First Seasonal Glacier Mass Balance Measurement in Bhutan: A Joint Initiative of NCHM and ICIMOD

Technical Report (Version 1)

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Contents

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1. Background

Bhutan has approximately 700 glaciers, covering an area of around 630 km^2. These glaciers are a vital water resource providing water to the downstream communities and contributing to the base flow of rivers serving Bhutan's major hydropower plants. In addition, glaciers in Bhutan are sensitive to changes in the Indian Monsoon and Westerlies systems. Provided glaciers in Bhutan are crucial for both hydrological and climate studies, National Centre for Hydrology and Meteorology (NCHM) benchmarked a network of three glaciers for long term monitoring and annual mass balance studies viz. Gangju La, Thana, and Shodug glaciers.

NCHM has been collecting annual glacier mass balance data from its benchmark glaciers since 2012. Annual mass balance reflects the net gain or loss of ice over a hydrological year and is a crucial indicator of glacier's long-term response to climate variability and change. Seasonal mass balance on the other hand can capture the seasonal dynamics of glacier change, specifically winter accumulation and summer ablation, which are essential for understanding short-term glacier dynamics. The seasonal-scale monitoring is particularly important because glaciers in Bhutan are strongly influenced by two contrasting climate systems: the Indian Summer Monsoon, which brings both melt and accumulation during summer, and the Winter Westerlies, which deliver snowfall during winter. These dual systems create a complex seasonal signal that annual measurements alone cannot resolve. However, Bhutan lacks a seasonal mass balance monitoring program. In 2025, NCHM and ICIMOD signed a joint agreement to conduct seasonal glacier mass balance monitoring, complementing NCHM's ongoing annual measurements. Among the three benchmark glaciers, the Shodug glacier, located at the headwaters of Thim Chhu, has been chosen as a priority site for expanding the monitoring program in partnership with ICIMOD. Shodug glacier has been monitored annually by NCHM since 2022 and is relatively more accessible from Thimphu compared to the other sites, making it an ideal candidate for additional field campaigns.

By measuring glacier mass gain or loss across individual seasons, the initiative aims 1) to generate deeper insights into the processes driving seasonal glacier change in Bhutan; 2) strengthen glacier dynamics research and improve understanding of how Bhutanese glaciers respond to the region's unique monsoon–westerly climate regime. This field report presents methodologies adopted for summer glacier mass balance measurement and summarizes the preliminary results from the autumn field campaign 2025.

2. Objectives

The objectives of the fieldwork were:

- To expand NCHM's existing annual glacier mass balance program by adding seasonal-scale measurements on Shodug Glacier.
- To quantify winter accumulation and summer ablation and determine how each season contributes to the overall annual mass balance.
- To examine the relative influence of the Indian Summer Monsoon and Winter Westerlies on glacier mass gain and loss.

- To generate high-quality seasonal data needed for energy balance and glacier evolution modelling.
- To provide improved seasonal melt estimates that feed into rivers and water resources.
- To operationalize the joint NCHM–ICIMOD agreement through coordinated seasonal field campaigns.

3. Field site

Shodug glacier is a clean cirque-type glacier located in the headwaters of Thim Chu river (Figure 1 & 2). The meltwater from the glacier directly contributes to the base flow of Thim Chu river all seasons. The area of the glacier is around 3.71 km^2 with a gentle elevation ranging from 5100 to 5500 m. The base camp is located in Pam Luma (4700 m) which takes around two hours to reach the glacier. There are seven glacier stakes, differential Global Positioning System (dGPS) base station, and automatic weather station (AWS) installed in April 2024.

Figure 1. Upstream view of Shodug glacier taken in November 2025.

