



A wide-angle photograph of a vast, snow-covered mountain range under a clear blue sky. The foreground is a flat, white expanse of snow. In the middle ground, several jagged, rocky peaks are partially covered in snow. The sky is a deep, uniform blue.

2025

List of Acronyms:

- HKH – Hindu Kush Himalaya
- WGMS – World Glacier Monitoring Service
- WMO – World Meteorological Organization
- 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
- UNESCO – United Nations Educational, Scientific and Cultural Organization
- Gt – Gigatonnes
- m. a. s. l. – meters above sea level

Executive Summary

This technical report provides a comprehensive analysis of the mass balance and terminus dynamics of the Shodug Glacier, a designated benchmark glacier situated in Bhutan, monitored from 2024 to 2025 using geodetic methods, specifically differential GPS (dGPS) technology. The Shodug Glacier, crucial for regional hydrological systems and hydropower infrastructure, was evaluated through detailed field measurements, supported by satellite imagery and advanced spatial analysis techniques. Data acquisition included precise surface elevation measurements using RTK GNSS technology, with elevation differences processed through ArcGIS and interpolation techniques such as Inverse Distance Weighting (IDW). These methodologies facilitated the construction of accurate digital elevation models (DEMs), enabling reliable determination of glacier surface changes and terminus recession.

The findings highlight a pronounced negative mass balance for Shodug Glacier, registering a significant loss of -2791.08 and -2608.492 mm water equivalent (mm w. e.) annually over the studied period for *in-situ* geodetic and direct stake measurement respectively, underscoring accelerated melting predominantly at lower altitudes. Additionally, a notable terminus retreat of approximately 15.07 m was documented, reflecting the ongoing climatic stress and warming trends within the Himalayan region. This mass loss is consistent with broader regional and global observations, emphasizing the critical need for continued monitoring and adaptive management strategies. The study's robust uncertainty analysis, accounting for altitudinal variability, boundary delineation accuracy, and assumed ice density variations, reinforces the reliability of its findings, providing a crucial baseline for climate impact assessments and long-term water resource management planning in Bhutan and the broader Hindu Kush Himalaya region.

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1 Introduction

Can Bhutan's glaciers continue to sustain downstream agriculture amid intensifying climate change impacts? Situated in the eastern Himalayas, Bhutan hosts over 700 glaciers (BGI, 2018) that form an integral part of the country's fragile high-mountain ecosystems. These glaciers are not only reservoirs of biodiversity but also serve as vital freshwater sources for communities living in downstream valleys. Agriculture remains the cornerstone of Bhutan's rural economy, with a majority of the population—particularly women—engaged in farming. As of late 2024, more than 95% of economically active women were involved in agricultural activities (Bhutan Agriculture, 2024). A large share of this agricultural productivity hinges on reliable irrigation, with glacier-fed meltwater playing a crucial role, especially during the dry seasons when precipitation is scarce.

Hydrological studies in major river basins such as the Chamkhar Chhu and Pa Chhu have revealed that glacier melt contributes approximately 45% and 49.5% of annual surface runoff, respectively. These findings underscore the crucial role of glaciers in maintaining river discharge, buffering seasonal water variability, and sustaining ecological processes in downstream regions. However, field observations and remote sensing studies have confirmed accelerated retreat and thinning of glaciers such as Thana and Gangju La, signaling a growing threat to Bhutan's long-term water and food security.

Bhutan's glaciers are predominantly classified as summer-accumulating types, rendering them highly susceptible to rising temperatures. Unlike winter-accumulating glaciers (gaining mass during winter due to cold westerlies), these glaciers receive the majority of their mass through monsoon-season snowfall while simultaneously experiencing peak melt due to elevated summer temperatures. This temporal overlap intensifies ablation during the very season intended for accumulation. Tshering and Fujita in 2016 documented that the Equilibrium Line Altitude (ELA) has consistently remained above the glacier surface for over a decade, signifying a sustained state of negative mass balance. This prolonged mass loss underscores the inherent vulnerability of Bhutanese glaciers to climatic fluctuations—and, by extension, the vulnerability of the downstream socio-economic systems that depend on their meltwater contributions.

Institutional knowledge and capacity related to the cryosphere in Bhutan were limited until 2001, when the International Centre for Integrated Mountain Development (ICIMOD) released

the first comprehensive glacier inventory for the country. This publication marked a turning point, laying the foundation for systematic glaciological research. Since then, Bhutan has made significant strides in formalizing glacier monitoring through the establishment of the Cryosphere Services Division (CSD) under the National Center for Hydrology and Meteorology (NCHM). As the principal agency overseeing cryospheric research, the CSD has led efforts to monitor glacier dynamics using robust scientific methodologies.

To enhance the understanding of glacier-climate interactions and address the escalating challenges posed by glacial retreat, Bhutan has identified three benchmark glaciers—Gangju La, Thana, and Shodug—for long-term mass balance monitoring. These reference glaciers are monitored using an integrated approach that combines *in-situ* based geodetic techniques with direct glaciological methods (stake-based measurements).

