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Basin-scale inventory and exposure assessment of hanging glaciers, Central Himalaya

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Himalayan glaciers increasingly exhibit geometric and dynamic instability under rapid warming and climate variability. This instability has led to the development of hanging glaciers on steep slopes, which pose significant risk of ice break-offs with severe downstream impacts. While these glaciers have been extensively studied in the Alps, basin-scale assessments in the Himalaya remain limited. This study presents a comprehensive inventory of hanging glaciers in the Alaknanda basin, Garhwal Himalaya, and proposes a classification framework for their characterisation. A total of 219 hanging glaciers covering 71.7 ± 3.5 km² are identified, with an estimated ice volume of 2.39 ± 0.42 km³, including 0.74 ± 0.14 km³ of hanging ice mass, derived using the GlabTop2 model. These glaciers occupy steep slopes (mean ~33°) and predominantly face SE-W and N-NE, with the Upper Alaknanda basin containing ~30% of the total hanging mass volume. Avalanche simulations using r.avaflow indicate that potential runouts could impact major settlements and infrastructure, with flow heights exceeding 50 m in the Badrinath-Mana sector. Exposure is projected to increase sharply, with built-up surfaces rising from ~8000 m² in 2000 to ~152,000 m² by 2030, and the exposed population increasing from ~380 to ~8500. These findings highlight the need for targeted monitoring and risk-informed planning.

Glaciers in high-elevation alpine environments are highly sensitive to climate variability and warming[1–5]. This sensitivity is particularly pronounced in the Himalaya, where warming over the past two decades has exceeded the global average[6,7], resulting in accelerated glacier retreat. Such retreat has led to the detachment of tributary glaciers from trunk glaciers and has destabilised mountain glaciers (glaciers located on mountain sides[8]) that were previously stable[9–11]. These instabilities are often compensated by mass shedding in the form of snow and/or ice avalanches[12,13], a process characteristic of hanging glaciers[14]. In addition to thermally driven mass loss, erratic precipitation and increasing land degradation have further intensified the frequency and magnitude of slope failures[14,15]. The Himalayan range, situated along an active convergent plate boundary, is also characterised by high seismicity and extensively fractured bedrock[6,16]. Consequently, the interplay between glacio-geological processes and climatic forcing exerts a strong control on hanging glacier dynamics and associated downstream hazards[13,17–21]. Rapid urbanisation across the Himalaya has further increased the exposure of settlements and infrastructure to these hazards[22]; however, the resulting risk is governed by both the proximity to critical hanging glaciers and the magnitude of potential avalanche events[23,24].

The term *hanging glacier* generally refers to glaciers situated on steep valley walls or within hanging valleys and detached from trunk glaciers[25]. The Global Land Ice Measurements from Space (GLIMS) Glacier Classification Manual[8] defines 'hanging' as a longitudinal glacier characteristic, consistent with the World Glacier Monitoring Service description of glaciers 'perched on steep mountainsides or issuing from steep hanging valleys'. A more process-based definition is provided by Pralong and Funk[26], who define a hanging glacier as an 'unbalanced avalanching glacier'—a glacier that undergoes dry calving on slopes sufficiently steep for calving, or that terminates abruptly on a cliff, shedding a considerable amount of ice to sustain its finite size geometry. Owing to their high sensitivity to climate forcing, short response times, and significant mass movement potential, hanging glaciers necessitate investigation at regional scales[21,25,27,28].

Detailed studies have largely been confined to specific hanging glaciers, notably those in the Alps, which are known for their high disaster potential and recurring icefall cycles. Early investigations into their avalanche

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dynamics and triggering mechanisms have provided valuable empirical foundations for subsequent modelling efforts[29–32]. For instance, Alean[33] analysed the correlation between sliding activity and mass balance of a high-hanging glacier by quantifying the volumes of its recurrent avalanches. Building on modified classifications of avalanching glaciers, the combination of field observations and numerical simulations of crevassing has further improved understanding of fracture processes and icefall recurrence[26]. In addition, scenario-based avalanche modelling of hazardous hanging glaciers such as Eigergletscher and Whymper Glacier has led to the development of effective closure plans and early warning systems (EWS)[28,34]. These studies have been complemented by efforts to predict hazardous break-off events, suggesting that while changes in ice/snow volume and glacier geometry may be considered the most reliable indicators for prediction, these alone are insufficient as triggering conditions for large avalanches[21]. Instead, modelling the time-series behaviour of surface velocities and icequake activity prior to rupture offers greater potential for forecasting the timing of collapse[9,35–37].

In contrast, research on the morphometry and mechanics of hanging glaciers in the Himalaya remains relatively unexplored, despite the high frequency of snow and ice avalanches across the broader High Mountain Asia (HMA) region. Although scientific literature and systematic documentation are still limited, existing records clearly highlight the scale of this hazard. For instance, the Snow and Avalanche Study Establishment (SASE) documented 1452 fatalities in the Western Himalaya up to 2003[38], while Acharya et al.[39] reported 681 avalanche events causing over 3100 deaths across HMA over the past half-century, including 60 events resulting in more than 1400 deaths in the Indian and Nepal Himalaya. Several major disasters have been linked to hanging glacier collapse, underscoring their role in generating high-magnitude mass movements. These include the 2015 Gorkha earthquake-triggered avalanche that destroyed Langtang village in Nepal[40–42], and the 2021 Chamoli rock-ice avalanche in India, which resulted in over 200 fatalities and severe damage to two hydropower projects[17,43,44]. The Chamoli event, in particular, stimulated extensive global research interest and a detailed reconstruction of the avalanche cascade[24,45–53], owing to the availability of high-resolution pre- and post-event remote sensing, seismic and meteorological data, and field observations. Numerical flow modelling primarily using Rapid Mass Movement Simulation (RAMMS) has been instrumental in reconstructing such events[7,14,54–56], while frameworks such as r.avaflow provide enhanced capability for simulating complex multi-phase and cascading mass-flow processes[57–59]. Nevertheless, their systematic application to understanding hanging glacier dynamics across the Himalaya remains limited.

While these individualised studies have yielded valuable insights, a significant gap still exists in understanding hanging glacier dynamics and their response to climate forcing at larger spatial scales[25]. Moreover, there is a lack of morphometric analyses and dedicated inventories for hanging glaciers at basinal, regional, or global scales. Mishra et al.[60] provided an initial account of hanging glaciers within a glacier inventory for the Upper Alaknanda Basin in the Central Himalaya. More recently, Laha et al.[61] assessed the potential avalanche risk from hanging glaciers to downstream

Fig. 1 | Spatial distribution of glaciers and their elevation ranges in the Alaknanda basin, Garhwal Himalaya. The main map shows glacier outlines from RGI 7.0 over a color-coded elevation gradient, illustrating terrain variations. Major streams draining the basin, prominent townships and highway near the glaciated region are indicated. Settlements and infrastructure previously affected by avalanches or secondary hazards are also marked with yellow stars. The upper-right inset shows the location of the study area within its broader physiographic and tectonic setting. The lower-right inset highlights the fieldwork location within the basin. The upper-left inset presents the area-altitude distribution of glaciers, showing that the majority of glacierised area lies between 4500-6000 m.a.s.l elevation range. *Base layer / image sources: ALOS PALSAR DEM, ArcGIS Online World Topographic Map and World Imagery.*

hydropower infrastructure in the Himalaya using a simplified physics-based probabilistic approach. However, a comprehensive regional inventory of hanging glaciers in the Himalaya is still absent. This limitation poses a major challenge for providing essential baseline data required for large-scale modelling and downstream risk assessment. This study addresses these research gaps by undertaking the following objectives: (1) to develop a comprehensive basin-scale Hanging Glacier Inventory (hereafter referred to as HGI) containing key morphometric parameters of the glaciers, as well as the hanging mass (hereafter, *hanging mass* refers to the unstable part of a hanging glacier); (2) to propose a classification scheme specific to hanging glaciers; and (3) to conduct preliminary avalanche flow modelling and exposure assessment within a selected sample area of the basin.

