engine', which uses java script as a commanding language. The whole image collection of Sentinel 2 and Landsat 7 and 5 images were freely available in the platform's dataset collection. For this study cloud free image collection for the summer month of the year (May-June- July) were selected to give maximum reliability and maximum lake volume. However, for images missing in this given period the best available cloud free images were selected for the delineation. The CLOUD_COVER filter function was applied using the AOI polygon of the lake to give the least cloud cover over the area. The image's best fitting the above criteria were selected and exported in geo-tiff format.

| $ | Satellite Type | Image ID | Date |
|---|---|---|---|
| **1** | Sentinel 2 MSI | COPERNICUS/S2/20190828T043709_20190828T044335_T45RYM | 28/08/2019 |
| **2** | Sentinel 2 MSI | COPERNICUS/S2/20180917T043701_20180917T044308_T45RYM | 17/09/2018 |
| **3** | Sentinel 2 MSI | COPERNICUS/S2/20170912T043701_20170912T044834_T45RYM | 12/09/2017 |
| **4** | Sentinel 2 MSI | COPERNICUS/S2/20160101T045654_20160101T101451_T45RYM | 01/01/2016 |
| **5** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20151026 | 26/10/2015 |
| **6** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20141124 | 24/11/2014 |
| **7** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20131105 | 05/11/2013 |
| **8** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20121017 | 17/10/2012 |
| **9** | Landsat 5 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20111202 | 02/11/2011 |
| **10** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20101028 | 28/10/2010 |
| **11** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20091025 | 25/10/2009 |
| **12** | Landsat 7 MMS | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138041_20081209 | 09/12/2008 |
| **13** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20071121 | 12/11/2007 |
| **14** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20061017 | 17/10/2006 |
| **15** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20051115 | 15/11/2005 |
| **16** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20041214 | 14/12/2004 |
| **17** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20031126 | 26/11/2003 |
| **18** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20021107 | 07/11/2002 |

| | | | |
|---|---|---|---|
| **19** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138041_20011104 | 04/11/2001 |
| **20** | Landsat 7 TM | LANDSAT/LE07/C01/T1_RT_TOA/LE07_138040_20000930 | 30/09/2000 |
| **21** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19990413 | 13/04/1999 |
| **22** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138041_19981222 | 22/12/1998 |
| **23** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19970101 | 01/01/0997 |
| **24** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19961130 | 30/11/1996 |
| **25** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19950909 | 09/09/1995 |
| **26** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19940704 | 04/07/1994 |
| **27** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19931122 | 22/11/1993 |
| **28** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19920409 | 09/04/1992 |
| **29** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19911016 | 16/01/1991 |
| **29** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19901013 | 13/10/1990 |
| **28** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19891026 | 26/10/1989 |
| **29** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138040_19880601 | 01/06/1988 |
| **30** | Landsat 5 TM | LANDSAT/LT05/C01/T1_TOA/LT05_138041_19871224 | 24/12/1987 |

### 4.1.2 Data post-processing and output

The lake were digitized using both ArcGIS and QGIS software and the surface area was computed using the "calculate geometry" function. The lake shoreline of different years were then compared to track the changes over time.