The geodetic method involves repeated acquisition of high-resolution Digital Elevation Models (DEMs) through dGPS (differential global positioning system) survey. By comparing DEMs across different years, glacier mass balance is calculated. The direct glaciological method involves the installation of stakes on the glacier surface. These stakes are measured to determine annual melt rates by calculating the changes in stake height and snow thickness with snow and ice densities (Tshering & Fujita, 2016)

According to recent measurements from the NCHM, glaciers such as Gangju La have shown an average annual mass loss exceeding $-2198.359 \pm 265.74 \text{ mm w. e. a}^{-1}$ to $-2422.864848 \pm 197.036 \text{ mm w. e. a}^{-1}$, consistent with trends observed in the central and eastern Himalayas (Brun et al., 2017; Wagnon et al., 2023). Glacier mass balance is widely recognized as one of the most sensitive and direct indicators of climate change (Oerlemans, 2001). Monitoring this parameter is therefore critical for understanding the health of glaciers and for developing water resource strategies in a changing climate.

In this context, Bhutan's glacier monitoring program serves as a critical pillar for shaping national policies on water security, agricultural resilience, and climate adaptation. Through the integration of scientific analysis and systematic ground-based observations, the country is progressively establishing a strong evidence base for informed decision-making. This approach not only enhances the understanding of cryospheric changes but also strengthens Bhutan's capacity to implement climate-resilient water resource management strategies.

2 Aim and Objective

The primary aim of this study is to measure glacier mass balance and terminus position of Shodug glacier through *in-situ* geodetic method and glaciological method, thereby contributing to Bhutan's long-term glacier monitoring and climate adaptation efforts.

3 Study Area

3.1 Location

A clean type Shodug Glacier is located in WGS 84/UTM zone 45N of Bhutan at 27.940 N, 89.950 E (Fig.1) with an approximate area of 3.71 km² (NCHM Annual report, 2023). It extends from an elevation of 5100 to 5500 m.a.s.l.

3.2 Accessibility

This route can be accessed via Thimphu-Barshong-Shodug, which takes three days on foot to reach the study site. It takes almost 2 hours for an average person to reach the study site from the basecamp.

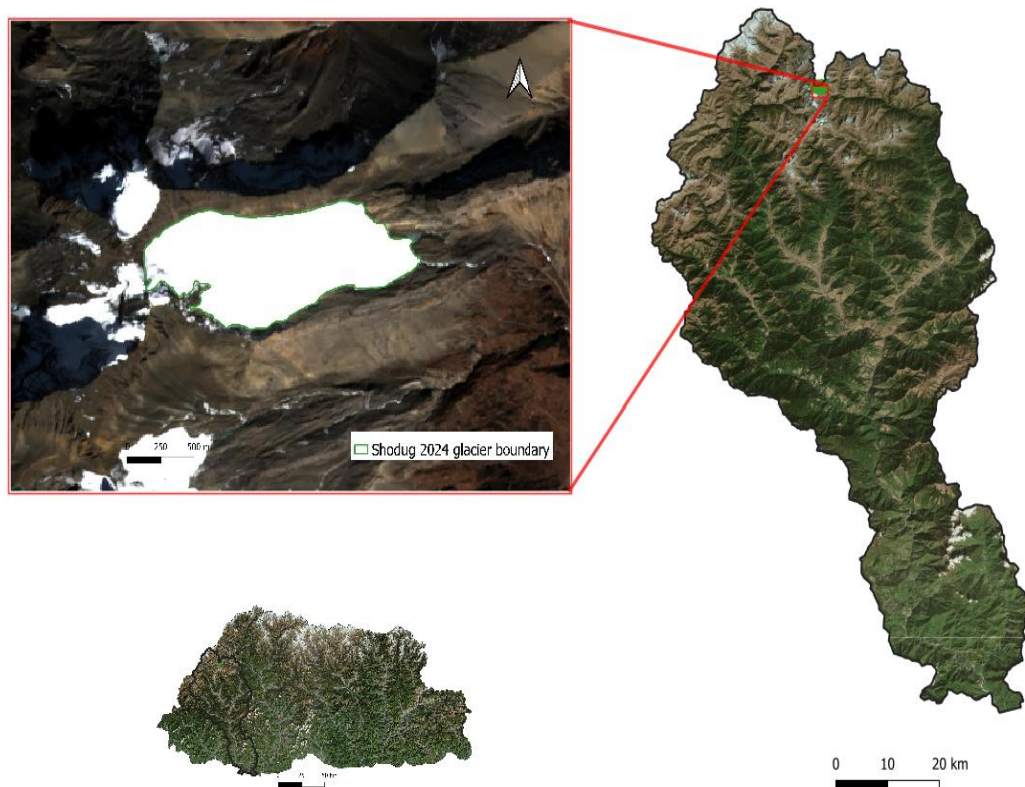


Figure 1. Location of Shodug at the headwaters of Thim Chu within the Wangchu basin (outlined in black). The background is a Sentinel-2 True Color Composite.

4 Methodology

4.1 Data Acquisition

4.1.1 In-situ Geodetic Method

During the 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 (Fig. 2B), which is at a certain distance away from the glacier snout and kept at the height of 2 m from the ground. Manually inserting the known coordinates of the base station in the TCS7 controller of Trimble R10-2, the base station was set to start for the collection of data. A rover was mounted on a backpack and the height of the rover from the ground was measured and entered in the controller accordingly. The logging distance of 1 m with a logging interval of one second was set for all survey profiles in continuous Topo mode. Glacier surface elevations data were collected (Fig.2A) by walking across the glacier following the survey track file (shape file) of the previous year. Several new points were collected for future reference.

Similarly, glacier terminus data were collected by walking on the glacier, following the snout 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. Therefore, a profile along the current terminus position is taken by walking along the terminus of the glacier and compared with the previous terminus profile line to determine the changes in terminus position of the glacier.

