Annual Glacier-Wide Mass Balance on Thana Glaicer 2019-20 October-November 2020

Cryosphere Services Division
National Center for Hydrology and Meteorology

2021

List of Acronyms

CSD: Cryosphere Services Division
BM: Benchmark
CMP-B: Cryosphere Monitoring Program in Bhutan
dGPS: Differential Global Positioning System
DEM: Digital Elevation Model
GLOF: Glacial Lake Outburst Flood
HMA: High Mountain Asia
ICIMOD: International Center for Integrated Mountain Development
IDW: Inverse Distance Weighted
IPR: Ice Penetrating Radar
RTK: Real Time Kinematic
ELA: Equilibrium Line Altitude
NCHM: National Center for Hydrology and Meteorology
NORAD-IV: Norwegian Development Agency
SWE: Snow Water Equivalent
TBM: Temporary Benchmark

Contents

Executive Summary

The cryosphere (including snow, glaciers, permafrost, and lake and river ice) is an integral element of high mountain regions, which are home to roughly 10% of the global population. As climate change is undeniable, Bhutan Himalayan glaciers are no excuse despite being carbon negative. As of now, Bhutan has 700 glaciers (National Center for Hydrology & Meteorology, 2018) and 587 glacial lakes in the Northern frontiers of Bhutan (BGLI 2020). The National Center for Hydrology and Meteorology is currently monitoring two bench marked glaciers and the potentially dangerous glacial lakes besides other activities such as updating of glacier and glacial lake inventories and study of melt contribution to surface runoff in selected river basins. One of the long-term bench marked glaciers is Thana Glacier, which has been monitored on an annual basis since 2013. On Thana glacier, *in situ* measurements such as glaciological and geodetic mass balance have been carried out since the monitoring started in 2013. Differential Global Positioning System (dGPS) survey was also conducted throughout the field survey to map the glacier surface elevation and to pick up precise location of the stakes. Thana glacier exhibits negative glacier mass balance indicating mass loss of -1259.14 mm w.e a^{-1} and -3223.35 mm w.e.a^{-1} from 2018 – 2019 and 2019 – 2020 respectively through direct method. Similarly mass loss of -2907.2 $\pm$ 282.45 mm w.e. a^{-1} through *in-situ* based geodetic method (2019-2020) was observed. Both Glaciological and geodetic methods of mass balance were carried out in the 2019 annual glacier-wide mass balance. The Equilibrium line altitude for Thana glacier 2019-2020 was found at 5653.4 m.a.s.l with a discharge of 0.576 m^3 s^{-1}at the Thana glacier outlet.

Introduction

Glacier mass balance information from Bhutan remains very scarce due to remoteness of Glaciers and due to late recognition of the cryosphere field by the government. Study of glaciers and glacial lakes in Bhutan was initiated only after the devastating Glacial Lake Outburst Flood (GLOF) of 1994 in the Pho Chhu basin. Studying glaciers is very important to understand the impact of past, present and future climate scenarios. Effect from climate change on mountain glaciers (Radić and Hock, 2011) and its contribution to rise in sea level change (Leclercq, Oerlemans and Cogley, 2011, Gardner *et al.*, 2013) is also significant in the long run. Moreover, glaciers in Eastern Himalaya receive much higher summer precipitation (Hoy et al., 2016) compared to the western Himalaya. This type of summer accumulating glaciers in Bhutan has a more negative mass balance (AGETA et al., 2001) resulting in higher recession rate. Bhutan Himalaya is also undergoing significant changes in terms of mass loss and terminus retreat in response to prevailing local and regional climate. These losses in mass of glaciers can even lead to change in river runoff pattern (Prasch, Mauser and Weber, 2013, Radić and Hock, 2014) downstream. The first program to monitor glaciers of Bhutanese Himalaya was carried out in the late 1990s in collaboration with foreign institutes such as Nagoya University, Japan and University of Vienna, Austria. Since then only longitudinal retreat was monitored and no specific mass balance on glaciers was reported until 2003 (Tshering and Fujita, 2016) for Gangju La Glacier.

Cryosphere Services Division (CSD) under the National Center for Hydrology and Meteorology (NCHM), Royal Government of Bhutan is mandated to study snow, glacier and glacial lakes to understand climate change impacts on the Cryospheric domain. The Division started monitoring glaciers in 2012 with a selection of benchmark (BM) glaciers in the headwaters of Chamkhar Chhu that flows through the valley of Bumthang. Since then Thana glacier has been identified for long term monitoring representing the glaciers of the North central region of Bhutan Himalaya. It lies towards the eastern ridge of Gangkar Puensum (7570 m a.s.l) range. Initially the monitoring activity on Thana glacier was conducted with support from the Norwegian Development Agency (NORAD-IV) project from 2012-2013 followed by Cryosphere Monitoring Program in Bhutan (CMP-B) in collaboration with the International Center for Integrated Mountain Development (ICIMOD) from 2014-2017. From 2018, the monitoring activity was fully undertaken by the Royal Government of Bhutan under the annual motoring program of the Cryosphere Services Division (CSD). This year the team successfully carried out the field activity despite the covid-19 disruption.

Objectives

The field expedition was conducted with the following objectives:

1. Collect field based data from Thana glacier for computing mass balance using both glaciological and geodetic methods.
2. Conducted snow pit measurements.
3. Conduct river discharge measurement survey

Study Area

Location

Thana Glacier is located in the Northern part of Central Bhutan Himalayan (28°0.953´N, 90°36.781´E). It contributes its melt water to Chamkhar Chhu *(Figure.1)*.The elevation of this clean type glacier ranges from 5100 m.a.s.l to 5700 m.a.s.l covering an area of 3.41km^2 (approximately). Thana glacier is a land-terminating glacier, which is mostly influenced by local climatic conditions. From the basecamp to the glacier site, it takes about 4 hours to reach the transit camp of Thana Glacier beyond which there is no access for the horses or yaks. Further from the transit camp to the glacier site, it takes around 2-3 hours by walk through unstable moraine features and steep path entangled with risk of falling boulders, sliding over slippery rocks and icefalls. Besides life threatening risks, the short stretch of the journey is debilitating due to the surrounding nature of extreme high altitude. The continuous journey on the glacier surface (terminus to top saddle) when snow-free itself takes around 3 hours.