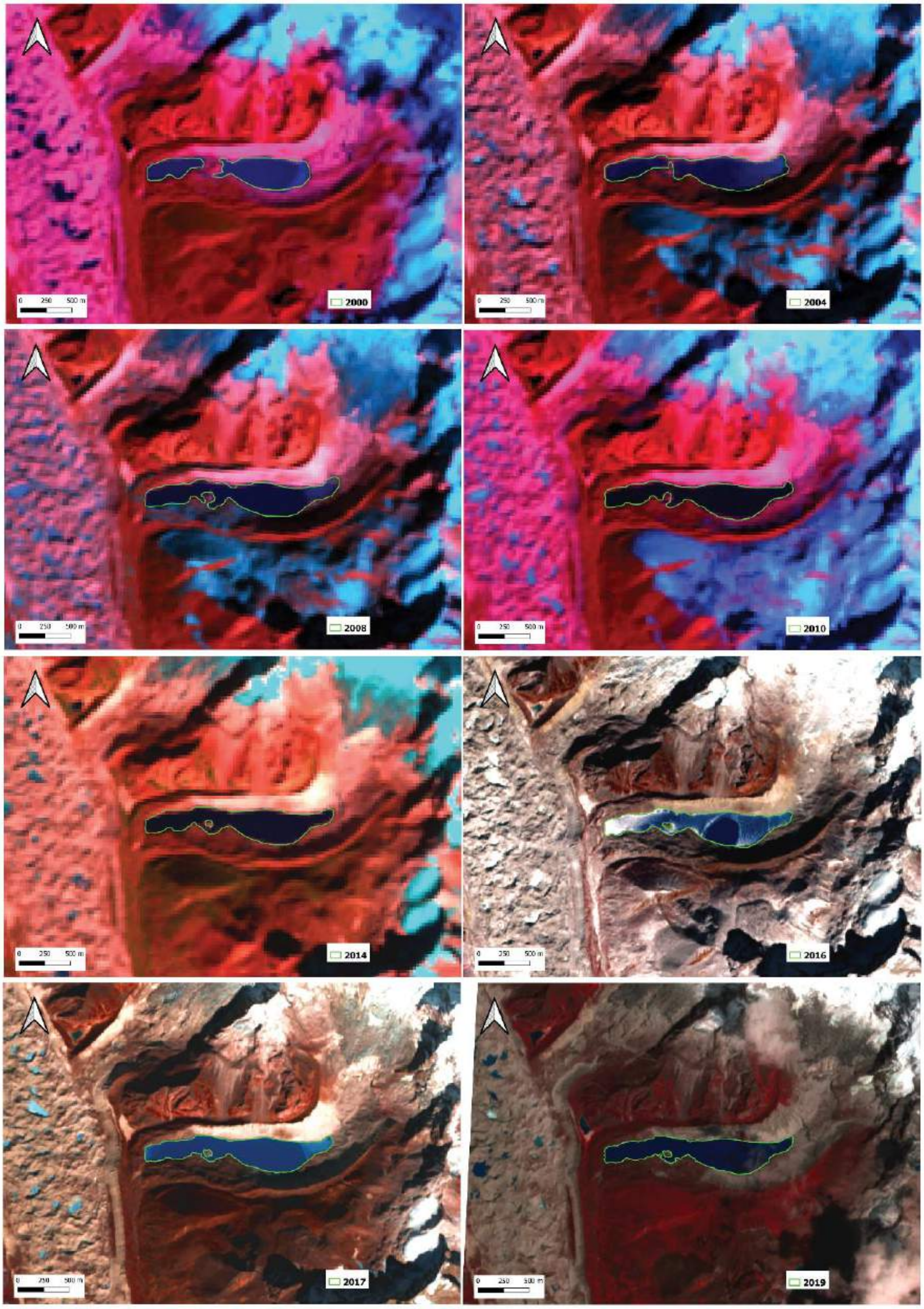



*Figure 2 Time Series map of Wachey glacier lake GLP 6.5 using Landsat TM 5, 7 and Sentinel 2 MSI in False Color Composite (FCC).*

## 4.2 Bathymetry Survey

Wachey Glacial Lake GLP 6.5 has been observed to have a high surface area in the vicinity. There is no previous record of bathymetry survey done in this lake although it was deemed as dangerous by komori et al, 2008. The field survey team of 2019 conducted the bathymetry survey on the lake to map the bottom topography and estimate lake volume using echo sounder.

*Figure 3 Bathymetry survey on the Wachey lake GLP 6.5*

### 4.2.1 Equipment and Data Acquisition

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 was then saved to MMC card consisting of its position (Latitude, Longitude, and Depth).

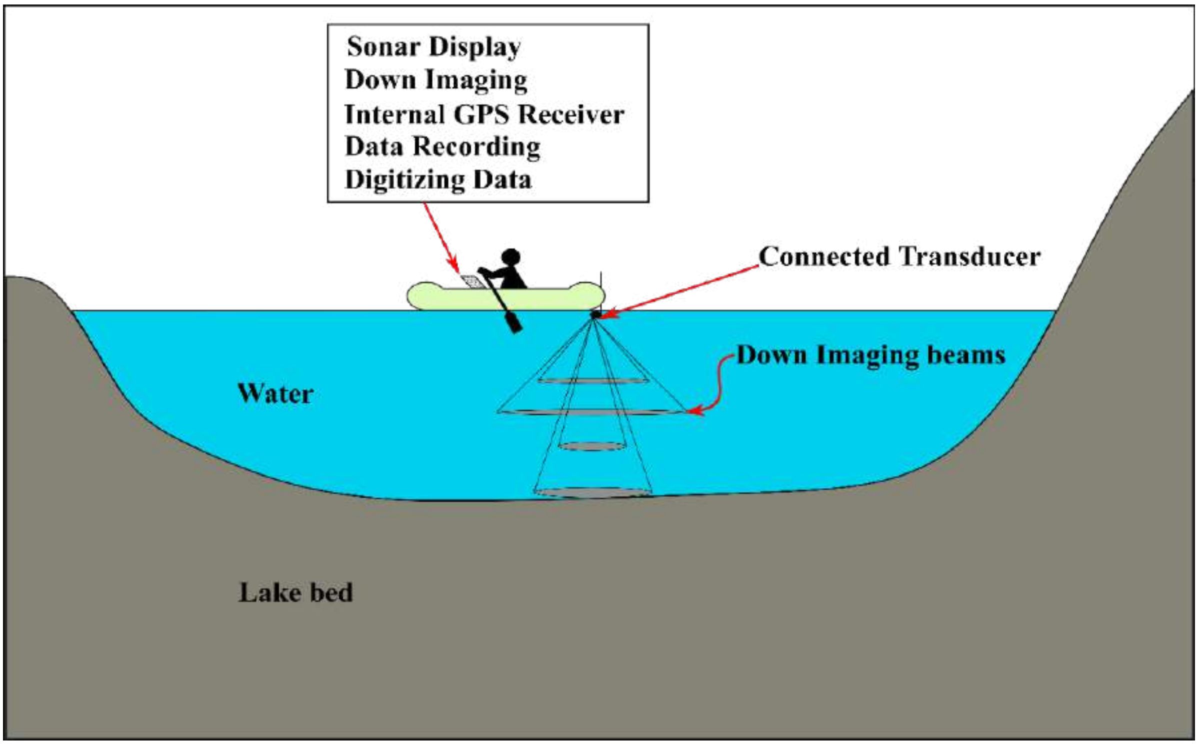



*Figure 4 Schematic diagram of Bathymetry Survey using SONAR*

4.2.2 Data post-processing and output

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 Hummingbird Autochart Pro software. In Hummingbird 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 (fig. X3). In order to estimate the lake water volume, the lake shoreline for Wachey headwater Lake A was delineated by conducting shoreline mapping using the Trimble R-10 2 GNSS system.