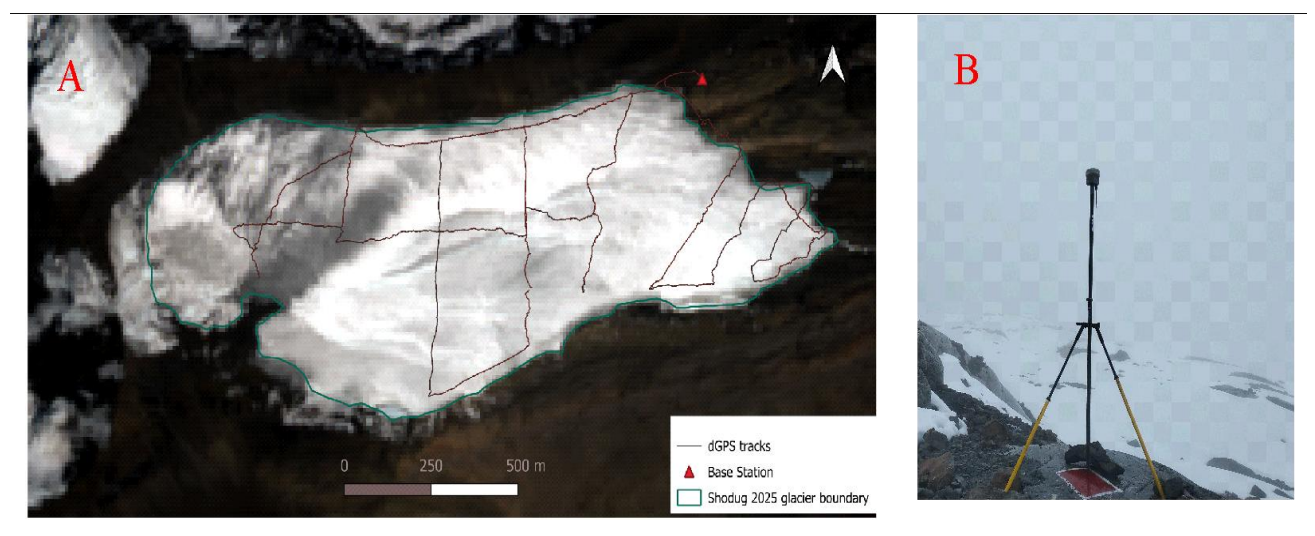


Figure 2. A) dGPS survey tracks. B) Base set up. The background is a Sentinel-2 True Color Composite. The red-triangle mark in A shows the location of the base station

4.2 Direct/Glaciological Method

Shodug Glacier's remoteness and minimal human disturbance make it ideal for direct/stake-based mass balance measurements. In May 2025, the team installed seven bamboo ablation stakes spanning the glacier's elevation gradient from the accumulation zone at the head to the lower ablation zone to capture the known dependency of melt on elevation (Tshering & Fujita, 2016) along the centerline of the glacier (Fig. 4).

Installation proceeded in four main steps:

1. **Drilling the Hole**

We used a portable drill equipped with a long auger bit to bore through the ice to a depth exceeding the previous year's maximum ablation (Fig. 3A). This ensures the stake remains anchored throughout the melt season.

2. **Positioning and Naming the Stakes**

Stakes are segmented in 1.5 m bamboo sections and pre-marked with Roman-numeral labels. Alongside the 2024 stake, a new 2025 stake was installed at the same elevation band to maintain continuity. Exact coordinates for each stake were logged with differential GPS (dGPS) for year-to-year tracking.

3. **Recording Initial Measurements**

Immediately after installation, we recorded the stake's height above the snow surface and its dGPS position in the field notebook (Fig.3B). These baseline readings are critical for calculating annual surface lowering during follow-up visits.



Figure 3. A) Drilling hole. B) Recording measurements for the discovered old stake and the newly installed stake.

Over the next glaciological year, seasonal surveys will measure the exposed stake length at each site, directly yielding cumulative ablation in millimeters water equivalent. These point-scale observations will later be interpolated across the glacier surface and compared with geodetic mass balance estimates.

4.3 Naming Conventions:

Each stake segment is uniquely identified using a three-part Roman-numeral code:

- **Year of installation** (XXV for 2025)
- **Stake number**, assigned from the glacier's head downward (I, II, ... VII)
- **Segment label**, marking each 1.5 m section from top (I) to bottom (e.g., IV)

An example label for the first stake installed in 2025 with four segments is:

XXV I (I II III IV)

- **XXV** → Installation year 2025
- **I** → Stake number (uppermost)