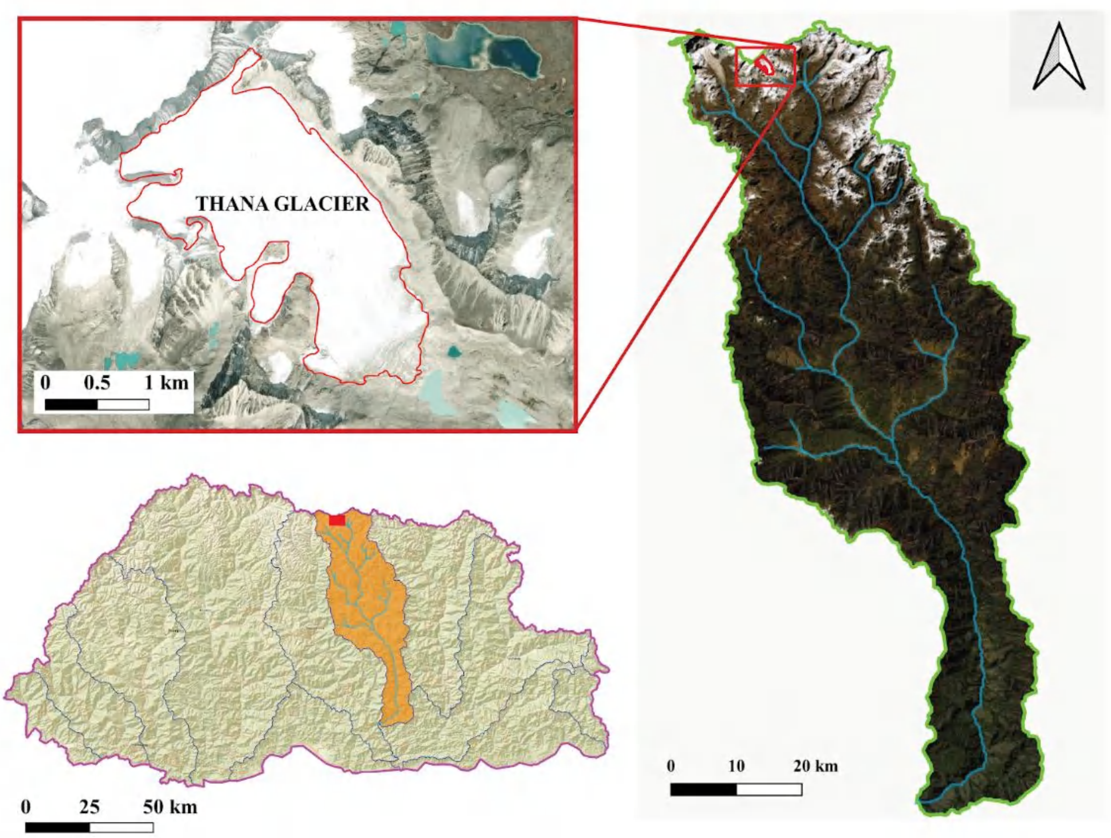

Figure 1: Location of Thana glacier in the Northern frontier of Bhutan in Chamkhar Chhu Sub-basin (filled with light green is Chamkhar Chhu river basin map).

Accessibility

Thana glacier can be visited only once in a year in the autumn season (July- sept). It can be accessed via two routes; the first route is via Dhur –Tshampa- Thana, which takes seven days on foot. While the other route is via Choekhor Toe –Tshampa - Thana and takes six days on foot to reach the study site. The basecamp is located at Churuthang at 28.000°N, 90.671°E, 4535 m,a.s.l. Autumn season is considerably favorable season to visit the glacier sites as the glaciers in the Eastern frontier of the Bhutan Himalayas are summer accumulation type leading to excess snow cover on the glacier surface hindering the installation of mass balance stakes on the ice surface.

Data Acquisition and Methodology

Geodetic Survey

Geodetic Method of mass balance is also reliable and commonly practiced and recommended (Beedle, Menounos and Wheate, 2014). Thana Glacier has a geodetic mass balance record from 2016 onwards till date. The survey involves setting up a base station (*Figure. 2b*) on a known point with previously fixed coordinates. Base station used for this study is Trimble R10-2. Base station was kept up and running for at least 3 hours prior to the commencement of survey work, this is done to have higher accuracy of position data. The base station here is set up in Real Time Kinematic (RTK) logging mode. Real time corrected data were logged in the receiver. Another three Trimble R10-2 receivers are set as a rover mounted in a backpack *(Figure .2c)* carried by the operator's. Rover station set were carried in a backpack and the operator walks along the previous years (2019) profile that were uploaded in a hand held device of Trimble TSC7.

Rover logging interval is set at every 1 meter in continuous topo mode. Profiles on glaciers are as shown in *Figure.2a* with one profile through the centerline of the glacier and others in zigzag manner evenly distributed over the span of glacier elevation.