## 4.3 Geomorphological Survey

### 4.3.1 Equipment and Data Acquisition

For mapping the shorelines of the glacial lake, we used two sets of Trimble R10-2 GNSS equipment, one as base and the other as rover. The base was set in a continuous fast static mode and the rover in continuous topo mode. The rover was connected to the base via Bluetooth in RCMX mode via Trimble assess software which gives continuous Real Time Kinematic (RTK) correction of the rover data. The rover was mounted on the backpack and walked over the moraine to collect the geo-point of the vicinity. The points were logged with an interval of one second with a logging distance of one meter.

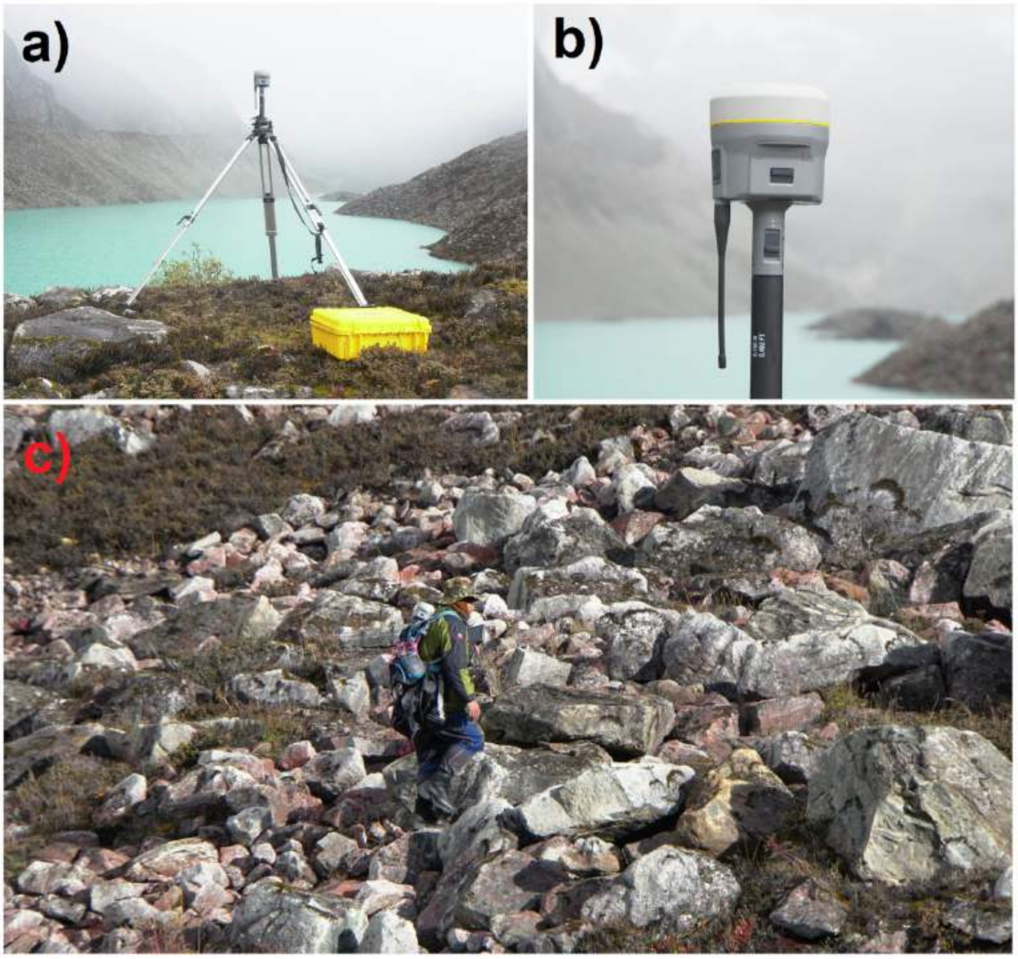



*Figure 5 a) Base Station in fast static mode; b) Trimble R-10 2 antenna; c) Rover station in continuous Topo mounted on the backpack and walked over the moraine*

### 4.3.2 Data post-processing and output

The survey points collected were converted into shape files in ArcGIS using the WGS 1984 UTM zone 45 Projection. The shape file were then converted into TIN file to correctly measure the height and the slope of the lake outlet. Using the Satellite Imagery of 2019 from Sentinel 2 as base map the geomorphological features from the point data was used to generate a topographical map.

## 4.4 Shoreline Mapping

### 4.4.1 Equipment and Data Acquisition

We used the same method as mention above (base in static mode and rover in continuous topo mode). We then mounted the rover on a boat and set a data interval for one meter.The shoreline data was taken by rowing along the shoreline of the lake since there was no accessible route along the lake shoreline due to steep active slides.

### 4.4.2 Data post-processing and output

The survey points collected were converted into shape files in ArcGIS using the WGS 1984 UTM zone 45 Projection. Using the point shape file a polygon is digitized and compared with shoreline digitized using the sentinel 2 MSI satellite imagery of 2019. The shoreline data achieved are to be used as validation data for future glacial lake inventory.

## 4.5 Geotechnical studies

### 4.5.1. Apparatus and sample collection

The geotechnical soil sampling of the moraines was carried out near the outlet of the lake. (Figure 1). Since the lake was already breached with huge V shaped trust formed near the outlet, the team limited to only one soil sample. The following parameters will be used as input for the GLOF Breach Model (BRCH GUI – BRCH-J) for future studies.

- Grain Size Distribution

A pit of dimension (30 x 30 cm) with a depth of 20 cm is 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 than 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:

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

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);

$\rho_p$ 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,

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

Where,

$M_s$ is the mass of the soil sample;

$V_s$ is the volume of the specimen;

Hence the density ($\rho$) 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.