- I II III IV → Sequential 1.5 m segments

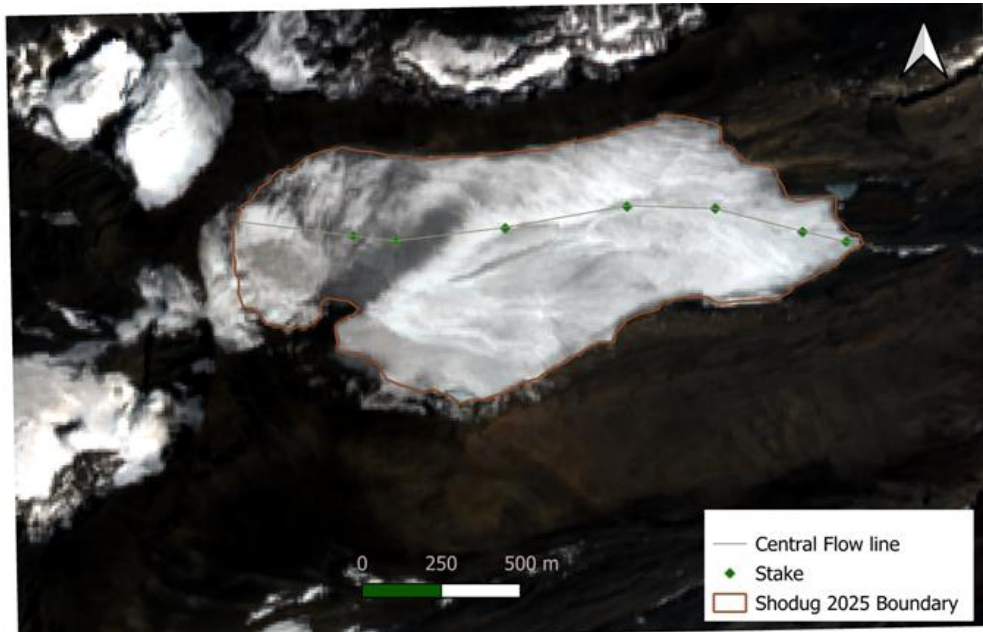


Figure 4. Stake Locations and the Central Flowline of the glacier

4.4 Data Post Processing

4.4.1 In-situ Geodetic Method

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.

This data is integrated to construct 1 m Digital Elevation Model (DEM) using inverse distance weighting (IDW) interpolation tool in ArcGIS with a search result of 0.7 m, for the year 2024-2025. 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. 5). 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 ($\text{kg m}^{-2} \text{ a}^{-1}$ 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 (m^2) 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.

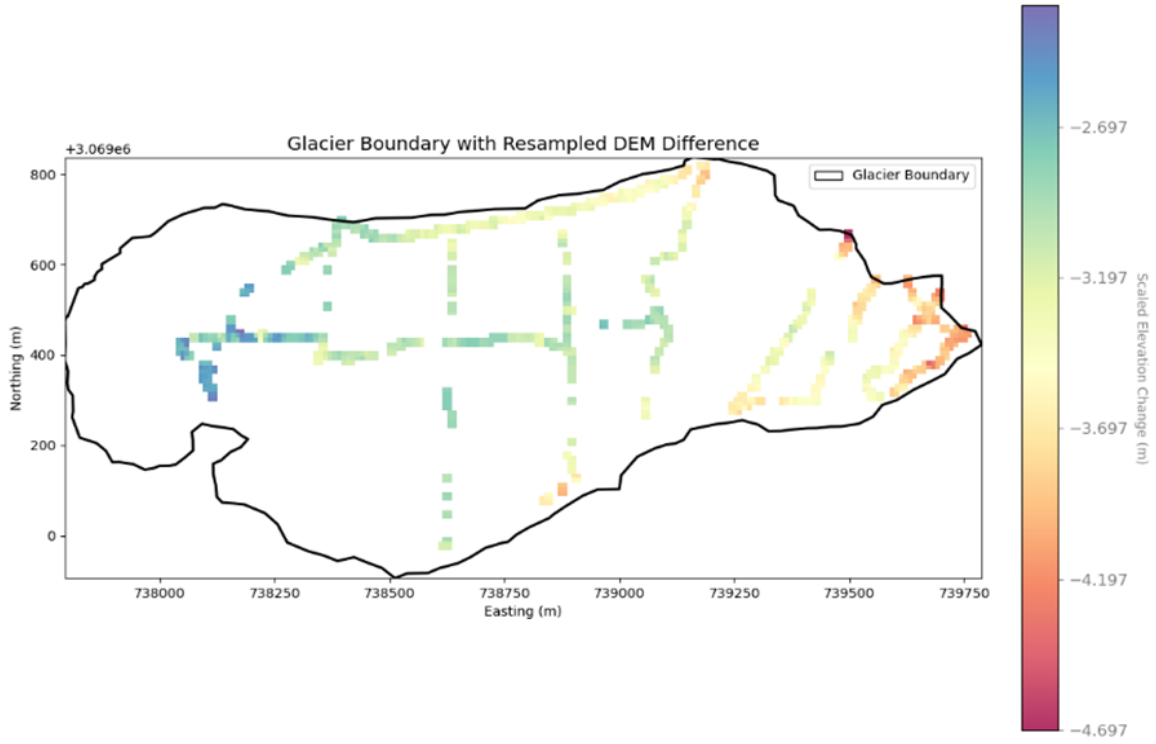


Figure 5. DEM difference calculated for the years 2024–2025. The raster values were resampled using a factor of 10 to enhance visual clarity

4.5 Direct Mass Balance

The direct annual mass balance at each stake is calculated by measuring the melt observed between the two consecutive years. Glacier Mass Balance using direct method is calculated by:

$$b_d = \frac{\Delta h_d \rho_i + (s_{t1} + s_{t2})(\rho_s - \rho_i)}{(t1 - t2)}$$

Where Δh_d is the difference in stake height between years $t1$ and $t2$ (m). To account for the insufficiency of the stakes to calculate the average mass balance within a 50 m altitude band, linear regression is computed to obtain the mass balance at each 50 m altitude band. The mean value of Glacier Mass Balance changes is calculated at a 50 m altitude band, according to the assumption that pixels at an altitude interval usually experience similar elevation changes (Berthier and others, 2004; Gardelle and others, 2012). Based on this assumption, mean glacier mass balance values were estimated for each 50-meter band using the regression outputs.

