Glacier Mass Balance Studies on Thana Glacier

2023-2024

Cryosphere Services Division
National Center for Hydrology and Meteorology
2024

List of acronyms:

- MSI – Multispectral Instrument
- RTK – Real-Time Kinematic
- GNSS – Global Navigation Satellite System
- mm w.e. a^{-1} – Millimeter Water Equivalent per Annum
- DEM – Digital Elevation Model
- IDW – Inverse Distance Weighting
- AGMB – Annual Glacier Mass Balance
- CGMB – Cumulative Glacier Mass Balance
- ICIMOD – International Centre for Integrated Mountain Development
- TCS7 – Trimble Controller Series 7
- WGS 84 – World Geodetic System 1984
- CSV – Comma-Separated Values
- IPCC – Intergovernmental Panel on Climate Change
- Gt – Gigatonnes
- m.a.s.l. – meters above sea level

Executive Summary

This report presents the results of the 2023–2024 annual glacier mass balance monitoring of Thana Glacier, one of Bhutan's benchmark glaciers under the Cryosphere Services Division of the National Center for Hydrology and Meteorology (NCHM). Situated in the northern part of Central Bhutan Himalayas, Thana Glacier plays a critical role in sustaining the Chamkhar Chhu River and downstream water systems. Deploying high-precision Real-Time Kinematic (RTK) GNSS techniques (Trimble R10-2) and geodetic analysis, the study focused on assessing surface elevation changes and terminus recession over the monitoring year. The methodology included a detailed digital elevation model (DEM) construction, DEM differencing, and hypsometric analysis within 50 m elevation bands to quantify elevation change and mass loss with accuracy. Supporting satellite imagery and field-based data collection allowed precise glacier delineation and enhanced the reliability of mass balance estimates.

The glacier recorded a negative geodetic mass balance of –2,422.86 mm w.e. a^{-1}, accompanied by an average terminus retreat of 30.7 meters over the observation period. Spatial analysis revealed that the glacier's surface area decreased by 3.87%, resulting in an estimated 67.57 billion liters of ice loss over the monitoring year.

The cumulative mass balance between 2016 and 2024 stands at –17,903.3 mm w.e., confirming a persistently negative trend consistent with broader cryosphere changes observed across the Eastern Himalayas. Additionally, the study integrated uncertainty estimation across key variables including boundary delineation, ice and snow density assumptions, and elevation-band variability, concluding a ±197.04 mm w.e. a^{-1} uncertainty margin for the 2024 annual mass balance estimate.

The findings from this assessment reinforce the urgent need for sustained and precise glacier monitoring in Bhutan, especially given the country's reliance on hydropower and glacial meltwater for agriculture, energy, and drinking water. Thana Glacier's continued retreat signifies broader climatic changes impacting the Eastern Himalayas, echoing IPCC projections and global cryospheric trends. This report not only contributes to Bhutan's long-term glacier dataset but also provides actionable scientific evidence for national climate resilience planning and international reporting. With the designation of the World Day for Glaciers by UNESCO, the continued efforts of NCHM to generate high-quality cryospheric data underscore Bhutan's leadership in monitoring Himalayan glacier health amidst accelerating global climate change.

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1.Introduction

Glaciers today are the remnants of the massive ice sheets that once covered large portions of the Earth during the Last Glacial Maximum, which ended approximately 10,000 to 11,700 years ago. These glacial ice masses, along with ice sheets in Greenland and Antarctica, are the largest reservoirs of fresh water on the planet, containing about 69 percent of the world's freshwater resources (National Snow and Ice Data Center, 2021). Over the Holocene epoch, glaciers have generally been retreating, with a significant acceleration in recession observed in the 20th and 21st centuries due to anthropogenic climate change (WGMS, n.d.). According to Barry (2006), this post-glacial retreat has been globally consistent, and the Himalayas are no exception.

The Himalayas, often referred to as the "Third Pole" due to their vast ice reserves, are home to around 54,000 glaciers (International Water Security Network,2016). Recent studies have shown that the region is warming at a rate almost twice the global average, exacerbating glacier melt (King et al., 2019). According to the Intergovernmental Panel on Climate Change (IPCC, 2023), glaciers worldwide are currently losing ice at an average rate of 267 gigatons per year. In the Himalayas specifically, glaciers are thinning at an average rate of approximately 0.2 m w. e per year, depending on the sub-region and elevation year (Maurer et al., 2016; P.Wester et al., 2019).

Glaciers are vital freshwater sources, particularly for arid and semi-arid downstream regions that depend heavily on glacial melt during dry months. In the Himalayan range, glacier-fed river systems, including the Ganges, Brahmaputra, and Indus, support nearly two billion people across South Asia (Immerzeel et al., 2010). In Bhutan, a predominantly mountainous country, glaciers serve as a critical and perennial source of freshwater. They contribute significantly to river flows during the dry season (November to April), playing a vital role in agriculture, hydropower generation, and drinking water supply. Bhutan's dependency on hydropower for economic development makes glacier health a national concern. The recession of these glaciers poses a serious threat to Bhutanese communities, especially those residing along glacier-fed river valleys such as the Pho Chhu, Mo Chhu, Chamkhar Chhu, and Mangde Chhu basins.