# 5. Result

## 5.1 Geomorphology Survey

The moraine dammed glacial lake have breached in the past as described by (Komori, Koike, Yamanokuchi, & Tshering, 2012). The morphological characteristics such as V-shaped trenches at the outlet, debris fan deposition and riverbed erosion downstream are all clearly shown downstream. The terminal moraine wall is now well vegetated with stable soil and rock boulder in the vicinity and the lake has a wide and free-flowing outlet. The glacial feeding the lake have retreated way above the glacial lake and poses no direct triggers from the active ice avalanche.

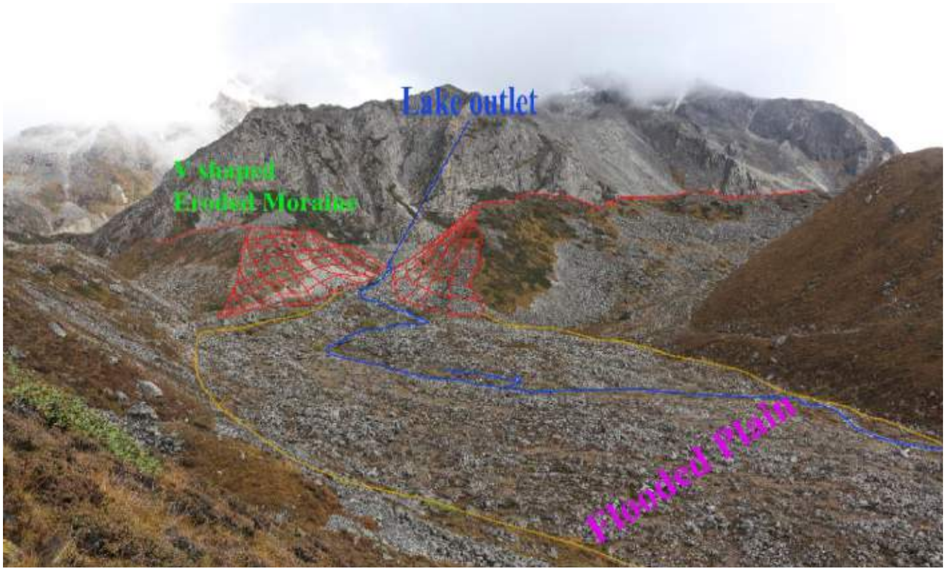



*Figure 6. The characteristics of past GLOF at wachey glacial lake GLP 6.5 as mention by Komori et al 2012*

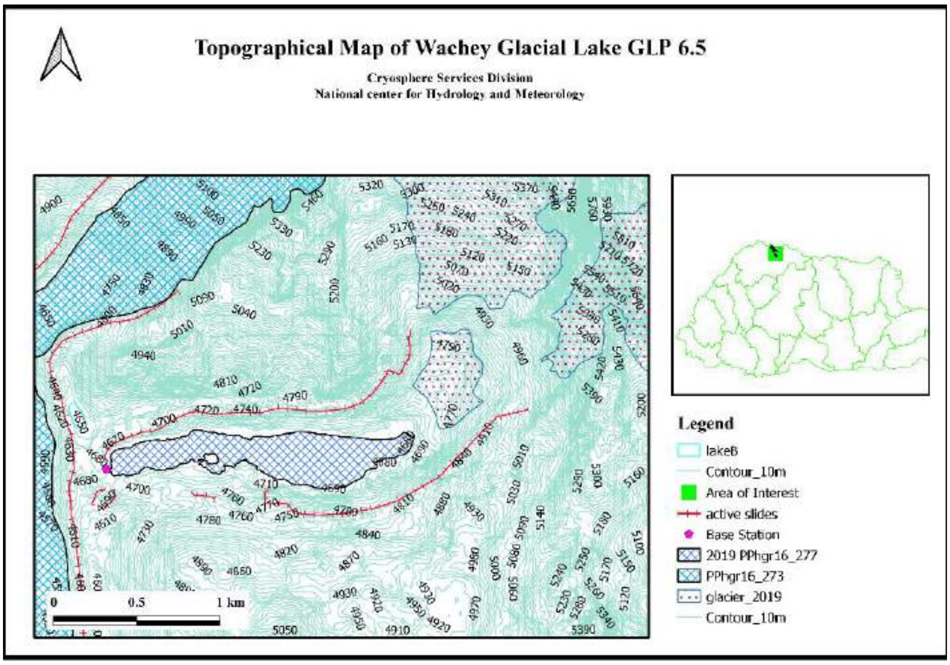



*Figure 7 Topographical Map of Wachey Glacial lake GLP 6.5*

However, there are few active slides on the inner slopes of the lateral moraines towards the upper end. The terminal moraine has an outer slope of 12 degree and average in slope angle of 3º degree measured from the outlet. The water moves 50 m downstream before seeping into the left moraine of Wachey glacier. In addition, the outlet of this seepage is not found downstream.