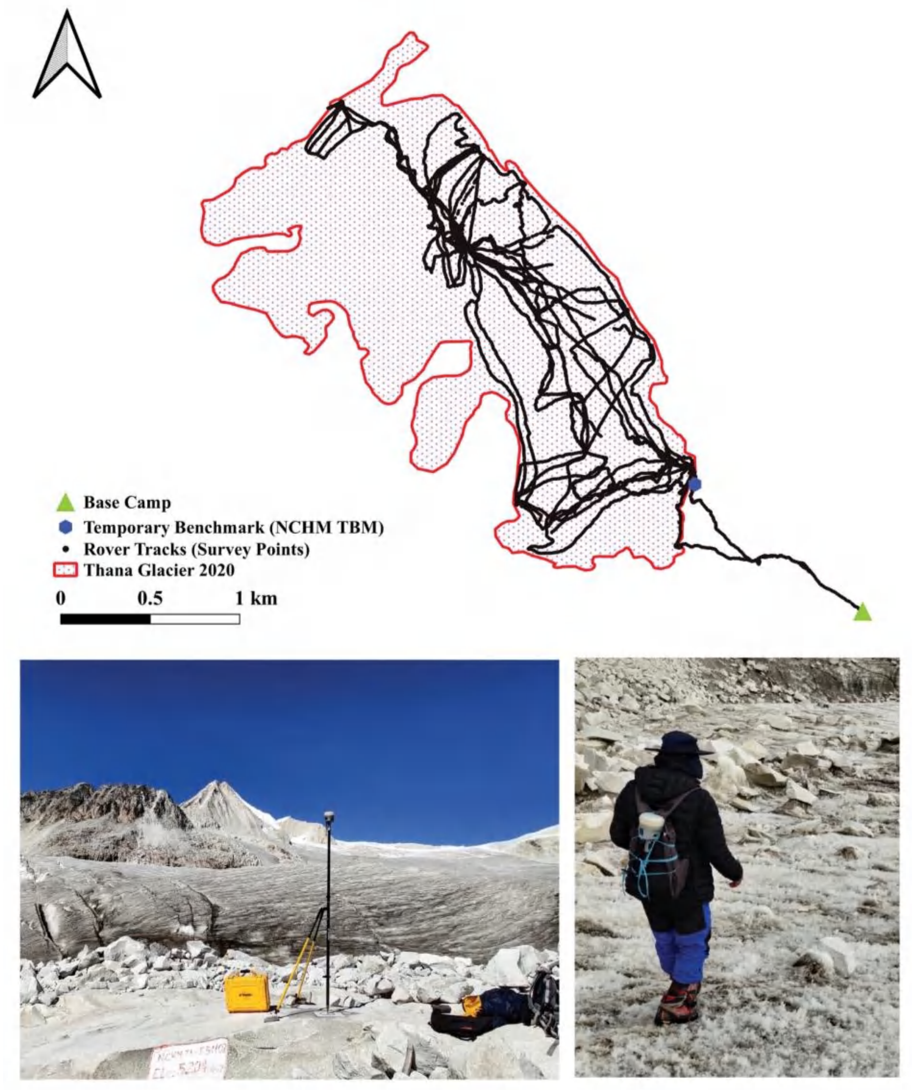

Figure 2: GPS track performed in a) 2019 (black) b) Base Station, and c) Rover station.

Stake Measurement

Traditional way of measuring glacier mass balance through glaciological methods (Brugman and Ostrem, 1991) is still common. Stakes are installed through the central line, which is the flow line of the glacier. This involves drilling holes on glaciers for inserting stakes using ice auger/steam drill for depth of around 4 meter plus depending on the length of stake and annual melt rate of the glacier. Bamboo stakes are used in this case where the segments are prepared at the field site with each stake measuring a length of 150cm. Considering the highest rate of ablation from the previous season, three to four of such segments are joined with G.I wire through a hole drilled in each bamboo. Stake identity is maintained by giving a number with roman numerical and segment number (XXII-XIX-I and XXVII-XIX-II) as per the WGMS standard.

The style of installing stakes are kept along the longitudinal profile of glacier covering different altitude bands distributed evenly over the altitude band. Thana glacier has twelve stakes throughout the glacier as shown in figure 3.

Alternatively, the data of all the stakes installed in 2020 were retrieved tracing the location of old 2019 stake using stakeout method in TSC7 controller.

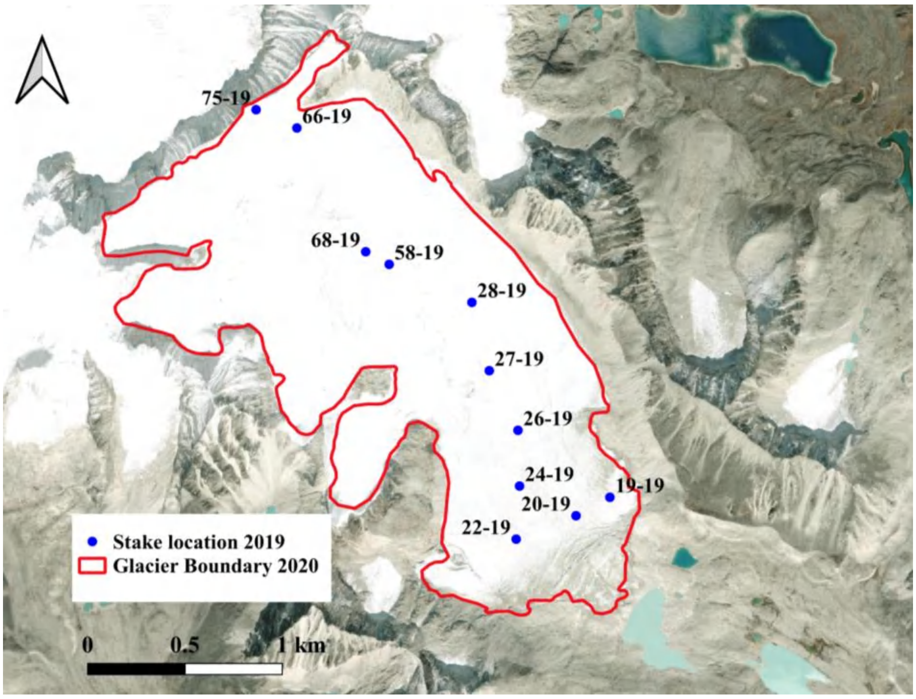

Figure 3: Stake Location map

The team was divided into two groups for this task. First team retrieved data from old stakes, which were installed in the previous year and replaced the new stake wherever necessary and data were recorded. The second team collected the stakes geolocation (Latitude, Longitude and Elevation) using TSC7 controller. The detailed measurements were recorded in the field notebook. The data has were then compiled and digitized in the standard format in excel sheet.

Snow pit measurement

Snow plays an important role in accumulation of glaciers since the input to glaciers from the atmosphere comes in the form of snow precipitation. A snow pit is a trench exposing a flat, vertical snow face from the snow surface to the ground or firn (NASA, n.d.). It helps to study the density, snow water equivalent, snow type (fresh, ice lens, depth hoar etc.) at the different layers that have been developed over the year or season. A snow pit also represents the measurement of snow such as snow density and water content that are essential for calculating mass balance using a stake method, wherever only snow depth is accounted for on that particular glacier.