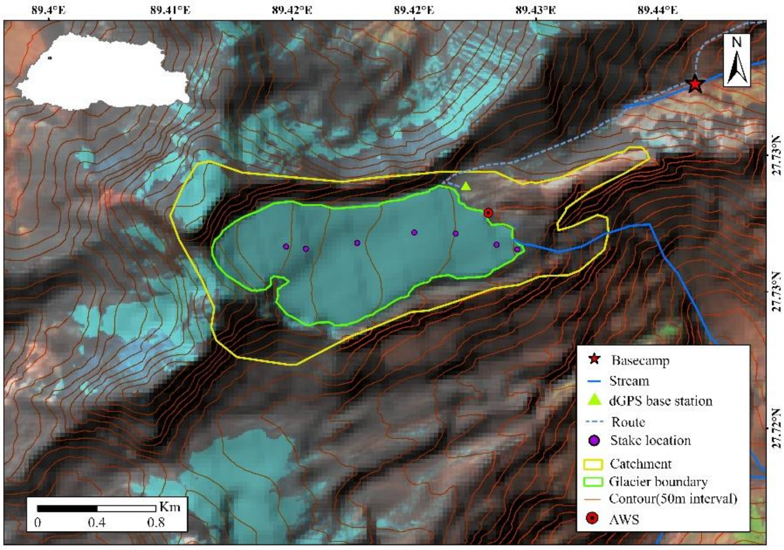

Figure 2: Map showing the location of Shodug glacier. The background is median Sentinel-2 False Colour Composite image acquired in September 2025.

4. Methodology

4.1 In-situ geodetic method

The dGPS points of the glacier surface in Autumn 2025 were collected using a calibrated Trimble R10-2 RTK GNSS. The dGPS system can collect glacier surface points with centimeter-level accuracy in both horizontal position and elevation. The base station was set on a previously marked point, 2 m above ground, with known coordinates entered into the TCS7 controller. A rover, mounted on a backpack, recorded data at 1 m interval with 1s logging in continuous Topo mode, following previous year's survey track (Figure 3). A same approach was followed while collecting dGPS points in Spring 2025.

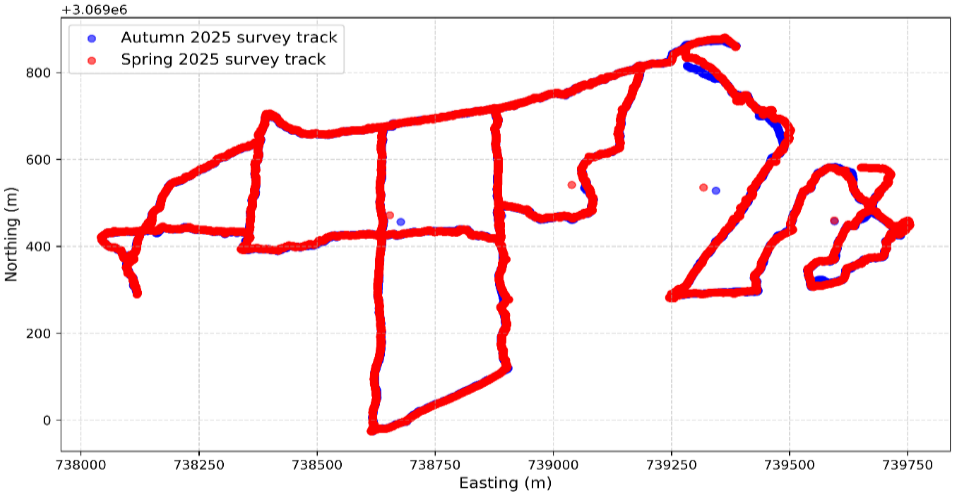

Figure 3: dGPS survey tracks (points) on Shodug glacier in Spring and Autumn 2025.

4.2 Snow depth measurement

During the field visit, glacier surface was fully covered by snow bought by Cyclonic Storm Montha from 26 October – 1 November 2025. As a result, five glacier stakes towards the accumulation zone were fully submerged by snow. To determine the impact of this unusual snow cover on the glacier health, we installed snow stakes in close proximity to the glacier stakes. Snow depth was measured within a 1m x 1m square sampling plot (Figure 4). Within the square sampling plot, nine snow-depth measurements were taken: one at each corner, one at the midpoint of each side, and one at the centre. All measurements were obtained by inserting a probe vertically into the snow layer. A 50 x 50 cm sawdust surface marker was used to asses snow accumulation and melt during winter.