Recognizing the strategic importance of glaciers, the Cryosphere Services Division (CSD) under the National Center for Hydrology and Meteorology (NCHM) has established a long-term glacier monitoring program. As part of this initiative, three glaciers—Gangju La, Thana, and Shodug—have been benchmarked for annual in-situ mass balance monitoring (NCHM, 2018). These glaciers were selected based on criteria such as representativeness of regional glacier types, accessibility, and hydrological significance. Annual monitoring involves both glaciological methods (using stake networks and snow pits) and geodetic methods (using high-resolution DEMs from UAVs, satellite photogrammetry, or dGPS). These studies help assess not only the net gain or loss in glacier mass but also terminus (snout) retreat, surface elevation changes, and snow cover distribution.

The Gangju La Glacier, located in northern Bhutan, was the first to be monitored systematically, with mass balance studies dating back to 2003 (Tshering & Fujita, 2016). These early studies laid the groundwork for Bhutan's glacier monitoring protocols. Thana Glacier, located in the northern part of the Central Bhutan Himalayas near Bumthang, became the second benchmark glacier with long-term monitoring initiated in 2013 (NCHM, 2024, p.41). The glacier spans approximately 5 km in length and is a significant contributor to the Chamkhar Chhu River, which flows through one of Bhutan's most agriculturally important valleys. Recession of this glacier could significantly alter seasonal water availability in the region, impacting livelihoods and local ecosystems.

Together, the monitoring of these benchmark glaciers provides critical insights into the impacts of climate change on Bhutan's cryosphere and informs adaptation strategies for water resource management, disaster risk reduction (e.g., glacial lake outburst floods—GLOFs), and sustainable development planning in glacier-fed regions.

2.Aim and Objective

The primary aim of this study is to assess recent changes in the mass balance and terminus position through in-situ based geodetic method, thereby contributing to Bhutan's long-term glacier monitoring and climate adaptation efforts.

3.Study Area

3.1 Location

Thana glacier, a clean type glacier, is located in Northern part of Central Bhutan Himalayan (28° 57' 11" N, 90° 21' 17" E). Its elevation ranges from 5,100 m a.s.l. to 5,700 m a.s.l. covering an area approximately about 3 km^2, sourcing Chamkhar Chhu (Fig.1). It is referred to as Mchgr16_546 as per the Bhutan Glacier Inventory (NCHM, 2018).

3.2 Accessibility

Thana glacier can be accessed via two options; the first route is via Dhur- Tshampa- Thana via Toley La, which takes seven days on foot to reach the study site. The other route is via Choekhor Toe- Tshampa- Thana and takes six days on foot to reach the study site. Autumn season is favorable season to visit the site as the glaciers in the Eastern frontier of the Bhutan Himalayas are summer accumulation type leading to excess snow cover on the glacier surface intervening the installation of mass balance stakes on the glacier surface.

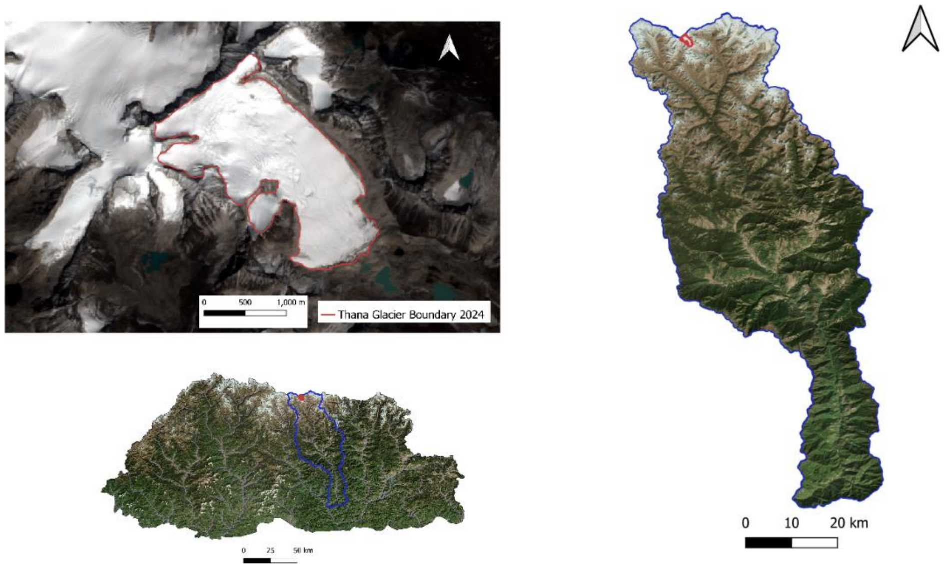

Figure 1: Location of Thana at the headwaters of Chamkhar chu within the Chamkhar chu sub-basin (outlined in blue). The background is a Sentinel-2 True Color Composite.