Discharge Measurement

The melting of glaciers at upstream has direct impact on downstream streams or river by changing the total discharge (cite). The regularly monitored discharge measurement at downstream can be correlated to the melt contribution to the surface runoff from snow and glacier melt in upstream. Discharge measurement downstream is one of the additional methods of recording, which contributes to better understanding of the hydrologic process impacted by the shrinking glaciers. There are various techniques and equipment for discharge estimation suitable for mountain region (Gravelle, 2015). Aqua Profiler is one of the method to determine the river discharge measurement at a glacier outlet. The team used the mobile ultrasonic flow profiler AquaProfiler® M PRO that is an acoustic doppler velocimeter used to measure water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column.

Data Post Processing.

Geodetic Survey

The raw data's obtained from the field in Trimble TSC7 is exported in .csv format using the Trimble access software inbuilt in the rover Trimble TSC7 controller.

This data set obtained were checked for quality. The data set is then used to construct a Digital Elevation Model (DEM) for the year 2019-20. DEM with 1 m resolution is generated from this dGPS dataset, using inverse distance weighting (IDW) interpolation tool in ArcGIS with a search result of 0.7 m. Since this method, remains the same every year the DEMs produced in 2019 and 2020 have the same reference grid. The two DEMs of 2019 and 2020 were compared to get elevation change in each grid. DEM differencing technique of two consecutive years using map algebra tool in ArcGIS was used to obtain the change in elevation in each grid.

The change in elevation is exported to excel sheet and cleansed to find average change of elevation i.e. h_g for every altitudinal band. The annual mass balance (geodetic) at a point is calculated following Tshering and Fujita, 2016 as follows:

$$b_g = h_g i + (S_{t2} - S_{t1}) (S - i) / (t_2 - t_1)\ldots\ldots(1)$$

Where; bgis the annual mass balance at a given point by the geodetic method (kg m^{-2} a^{-1} equivalent to mm w.e.a^{-1}).hg is the elevation change (m) obtained from different DEMs. s and i are density of snow and ice (kg m^{-3}) respectively, where s is assumed to be 400±100 kg m^{-3} and i is assumed to be 880±30 kg m^{-3}. St2 and St1 are the thickness of snow (m) for year's t_1 and t_2. Here t_2 refers to recent years and that of t_1 to the past year.

From equation 1, the result obtained is the mass balance at a given point. So to obtain the area averaged annual mass balance, area was calculated from the number of counts of pixels obtained from the IDW of dGPS data. Finally, the area averaged annual mass balance is (b_g ; mm w.e.a^{-1}) estimated as:

$$b_g = A_z\, b_g / A\ldots\ldots(2)$$

Where; A_z and A_T are glacier areas within 50 m altitude band and total area (m^2) respectively. Regarding the area (A_z), the average of the area within 50 m altitude band of two different survey years is considered bg_z is the average mass balance within the 50 m altitude band.

Hypsometry

In order to map the glacier boundary, recently available free Sentinel-2 image of 2020 was used for delineating the boundary of glaciers. The terminus of the glacier was delineated using DGPS data collected during the field survey. In order to get the hypsometry, 1m DEM data from 2020 was used and extracted by superimposing 2020

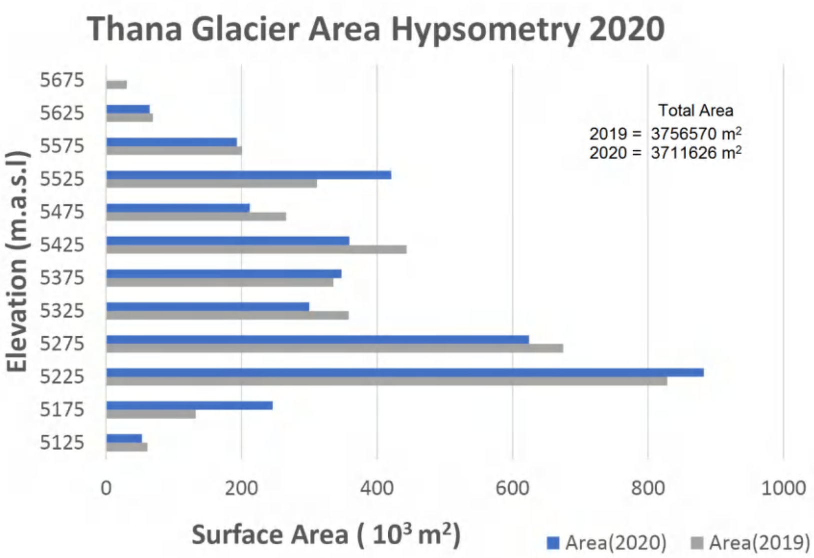

Figure 4Altitudinal variation of glacier mass with elevation

glacier boundary polygons. *Figure 4* shows altitude band wise distribution of glacier surface. Comparing the altitudinal glacier distribution between 2019 and 2020 the glacier has suffered a loss of mass in higher and lower elevation bands and increased in mid elevation band. This could be due to the glacier dynamics whereby less input from accumulation and high melting from ablation could have led to these losses. The gain in the mid-elevation bands could be due to glacial ice movement as suggested by (Yanan Li). Overall the surface area of the glacier have a net loss of 44944 m^2 compared to previous year.

Stake Measurement

The direct annual mass balance was calculated by formulating the changes in stake height (glacier ice thickness change) and incorporating changes in snow thickness. The specific mass balance at a point was calculated following Tshering and Fujita, 2016:

$$B_d = \Delta h_d \, i + (S_{t2} - v_{t1})(s - i)(t2 - t1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where b_d is the annual mass balance at a given point by the direct method (kg m^{-2} a^{-1} equivalent to mm w.e.a^{-1}) ; Δh_d is the difference in stake height (m) between years t1 and t2 and it is negative when the glacier surface lowers ; s and i are the density of snow and ice (kg m^{-3}) respectively. The density of snow was considered 488.8 kg m^{-3} (calculated from snow pit analysis) in elevations having snow more than 1 m thick and 400 kg m^{-3} in places having snow less than 1 m thick. Following Tshering and Fujita (2016), the density of ice was assumed to be 880 kg m^{-3}. S_{t2} and S_{t1} are the thickness of snow (m) for year's t2 and t1 respectively. Snow thickness was measured at the stake locations and the snow pit measurement was carried out near the upper most stake. The thickness of the snow for both the years (2018, 2019) at respective elevation bands were estimated from the linear regression fit (*Fig. 5b*). In order to represent the glacier elevation change at respective 50 m elevation bands, the elevation changes were estimated from the linear regression fit (*Fig. 5a*) and thus obtained the mass balance at each 50 m altitude band (b_{dz}; mm w.e.a^{-1}). The area-averaged specific mass balance (b_d; mm w.e.a^{-1}) was calculated from equation (i)

$$b_d = A_z\, b_{dz} A_T \text{ ……………………………………………………….. (4)}$$

Where A_z and AT are glacier areas within 50 m altitude band and total area (m^2) respectively. b_{dz} is the average mass balance within the 50 m altitude band. The glacier surface area was extracted from High Mountain Asia (HMA) DEM, 8 m resolution of 2014 and 2015 imageries. The area (A_z) of each 50 m altitude band was then extracted from the same