The study is conducted in the Alaknanda basin, a fourth-order basin of the Ganga River System[62], located in the eastern Garhwal Himalaya of Uttarakhand, India (Fig. 1). The basin extends between 30°00'–31°05' N and 78°35'–80°15' E, covering an area of ~11,055 km^2. With a mean elevation of 3368 m.a.s.l, the basin features glaciers between 3640 m.a.s.l and 7780 m.a.s.l. The Alaknanda River, one of the two headstreams of the Ganga, originates from the Bhagirath Kharak and Satopanth glaciers in the Vishnuganga sub-basin and flows southward to meet the Bhagirathi River at Devprayag, forming the Ganga[63,64]. According to the Randolph Glacier Inventory (RGI) 7.0, the basin contains 848 glaciers covering 1089.26 ± 54 km^2, representing ~10% of the total basin area[65]. These glaciers are distributed across eight fifth-order sub-basins: Mandakini, Pindar, Mena Nala, Nandakini, Vishnuganga, Rishiganga, Dhauliganga, and Girthiganga[62]. The basin hosts several pilgrimage sites (e.g. Kedarnath, Badrinath, Hemkund Sahib), major settlements (e.g. Joshimath, Chamoli, Tapovan, Mana), trekking routes (e.g. Valley of Flowers, Roopkund, Nanda Devi Base Camp), and hydropower projects (e.g. Vishnuprayag, Tapovan-Vishnugad, Pipalkoti), all located in close proximity to glacierised terrain. With elevations ranging from ~400 m.a.s.l to ~7800 m.a.s.l, the basin exhibits climates from sub-tropical to alpine and highly variable rainfall, with maxima occurring during the southwest monsoon period[66,67]. The mean winter maximum and minimum temperatures, along with total snowfall at the SASE observatory located in Mana, are observed to be 14 °C, −11 °C, and 610 cm, respectively[68]. The region experiences substantial winter snowfall from December to March, frequently triggering snow avalanches.

In recent decades, the basin has undergone rapid urbanisation and population growth, with settlements increasingly encroaching into upper catchment areas close to glaciers. The ongoing infrastructure development, such as hydropower plants, has further accelerated this trend[69,70]. Concurrently, the glaciers are experiencing negative mass balance and rapid retreat[63,71], with a growing proportion evolving into hanging glaciers. Nearly 80% of glaciers in the basin are small and situated on steep ridges, making them particularly vulnerable to instability. The 2021 Chamoli disaster in the Rishiganga sub-basin exemplifies the complex interaction of glacier retreat, geomorphic instability, and anthropogenic pressure, underscoring the need for detailed investigation of this region.

Results

Hanging glacier inventory: overview

A total of 219 hanging glaciers have been identified and mapped in the Alaknanda basin. These glaciers cover an area of 71.7 ± 3.5 km^2, constituting approximately 7.3% of the total glaciated area of the basin. The elevation range of these glaciers extends from 4018 m.a.s.l to 6759 m.a.s.l, averaging at 5385 m.a.s.l. The recorded mean surface and bed slopes are 33.65° and 32.12°, respectively, with the glaciers predominantly oriented in the N-NE and SE-W directions. Figure 2 shows the distribution of these hanging glaciers across the sub-basins of Alaknanda basin. A detailed description of their morphometric parameters is provided in Table 1A. Understanding the morphology of hanging mass is crucial alongside the overall morphology, as it represents the unstable region which undergoes mass wastage. Spanning elevations from 4018 m.a.s.l to 6605 m.a.s.l, the total hanging mass area in the basin constitutes ~46% of the mapped glaciers, covering 33.19 ± 2.45 km^2. These ice masses have a mean surface slope of 36.91° and mean bed slope of 40°, with the steepest surface slope recorded at 55.74° and the steepest bed slope at 54.48°. Table 1B provides a more detailed description of hanging mass morphometry, which will be further discussed in subsequent sections for comparative analysis.

All delineated hanging glaciers are categorised based on their bedrock morphology and fracture type (see *Attributes of the HGI*). Among the 219 glaciers, 117 are classified as ramp-slab type, 99 as terrace-slab type, and 3 as terrace-wedge type. Figure 3 illustrates examples of each type and demonstrates their morphometric differences in longitudinal profiles. The highest numbers of ramp-slab and terrace-slab glaciers are found in the Pindar (Lower Alaknanda) and Vishnuganga (Upper Alaknanda) sub-basins, respectively. Only three terrace-wedge glaciers are identified across the entire basin, with one each in the Mena Nala, Vishnuganga, and Rishiganga sub-basins. As described in *Attributes of the HGI*, the classification scheme is evaluated using a Fleiss' Kappa (κ) inter-rater reliability test applied to a subset of 55 hanging glaciers independently classified by three raters. The analysis yields $\kappa = 0.82$ ($\bar{P} = 0.90$, $\bar{P}_e = 0.45$), indicating strong agreement among raters. Most glaciers (47 of 55) are classified identically by all three raters, while the remaining cases involve minor disagreements between ramp-slab and terrace-slab types. Notably, all terrace-wedge glaciers are consistently identified by all raters, indicating that this type is clearly distinguishable despite its limited occurrence.

Area distribution of hanging glaciers

The hypsometry of the delineated glaciers (Fig. 4c) suggests that the greatest areal extent, approximately 38%, lies between elevations of 5000 m.a.s.l and 5400 m.a.s.l. The smaller glaciers, which are mostly ramp-slab types, are located at higher elevations and on steeper gradients than the larger glaciers (Table 2A). Half of the delineated glaciers have areas between 0.1 and 0.5 km^2 and are predominantly ramp-slab type glaciers oriented towards the SW direction. Since the calving area of this glacier type constitutes a significant fraction of the glacier, a similar situation may be observed in the case of hanging masses within the same area range (Table 2B).

The Vishnuganga sub-basin, hosting 69 hanging glaciers, contains the highest number (~32% of the total count) and the largest area coverage (~39% of the total hanging glacier area) of hanging glaciers in the basin (Table 1A). Most of the glaciers in this sub-basin are located on the western slopes of the mainstream. However, the hanging mass area in this sub-basin only forms ~35% of its total hanging glacier area (Table 1B). In contrast, the Girthiganga sub-basin, which accounts for only ~12% of the total count and ~6% of the total area of delineated glaciers, has hanging masses that comprise ~80% of its total hanging glacier area. This may be attributed to the fact that most of the glaciers in this sub-basin are ramp-slab type glaciers with high slope values.

Volume distribution of hanging glaciers

The ice volume of 219 hanging glaciers, as calculated using the slope-based method, totals 2.39 ± 0.42 km^3. Approximately 31% of this volume (0.74 ± 0.14 km^3) is in a hanging state with high mean slope values (Table 1). Even though around half of this ice volume is contained in just 11 glaciers with areas >1 km^2, only ~15% of their total volume is in a hanging state. All of these are terrace-slab type glaciers characterised by smaller calving areas relative to their overall size. On the other hand, the hanging ice volumes of glaciers in smaller area intervals (<0.05 km^2, 0.05 km^2 to 0.1 km^2), which are largely ramp-slab types, constitute a major portion of their total volumes (Table 2). Around 68% of the hanging mass volume has an areal extent of 0.1–0.5 km^2, primarily oriented in the SW direction (Table 2B). The Vishnuganga sub-basin alone reserves ~40% of the total hanging glacier volume and ~30% of the total hanging mass volume (Table 1). However, the ratio of hanging mass volume to the hanging glacier volume in this sub-basin is only about 24%. This ratio is the highest in the Githiganga sub-basin (~79%), with the unstable ice masses predominantly oriented in the N-NE directions.