4. Data and Methodology

4.1 Data Acquisition

Thana glacier has a geodetic mass balance record since 2016. During the current field expedition, glacier surface elevation data were collected using RTK GNSS (Trimble R10-2). Prior to the survey, Trimble R10-2 was calibrated for higher precision to avoid errors. The base station was set up accurately on the previously marked point (reference point), which is at a certain distance away from the glacier snout and kept at the height of 2m from the ground. Manually inserting the known coordinate of the base station in the TCS7 controller of Trimble R10-2, the base station was set to start for the collection of data (Fig. 2 b). A rover was mounted on a backpack and the height of the rover from the ground was measured and entered in the controller accordingly. With the logging distance of 1m and a logging interval of one second in continuous Topo-mode, the glacier surface elevation data were collected by walking across the glacier following the survey track file (shape file) of the previous year to obtain maximum coinciding points (Fig. 2 a). Several new points were collected for future reference.

Similarly, glacier terminus data were collected by following the snout of position of the glacier for that given point of time. Unlike glacier surface elevations, there is no reference to previous year's data to walk through it. In order to track the glacier terminus changes, the terminus position dataset was compared with the previous year and calculated.

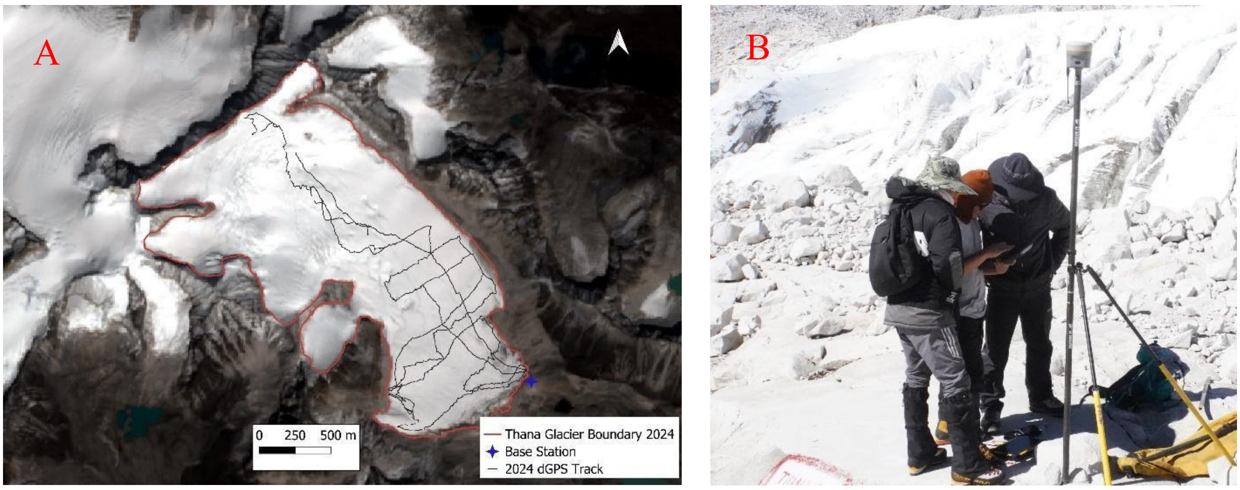

Figure 2: A) dGPS survey tracks. B) Base set up. The background is a Sentinel-2 True Color Composite.

4.2 Data Post Processing

The raw data obtained in Trimble TSC7 were exported in CSV format using the inbuilt software (Trimble Access) in the Trimble TSC7 controller.

The exported CSV file was scrutinized in excel sheet for abnormal data points and then the shape file (.shp) was generated in ArcGIS. Accordingly, the shapefile generated was loaded back to the TSC7 controller to be used the following year while collecting the glacier surface elevation using Trimble R10-2.

In ArcGIS software, the data was integrated to construct 1m Digital Elevation Model (DEM) using inverse distance weighting (IDW) interpolation tool with a search result of 0.7m, for the year 2023-2024 following earlier methods. The difference in DEMs produced in the current year and the previous year with the same reference grid, provides a change in elevation in each grid point (Fig. 3). This difference in DEMs is calculated using the DEM differencing technique of two consecutive years using an incorporated map algebra tool in ArcGIS.

The change in elevation is further filtered in excel sheet and, an average change of elevation i.e. Δh_g for every 50 m altitudinal band was calculated by averaging the available elevation change values. The annual mass balance (geodetic) at a point is calculated following (P. Tshering & Fujita, 2016) as follows:

$$b_g = \frac{\Delta h_g \rho_i + (S_{t2} - S_{t1})(\rho_s - \rho_i)}{(t2 - t1)}$$

Where b_g is the annual mass balance at a given point by the geodetic method (kg m^{-2} a^{-1} equivalent to mm w.e.a^{-1}); Δh_g is the elevation change (m) obtained from differenced DEMs; ρ_s *and* ρ_i are the density of snow and ice (kg m^{-3}) respectively. S_{t2} *and* S_{t1} are thick of snow (m) for years t1 and t2.

Finally, the area averaged annual mass balance ($\overline{b_g}$mm w.e.a^{-1}) estimated by:

$$\overline{b_g} = \frac{\sum A_z b_{gz}}{A_T}$$

Where A_z and A_T are glacier areas within 50 m altitude band and total area (m2) respectively. b_{gz} is the average mass balance within the 50 m altitude band. Regarding the area (A_z), we use

$A_z=(A_{t1}+A_{t2})/2$, where A_{t1} and A_{t2} represent the areas of the measurements taken in years $t1$ and $t2$ at a given altitude band(m^2), respectively.