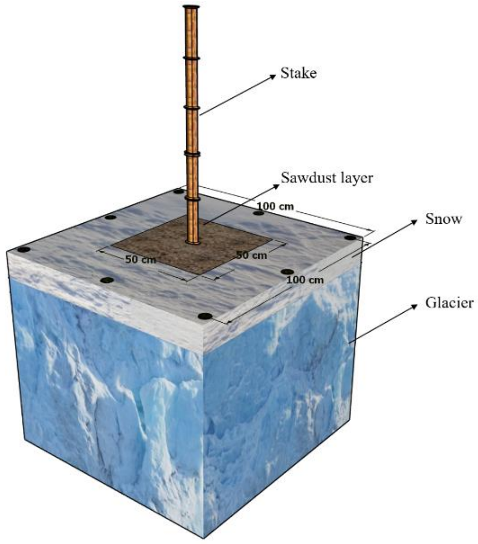

Figure 4: Setup of snow stake and 50 x 50 cm wide sawdust surface marker to monitor seasonal snow melt and accumulation. Black dots along the edges represent sampling locations for snow depth.

5. Data post processing

5.1 In-situ geodetic method

The dGPS points from the Autumn 2025 survey were used as reference locations, and each Spring 2025 point was matched to its nearest Autumn point within a three-meter distance. Once matched, elevation change was calculated by subtracting the Spring elevation from the corresponding Autumn elevation, providing a point-wise estimate of seasonal surface elevation change. To calculate elevation change within each 50-m altitudinal band, all points falling inside a given elevation band were grouped together, and the available elevation-change values within each band were averaged to obtain a representative mean elevation change for that altitude range. Using these band-averaged values, a Theil–Sen regression line was then fitted to predict the elevation change across bands (Figure 5), and the resulting regression-derived elevation change values (Δh_s) were used for the mass balance estimation.

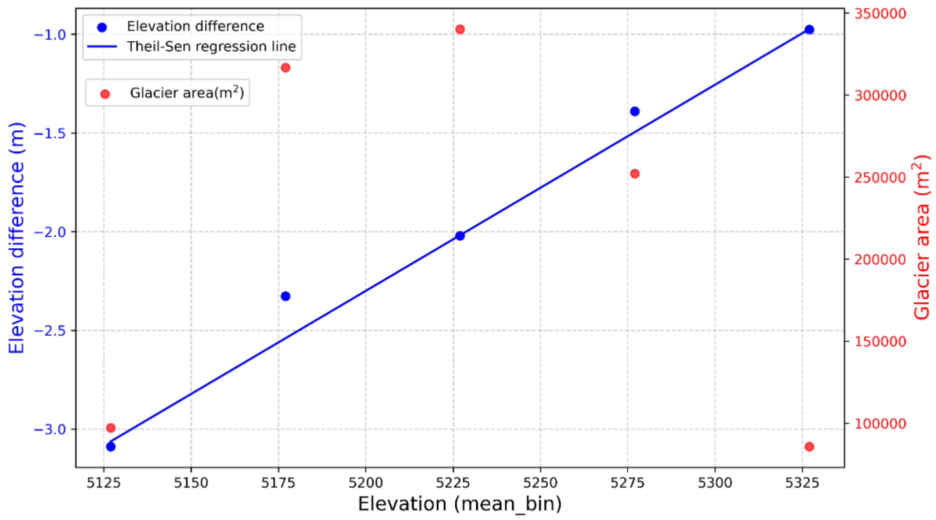

Figure 5. Band-averaged elevation change values and a Theil–Sen regression line for predicting elevation change across bands for the mass balance estimation.

The seasonal specific mass balance was calculated as:

$$b_s = \Delta h_s \rho_i \; + \; (S_{t2} - S_{t1})(\rho_s - \rho_i)$$

where b_s is the summer mass balance at a point within 50-m altitudinal band (kg m^{-2} equivalent to mm w.e.); Δh_s is the summer elevation change (m) obtained from differenced dGPS measurements and a Theil–Sen regression equation; ρ_s and ρ_i are the density of snow and ice (kg m^{-3}) assumed to be 400 and 880 respectively. S_{t2} *and* S_{t1} are thickness of snow (m) in November 2025 and April 2025 respectively.