Fig. 2 | Spatial distribution of hanging glaciers across the sub-basins of the Alaknanda basin. a Map showing the locations of mapped hanging glaciers across the sub-basins. The lower-left inset bar graph compares the total number of each hanging glacier type within individual sub-basins. Glacier types are colour-coded, with ramp-slab glaciers shown in red, terrace-slab glaciers in blue, and terrace-wedge glaciers in green. Mapped hanging glacier polygons across individual sub-basins: **b** Mandakini; **c** Vishnuganga and Mena Nala; **d** Rishiganga, Pindar, and Nandakini; **e** Girthiganga; and **f** Dhauliganga. *Base layer / image source: ALOS PALSAR DEM.*

In conjunction with areal and volumetric studies, the analysis of the slope-aspect distribution of hanging masses is critical for modelling and risk assessment. Figure 4 presents a detailed overview of the volume distribution and corresponding slope values of various hanging glacier types across different aspect ranges. A clustering of significant hanging volumes can be observed in the W-SE aspect range. Similarly, the N-NE aspect range also exhibits clustering, though with relatively smaller volumes. The largest volume, however, is oriented in the NE direction with a comparatively lower slope and belongs to a terrace-slab type in the Rishiganga sub-basin.

Uncertainty and limitations of the HGI

Initially, the False Colour Composite (FCC) pixels within the one-pixel buffer zone along the glacier and hanging mass outlines are extracted separately (see *Uncertainty analysis*). Following Eq. (3), the total pixel count is multiplied by half the pixel area, resulting in area uncertainties of ±4.9% for hanging glacier and ±7.4% for hanging mass.

The parameter τ has a relative uncertainty of ±5%, as calculated from the relationship proposed by Driedger and Kennard[72] and Eq. (2)[73,74]. Since $f = 0.7$ and $f = 0.9$ constitute the lower and upper bounds, respectively, of the shape factor used in the model[75,76], the uncertainty relative to the fixed average value of $f = 0.8$ is calculated as ±12.5%[77,78]. A relative uncertainty of ±10% is considered for ρ[79]. An overall Root Mean Square Error (RMSE) of 13.97 m is calculated for the elevation errors of ALOS PALSAR Digital Elevation Model (DEM) in the Upper Alaknanda basin (Fig. 5). This value is considered representative of the entire Alaknanda basin, and therefore, the uncertainty in $sin(\alpha)$ is assumed to be ±0.14[73]. Substituting all these values into Eq. (4), the maximum uncertainty in thickness measurement is found to be ±16.8%. Thus, using Eq. (5), the net uncertainties in volume estimates of hanging glacier and hanging mass are calculated as ±17.5% and ±18.3%, respectively.

Since no dedicated inventory of hanging glaciers exists for the Alaknanda basin, the HGI is compared with the Upper Alaknanda glacier inventory of Mishra et al.[60], which reports 47 hanging glaciers with a total area of 23.6 km^2. The HGI, in contrast, identifies 69 hanging glaciers covering 28.21 ± 1.38 km^2 in the region. A georeferenced overlay of the two datasets shows strong spatial agreement in glacier outlines, consistent with both using Sentinel-2 imagery from comparable periods. However, only 28 glaciers coincide in both studies as hanging glaciers. The remaining glaciers

Table 1 | Details of morphometric parameters derived for hanging glaciers and their corresponding hanging masses in different sub-basins of the Alaknanda basin

Parameters		Alaknanda basin	Sub-basins							
			Mandakini	Pindar	Mena Nala	Nandakini	Vish-nuganga	Rishiganga	Dhau-ligang-a	Gir-thig-anga
A. Hanging glacier										
Count		219	22	41	3	10	69	28	19	27
Area (km^2) ± 4.9%		71.7	6.52	13.04	0.34	5.13	28.21	10.81	3.59	4.05
Volume (km^3) ± 17.5%		2.387	0.164	0.417	0.004	0.290	0.946	0.411	0.079	0.075
Predominant orientation ranges		N-NE, SE-W	S-SW	SE-W	SW	W, SE	N-NE, SE-W	N, W	SE, SW	N-NE
Elevation range (m.a.s.l)	Minimum	4018	4018	4258	4478	4490	4085	4446	4770	4572
	Maximum	6759	6605	6273	4843	6299	6759	6550	6340	6403
	Mean	5385	5207	5192	4697	5528	5319	5669	5655	5531
Mean slope (°)	Surface	33.65	34.76	34.24	25.47	38.29	30.75	37.11	33.07	35.27
	Bed	32.12	33.12	32.25	23.89	36.43	29.64	35.52	31.78	33.47
Type count	Terrace-Slab	99	11	14	2	1	47	5	11	8
	Ramp-Slab	117	11	27	0	9	21	22	8	19
	Terrace-Wedge	3	0	0	1	0	1	1	0	0
B. Hanging mass										
Area (km^2) ± 7.4%		33.19	3.39	6.84	0.06	2.51	9.85	5.43	1.85	3.26
Volume (km^3) ± 18.3%		0.742	0.067	0.161	0.0005	0.064	0.225	0.135	0.030	0.059
Predominant orientation ranges		N-NE, SE-W	S-SW	SE-W	W	W	N, SE, SW-W	N, W	E, SW	N-NE
Elevation range (m.a.s.l)	Minimum	4018	4018	4258	4478	4490	4085	4446	4770	4572
	Maximum	6605	6605	6273	4754	6299	6574	6550	6301	6403
	Mean	5318	5164	5130	4628	5486	5216	5612	5588	5507
Mean slope (°)	Surface	36.91	37.49	37.08	31.7	40	35.44	38.81	37.77	36.8
	Bed	40	34.86	34.03	26.8	37.51	32.35	36.22	34.37	34.41

in Mishra et al.[60] are categorised as mountain (21), compound (4), simple (5), or cirque (3) glaciers, while eight glaciers mapped in the HGI are not included in their inventory. Conversely, 21 glaciers designated as hanging in their inventory are absent from the HGI. These variations mainly result from differences in identification and classification criteria rather than inconstancies in delineation. Mishra et al.[60] categorised hanging glaciers primarily based on observable morphological characteristics, while the HGI applies an integrated framework incorporating morphology, slope parameters, and pre-defined area and slope thresholds. Notably, the mean slope of hanging glaciers reported in their study is 27°, suggesting that some glaciers identified morphologically as hanging do not meet the slope-based criteria adopted here. Furthermore, their study distinguishes mountain glaciers as a separate class, whereas in the HGI, hanging glaciers are considered a subtype of mountain glaciers in line with the GLIMS classification framework[8].

Assessment of avalanche exposure

Exposure assessment is conducted for a selected sample area around the central part of the basin (Fig. 8). This region represents a highly sensitive zone, with major townships, pilgrimage sites, and trekking routes located in close proximity to hanging glaciers and experienced a major avalanche event in 2021.

A total of 25 hanging glaciers within the sample area are modelled to evaluate potential exposure under a worst-case scenario involving complete hanging mass failure (see *Avalanche modelling and exposure assessment*). Flow simulation indicates that settlements such as Mana, Badrinath, Hanuman Chatti, and Ghangharia are potentially exposed to avalanche inundation (Fig. 8). Simulated maximum flow heights reach 51 m at Badrinath, 48 m along the Badrinath-Mana road, 61 m near the Neelkanth base camp upstream, and 40 m at Hanuman Chatti. The highest modelled flow height (118 m) occurs within the valley opposite Hanuman Chatti, further upstream; however, flow intensity decreases before reaching the nearest settlement.

Analysis of projected built-up surface and residential population data indicates substantial growth in exposure by 2030 relative to the 2000 baseline. Basin-wide built-up area is projected to increase by ~120%, while population is expected to grow by ~17%. When overlaid with simulated avalanche runout extents, these projections indicate a marked escalation in exposure. Within the sample area, exposed built-up surface increases from 8025 m^2 in 2000 to 151,800 m^2 in 2030. Similarly, exposed population rises from 380 individuals in 2000 to 8540 in 2030. The corridor between Badrinath and Mana exhibits the most pronounced growth in exposure. In this sector alone, exposed built-up surface increases from 3560 m^2 to 141,490 m^2 while exposed population rises from 170 to 8285 between 2000 and 2030 (Fig. 8).

The present modelling framework is intended primarily to identify elements potentially exposed to avalanche hazard within the sample area and to demonstrate the applicability of the HGI for large-scale hazard and exposure assessment. Detailed basin-scale scenario-based simulations, including varying release volumes and probabilistic assessments, are beyond the scope of this study and will be addressed in future work.