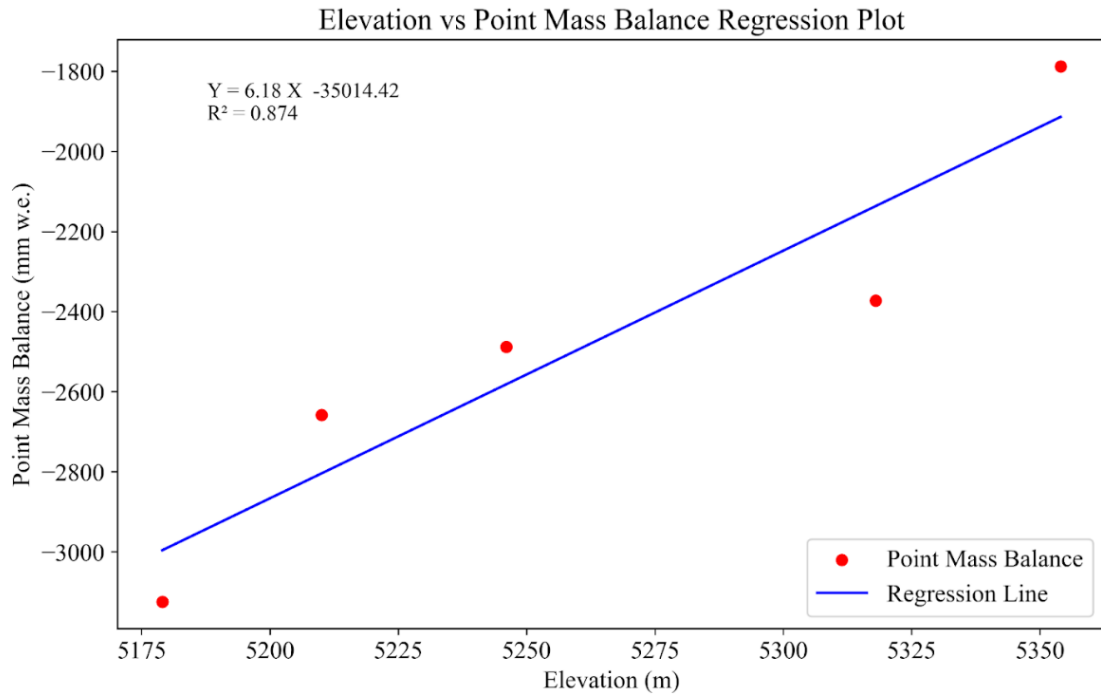


Figure 6. Elevation-Point Mass Balance Regression Plot

5 Hypsometry

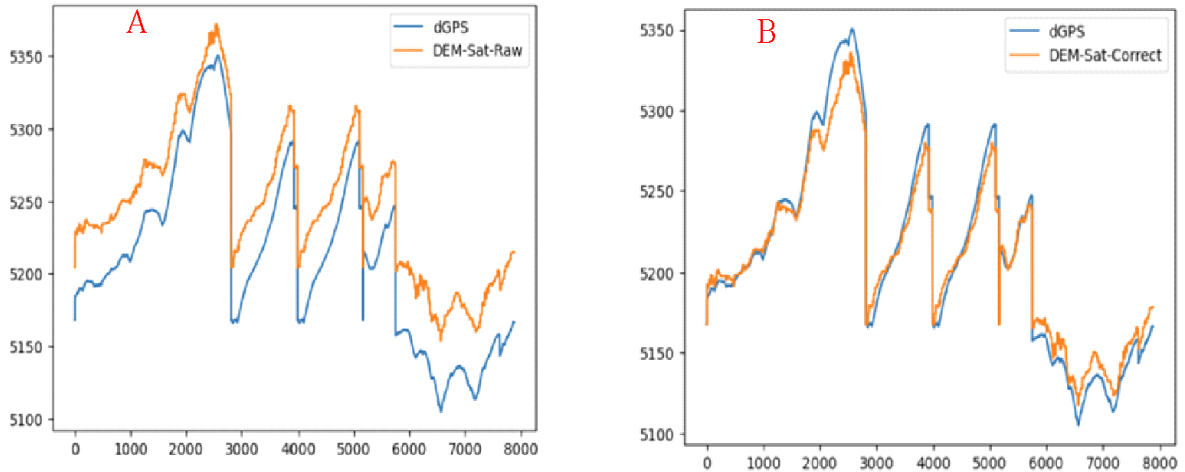


Figure 7. A) Observed Difference in the field-based surface elevation and the Satellite obtained Elevation. B) Corrected DEM, accurately in aligned with the field obtained data)

To delineate the glacier boundary, a recently available free Sentinel-2 image from 2025 with a spatial resolution of 10 m was used. The glacier terminus was mapped using data collected during the field survey. A 1-meter resolution DEM, 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. 7A). Finally, a correction factor was applied to lower down the DEM surface elevation and match with the field-based surface elevation (Fig. 7B) and were used for the calculation of area-averaged glacier mass balance. The extracted hypsometry within the 50 m elevation band for 2024 and 2025 is shown in figure 8.