Finally, the area averaged summer mass balance ($\overline{b_s}$mm w.e.) was estimated by:

$$\overline{b_s} = \frac{\sum A_z b_s}{A_T}$$

where A_z and A_T are glacier areas within 50 m altitude band and total area (m^2) respectively. b_s is the specific mass balance within 50 m altitude band.

5.2 Hypsometry

We delineated the glacier boundary using Sentinel-2 imagery (10 m spatial resolution) to support area-wide estimation of summer glacier mass balance. A median composite of images acquired between September and October 2024 was generated to minimize cloud cover, and the glacier outline was manually digitized from this composite. Glacier surface elevations were obtained from the Shuttle Radar Topography Mission (SRTM) DEM. Because the SRTM DEM represents conditions from the year 2000, we applied a vertical bias correction using our Autumn 2025 dGPS) measurement (Figure 6). SRTM elevation values were extracted at the precise coordinates of the dGPS points. For each point, the elevation difference (Δh) between the SRTM DEM and the dGPS measurement was computed as:

$$\Delta h = h_{SRTM} - h_{dGPS}$$

The mean absolute difference across all points was taken to represent the systematic vertical offset of the DEM. This mean bias was subtracted from every pixel of the original SRTM DEM to produce a bias-corrected elevation model. The corrected SRTM DEM was subsequently used to derive glacier hypsometry in 50 m elevation bands for mass-balance calculations (Figure 7).

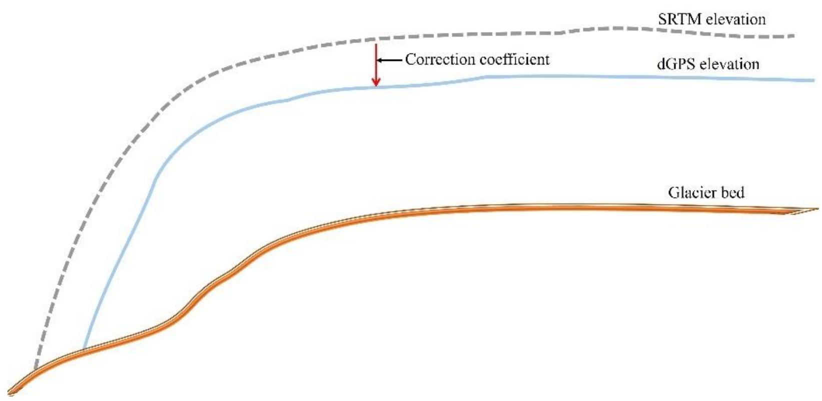

Figure 6. Schematic for elevation difference between SRTM DEM and dGPS and vertical bias correction of the SRTM DEM.

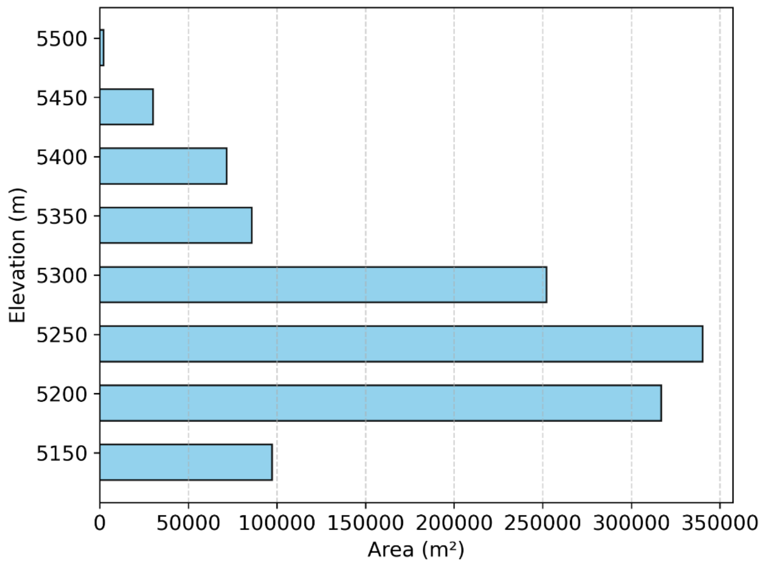

Figure 7. Distribution of glacier area with respect to elevation within a 50 m altitude band derived from a bias corrected SRTM DEM.