Discussion

Recent climate variability and global warming trends have triggered accelerated changes in Himalayan glaciers, leading to instabilities and associated mass movements. The once stable glaciers have evolved into hanging glaciers, making these regions susceptible to avalanches. Break-offs from these glaciers can destroy downstream infrastructure, population, ecosystem, and

Fig. 3 | Examples of the three hanging glacier types classified by bed topography and fracture type. a Ramp-slab type, **b** Terrace-slab type, and **c** Terrace-wedge type. The top row shows true-colour composite images of the three hanging glacier types, with their respective glacier IDs indicated in the top-left corners. The bottom row presents corresponding longitudinal profiles along the central flowline (black solid lines on the ice depth maps). The ice-depth maps for each glacier are shown in the bottom-left corners of the profile plots. Black dashed lines in the profiles indicate the slope break zones and black arrows denote the glaciers' flow direction. *Base layer / image source: Sentinel-2 imagery*.

physiographic features, and blockade the river downstream[17,28,44,61,80]. In addition to being a direct or primary hazard, hanging glaciers have huge potential to induce indirect or secondary hazards. For instance, mass failure from hanging glaciers overhanging glacial lakes can result in surging of the lake's water and breaching of its dam, leading to a glacial lake outburst flood[5,23,81–85]. Some of these failures can evolve into a cascading hazard, for example, the 2015 Langtang avalanche and 2021 Kobang avalanche in Nepal[39] and 2018 Sedongpu glacier hazard chain event in China[86]. However, along with the disaster potential of the avalanche, exposure of downstream entities also determines the scale of disaster. Dense population in Central Himalaya is the most exposed to mass movements at present and in the future[87]. Moreover, this region has the highest density of waterways exposed to potential mass wasting.

The Alaknanda basin, a part of the Central Himalaya, is a hotspot for mass movement hazards and has historically experienced numerous small- and large-scale events[88]. The risk of avalanches in the basin requires special attention due to the presence of a significant number of hanging glaciers. These glaciers collectively hold a total hanging volume of $0.74 \pm 0.14\ km^3$, unevenly distributed across various sub-basins at elevations ranging from approximately 4000 m.a.s.l to 6600 m.a.s.l (Fig. 6). However, ~55% of these glaciers overhang larger trunk glaciers and therefore pose minimal threat to downstream infrastructure and communities. The remaining glaciers overhang deglaciated valleys and river valleys, where their hazard potential depends on multiple factors such as hanging mass volume, velocity, runout distance, etc. Although a detailed risk analysis is beyond the scope of this study, exposure assessment conducted within the selected sample area (see *Assessment of avalanche exposure*) enables the identification of potential primary impact zones like settlements, agricultural lands, bridges, campsites, roads, trekking routes, and ancillary structures.

The basin is located on the southern slope of the Central Himalaya, with hanging glaciers lying on beds with slopes as high as 54.48° (see *Hanging glacier inventory: overview*). A significant number of these glaciers have hanging volumes oriented within the W-SE aspect range (see *Volume distribution of hanging glaciers*). These southern slopes are strongly influenced by monsoon precipitation and exhibit accelerated glacier retreat[89], thereby promoting mass wasting processes. The central part of the basin, near Vishnuprayag and Joshimath, marks the junction of four major sub-basins: Vishnuganga, Dhauliganga, Girthiganga, and Rishiganga. These sub-basins collectively host 143 hanging glaciers, of which 53 overhang deglaciated valleys or river valleys. Figure 6 highlights the dense distribution of significantly larger hanging volumes in the Vishnuganga sub-basin at elevations ranging from ~4350 m.a.s.l to ~5300 m.a.s.l. Meanwhile, the Pindar sub-basin to the south shows a similar dense distribution, but at a lower elevation range of ~4250 m.a.s.l to ~4950 m.a.s.l. The largest hanging mass is located in the Rishiganga sub-basin; however, lies above a trunk glacier and has a surface slope of 30.25° and a lower bed slope of 27.93°. Although only 10 glaciers overhang beyond trunk glaciers in this sub-basin, all are ramp-slab types characterised by high slope values and substantial hanging volumes (Fig. 6). Seven of these glaciers are situated in the Raunti-gad region, including the glacier associated with the 2021 rock-ice avalanche in Chamoli. Hence, analysis of critical parameters derived from the HGI, combined with the spatial distribution and correlation of glaciers and human activity within the basin, is crucial for assessing hanging glacier hazard potential.

The Alaknanda basin is characterised by fragile terrain and increasing population pressure, coupled with being disadvantaged in terms of economy and development[70]. The basin has, however, undergone substantial geo-environmental and infrastructural changes over the past couple of decades. Land Use Land Cover (LULC) analysis over the last five decades reveals a major expansion of settlements (+616%), which has contributed to a decline in agricultural land (−57%) and barren land (−33%)[69]. Figure 7 illustrates recent annual LULC changes from 2017 to 2023 for the sample area, where a

Fig. 4 | Morphometric characteristics of the hanging mass volumes. Polar bubble plots showing the orientation and slope of hanging mass volumes categorised by type: **a** surface slope and **b** bed slope. Each bubble represents an individual hanging mass, with its size proportional to ice volume and its colour indicating the glacier type. Angular and radial coordinates indicate aspect (orientation) and slope, respectively. The bubble legend shows volume distribution using quartiles (Q_0–Q_4), where Q_0 represents the smallest volume, Q_4 the largest, and Q_2 the median, providing a relative scale for comparing hanging masses. The plots highlight clustering of significant volumes within the 135°–270° aspect range. **c** Hypsometric curves illustrating the distribution of hanging glacier and hanging mass areas across different elevation levels.

Table 2 | Details of morphometric parameters derived for hanging glaciers and their corresponding hanging masses across different area ranges

Parameters	Area interval (sq. km)				
	<0.05	0.05–0.1	0.1–0.5	0.5–1	>1
A. Hanging glacier					
Count	15	54	109	30	11
Mean elevation (m.a.s.l)	5654	5449	5388	5066	5547
Volume (km^3) ± 17.5%	0.004	0.043	0.515	0.673	1.152
Mean surface slope (°)	40.77	36.81	33.8	27.68	23.19
Mean bed slope (°)	38.82	34.84	32.22	26.85	22.92
Orientation with highest count	W	S	SW	NE, SW	SE-W
Predominant hanging glacier type	Ramp-Slab	Ramp-Slab	Ramp-Slab	Terrace-Slab	Terrace-Slab
B. Hanging mass					
Count	54	51	107	6	1
Mean elevation (m.a.s.l)	5332	5426	5274	5028	5424
Volume (km^3) ± 18.3%	0.017	0.048	0.504	0.123	0.049
Mean surface slope (°)	37.73	38.43	35.98	34.39	30.25
Mean bed slope (°)	33.74	35.71	33.51	31.65	27.93
Orientation with highest count	S	S	SW	S, W	NE
Predominant hanging glacier type	Terrace-Slab	Ramp-Slab	Ramp-Slab	Ramp-Slab	Terrace-Slab

Fig. 5 | Comparison of DGPS and DEM-derived elevations at 19 survey points. Blue dots represent DGPS-measured elevations, and black crosses represent DEM-derived elevations at the base and rover locations marked along the *X*-axis. The left *Y*-axis shows elevation values (m.a.s.l), while the right *Y*-axis shows absolute elevation error (m), represented by grey bars. The plot indicates a slight underestimation of elevation by the DEM.

Fig. 6 | Sub-basin-wise distribution of hanging glacier types and their hanging mass volumes across different elevation ranges. Bubble size indicates the volume of each hanging mass, and bubble colour represents the hanging glacier type. The bubble legend (upper right) illustrates quartile values (Q_0–Q_4) of the volume distribution, providing a relative scale for comparison across sub-basins and elevation bands; where Q_0 denotes the smallest volume, Q_4 the largest, and Q_2 the median.

noticeable increase in built areas and the emergence of new croplands is evident even within this short period. At the basin-scale, the highest positive rate of land-use change is observed in built areas (+98.5%), while the highest negative rate is recorded for bare ground (−24.5%). A similar pattern is reflected in the sample area, where built areas exhibit the largest increase (+79.7%), while bare ground shows the largest decline (−33.3%). This continued expansion of infrastructure and croplands in and around settlements located along the potential flow paths of several hanging glaciers is progressively increasing their exposure (Fig. 7).