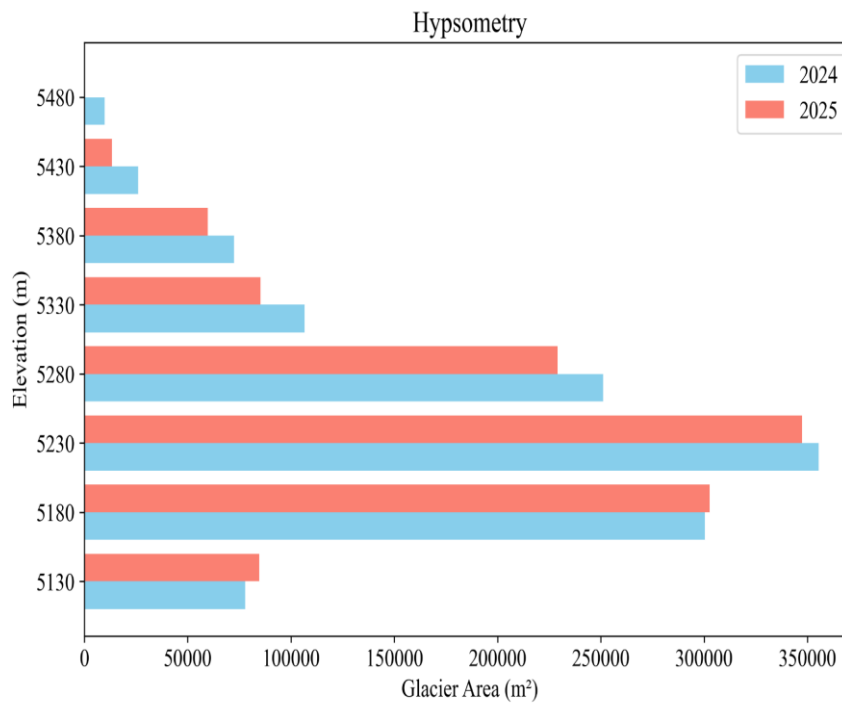


Figure 8. Shodug glacier hypsometry for the year 2024 and 2025

6 Result

6.1 Geodetic Mass Balance

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 2024 and 2025. By comparison, the 2024 GMB gave an annual mass balance of $-1897.6 \text{ mm w. e. a}^{-1}$, so Shodug Glacier lost an additional $\sim 893.5 \text{ mm w. e. a}^{-1}$ in 2025.

Table 1. Shodug glacier Mass Balance

Elevation (m)	Average Elevation difference	Average Area 2024- 2025 (m ²)	Point Mass Balance mm w.e.a ⁻¹	Area Average Mass balance mm w.e.a ⁻¹
5105-5155	-3.683449	81204.24	-3307.09	-231.34
5155-5205	-3.43721	301525.15	-2884.33	-749.2
5205-5255	-3.190971	351448.21	-2843.44	-860.87
5255-5305	-2.944732	240061.87	-2815.82	-582.32
5305-5355	-2.698492	95914.84	-2366.63	-195.55
5355-5405	-2.452253	66028.64	-2263.44	-128.75
5405-5455	-2.206014	19656.41	-2067.53	-35.01
5455-5505	-1.959775	4988.08	-1871.63	-8.04
Glacier Mass Balance				- 2791.08

6.2 Direct Glaciological Mass Balance

Table 2 summarizes the point and area-averaged mass balance derived from stake measurements. The glacier-wide annual mass balance derived from stake measurements was calculated to be $-2608.492 \text{ mm w. e. a}^{-1}$. The observed pattern of ablation supports the geodetic findings, confirming increased melt rates at lower elevations.

Table 2. Direct/glaciological Mass Balance

Elevation(m)	Average Area 2024-2025 (m ²)	Point Mass Balance mm w.e.a ⁻¹	Area Average Mass balance mm w. e. a ⁻¹
5105-5155	81204.24	-3298.531959	-230.744689
5155-5205	301525.15	-2989.410209	-776.499873
5205-5255	351448.21	-2680.288459	-811.475119
5255-5305	240061.87	-2371.166709	-490.362905
5305-5355	95914.84	-2062.044959	-170.379084
5355-5405	66028.64	-1752.923209	-99.707442
5405-5455	19656.41	-1443.801458	-24.448042
5455-5505	4988.08	-1134.679708	-4.875722
Area-averaged glacier Mass Balance			-2608.492

From the point mass balance observed for both dGPS and direct glacier mass balance studies, 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 Shodug Glacier exhibits a negative mass balance, consistent with the trends observed in the two other benchmark glaciers. Between 2024 and 2025, it experienced a mass loss of -2791.08 mm w. e. a⁻¹ (Table 1) and -2608.492 mm w. e. a⁻¹ (Table 2) for *in-situ* geodetic and the direct method respectively, over a total surface area of 1.16 km². The difference in glacier mass balance between geodetic and glaciological method well agrees with earlier trends observed, with the higher values in case of geodetic and less in case of glaciological method.

In addition, the glacier terminus retreated by 15.07 m. To account for spatial variability along the terminus front, multiple transect lines were drawn, and the average retreat was computed to determine the final terminus recession (Fig. 8).