6. Photographic documentation

To ensure consistent site documentation, snow stakes were photographed with clearly visible landmarks (see Annex).

7. QField App

The QField mobile application (https://qfield.org/) was utilized for field navigation and for tracing the old stakes.

8. Result

The total number of matched dGPS points between Spring and Autumn 2025 was around 17769 (N). The glacier surface lowering was more negative towards the tongue compared to the upstream glacier part (Figure 8). The mean glacier surface lowering in summer 2025 was around 2.09 m (Figure 9). The summer glacier mass balance was negative (–1876.70 mm w.e.). The average snow depth bought by the Cyclone Montha was around 0.94 m. The SRTM DEM bias correction factor was 10.88 m.

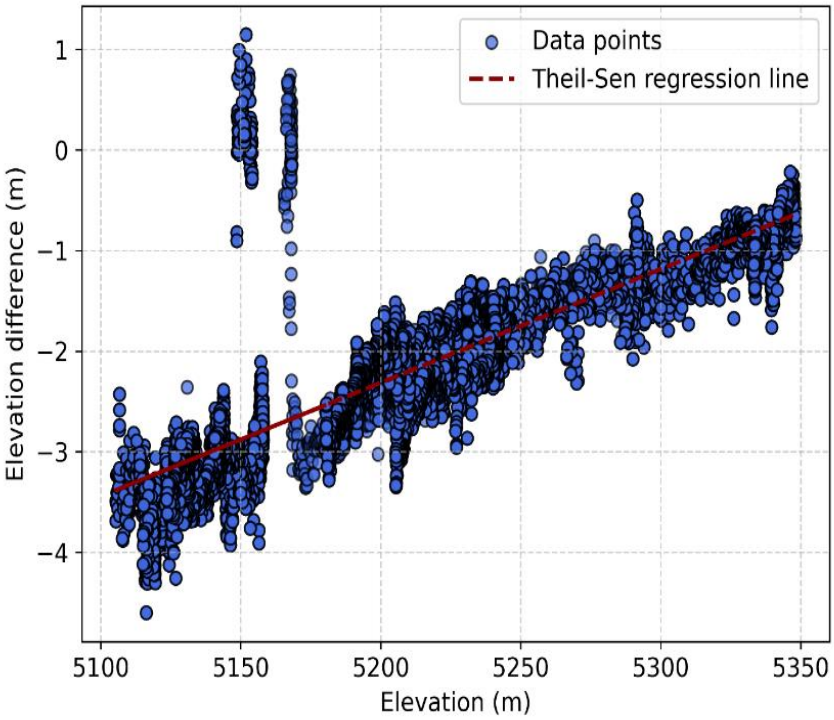

Figure 8: Glacier surface elevation change between Spring and Autumn 2025 generated using dGPS elevation differencing.