Figure 8 illustrates the past and projected distribution of built-up surfaces and population at 5-year intervals from 2000 to 2030[90,91], together with simulated potential avalanche maximum flow heights. Consistent with the LULC-based classification, these projections indicate substantial growth in built-up surfaces (~99%) and population (~14%) within the sample area. When intersected with simulated avalanche runout zones, these trends indicate a progressive increase in exposure, particularly in the settlements of Badrinath and Mana and along the Badrinath-Mana stretch of NH-7. Figure 11 presents field observations in this region, showing the location and morphology of three hanging glaciers overhanging this stretch (50132 06 HG57, 50132 06 HG58, 50132 06 HG59), with the nearest located ~1.4 km above the settlements. These glaciers exhibit high crevasse density (Fig. 11b, c) and a combined hanging mass volume of 0.012 ± 0.002 km^3. Modelled flow heights from these glaciers reach up to 51 m at Badrinath and 48 m along the Badrinath-Mana road, indicating significant impacts under such avalanche scenarios (Fig. 8e). The analysis reveals a dramatic increase in exposure in this sector by the end of the decade (see *Assessment of avalanche exposure*). Nearby regions are also at risk of potential inundation. Immediately downstream of Badrinath, the entire settlement of Hanuman Chatti lies within the runout zone, with maximum flow heights reaching up to 40 m (Fig. 8f). The valley opposite Badrinath, a key trekking and pilgrimage corridor containing the Neelkanth Base Camp, is similarly exposed (Fig. 8h). Further downstream, the village of Ghangharia, another important trekking and pilgrimage hub, faces inundation in its upper reach under this worst-case scenario (Fig. 8g).

The development in this region largely follows the Alaknanda River, where high volumes of entrained ice and debris could potentially generate

Fig. 7 | Spatiotemporal changes in Land Use and Land Cover (LULC). a, **b** LULC maps at 10 m resolution for 2017 and 2023 in a sample area within the basin. Enlarged subsets highlight regions and settlements situated along potential flow paths of hanging glaciers, where a notable expansion in built areas and croplands is evident. Dotted black circles in the 2023 map indicate newly converted cropland areas. The upper-right locator map shows the position of the sample area within the basin. **c** Percentage change in annual LULC for different classes across the basin from 2017 to 2023, with built area (red line) demonstrating a progressive increase over the years. *Base layer / image sources: Sentinel Hub LULC 10 m dataset; ArcGIS Online World Terrain Map*.

secondary cascading hazards. In such cases, deposition within the valley may temporarily obstruct the river channel, resulting in the formation of short-lived impoundments with significant downstream hazard potential. Historical events in the region provide evidence of such cascading processes. In July 1970, an avalanche blocked the Alaknanda and Dhauliganga rivers, forming temporary lakes at Hanuman Chatti near Badrinath, which eventually burst, causing considerable fatalities[45]. A similar event occurred in April 1978, when an avalanche from the Rishiganga valley blocked the Alaknanda River above Bamni village near Badrinath, and the subsequent breach destroyed the village[92]. More recently, the February 2021 Chamoli rock-ice avalanche left behind an unstable debris dam at the crash zone, which may become hazardous in the future as summer snowmelt can accumulate behind it and potentially breach the dam[80,93].

Beyond direct impacts, avalanches reaching transportation corridors can disrupt connectivity within the basin. Highways and mountain roads in this region play critical roles in pilgrimage access, local livelihoods, and strategic mobility in high-altitude border areas. For instance, the former NH-58 (now NH-7) has historically experienced recurrent damage from avalanches, leading to repeated disruptions of transport and communication networks[94]. Furthermore, the progressive advancement of settlements and infrastructure at higher elevations (Fig. 8c), moving closer to the hanging glaciers, further increases exposure and vulnerability to potential avalanche hazards. The modelling results show that settlements located immediately below hanging glaciers exhibit the highest level of exposure, as expected. Several downstream settlements remain outside the simulated runout zones and therefore appear not exposed under the current modelling framework. However, the present simulations consider ice-avalanche release alone and do not explicitly incorporate complex cascading processes that may occur during glacier failure events. As demonstrated by the Chamoli disaster, large-scale detachments can entrain underlying rock and debris, transforming the initial avalanche into a large, highly mobile debris flow capable of travelling much greater distances[17]. Under such compound hazard scenarios, areas currently outside the exposure zones may also become vulnerable to downstream impacts. With these ongoing expansions, appropriate monitoring and mitigation strategies are necessary to reduce future hazard risks in the region.

Monitoring hanging glaciers is a complex and challenging task due to their inaccessibility, small-scale geometry, and unpredictability. While satellite-based observations have proven very useful, real-time ground-based measurements are essential for capturing micro-scale fluctuations in glacier dynamics. Although such efforts at a basin- or regional-scale have not yet been undertaken, individual hanging glaciers have received focused monitoring. Hanging glaciers like Eigergletscher, Whymper glacier, and Montitaz lobe of the Planpincieux glacier in the Alps, with their notable history of break-off events and repeat cycles, are examples of such intensively monitored glaciers. Terrestrial radar interferometry systems, such as Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) and Real-Aperture Radar, are deployed alongside time-lapse cameras to observe the surface kinematics of these glaciers and create deformation maps[28,34,95]. Techniques involving the analysis of icequake signals[9,36,37,96–99] and infrasound signals[100,101] are also utilised to detect break-off precursors, track englacial damage and crack evolution during events, and examine post-event avalanche dynamics. Additionally, Doppler radars serve as reliable EWS, capable of detecting break-offs in real-time and automatically triggering alarms and road closures. These methods are further strengthened by data gathered from airborne Ground Penetrating Radar surveys, laser scanning and photogrammetric surveys, robotic total station surveys, and thermistor and hydrometer measurements[28,34,95]. This integrated network of monitoring systems and EWS has been highly successful in detecting and mitigating numerous snow and ice break-offs in the Alps. Adopting similar strategies in the Himalaya could be beneficial. Although full-scale implementation may be impractical and unfeasible, targeted studies are possible. Identifying high-risk hanging glaciers using the HGI, flow modelling, and comprehensive risk analysis studies enable such focused investigations in locations where they are most essential. In this context, the outcomes of this study provide foundational data to support decision-making by relevant authorities, stakeholders, and policymakers.

Fig. 8 | Simulated avalanche runouts and associated exposure of built-up surfaces and population. a, **b** Maps showing potential avalanche runouts from hanging glaciers and the resulting exposure of built-up surfaces and population, based on projected conditions for 2030 relative to 2000. Built-up structures and population located closest to these glaciers along potential flow paths – both within and outside the simulated avalanche runout zones – are marked. **c** Heatmap illustrating changes in the spatial extent of built-up surfaces at higher elevations within the basin from 2000 to 2030 (5-year intervals), measured at 50 m elevation bands. Colours indicate a progressive upward expansion of development up to ~5800 m.a.s.l, suggesting increasing proximity to glacierised terrain. **d** Temporal trends in basin-wide built-up surface and associated population growth. **e**–**h** Enlarged maps of the exposed localities highlighted in **a**, indicating several settlements, agricultural lands, trekking routes, base camp, and other critical infrastructure exposed within potential impact areas. National Highway 7 (NH-7), running parallel to the Alaknanda River, is also exposed at multiple locations. *Base layer / image sources: GHSL built-up surface and population dataset; ALOS PALSAR DEM; ArcGIS Online World Terrain Map.*

However, as an initial implementation, the limitations of the HGI need to be acknowledged. Even though the HGI applies an integrated framework incorporating morphology, slope break delineation, and threshold criteria, it may introduce a degree of subjectivity for certain glaciers. Future work could improve this through automated or machine-learning-based delineation and classification approaches incorporating additional terrain and spectral metrics. Reliable glacier velocities could not be obtained for most glaciers, as velocity retrieval is particularly challenging for small, steep glaciers due to decorrelation in optical sub-pixel correlation and low coherence in radar interferometry. Integration of advanced InSAR time-series techniques or high-resolution feature tracking could be explored to address this limitation. Ice thickness estimates derived from the Glacier Bed Topography (Glab-Top2) model are subject to model assumptions, such as idealised τ and f parameters, which may influence thickness and volume estimates. Although the calculated uncertainty calculated remains within acceptable limits, it could be further reduced by incorporating higher-resolution DEMs, alternative thickness modelling approaches, or field-based constraints. As mentioned in *Data sources*, the temporal offset between the DEMs and satellite imagery may also introduce some uncertainty into surface-based metrics, which could be minimised by using temporally consistent or more recent DEMs.