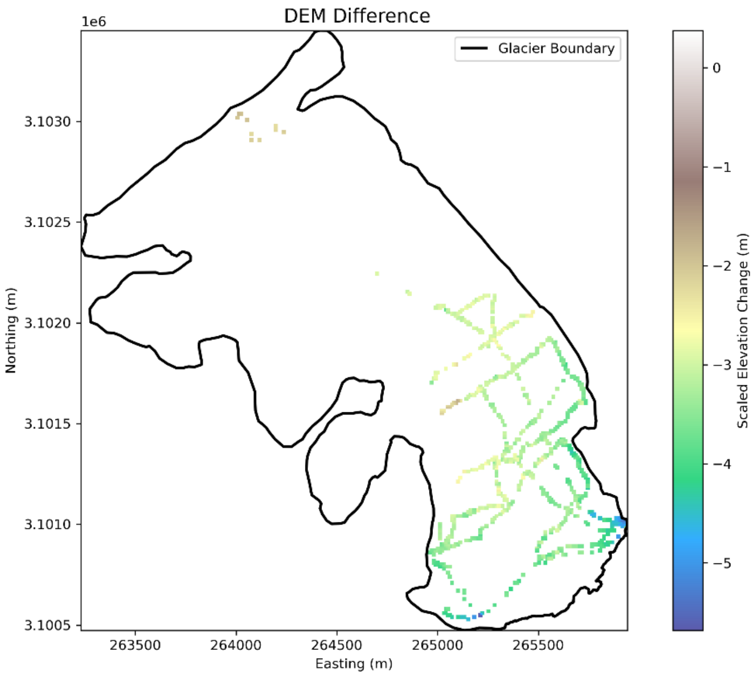

Figure 3:DEM difference calculated for the years 2023–2024. The raster values were resampled using a factor of 10 to enhance visual clarity.

5. Hypsometry

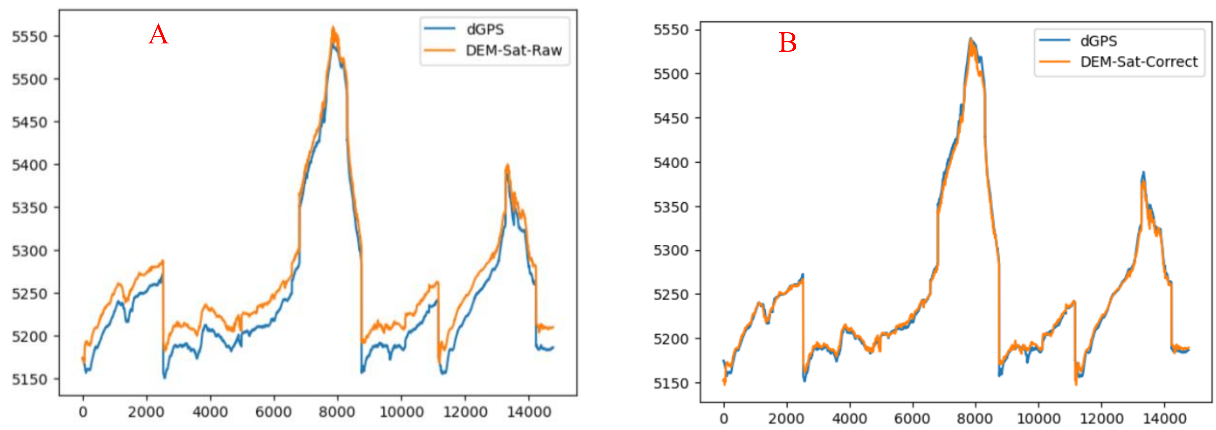

Figure 4: A) Observed Difference in the field-based surface elevation and the Satellite obtained Elevation. B) Corrected DEM, accurately in aligned with the field obtained data)

To delineate the glacier boundary, a recently available free Sentinel-2 image from 2024 with a spatial resolution of 10 m was used. The glacier terminus was mapped using *in-situ* based dGPS data collected during the field survey. A 1 m resolution DEM (Maxer), acquired a few years ago, was utilized to extract glacier surface area using the glacier boundary polygons. However, the acquired 1 m DEM had some elevation difference with the actual field based dGPS glacier surface elevation (Fig. 4a). A numeric algorithm was used to modify the surface elevation of satellite-based DEM and corrected with the field-based glacier surface elevation to extract the glacier surface area. (Fig. 4b). The corrected surface elevation obtained was then used for the calculation of area-averaged glacier mass balance. The extracted hypsometry within the 50 m elevation band for 2023 and 2024 is shown in figure 5.