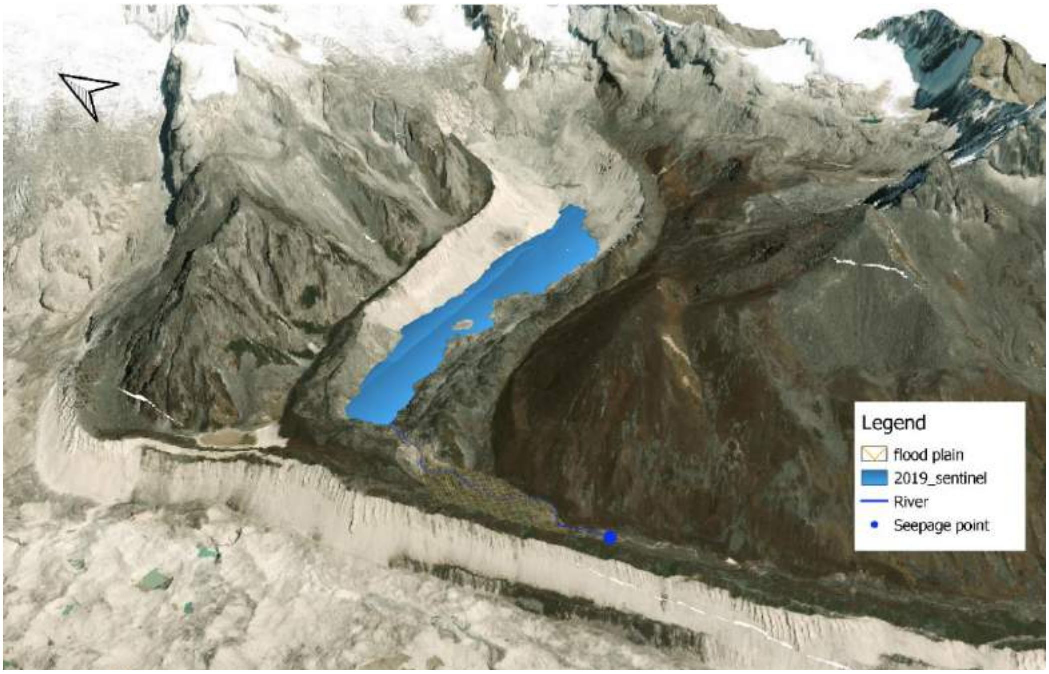


*Figure 8 Seepage point of the river into moraine wall*

## 5.2 Geological Morphology

Geologically the lake falls under the Structurally Higher Greater Himalayan section consisting mostly of upper amphibolite-granulite and locally eclogitic -facies migmatitic orthogneiss and metasedimentary rocks, including schists, paragneiss, quartzites and marbles. (Long et al. 2011b). The Structurally Higher Southern Tibetan detachment fault runs from western to eastern northern frontier is located just above the glacier lake and have lifted the Jejekhangphu Khang ranges which is feeds the glacier.

## 5.3 Remote Sensing

By analyzing the satellite imageries of 1987, three-supraglacial lake were observed with a surface area of 74,220.43 $m^2$, 78522.66 $m^2$ and 9759.91 $m^2$ respectively. By 1990, (Landsat 5 TM) two-supraglacial lakes located upstream have merged and formed a bigger lake. The two-supraglacial lake now have an area of 76944.69 $m^2$ and 105037.60 $m^2$ respectively. By 2004 the two existing supraglacial lake have both merged and the lake was found to have a surface area of 347125 $m^2$. By 2008, the glacier have retreated and the lake have attained its full growth having a surface area of 363625.41 $m^2$. Then here after from 2008 until 2019 the glacial lake was found to show little variation in surface area mainly due to seasonal phenomenon whereby the lake surface area decreases during winter due to freezing and increases during summer due to melting and precipitation.

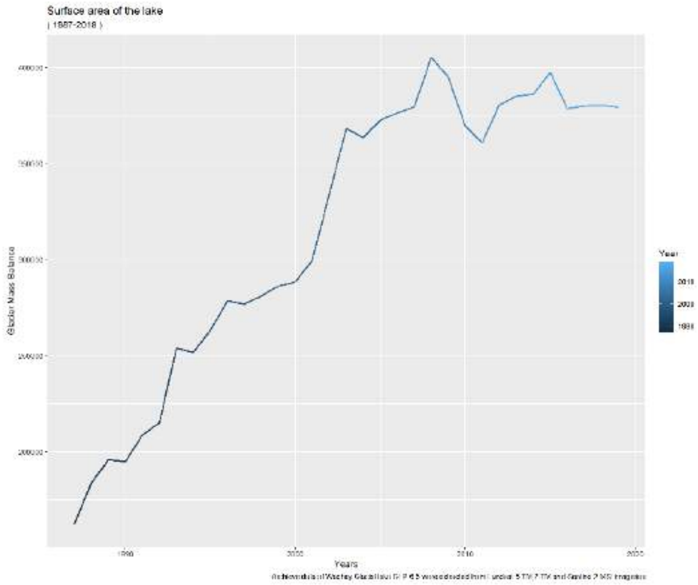



*Figure 9 Expansion of Glacial lake surface area of Wachey glacier Lake GLP 6.5*

Komori and his team found that the lake was expanding at rate of 32.0 meter per year from 1990-2001 detected from satellite imageries(Komori, 2008). From the current analysis, the rate of expansion from 1987 to 2001 was 28.95 m per year. From 2001 until 2008, the expansion rate was 49.50 m per year showing abnormal expansion during this period when the lake attained its full growth. After 2008 - 2019, the expansion rate was just 5.50 m per year. Over all the lake expansion rate from 1987-2008 was 39.76 m per year as the lake have already expanded by then.

| # | Year | Length | Expansion Rate |
|---|---|---|---|
| **1** | 1987-2001 | 405.337 | 28.95 |
| **2** | 2001-2008 | 347.184 | 49.50 |
| **3** | 2008-2019 | 60.487 | 5.50 |
| Overall | **1987-2008** | **837.951** | **39.76** |

*Table 1 Expansion rate of Wachey Glacial Lake GLP 6.5*

## 5.3 Bathymetry Survey

Bathymetry survey on Wachey glacial Lake GLP 6.5 was conducted on October 6 and 7, 2019 by a field survey team. The lake has an estimated volume of 7.49 million $m^3$ with a surface area of 0.37 million $m^2$ and mean depth of 20.4 m. The deepest part of the lake was found towards the upper side of the lake measuring a depth 65 m deep. Towards the outlet part, the lake is shallow and has a gentle bottom topography.