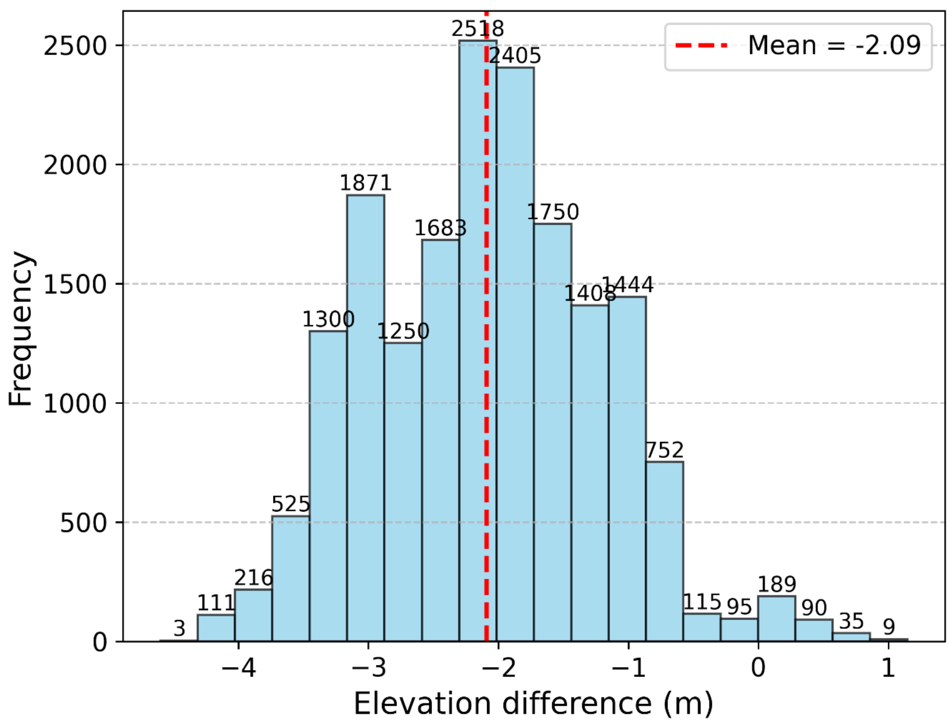

Figure 9: Distribution of glacier surface elevation change between Spring and Autumn 2025.

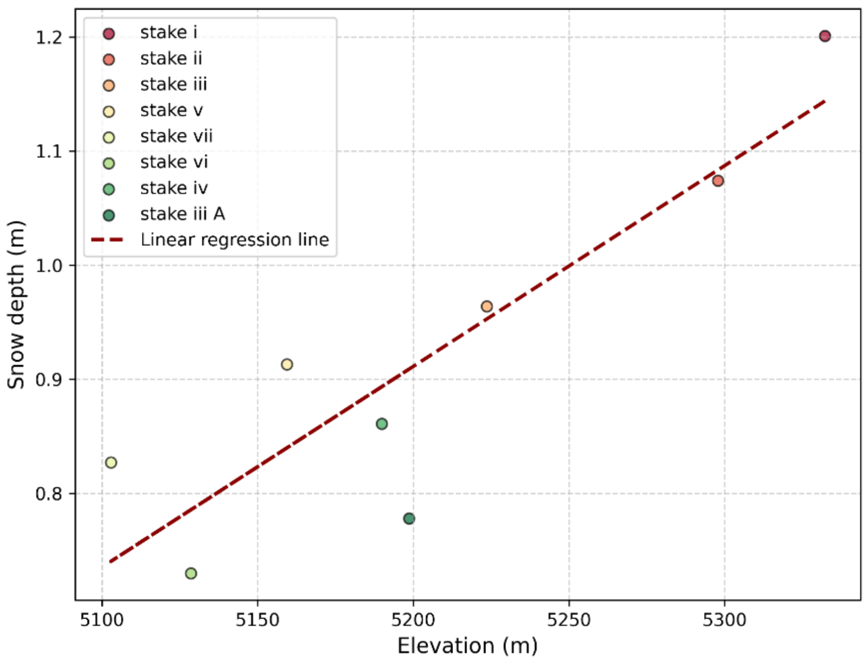

Figure 10: Snow depth distribution across elevation measured at stake locations following Cyclone Montha.

Annex

Table 1. Elevations from Spring and Autumn 2025 and respective snow depths.

sl.no	Stake	Latitude	Longitude	Spring elevation	Spring snow depth (m)	Autumn elevation	Autumn snow depth (m)
1	XXV I	3069447	738173.37	5333.126	0.63	5332.193	1.20
2	XXV II	3069432	738307.85	5304.789	0.61	5297.791	1.07
3	XXV III	3069472	738653.74	5227.191	0.44	5223.612	0.96
4	XXV IV	3069542	739038.85	5193.664	0.54	5189.873	0.86
5	XXV V	3069535	739318.03	5164.619	0.39	5159.434	0.91
6	XXV VI	3069460	739594.50	5130.89	0.46	5128.533	0.73
7	XXV VII	3069428	739732.87	5106.106	0.43	5102.864	0.83