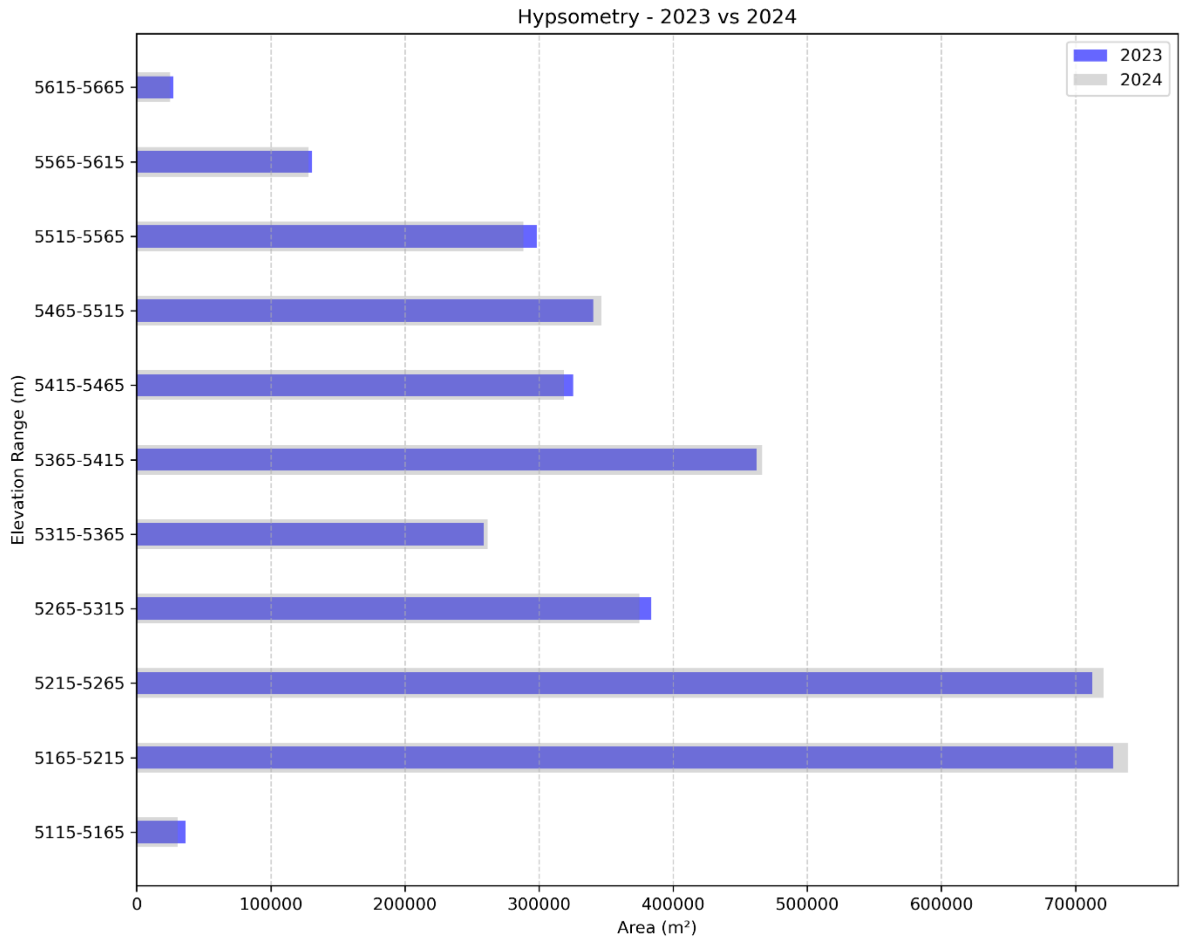

Figure 5: Thana glacier hypsometry for the year 2023 and 2024

6. Result

Table 1: Thana glacier Mass Balance

Elevation (m)	Average Elevation difference	Average Area 2023-2024(m^2)	Point Mass Balance mm w.e.a^{-1}	Area Average Mass balance mm w.e.a^{-1}
5115-5165	-3.56223	33569.26	-3134.76	-28.422
5165-5215	-3.36679	733733.40	-2962.77	-587.16
5215-5265	-3.07045	716722.93	-2702.00	-523.07
5265-5315	-2.95478	379238.08	-2600.21	-266.34
5315-5365	-2.7600	260109.85	-2428.80	-170.63
5365-5415	-2.5700	464319.90	-2261.60	-283.63
5415-5465	-2.3700	322055.71	-2085.60	-181.41
5465-5515	-2.1703	343570.36	-1909.88	-177.23
5515-5565	-2.0063	293299.90	-1765.62	-139.87
5565-5615	-1.790	129422.64	-1575.20	-55.06
5615-5665	-1.600	26307.11	-1408.00	-10.00
		Glacier Mass Balance		-2,422.8648

The table 1 shows the point mass balance, area-averaged mass balance and a total glacier mass balance. It also shows the average surface elevation difference for the year 2023 and 2024.

From the point mass balance, we can deduce that surface lowering decreases with increasing elevation. This is consistent with the findings of Tshering and Fujita (2016), who reported maximum surface lowering at lower elevation and less at higher elevations.

The Thana glacier has been exhibiting negative mass balance since 2016. For the year 2023 to 2024, it recorded mass loss with Glacier Mass Balance of -2,422.86 mm w.e.a^{-1} (Table 1), over total glacier surface area of 3.702 km^2.

The glacier terminus retreated by an average of 30.7 meters during the observation period (2023–2024). To account for spatial variability along the glacier snout, six representative points (as shown in Figure 6) were used to measure the terminus recession. These values were then averaged to obtain the final retreat estimate.