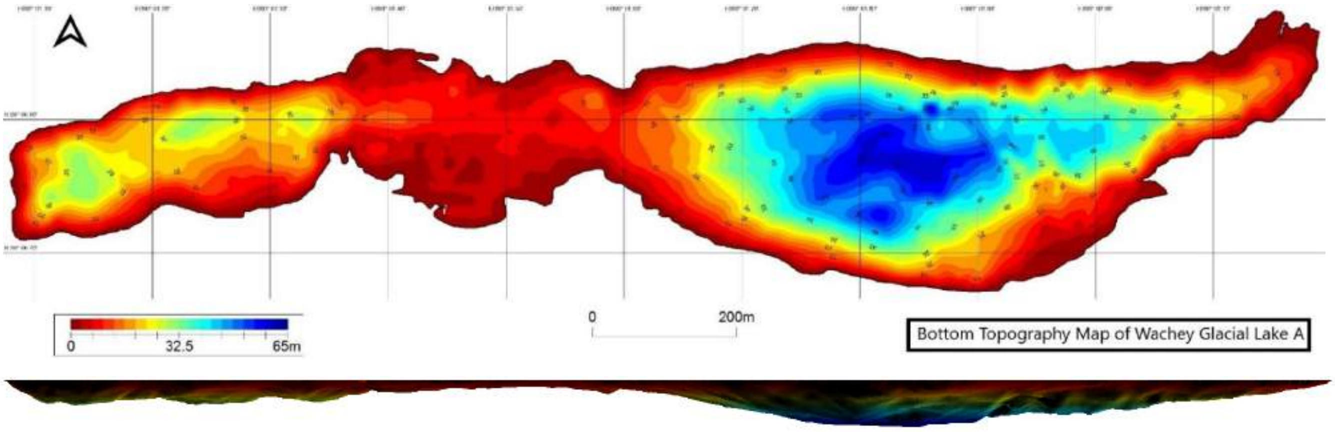



*Figure 10 Bathymetry Map of Wachey Glacial lake GLP 6.5*

## 5.4 Shoreline Mapping

This shoreline points were used for rectification of the 2019 lake shoreline (lake boundarY) which was delineated using Sentinel 2 MSI satellite imagery. The Sentinel 2 satellite imageries have a spatial resolution of 10x10 meter per pixel. This shoreline data will be used as field validation of the future glacial lake inventory.

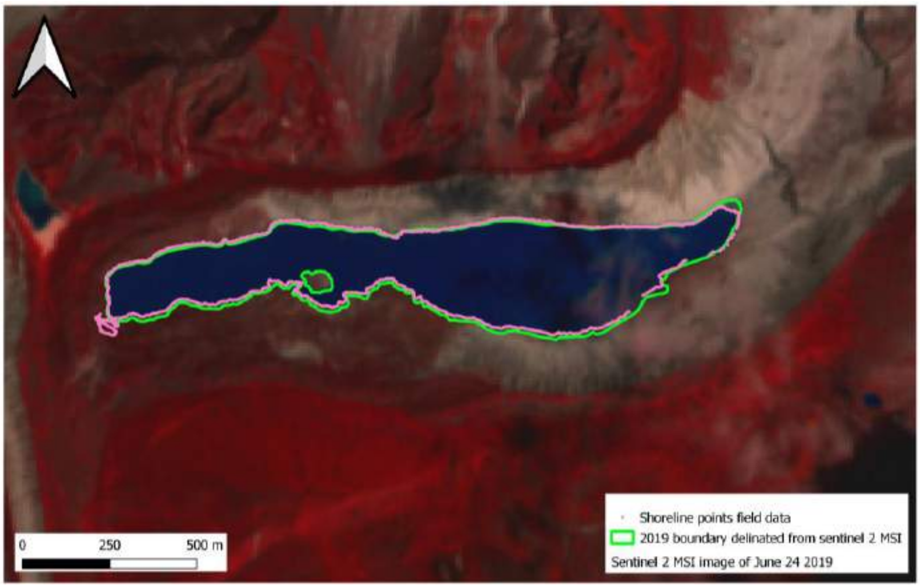



*Figure 11 Map showing the comparison between shoreline data from the field and the shoreline delineated using Sentinel 2 MSI image of June 24 2019.*

## 5.4 Geotechnical Studies

The moraine sample WSS1 (figure 6) was collected from the coordinate $28^{0}05'53.07093''$ N and $90^{0}15'08.32129''$ E near the outlet of the lake. Sandy and gravelly soils was found near the sampling pit. The area had patches of vegetated shrubs, boulders and gravels with stable moraine. The result of the wet sieve analysis of the sample shows that the grading curve to be a well graded sandy gravel with an internal friction angle of 42 degree. This type of soil is poorly stable with the major soil particle distribution falling under the sand particle size and remaining in gravel particle size. This type of soil shows a low stability characteristic and are susceptible to change when introduce with water. (Jackson, 2015)

The geotechnical parameters are given below:

| **Soil mechanical parameters of TSS-01** | | |
|---|---|---|
| **Unit weight ($\gamma$)**<br>**($\delta$ * $g$)** | kN/m$^3$ | **22.43** |
| **Density ($\delta$)**<br>**(m/V)** | g/cm$^3$ | **2.37** |
| **Angle of internal friction (ϕ)** | Degree | **42** |
| **Cohesion c** | kN/m$^2$ | **0-10** |
| **Manning's N** | | **0.07** |
| **Unconformity coefficient (Cu)**<br>(d60/d10) | | **12.5** |
| **Coefficient of Curvature (Cc)**<br>((d30$^2$)/ (d10 * d60 )) | | **0.376** |