River Discharge Measurement

A minimum of 20 vertical cross-section were taken in a lean flowing cross-section of the river. The mean velocity (ū) acquired and area of each cross-section (*A*) calculated were then used as an input to determine the discharge (*Q*) of each cross-section. The total average discharge were taken to achieve overall discharge measurement of the river.

$$Q = A\bar{u} \text{ ……………………………………………………. (5)}$$

Where

- Q is the discharge ($[L^3T^{-1}]$; m^3/s or ft^3/s)
- A is the cross-sectional area of the portion of the channel occupied by the flow ($[L^2]$; m^2 or ft^2)
- ū is the average flow velocity ($[LT^{-1}]$; m/s or ft/s)

Uncertainty Estimation

The mass balance of area average is assumed to associate with three types of uncertainties including uncertainty from the mass balance at each altitudinal band (db_z; mm w.e.a^{-1}) uncertainty from the boundary delineation (dA_z ; m^2), and uncertainty from the density assumption for ice and snow(db_p;mm w.e.a^{-1}). Uncertainties value depicts that the area average mass balance can vary with plus or minus of that value. It is calculated using the formula as per Tshering and Fujita, 2016;

$$\sigma = \frac{\sum A_Z\, db_Z + \sum dA_Z |b_Z| + \sum A_Z\, db_\rho}{A_T} \quad \ldots\ldots (6)$$

$$SD = \sqrt{\frac{1}{N}\Sigma(bz - \overline{bz})^2} \quad \ldots\ldots (7)$$

The uncertainty from the area average mass balance is the standard deviation (SD) of the mass balance at each altitude band. It is calculated as shown in equation 4. The uncertainty from the boundary delineation (dA_z) is calculated as half of pixel of Sentinel 2 MSI image (*10 m resolution*) multiplied by perimeter of boundary delineated at each 50 m altitudinal band. Moreover, the last uncertainty that is from density assumption for ice and snow (db_ρ), density uncertainties was assumed as 30 kg m^{-3} for ice and 100 kg m^{-3} for snow. From these two uncertainties are found and averaged to be considered as uncertainty from density assumption. A_z is the area within a 50m altitudinal band, A_T the total area and $|b_z|$ is the absolute mass balance.

The uncertainty estimation was **282.45** mm **w.e.a^{-1}**, which signifies that the area average mass balance for the glacier for the year 2020 can vary by $\pm$ 282.45 mm w.e.a^{-1} i.e. the annual glacier-wide mass balance is **-2907. $\pm$ 282.45 mm w.e.a^{-1}**

Result and Discussion

Annual Glacier-wide mass balance

The annual glacial-wide mass balance of Thana glacier was reported to be -3223.35 mm w.e.a^{-1} and -2907.2 $\pm$ 282.45 mm w.e.a^{-1} for glaciological and geodetic methods respectively. Comparing the obtained result to earlier reported mass balance of the same glacier, it can be concluded that the Thana glacier continues to lose its mass.

Approximate Equilibrium line altitude (ELA) for this glacier is about 5653.4 m.a.s.l as shown in figure 5 which shows that a major portion of glacier area falls under ELA.

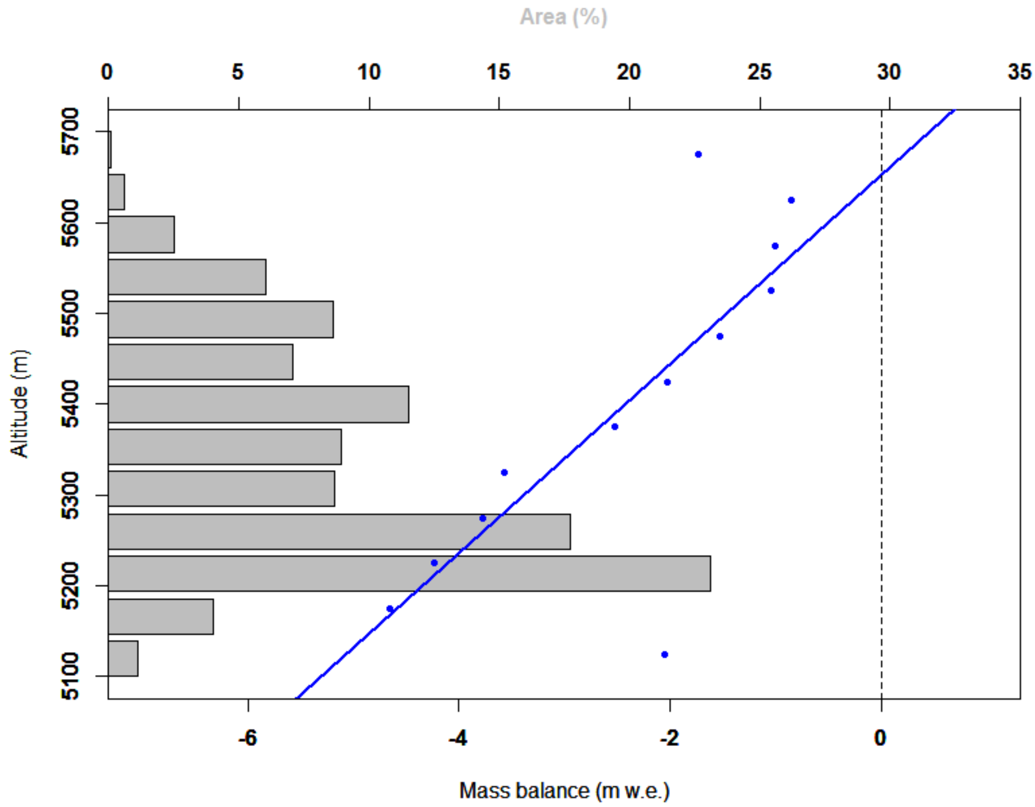

Figure 5: Annual Glacier-wide mass balance gradient along with areal distribution histogram

Using the linear regression model, the specific-mass balance data of each elevation band, The glacier was projected to have lost most of the masses from the terminus area and least from the accumulation area as shown in figure 7.