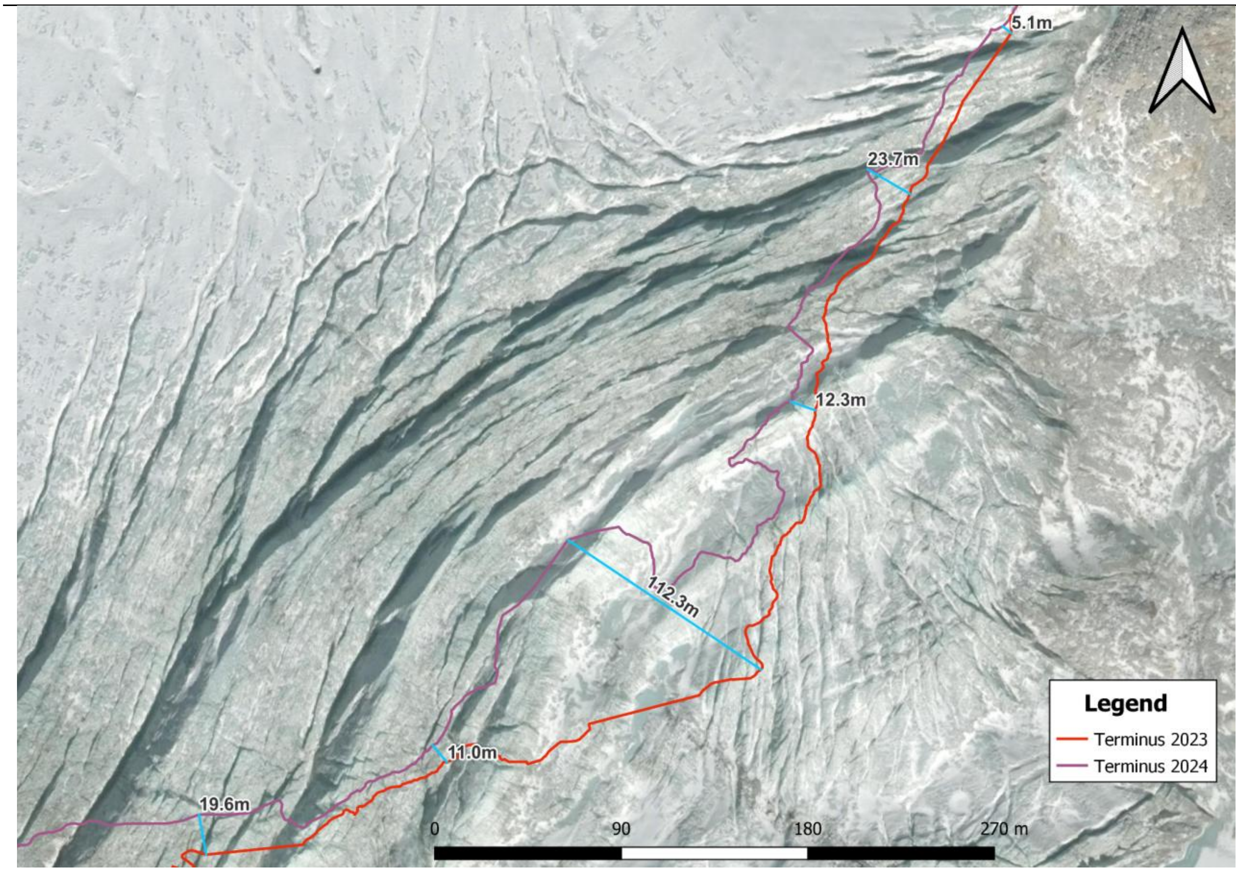

Figure 6: Thana Terminus recession over the time

7. Cumulative Glacier Mass Balance and Terminus Recession

The graph illustrates the trend in Cumulative Glacier Mass Balance (CGMB) from 2016 to 2024 (Fig.7, Table 2).

The Cumulative Glacier Mass Balance (CGMB) shows a consistently declining trend throughout the observed period, indicating a continuous loss of glacier mass. This reflects a net negative mass balance, which is characteristic of glaciers undergoing sustained melting. Between 2016 and 2018, the rate of mass loss was relatively moderate. However, from 2019 onwards, the cumulative mass balance slope shows steeper, suggesting an increased rate of glacier mass loss in recent years. In the most recent period, from 2022 to 2024, the glacier continues to lose mass with no indication of stabilization. This ongoing decline suggests that current climatic conditions remain unfavorable for any recovery in glacier mass balance.