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 1

Observer: Tshewang Jamtsho **Agency**: NCHM **Date**: 10-11-2025

Sl,No	Parameter Name	Descriptions	Unit
1	Stake ID (Field ID)	Near stake 1	
2	Latitude	27.7024	DD,EPSG:4326
3	Longitude	90.5281	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5332	m
5	Stake Status (Intact / Titled / Broken / Replaced)		
6	Exposed stake length above current surface	60	cm
7	Snow depth at stake (if snow present)	120, 120, **120,** 120, 120, 120, 120, 120, 120	cm
8	Segment length	1.57	m
9	Overlap between stake segments		cm
10	Total number of visible segments		count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] Seasonal [Yes]	
13	This reading Date/time	10-11-2025	dd-mm-yyyy
14	Photographs	Yes [ ] No [ ] Name &Affiliation: T.Jamtsho	
15	Remarks (incl. melt features, slush, stake tilt, hazards, crevasses)	• Photograph was taken towards the NW (319^0) direction	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 2

Observer: Tshewang Jamtsho **Agency**: NCHM **Date**: 08-11-2025

Sl,No	Parameter Name	Descriptions	Unit
1	Stake ID (Field ID)	Near stake 2	
2	Latitude	27.6937	DD,EPSG:4326
3	Longitude	91.6304	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5298	m
5	Stake Status (Intact / Titled / Broken / Replaced)	Glacier stake invisible due to snow cover	
6	Exposed stake length above current surface	63	cm
7	Snow depth at stake (if snow present)	104, 104, 112, 107, 108, **108**, 108, 108, 108	cm
8	Segment length	160	m
9	Overlap between stake segments		cm
10	Total number of visible segments	Only one segment installed	count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] Seasonal [yes]	
13	This reading Date/time	08-11-2025	dd-mm-yyyy
14	Photographs	Yes [No [ ] Name & Affiliation: T.Jamtsho	
15	Remarks (incl. melt features, slush, stake tilt,	• Centroid snow depth measurement (bold)	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 3

Observer: Tshewang Jamtsho **Agency**: NCHM **Date**: 08-11-2025

Sl,No	**Parameter Name**	**Descriptions**	**Unit**
1	Stake ID (Field ID)	Near stake 3	
2	Latitude	27.7028	DD,EPSG:4326
3	Longitude	90.5348	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5223	m
5	Stake Status (Intact / Titled / Broken / Replaced)		
6	Exposed stake length above current surface	60	cm
7	Snow depth at stake (if snow present)	96, 100, 94, 100, 98, **100**, 94, 93, 93	cm
8	Segment length	1.6	m
9	Overlap between stake segments		cm
10	Total number of visible segments		count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] Seasonal [yes]	
13	This reading Date/time	08-11-2025	dd-mm-yyyy
14	Photographs	Yes [● No [ ] Name & Affiliation: T.Jamtsho	
15	Remarks (incl. melt features, slush, stake tilt,	• Only one snow stake segment installed	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID: **] Form No**: 4

Observer: Tshewang Jamtsho   **Agency**: NCHM   **Date**: 08-11-2025

Sl,No	Parameter Name	Descriptions	Unit
1	Stake ID (Field ID)	Stake 3 A	
2	Latitude	27.7033	DD,EPSG:4326
3	Longitude	90.5377	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5199	
5	Stake Status (Intact / Titled / Broken / Replaced)		m
6	Exposed stake length above current surface	84	cm
7	Snow depth at stake (if snow present)	76, 79, 79, 79, 79, 79**, 78,** 76, 77, 78	cm
8	Segment length	1.59	m
9	Overlap between stake segments		cm
10	Total number of visible segments		count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] seasonal [yes]	
13	This reading Date/time	08-11-2025	dd-mm-yyyy
14	Photographs	Yes [●No [ ] Name & Affiliation: T. Jamtsho	
15	Remarks (incl. melt features, slush, stake tilt,	• Only one snow stake segment installed	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 5