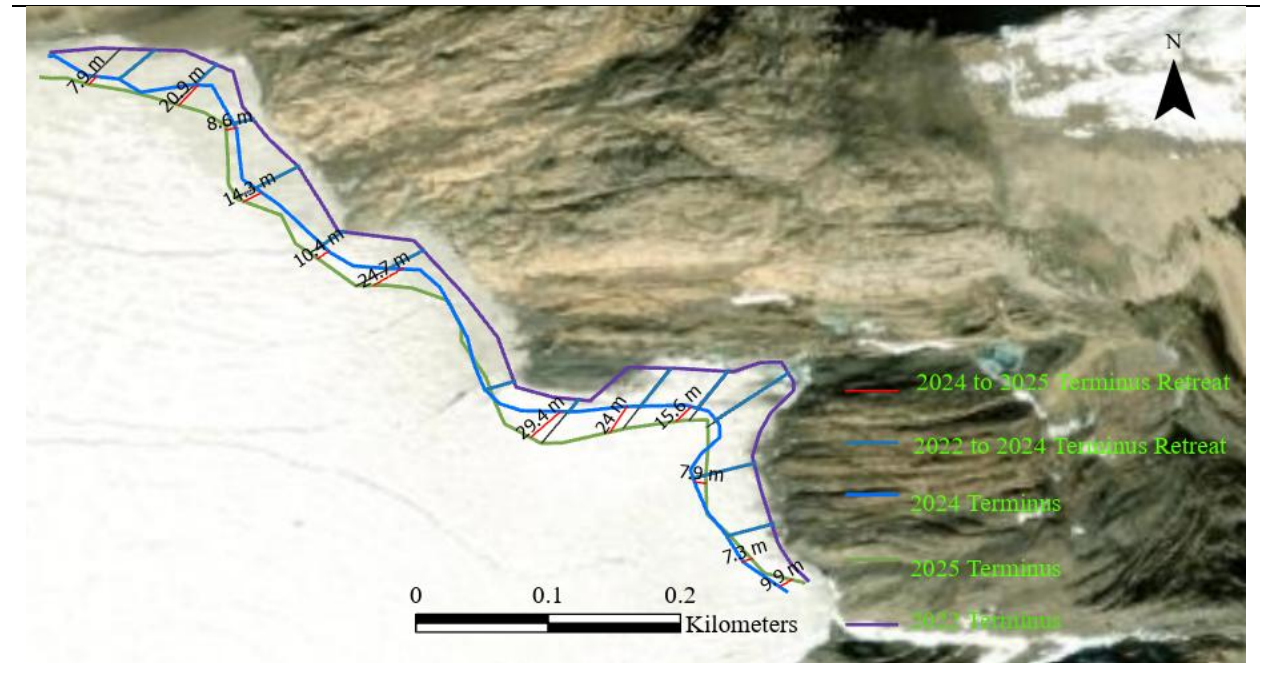


Figure 9. Shodug Terminus recession over the time

7 Uncertainty Estimation in Area-Average Mass Balance

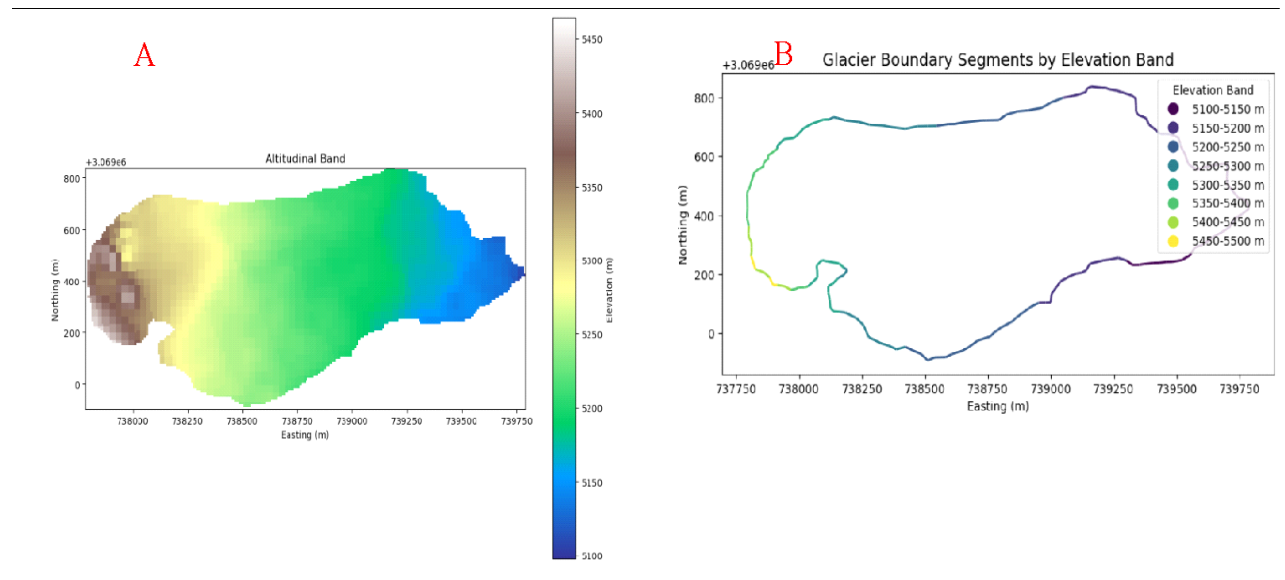


Figure 10. A) Altitudinal band. B) Perimeter over different elevation band

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 Fig. 10A.
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 $\pm$ 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:

$$dA_Z = 0.5 \times \text{pixel resolution} \times \text{perimeter at each 50 m band}$$

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.9b).

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:

$$db_z = \sqrt{\frac{1}{N} \sum (b_z - \bar{b}_z)^2}$$

Where N is the number of elevation bands and $\bar{b}_z$ is the mean mass balance.