Table 2: Cumulative Glacier Mass Balance

Sl.No	Year	AGMB	CGMB
1	2016	-1036.8	-1036.8
2	2017	-1565.57	-2602.37
3	2018	-1259.14	-3861.51
4	2019	-2974.00	-6835.51
5	2020	-2441.71	-9277.22
6	2021	-2379.23	-11656.4
7	2022	-1912	-13568.4
8	2023	-1912	-15480.4
9	2024	-2422.86	-17903.3

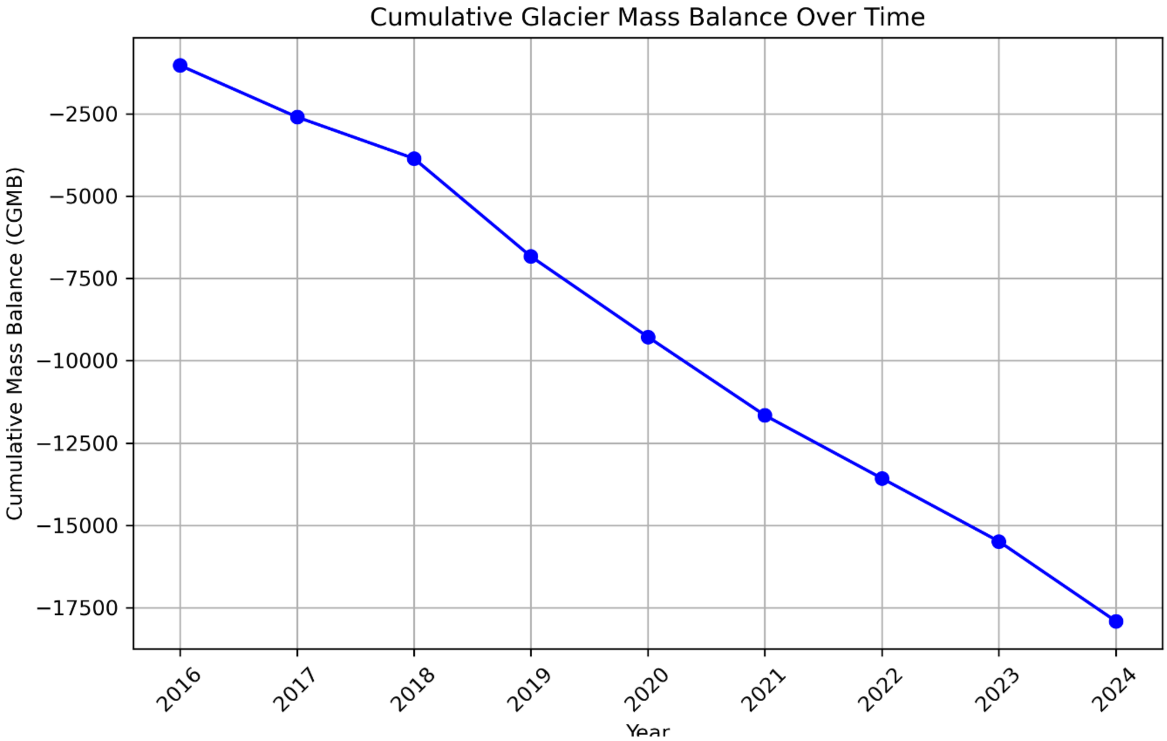

Figure 7: Cumulative Glacier Mass Balance over time

Using the available data, terminus retreat was calculated due to its importance in understanding glacier dynamics. Terminus data was collected using differential GPS (dGPS) to precisely track the glacier's terminus position over time. The glacier terminus is retreating over time, and the recession is shown in (Fig 6.)

8. Uncertainty Estimation in Area-Average Mass Balance

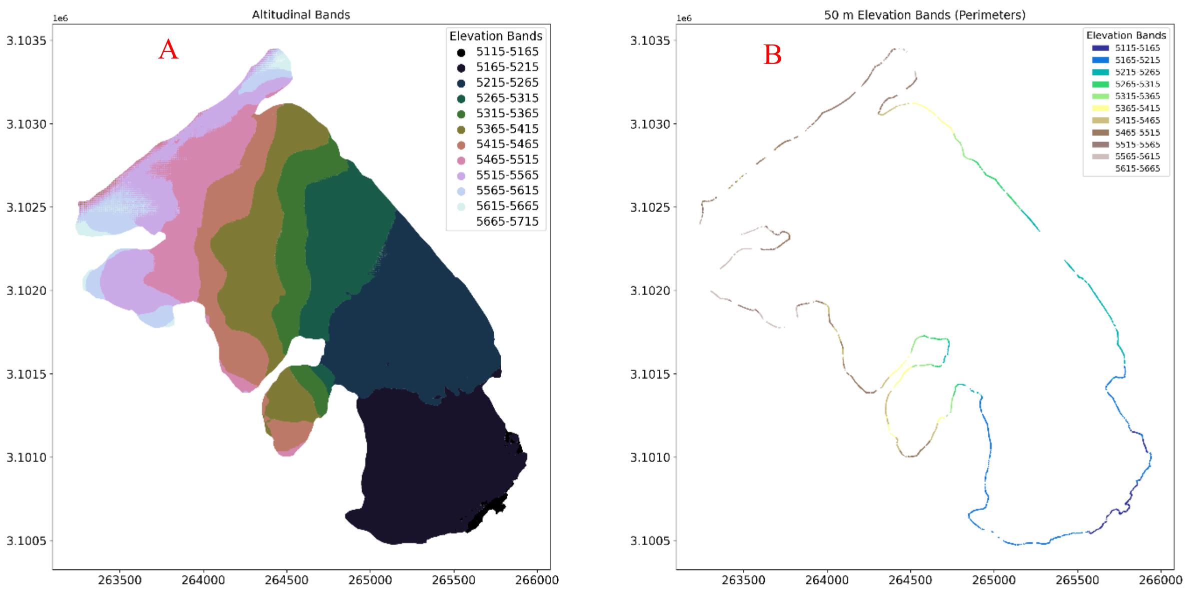

Figure 8:A) Altitudinal band. B) Perimeter over different elevation band

The area-average mass balance estimation is associated with three main uncertainties:

1. Uncertainty in the mass balance at each altitudinal band (db_Z; mm w.e. a^{-1}) is calculated for the bands shown in Figure 8a.