Glacier terminus of Thana glacier has been mapped using dGPS technique to track the terminus recession in future. To see the terminus retreat rate, 2020 dGPS field data was overlaid on the manually mapped boundary of Thana glacier on Sentinel-2 for 2018 and 2019. This shows that glacier terminus has more or less remained the same. Where some part of terminus has receded while some part has advanced as shown in *figure 6*.

Exact recession or advance in glacier terminus can be quantified only after mapping glacier boundary with dGPS in later years.

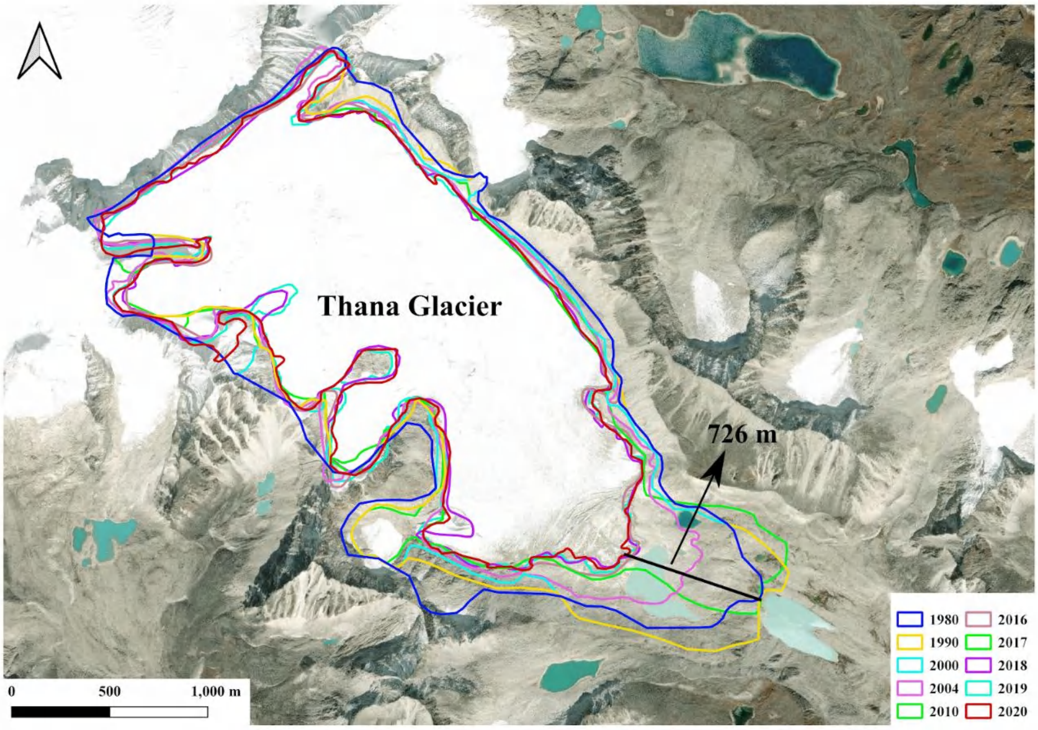

Figure 6: Showing the changes of terminus of Thana Glacier in Thanagang, Bumthang.

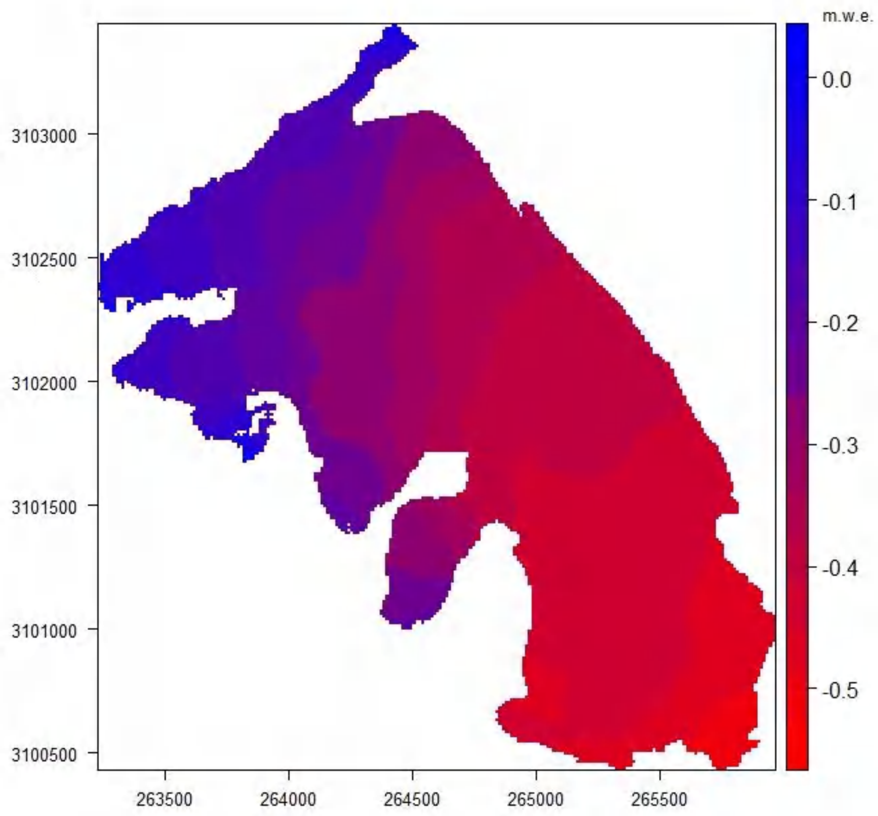

Figure 7: Glacier-wide specific mass balance distribution on Thana Glacier

Cumulative Glacier-Wide Mass Balance

The Cumulative Glacier-wide Mass Balance of Thana glacier since 2016 (figure 8) exhibits linear receding line from 2016-2019 as there were no field data during that time interval. Annual glacier-wide mass balance was arranged exhibiting through linear cumulative balance. The figure 8 shows the Cumulative Glacier-wide Mass Balance of Gangju La Glacier along with its annual glacier-wide mass Balance