Combining DEM-differencing noise, boundary-delineation error, and snow-depth measurement error:

- **Ice-surface elevation uncertainty** ($\Sigma\sigma_{ice, i}$) = 355.55 mm w. e. a^{-1}
- **Snow-depth uncertainty** ($\Sigma\sigma_{snow, i}$) = 425.55 mm w. e. a^{-1}

Averaging these two independent error sources yields an overall uncertainty of:

$$\sigma_{total} = \frac{355.55 + 425.55}{2} = 390.55 \text{ mm w. e. } a^{-1}$$

Therefore the 2025 mass-balance uncertainty: $\pm 390.55 \text{ mm w. e. } a^{-1}$

This means the annual area-average mass balance for the glacier in 2025 is: **-2791.08 $\pm$ 390.55 mm w.e. a^{-1}** , indicating that the actual value may vary by this margin due to the cumulative uncertainties discussed above.

8 Discussion

The glacier change assessment of Shodug Glacier over the 2024–2025 monitoring period highlights clear signs of mass loss and dynamic retreat in response to ongoing climatic stress. Using high-precision RTK GNSS data and Inverse Distance Weighting (IDW) interpolation, surface elevation differences were calculated and applied to generate digital elevation models (DEMs) that allowed for accurate estimation of glacier-wide geodetic mass balance. 2025's –2791 mm w. e. exceeds 2024's –1897.6 mm by ~47 % (–893.5 mm), indicating a distinct increase in net ablation. This loss is most pronounced at lower elevations, where surface melting dominates due to increased exposure to warmer atmospheric conditions. These findings are consistent with the results of Tshering and Fujita (2016), who observed markedly enhanced mass loss at lower elevations of benchmark glaciers in the Bhutan Himalaya, highlighting elevation-dependent sensitivity to climatic warming. Their work also noted that the mass loss was dominated by melt at the glacier tongue, with minimal input from snowfall in lower accumulation zones. Regional meteorological records for spring–summer 2025 show

above-average air temperatures and below-normal snowfall, reinforcing the interpretation from the 2024 report that temperature and accumulation anomalies drive year-to-year variability.

The magnitude of ice loss observed at Shodug Glacier is consistent with other benchmark glaciers in Bhutan, such as Gangju La and Thana, and aligns with regional estimates across the eastern Himalaya. Previous studies (e.g., Brun et al., 2017; Wagnon et al., 2023) have reported annual mass balances ranging between -0.4 and -1.2 m w. e., with clean, debris-free glaciers such as Shodug falling toward the higher end of this range. These results highlight the sensitivity of small, low-lying valley glaciers to even slight shifts in climatic conditions.

To ensure the robustness of these findings, uncertainty analysis was conducted following the established methodology of Tshering and Fujita (2016). This approach integrates cumulative potential errors arising from GNSS measurement precision, glacier boundary delineation, elevation interpolation, and assumed ice density, thereby providing a transparent and consistent quantification of uncertainty. Importantly, the total uncertainty of ± 390.55 mm w. e. a^{-1} observed in this study lies well within the range reported by Tshering and Fujita (2016), confirming the comparability and reliability of the results. This consistency strengthens confidence in the reported mass balance estimates and supports their use as a credible benchmark for ongoing and future glacier monitoring efforts in the Bhutan Himalaya.

In addition to surface thinning, the terminus of Shodug Glacier exhibited a horizontal recession of approximately 15.07 m during the assessment period. This observed retreat corresponds with documented terminus shifts in comparable glaciers across Bhutan, such as Thana and Gangju La, which have shown annual retreats in the range of 25 to 60 m. The spatial variability along the terminus front at Shodug—where the central section showed the greatest recession—is likely influenced by variations in local slope, ice thickness, and surface energy balance. Such differential retreat patterns are supported by previous research (Bhambri et al., 2011; Dehecq et al., 2015) that link the geometry and dynamics of the glacier tongue to localized responses to warming.

Overall, the findings from Shodug Glacier provide further evidence of sustained glacier recession in the Bhutan Himalaya, driven by rising temperatures and potential changes in precipitation regimes. The consistency of these results with regional trends emphasizes the urgency of maintaining long-term glacier monitoring initiatives, particularly in light of Bhutan's heavy reliance on cryosphere-fed river systems for hydropower and water resources.

As a designated benchmark glacier, Shodug offers critical insights into the behavior of clean glaciers under changing climatic conditions, and its continued observation contributes to the regional understanding promoted by broader frameworks such as the Third Pole Monitoring Programme and the HKH Cryosphere Monitoring Initiative.

9 Conclusion

The mass balance estimate of Shodug Glacier in 2025 reveals the existence of a persistent and growing negative balance in the glacier and the losses across the glacier (using the geodetic estimates) with the values of $-2791.08 \text{ mm w. e. a}^{-1}$ and (with the help of stake estimates) $-2608.492 \text{ mm w. e. a}^{-1}$. Both methods strengthen the trend of stronger ablation at lower elevation which shows glaciers are sensitive to climatic warming. In comparison to 2024, net mass loss has increased subsequently and it is fueled by the abnormally high temperatures and reduced snowfall during the accumulation season. The observed 15.07 m terminus retreat is additional evidence of dynamic thinning particularly in the midpoint flowline. The results indicate that there is extreme necessity to maintain a long-term glacier monitoring since Glaciers are important to the water security of Bhutan and hydrological downstream processes. Future monitoring of glaciers and planning of climate adaptations will benefit on its validity and reliability due to the success achieved in the integration of the geodetic and direct glaciology approaches.

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