2. Uncertainty from the glacier boundary delineation (dA_Z; m^2), and

3. Uncertainty from the assumed density of ice and snow (db_ρ; mm w.e. a^{-1}).

These uncertainties affect the reliability of the estimated area-average mass balance and are incorporated into the final value as a ± range, indicating possible variation. The combined uncertainty (σ) is calculated following the methodology described in Tshering and Fujita (2016) as:

$$\sigma = \frac{\sum A_Z db_Z + \sum dA_Z |b_Z| + \sum A_Z db_\rho}{A_T}$$

Where:

- A_Z is the area within a 50 m altitudinal band,

-$A_T$is the total glacier area,

- b_Z is the mass balance at each band, and
- $|b_Z|$ is the absolute mass balance.

The uncertainty from the boundary delineation (dA_Z) is computed as:

dA_Z = 0.5 × pixel resolution × perimeter at each 50 m band

Given the Sentinel-2 MSI image resolution of 10 m, dA_Z is based on half the pixel size (i.e., 5 m) multiplied by the perimeter of the glacier outline at each altitudinal band (Fig.8b).

The uncertainty from the density assumption db_ρ arises from variability in the assumed densities of ice and snow. Following standard assumptions, a density uncertainty of 30 kg m^{-3} for ice and 100 kg m^{-3} for snow is used. These two values are averaged to represent the overall density-related uncertainty in mass balance estimation.

The standard deviation (db_Z) of the mass balance across altitudinal bands, representing the uncertainty from spatial mass balance variation, is calculated as:

$$db_Z = \sqrt{\frac{1}{N}\sum(b_Z - \overline{b_z})^2}$$

Where N is the number of elevation bands and $\overline{b_z}$ is the mean mass balance.

The total uncertainty estimated for the area-average mass balance is ±197.036 mm w.e. a^{-1}. This means the annual area-average mass balance for the glacier in 2024 is:

-2422.864848 ± 197.036 mm w.e. a^{-1}

indicating that the actual value may vary by this margin due to the cumulative uncertainties discussed above.

9. Results and Discussion

The 2023–2024 study of Thana Glacier reveals a continued negative mass balance trend, with an annual glacier mass loss of –2422.86 mm w.e. a^{-1} observed across an area of approximately 3.70 km^2. This loss is consistent with long-term geodetic monitoring data, which indicate a sustained pattern of glacier recession since 2016. Over the nine-year observation period, Thana Glacier has consistently lost mass, showing no signs of recovery. This trend aligns with observations from another benchmark glacier, Gangjula, which has also experienced continuous annual mass loss during the same period.

Elevation dependent surface lowering was evident, with the most intense melting observed in the lower altitude bands (5115–5215 m a.s.l.), where point mass balance values exceeded –3000 mm w.e. a^{-1}. This pattern of enhanced melt at lower elevations matches findings from other Himalayan studies, such as those by Tshering & Fujita (2016) and King et al. (2019), which have highlighted the role of rising regional temperatures and increased exposure of debris-free ice in driving accelerated ablation in the eastern Himalayas.

The glacier's terminus retreated by a maximum of 112.4 m during the observation period, reflecting a dynamic response to negative mass balance and further conforming the ongoing trend of frontal retreat observed across Bhutanese glaciers. Similar recession rates have been reported for other benchmark glaciers in the Himalayas, such as Yala Glacier in Nepal and Gangju La in Bhutan, where sustained terminus retreat has been linked to increased summer melting and reduced snow accumulation.

Comparatively, the mass loss rate observed at Thana aligns with regional geodetic and glaciological studies across the Hindu Kush–Himalaya, where glaciers have been thinning at rates 0.2 m w.e. per year (Maurer et al., 2016; P.Wester et al., 2019).

These findings not only reinforce the regional scientific consensus on glacier recession in High Mountain Asia but also highlight the critical role of sustained field-based monitoring in Bhutan. The geodetic data collected at Thana contribute to national efforts to understand water resource vulnerability and inform climate adaptation strategies, especially in light of the glacier's significance to the Chamkhar Chhu catchment and downstream communities.

10. Conclusion

The findings confirm the continued and accelerated melting of Thana Glacier over the past nine years. The observed melt, terminus retreat, and reduction in glacier extent are not isolated events but part of a persistent trend of mass loss, underscoring the glacier's sensitivity to climatic warming, particularly at lower elevations. The surface area has declined by 3.87% since 2016, and the glacier has released an estimated 67.57 billion liters of water into the hydrological system, highlighting the tremendous glacier mass loss over the course of time. Such rapid changes carry significant consequences for Bhutan's water resources, ecosystems, and climate resilience. The reliability of the applied geodetic and remote sensing methods further strengthens confidence in these conclusions.

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