*Table 2. The detailed parameter results of the soil sample (TSS-01) obtained from Wachey glacial Lake GLP 6.5*

SIEVING ERROR: 4.2%

## SAMPLE STATISTICS

SAMPLE IDENTITY: **Wachey WSS-01** ANALYST & DATE: DGM,MoEA, 16-04-2020

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 ($\sigma$): | 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 |

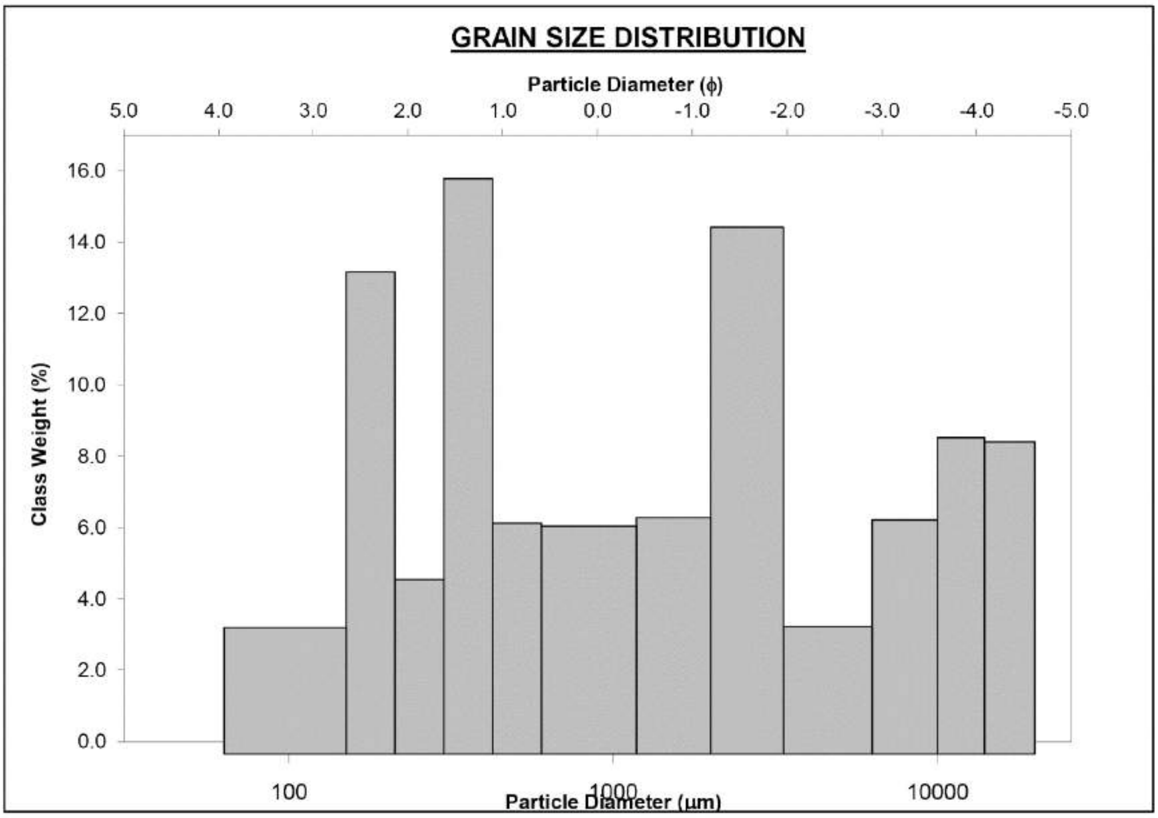



*Figure 12The Soil statics generated using the GRADISTAT version 8 software. The grain size distribution indicating 43.1% Gravel and 56.9% sandy*