Beyond inventory refinement, coupling the HGI with scenario-based avalanche modelling and quantitative risk assessment would substantially enhance its practical applicability. In parallel, effective communication of hazard information to local communities and stakeholders is essential to translate these findings into actionable risk reduction and preparedness strategies.

Methods

Data sources

The current study utilises multi-temporal satellite images and DEMs at various stages for mapping, characterising hanging glaciers at a basin-scale, and undertaking avalanche flow modelling and exposure assessment. Sentinel-2 optical imageries (Level-1C and Level-2A) from 2020 to 2023, accessible through the Copernicus Data Space Ecosystem via the Sentinel Hub API, are chosen as base images for glacier mapping (Table 3). These images have a high dynamic range, high radiometric resolution, and a spatial resolution of up to 10 m, making them suitable for detailed large-scale glacier mapping[102–104]. To minimise cloud cover and seasonal snow interference, only images from the end of ablation period (September and October) are utilised. Images from 2021 and 2023 are utilised to determine the glacier extents. No suitable images from the ablation season of 2022

Table 3 | Details of the satellite imagery used in this study

Sensor/Processing level	Acquisition date	Path and row ID	Bands used/ Spatial resolution (m)
Sentinel-2A MSI L1C, L2A	18 October 2020 13 October 2021	T44RLU, T44RLV, T44RMU	Green (10), Red (10), VNIR (10), SWIR (20)
Sentinel-2B MSI L1C, L2A	28 September 2023 08 October 2023	T44RLU, T44RLV, T44RMU	Green (10), Red (10), VNIR (10), SWIR (20)

MSI multispectral instrument, *VNIR* visible and near infrared, *SWIR* short wave infrared.
Images from the ablation seasons of 2020, 2021, and 2023 are utilised for mapping. No suitable mages from 2022 are available due to high cloud and snow cover. The NIR and SWIR bands are selected for glacier mapping owing to ice and snow's high reflectance in the NIR band and high absorption in the SWIR band.

could be found. Glacier outlines documented in the open-source Randolph Glacier Inventory (RGI 6.0 and 7.0) are utilised as reference outlines for delineating the hanging glaciers[105,106]. To extract glacial and terrain characteristics for HGI development and flow modelling, the Advanced Land Observing Satellite (ALOS) – Phased Array type L-band Synthetic Aperture Radar (PALSAR) DEMs are used, acquired from NASA's Alaska Satellite Facility Vertex portal. These are radiometrically terrain-corrected elevation models with a spatial resolution of 12.5 m, published worldwide in October 2014. Additionally, high-resolution images from Google Earth are employed to refine the delineated glacier boundaries and to ensure their spatial accuracy.

The DEMs predate the Sentinel-2 imagery by ~6–9 years. Bedrock-derived slope calculations are unaffected by this temporal offset, as the bed topography remains essentially invariant over such timescales. Glacier surface elevations, however, may have changed during the intervening period due to ongoing melt, introducing some uncertainty into surface-based metrics. DEM vertical accuracy is assessed using field data, and the resulting uncertainty is propagated into the thickness and volume calculations (see *Fieldwork investigations* and *Uncertainty analysis*). Although localised changes in surface slopes cannot be excluded, mean slope characteristics are expected to remain largely robust. To ensure consistency, both bed and surface slopes are analysed throughout the study.

LULC analysis is conducted using the Sentinel Hub Collections 10 m Annual LULC dataset (2017 to 2023)[107]. Built-up surface and population rasters for exposure assessment (2000 to 2030) are obtained from the Global Human Settlement Layer (GHSL), developed by the European Commission's Joint Research Centre (JRC)[90,91].

HGI: glacier outline delineation

The boundaries of glaciers are manually delineated at an approximate map scale of 1:20,000[60]. Since most of the glaciers to be mapped are smaller in size and given that decreasing surface area results in a significant increase in relative error[108,109], manual mapping is preferred over automated techniques for this study. Sentinel-2 FCCs generated using suitable band combinations: SWIR-VNIR-Red[102], and NIR-Red-Green[110,111] are used as base layers for the mapping. Ice and snow have high reflectance in the VNIR region and high absorption in the SWIR region[103,112]. These complementary spectral characteristics are exploited to create FCCs that highlight glaciers brightly against the dark surrounding topography, thereby enhancing the details of observations. By observing the differences in colour and textural characteristics, ice, snow, and glacial features such as moraines, crevasses, debris cover etc., can be clearly distinguished.

Alaknanda basin boundary is derived from ALOS-PALSAR DEMs using pour-point watershed delineation technique. The delineated boundary closely aligns with ICIMOD's open-source boundary file, with a minor area difference of about 0.5% of the total basin area. Similarly, boundaries of the glacierised sub-basins are also derived. A sub-basin wise mapping is conducted to ensure systematic progression of the process and to prevent any glaciers from being overlooked. The RGI 6.0 and 7.0 outlines are used as a reference layer to facilitate the identification and demarcation of glaciers. To prepare the HGI, the definition of hanging glaciers provided by Pralong and Funk[26] is followed, in conjunction with the GLIMS primary classification of glaciers (see *Introduction*). Consequently, for a glacier to be considered a hanging glacier, (i) it should lie on a slope or terminate abruptly on a cliff (detached from the valley glacier or valley floor), and (ii) its slope should be sufficient enough for dry calving to occur.

The mapping adheres to mountain glaciers and tributary glaciers detached from the trunk glaciers. Trunk/valley glaciers, ice caps and aprons, dead ice and seasonal snowfields identified in the multi-temporal FCCs and Google Earth historical imagery are excluded from the mapping. However, all identified perennial snow masses are considered as glaciers[113,114]. Paul et al.[115] suggested that, under optimal conditions, the smallest glacier that can be accurately identified on satellite imagery with a spatial resolution of 15 to 30 m has an area of 0.01 km². Since most glaciers being mapped are small, and the imagery used has a resolution of 10 m, the minimum area threshold for this HGI is set at 0.01 km². The boundary for accumulation area is drawn along the bergschrund line[77,114]. For adjacent glaciers and those emerging from the same cirque, identifying the ice divides can be challenging. These are carefully demarcated using slope and contour maps. The lateral boundaries and termini of glaciers are identified by examining the textural and chromatic differences between ice and nearby earth materials, such as moraines and rocks. Furthermore, recognition of features like dead ice, origin of streams, ice cliffs, etc., from Google Earth imagery aids in delineating these boundaries and termini with precision[111,116]. Since the mapping focuses on mountain glaciers and detached tributary glaciers with little to no debris cover, the challenge of identifying ice-land interface and glacial features is minimal. The outlines delineated in this initial phase of mapping are refined and verified in fine-resolution Google Earth imageries.