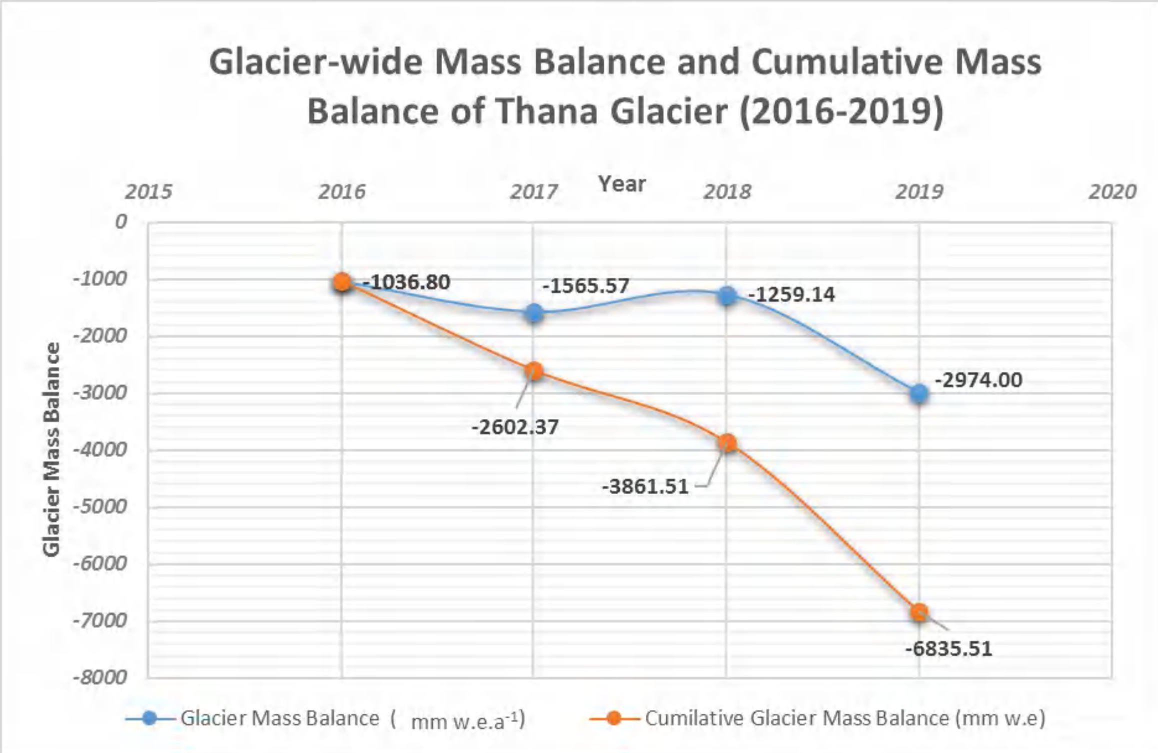

Figure 8: Glacier-wide Mass Balance and Cumulative Glacier Mass balance of Thana galcier

Snow pit Measurement

Snow was found in the higher elevation ranging from 5500 to 5700 m.a.s.l. The snow pit measurement done near the STK 75-19 at an elevation of 5570.35 m.a.s.l. A total of 13 sectional interval were taken for a depth of 115 cm when it met glacier ice.
The average density of the snow was 504.15 kg m^{-3}. Figure 9 shows the linear relationship between density of snow with depth and the corrusponding cumulative SWE with depth. This snow debsity were taken in the calculation of GMB for the elevation between 5500-5700 m.a.s.l. as the snow was found in this elevation during field survey.

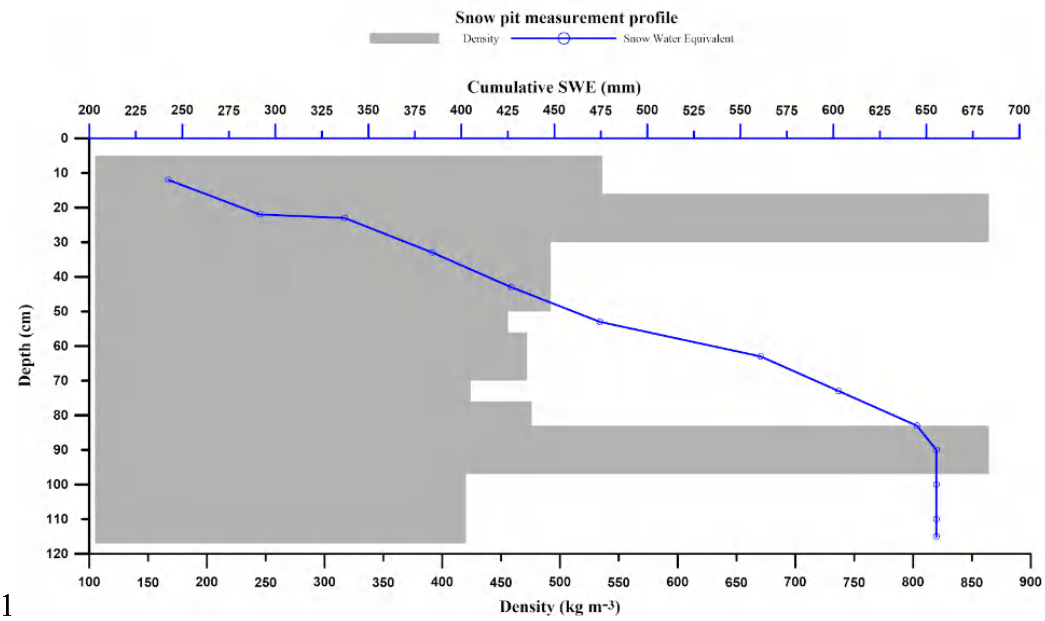

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Figure 9: Density of Snow with depth and Cumulative SWE with depth

Discharge Measurement

The discharge measurement using Doppler velocity meter (AquaProfiler M Pro™) was measured at Thanagang steam. The velocity meter reading shows discharge of 0.576 m^3 s^{-1}on 16th October 2020 (7:38 AM). The detailed result of the discharge measurement is given in figure 10.