Observer: Dr. Sonam Wangchuk **Agency**: ICIMOD **Date**: 08-11-2025

Sl,No	Parameter Name	Descriptions	Unit
1	Stake ID (Field ID)	Near stake 4	
2	Latitude	27.7036	DD,EPSG:4326
3	Longitude	90.54	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5190	m
5	Stake Status (Intact / Titled / Broken / Replaced)		
6	Exposed stake length above current surface	82	cm
7	Snow depth at stake (if snow present)	80, 89, 93, 91, 82, **86**, 90, 82, 82	cm
8	Segment length	1.59	m
9	Overlap between stake segments		cm
10	Total number of visible segments	Only one snow stake segment installed	count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] seasonal [yes]	
13	This reading Date/time	08-11-2025	dd-mm-yyyy
14	Photographs	Yes [ ] No [ ] Name & Affiliation: Dr. Sonam	
15	Remarks (incl. melt features, slush, stake tilt, hazards, crevasses)	• Photo taken towards the South West direction at 210^0	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 6

Observer: Dr. Sonam Wangchuk   **Agency**: ICIMOD   **Date:** 10-11-2025

Sl,No	**Parameter Name**	**Descriptions**	**Unit**
1	Stake ID (Field ID)	Near stake 5	
2	Latitude	27.7035	DD,EPSG:4326
3	Longitude	90.5426	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5159	m
5	Stake Status (Intact / Titled / Broken / Replaced)	Buried under the snow	
6	Exposed stake length above current surface	70	cm
7	Snow depth at stake (if snow present)	97, 97, 81, 101, **95**, 82, 84, 90, 95	cm
8	Segment length	1.6	m
9	Overlap between stake segments		cm
10	Total number of visible segments		count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] Seasonal [yes]	
13	This reading Date/time	10-11-2025	dd-mm-yyyy
14	Photographs	Yes [ ] No [ ] Name & Affiliation: Dr. Sonam	
15	Remarks (incl. melt features, slush, stake tilt, hazards, crevasses)	• Photograph taken towards the South West (210^0) direction at 11:12 am • Located near stake v	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 7

Observer:Dr. Sonam Wangchuk **Agency**: ICIMOD **Date**: 10-11-2025

Sl,No	Parameter Name	Descriptions	Unit
1	Stake ID (Field ID)	Stake 6	
2	Latitude	27.7034	DD,EPSG:4326
3	Longitude	90.5454	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5128	m
5	Stake Status (Intact / Titled / Broken / Replaced)	Intact (Glacier)	
6	Exposed stake length above current surface	108	cm
7	Snow depth at stake (if snow present)	70, 72, 71, 80, 80, 70, 72, 75, **67**	cm
8	Segment length	1.69	m
9	Overlap between stake segments		cm
10	Total number of visible segments		count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] Seasonal {yes]	
13	This reading Date/time	10-11-2025	dd-mm-yyyy
14	Photographs	Yes [ ] No [ ] Name & Affiliation: Dr. Sonam	
15	Remarks (incl. melt features, slush, stake tilt, hazards, crevasses)	• Photo taken towards the South West (230^0) direction • Installed near stake vi (visible); two glacier stake segments that had fallen were buried under the snow; 25 cm segment was exposed above the snow surface (Total snow depth 67cm).	

Data Collection Form for Snow Depth Measurement at Shodug Glacier [Glacier ID:] Form No: 8

Observer: Dr. Sonam Wangchuk **Agency**: ICIMOD **Date:** 10-11-2025

Sl,No	Parameter Name	Descriptions	Unit
1	Stake ID (Field ID)	Stake 7	
2	Latitude	27.7031	DD,EPSG:4326
3	Longitude	90.5470	DD,EPSG:4326
4	Elevation at Stake location (m a.s.l)	5102	m
5	Stake Status (Intact / Titled / Broken / Replaced)	Snow stake new; glacier stake intake	
6	Exposed stake length above current surface	89	cm
7	Snow depth at stake (if snow present)	85, 80, 80, 90, 89, 79, 82, 87, **72**	cm
8	Segment length	1.59	m
9	Overlap between stake segments		cm
10	Total number of visible segments		count
11	Overlapping length of segment		cm
12	Interval type	Annual [ ] Seasonal [yes]	
13	This reading Date/time	10-11-2025	dd-mm-yyyy
14	Photographs	Yes [● No [ ] Name & Affiliation: Dr. Sonam	
15	Remarks (incl. melt features, slush, stake tilt, hazards, crevasses)	• Glacier stake partially buried but still visible under the snow. • Photo taken at South West direction (270^0)