Avalanche starting zones in the Himalaya have critical slopes exceeding 30°[39,87,117], a slope angle essential for the initiation of slab avalanches[118,119]. In a recent study, Laha et al.[61] classified glaciers with mean slopes greater than 30° as hanging glaciers. Therefore, in this study, a slope threshold of 30° is used to identify and separate hanging glaciers from within the previously delineated group of glaciers. Given that ice flows along the maximum surface slope[120] and terrain slope is a crucial factor for avalanche release[119], both surface and bed slopes are being considered. Surface slopes are obtained directly from ALOS PALSAR DEMs and bed slopes by means of the DEMs and ice-depths (see *Attributes of the HGI*). Although mean slope can be a definitive factor for glaciers lying entirely on steep gradients, it may be misleading for flat-lying glaciers with hanging fronts. Therefore, mean slopes are calculated for different elevation zones (e.g. 50 m, 100 m increments) from the snout upwards and checked against the slope threshold (Fig. 9a, b). Additionally, slope maps are used to analyse the gradient distribution within glacier boundaries. Among these boundaries, those with an overall mean slope >30° and those with fronts hanging at slopes >30° are classified as hanging glaciers. The resulting outlines are saved in a GIS shapefile format for easy access.

HGI: hanging mass delineation

As defined in this study, the term 'hanging mass' refers to the unstable portion of a hanging glacier. The hanging mass boundaries are delineated using a combination of slope breaks and crevasses. Longitudinal profiles are first generated along the manually delineated central flowline of each glacier[121]. Elevation values for the profiles are extracted from ALOS PALSAR DEMs and from a glacier bed elevation raster obtained by differencing

Fig. 9 | Illustration of hanging mass delineation for a hanging glacier using slope breaks and crevasses. a, **b** Slope maps showing the mean surface and bed slopes of the hanging glacier at 100 m elevation zones, with slope values marked in black over the glacier. The slope break zone and glacier's flow direction are indicated. **c** Longitudinal profile along the central flowline of the glacier, highlighting a break in the slope at a surface elevation of 5160 m.a.s.l and a bed elevation of 5118 m.a.s.l. The lower-right subset shows an enlarged view of the slope break zone, with bed slope values (in degrees) marked along the bed topography; a noticeable increase in slope values can be observed within the slope break zone. **d** Google Earth image from September 2022 illustrating the slope break zone and associated crevasses, labelled with black dashed lines. The ice surface appears smooth above the slope break zone and rough below it. A black arrow indicates the glacier's flow direction. *Base layer / image sources: Sentinel-2 imagery, Google Earth (© 2025 Maxar Technologies, © 2025 Airbus, © 2025 CNES / Airbus).*

the thickness raster from the DEM (see *Attributes of the HGI*). Python-based batch-processing routines are developed to derive longitudinal profiles for all mapped glaciers and to quantify slope variations along them. For each profile, slope change along contiguous sections is calculated using central differences and subsequently smoothed using a filter to reduce noise. Contiguous sections of the profile where the slope exceeds a threshold of 30° are identified as slope break zones, and their uppermost extent represents potential hanging mass boundary. Minor slope fluctuations are excluded to avoid false detections. The slope break zones are then correlated with crevasse patterns observed in high-resolution Google Earth imagery to confirm the hanging mass boundary (Fig. 9c, d). The delineated hanging mass polygons are subsequently refined using slope and contour maps and exported as GIS shapefiles for further analysis.

Attributes of the HGI

The inventory is designed to incorporate all essential morphometric, locational, and classification information for each hanging glacier and its hanging mass. A total of 18 attributes is included in this HGI, as outlined in Table 4.

Glacier ID. The glaciers IDs are assigned based on Geological Survey of India's (GSI) standard identification coding system for glacier

Table 4 | Details of attributes in the HGI

Attribute Information	Unit	Example
Unique ID assigned to each glacier	-----	5O132 06 HG020
Location of centroid of the glacier	decimal degrees	30.7761, 79.363
Total area of the glacier	sq. km	0.2241
Minimum elevation of the glacier	m.a.s.l	5066
Maximum elevation of the glacier	m.a.s.l	5418
Total volume of the glacier	cub. m	3514473.44
Mean surface slope of the glacier	degrees	29.84
Mean bed slope of the glacier	degrees	29.12
Orientation of the glacier	-----	NE
Area of hanging mass	sq.km	0.12438
Minimum elevation of hanging mass	m.a.s.l	5066
Maximum elevation of hanging mass	m.a.s.l	5376
Volume of hanging mass	cub. m	1776881.25
Mean surface slope of hanging mass	degrees	32.66
Mean bed slope of hanging mass	degrees	30.95
Orientation of hanging mass	-----	NE
Bedrock morphology of the glacier	-----	Terrace
Fracture Type of the glacier	-----	Slab

The example provided in the table represents a hanging glacier in the Vishnuganga sub-basin.

inventory[62]. The IDs are 12-character codes (excluding spaces) in the format *"5O132 nn HGmmm"*, where *5* represents Asia, *O* denotes the first-order Ganga basin, *132* refers to the fourth-order Alaknanda basin, *nn* represents the fifth-order basins, *HG* stands for hanging glacier, and *mmm* is the serial number of hanging glaciers counted clockwise round the fifth-order basins. The fifth-order glacierised basins are: 5O132 02 (Mandakini), 5O132 03 (Pindar), 5O132 04 (Mena Nala), 5O132 05 (Nandakini), 5O132 06 (Vishnuganga), 5O132 07 (Rishiganga), 5O132 08 (Dhauliganga), and 5O132 09 (Girthiganga).

Location, area, and elevation. The locations of glaciers are represented by the latitude and longitude of their centroid points derived from the shapefile. The total area and hanging mass area are measured using the corresponding shapefiles and sentinel-2 imagery. Maximum and minimum elevations are derived from the ALOS-PALSAR DEMs.

Ice thickness and volume. Since the glaciers in this inventory are slope-controlled, the slope-based GlabTop2 model[75] is utilised for estimating ice-depths. Techniques like sub-pixel correlation and interferometry have been attempted for velocity estimation but have not yielded reliable results. This is due to the glaciers' small size and their confinement to mountain slopes, making velocity-based thickness models unsuitable. GlabTop2 applies the principles of shallow ice approximation and perfect plasticity to derive ice thickness[73,74,122]. The model requires three inputs: a shapefile of glacier boundaries, a high-resolution DEM, and a gridded map of glacier boundaries.

Initially, the ice depth of automatically selected random DEM cells within the glacier boundary is calculated. The depth values for all other inner cells are then calculated by interpolating these values and the ice-depth at the glacier margin, which is zero.

$$h_f = \frac{\tau}{f\rho g sin(\alpha)} \tag{1}$$

where h_f is the mean ice-thickness along the central flowline (m), τ is the average basal shear stress along the central flowline (kPa), f is the shape factor (0.8), ρ is the ice density (900 kg/m^3), g is the acceleration due to gravity (9.81 m/s^2) and α is the mean surface slope along the central flowline. The shape factor (f) is fixed at 0.8, following the recommendations by Linsbauer[123].

$$\tau[kPa] = \begin{cases} 0.5 + 159.8\Delta H - 43.5(\Delta H)^2 & : \Delta H \le 1.6\,km \\ 150 & : \Delta H > 1.6\,km \end{cases} \tag{2}$$

The value of τ is parameterised with the elevation range of glacier ΔH (km)[124], as given in Eq. (2). The sum of ice-thickness values for all cells within a glacier is then multiplied by the pixel area (156.25 m^2) to determine the glacier's volume. Finally, using the hanging mass shapefile, thickness specific to hanging front is extracted from the ice-depth raster, and hanging volume is determined accordingly. For more details about GlabTop2 model, refer to its documentation at GlabTop2-py webpage.

However, previous studies have noted that GlabTop2-derived ice thickness estimates may be influenced by uncertainties in input parameters, particularly basal shear stress and surface slope, which can affect the resulting thickness distribution and volume estimates. Earlier applications of the model have explored the sensitivity of these parameters and emphasised the importance of accounting for associated uncertainties when applying the model at regional scales[75,123,125].

Slope and orientation. Ice-depth raster from the GlabTop2 model is differenced from the corresponding DEMs to create a glacier bed elevation raster. This raster and the DEMs are then used to generate spatially distributed surface and bed slopes, from which average slope values for hanging glaciers and hanging masses are calculated. Aspect values extracted from the DEMs are used to determine their orientations through a python-based batch processing script. It divides the aspect values into predefined direction intervals (e.g., ≥0° to <22.5° for North, ≥22.5° to <67.5° for North East, etc.), computes the total number of cells within each interval, and then selects the interval with the highest count to represent the overall orientation.