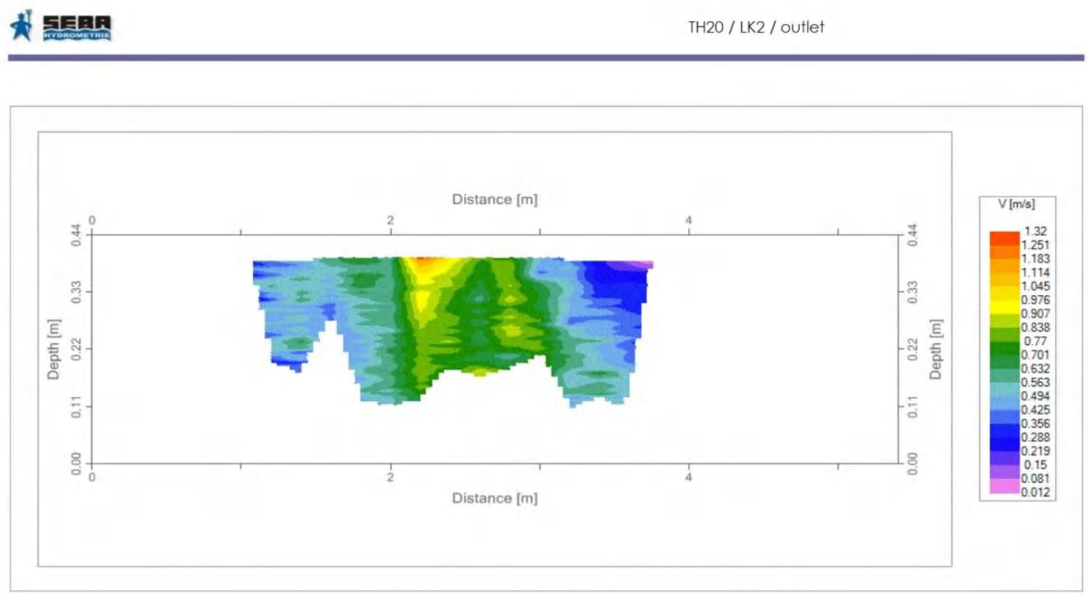

Figure 10: Discharge measurement of Thana Glacial outlet on 16th October 2020.

Conclusion

The fieldwork of Thana glacier for the glacio-hydrological year 2019-2020 was conducted on October 2020. Both direct and in situ geodetic method of mass balance method has been carried out in this glacier. Mass balance report from 2016 till date has shown negative results. Even for this year (2019-2020)

- The glacier has exhibited a mass balance of -3223.35 mm w.e.a^{-1} and -2907.2$\pm$ 282.45 mm w.e.a^{-1} for glaciological and geodetic methods respectively. Both the approach of mass balance has shown negative value, which indicates that glaciers are experiencing loss in mass over the time.

- The approximate Equilibrium line altitude (ELA) for Thana glacier have rose from 5550.4 m.a.s.l in 2018-19 to 5653.4 m.a.s.l in 2019-20.

- Hypsometry result shows that the overall glacier surface is decreasing at accumulation and ablation area however the mid-section band had increase in glacial surface area which could be due to glacial ice flow as mentioned by (Yanan Li)

- The cumulative glacier-wide mass loss accounts to -6835.51 mm w.e from 2016 till 2019. With maximum glacial mass loss accounted in the year 2019-20.

- The Thana glacier outlet river has a discharge of 0.576 $m^3 s^{-1}$.

Recommendation

As per the finding from current field program, team would recommend following:

- The local DEM of Thana was hard to generate provided its large surface area, therefore in future we would recommend a drone survey in Thana glacier for the generation of DEM. The earlier UAV drone survey conducted in 2017 failed due to local climate condition and due to rugged terrain. There for the use quadcopter drones for future glacier survey is recommended.
- With the setup of new accurate TBM near the glacier, the team would recommend all teams in future to use the TBM coordinates for the better accuracy.

Reference

Tshering, P., & Fujita, K. (2016). First in situ record of decadal glacier mass balance (2003–2014) Beedle, M. J., Menounos, B. and Wheate, R. (2014) ‘An evaluation of mass-balance methods applied to Castle Creek Glacier, British Columbia, Canada’, *Journal of Glaciology*. doi: 10.3189/2014JoG13J091.
Brugman, M. and Ostrem, G. (1991) *MASS-BALANCE MEASUREMENTS A manual for field and office work*.
Cogley, J. G. (2011) ‘Mass-balance terms revisited’, *Journal of Glaciology*. doi: 10.3189/002214311796406040.
Cryosphere Services Division (2018) ‘BHUTAN GLACIER INVENTORY 2018’, p. 5,19,25,28,29,31.
Dorji, L. and Statistics, N. (2016) ‘Bhutan’s glaciers meltdown, threats and the need for joint response mechanism socio-economic research and analysis division’, (May 2014).
Gardner, A. S. *et al.* (2013) ‘A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009’, *Science*. doi: 10.1126/science.1234532.
Leclercq, P. W., Oerlemans, J. and Cogley, J. G. (2011) ‘Estimating the Glacier Contribution to Sea-Level Rise for the Period 1800-2005’, *Surveys in Geophysics*. doi: 10.1007/s10712-011-9121-7.
Prasch, M., Mauser, W. and Weber, M. (2013) ‘Quantifying present and future glacier melt-water contribution to runoff in a central Himalayan river basin’, *Cryosphere*. doi: 10.5194/tc-7-889-2013.
Radić, V. and Hock, R. (2011) ‘Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise’, *Nature Geoscience*. doi: 10.1038/ngeo1052.
Radić, V. and Hock, R. (2014) ‘Glaciers in the Earth’s Hydrological Cycle: Assessments of Glacier Mass and Runoff Changes on Global and Regional Scales’, *Surveys in Geophysics*. doi: 10.1007/s10712-013-9262-y.
Tshering, P. and Fujita, K. (2016) ‘First in situ record of decadal glacier mass balance (2003–2014) from the Bhutan Himalaya’, *Annals of Glaciology*. doi: 10.3189/2016aog71a036.
Cryosphere Service Division. (2018). Scientific report on Gangju La glacier. Thimphu.

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