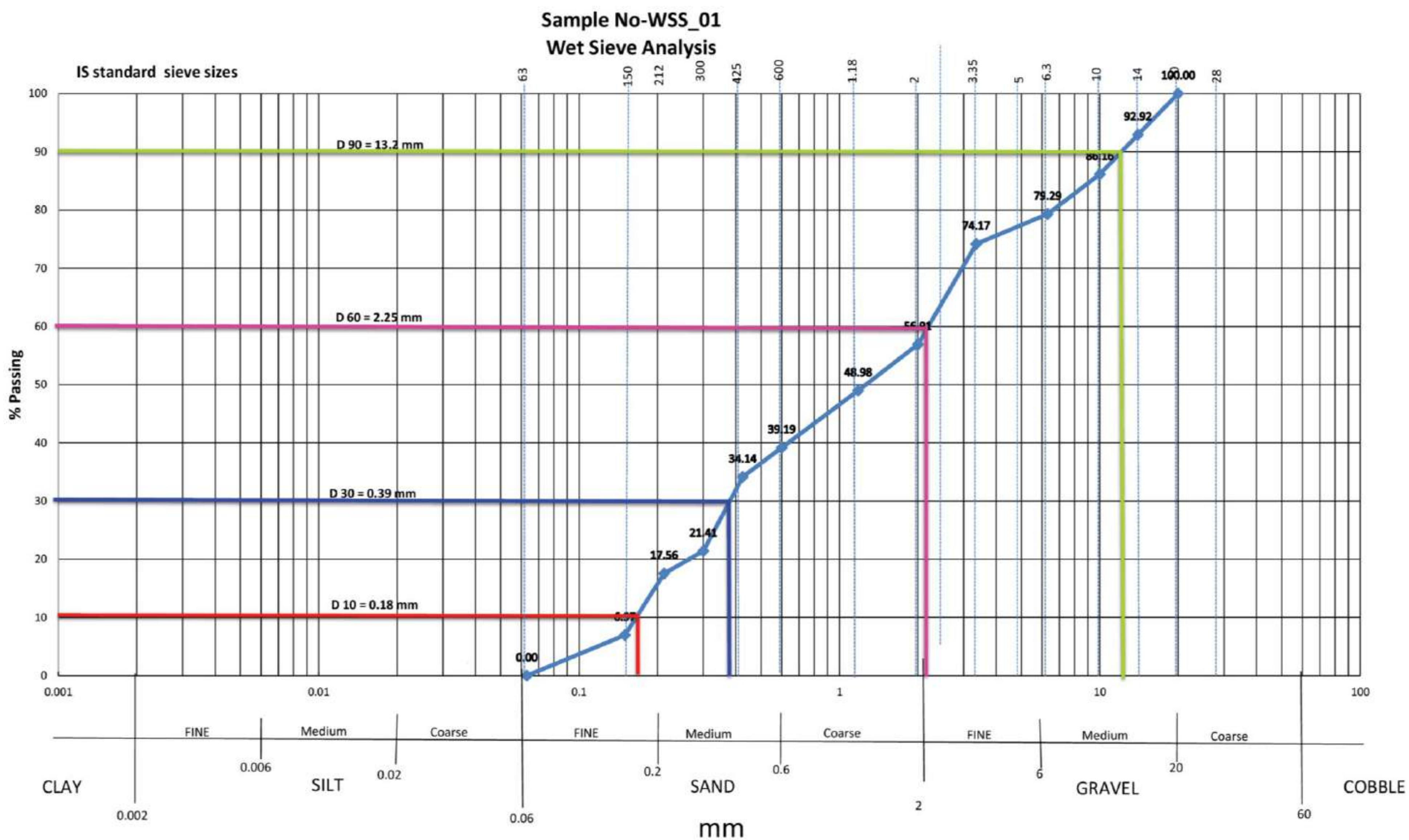



*Figure 13 The Soil Grain Analysis chart (log scaled) of Wachey Glacial lake GLP 6.5 (WSS_01) show a gap-graded curve. The D10, D30, D60 and D90 are indicated as red, blue, pink and green lines respectively*

# 6 Conclusion

Throughout the various activities carried out in the fieldwork, the following are the finding:

- The Wachey Glacial lake GLP 6.5 is a fully developed end moraine dammed glacial lake. The lake has a characteristic of an outburst lake, with V-shaped, deepened terminal moraine wall, damaged river channel and flood plain just below the lateral moraine. The growth of vegetation on both the inner and outer terminal slope suggest a stable terminal moraine with slight material movement along the lateral moraine. The terminal moraine has an outer slope of $12^o$ and average in slope angle of $3^o$ measured from the outlet. The moraine wall is well-graded soil with small vegetation's on the terminal moraine. The feeding glacier have detached itself from the lake and poses no direct threats from the ice calving or avalanches. The expansion rate of the lake was found to be 39.76 m per year from 1987 until 2008 when the lake attained its full growth. The growth rate from 2008-2019 was just 5.50 m per year. The bathymetry survey revealed an estimated volume of 7.49 million $m^3$ with a bottom topography revealing high depth on the upstream of the lake and shallow topography at the lake outlet.

# 7 Recommendation

Based on the field survey along with the remote sensing findings, the team would like to recommend the following for future activities:

i. The glacial lake GLP 6.5 is quite safe and stable in terms of major GLOF but future monitoring is recommended as the active slides on the lateral moraine was found to be predominant and the outlet of the seepage is not known.

ii. The freely available Landsat and Sentinel satellite Imageries were found to be critical in learning the characteristics of glacial lakes such as surface expansion and ice dynamics of the glaciers near the lake, therefore the use of the time series data are recommended for other time series monitoring of glacier lake in future.

# 8 Reference


Emmer, A., & Emmer, A. (2017). *Glacier Retreat and Glacial Lake Outburst Floods (GLOFs)*. *Oxford Research Encyclopedia of Natural Hazard Science*. https://doi.org/10.1093/acrefore/9780199389407.013.275

Jackson, R. (2015). Manual of Soil Laboratory Testing. *Environmental & Engineering Geoscience*, *21*(3), 247–248. https://doi.org/10.2113/gseegeosci.21.3.247

Komori, J. (2008). Recent expansions of glacial lakes in the Bhutan Himalayas. *Quaternary International*, *184*(1), 177–186. https://doi.org/10.1016/j.quaint.2007.09.012

Komori, J., Koike, T., Yamanokuchi, T., & Tshering, P. (2012). Glacial Lake Outburst Events in the Bhutan Himalayas. *Global Environmental Research*, *16*(February 2012), 59–70.

NCHM. (2018). Bhutan Glacial Inventory.

Tadono, T., Kawamoto, S., Narama, C., Yamanokuchi, T., Ukita, J., Tomiyama, N., & Tabuki, H. (2012). Development and Validation of New Glacial Lake Inventory in the Bhutan Himalayas Using ALOS 'DAICHI.' *Global Environmental Research*, *16*, 31–40.

Yang, F., McGraw, R., Luke, E. P., Zhang, D., Kollias, P., & Vogelmann, A. M. (2019). A new approach to estimate supersaturation fluctuations in stratocumulus cloud using ground-based remote-sensing measurements. *Atmospheric Measurement Techniques*, *12*(11), 5817–5828. https://doi.org/10.5194/amt-12-5817-2019