Classification. The classification of hanging glaciers follows the conceptual framework proposed by Pralong and Funk[26] for avalanching glaciers. According to this scheme, hanging glaciers-representing unbalanced avalanching glaciers-are categorised based on two primary parameters: bedrock morphology and fracture type (Fig. 10). While the original framework considered both balanced and unbalanced avalanching glaciers, hanging masses delineated in the present study correspond exclusively to an unbalanced condition. The classification applied here thus represents a specific adaptation of their scheme for hanging glaciers.

Considering bedrock morphology, two distinct categories can be classified: (i) *terrace* glaciers and (ii) *ramp* glaciers. Terrace glaciers are characterised by a stepped longitudinal profile, i.e. a pronounced steepening near the glacier head, a broad, gently sloping central reach containing most of the ice mass, and a second marked steepening towards the terminus (Fig. 10a, c). The unstable portion is relatively small compared to the overall glacier extent, resulting in potential break-off volumes that are minor relative to total glacier volume. In longitudinal profiles (see *HGI: hanging mass delineation*), these glaciers display a slope–flat–slope configuration, with the hanging mass confined to the lower part of the glacier. The hanging mass therefore occupies only a limited fraction of the total glacier length (examples: Fig. 3b, c). Ramp glaciers, in contrast, are located on steep and comparatively uniform bedrock (Fig. 10b). These are glaciers confined entirely to mountain sides, unlike flat-lying glaciers with hanging fronts. In longitudinal profiles, the steep gradient extends over a substantial proportion of the glacier length without an intermediate flattening. Hence, the delineated hanging mass constitutes a significant fraction of the total glacier extent, consistent with their potential for large break-off volumes (example: Fig. 3a).

Fig. 10 | Schematic diagram of hanging glacier types (adapted and modified from the classification by Pralong and Funk[26]). Stable and unstable (hanging) ice masses are shown in dark blue and light blue shades, respectively. Thick black arrows indicate the distribution of direct snow accumulation on both stable and unstable regions. In terrace glaciers (**a**, **c**), the unstable region is continuously supplied by ice flow from the glacier's upstream region, whereas in ramp glaciers (**b**), it is supplied by direct snow accumulation. Slab fractures (**a**, **b**) typically develop on steep slopes, whereas wedge fractures (**c**) form at glacier margins that extend beyond a discontinuous bedrock.

Two types of fractures are considered in relation to bedrock morphology: (i) *slab* fractures and (ii) *wedge* fractures. Slab fractures typically occur on steep beds, either on terrace glaciers or ramp glaciers, where the hanging mass exists as a coherent slab (Fig. 10a, b). These fractures have the potential to release large volumes of ice downstream. Wedge fractures develop on unbalanced terrace glaciers that terminate abruptly at a topographic discontinuity, such as a cliff (Fig. 10c). When the glacier margin extends beyond the discontinuous bedrock, it forms an ice-cliff, leading to localised calving events. Hence, fracture type is essentially determined by the geometry of the hanging mass, as inferred from longitudinal profiles and ice thickness rasters. Slab fractures are identified where a substantial hanging mass thickness (i.e. a slab) overlies a steep bed gradient (examples: Fig. 3a, b). In contrast, wedge fractures are identified as relatively small hanging mass confined to the extreme terminus, extending slightly beyond the glacier bed (example: Fig. 3c). To verify this terminal geometry and spatial extent of wedge fractures, high-resolution Google Earth images are used, providing visual confirmation for sections that are too small to resolve from profiles alone.

By combining bedrock morphology (terrace or ramp) with fracture type (slab or wedge), glaciers are assigned to one of three types: terrace-slab, ramp-slab, or terrace-wedge (Figs. 10 and 3). To evaluate the reproducibility of the proposed classification scheme, an inter-rater reliability assessment was conducted using three independent raters. A subset of 55 glaciers (~25% of the HGI) was classified independently following the same criteria and identification framework. Agreement among raters was quantified using Fleiss' Kappa (κ) test, defined as $\kappa = (\bar{P} - \bar{P}_e)/(1 - \bar{P}_e)$, where $\bar{P}$ represents the observed agreement among raters and $\bar{P}_e$ the expected agreement by chance based on category proportions.

Field investigations

Fieldwork is conducted in the Vishnuganga sub-basin (Upper Alaknanda) during the ablation period (September 2024), specifically in and around Badrinath township and the Bhagirath-Kharak valley (Fig. 11a). This sub-basin hosts a significant number of hanging glaciers in close proximity to settlements and infrastructure. Several of these glacier valleys are accessible, allowing for detailed field investigations.

To assess the accuracy of DEM, field-based Differential GPS (DGPS) readings are recorded at 19 locations within the valley on stable ground to minimise positional errors. A comparison between the DGPS-derived elevations and corresponding DEM pixel values yields an RMSE of 13.97 m and a Percent Bias (PBIAS) of −0.35, indicating a slightly underestimation of elevation by the DEM. Additionally, high-resolution close-range photographs of hanging glaciers are acquired, based on which crevasses are identified and remote sensing-derived crevasses and slope-breaks are validated (Fig. 11b, c, d). Stereo-photogrammetric analysis is conducted in conjunction with DGPS survey for two hanging glaciers visible from the valley. The captured imagery has potential applications in developing 3D Structure from Motion (SfM) models for future modelling and hazard assessment studies.

Uncertainty analysis

Even though high-resolution satellite imagery provides the most accurate base layers for mapping glacier boundaries[108], the accuracy of these boundaries is subject to multiple factors. The spatial resolution of the imagery, reflectance difference between glacier and its surrounding topography, and the period of image acquisition (accounting for cloud cover, shadows, seasonal snow cover etc.) generally affect the accuracy of delineated outlines[126]. In this study, the uncertainty in delineation of glacier boundaries, or mapping uncertainty, is calculated by applying a buffer of one pixel in size to the glacier outline[108,126,127].

$$\textit{Mapping Uncertainty}\,(U_M) = N \times (A/2) \tag{3}$$

where N is the total number of pixels along the glacier outline and A is the pixel area. Since glacier area is a measure of the spatial extent of the boundary shape files, the uncertainty in area (U_A) is considered equivalent to U_M.

The uncertainty in thickness estimation using GlabTop2 (U_T) is a function of the uncertainties in input parameters fed to the model[73]. These input parameters include the shape factor (f), ice density (ρ), mean surface slope angle (α) and average basal shear stress (τ). The parameter g is not considered here as it is a constant. Using the error propagation method, the thickness uncertainty is given by:

$$U_T = \frac{u(h_f)}{h_f} = \sqrt{\left[\frac{u(\tau)}{\tau}\right]^2 + \left[\frac{u(f)}{f}\right]^2 + \left[\frac{u(\rho)}{\rho}\right]^2 + \left[\frac{u(\sin\alpha)}{\sin\alpha}\right]^2} \tag{4}$$

Similarly, the uncertainty in volume estimation (U_V) is given by:

$$U_v = \sqrt{(U_A)^2 + (U_T)^2} \tag{5}$$

Since glacier volume is the product of ice thickness and glacier area calculated from its boundary, U_V depends on U_A and U_T, as given in Eq. (5).

Avalanche modelling and exposure assessment

The open-source mass-flow simulation framework r.avaflow is used in this study to model complex process chains associated with potential glacier-derived avalanches[57,58]. The simulations are based on the multi-phase mass-flow model proposed by Pudasaini and Mergili[59], which enables integrated representation of solid-fluid interactions and the propagation dynamics of gravitational mass flows. This approach allows the simulation of potential avalanche propagation originating from the mapped hanging glaciers.

Fig. 11 | Field observations of hanging glaciers and survey locations in the Vishnuganga sub-basin. a Map of the fieldwork site, highlighting DGPS survey points, nearby hanging glaciers, and built-up areas. The upper-right inset shows the location of the fieldwork site within the sub-basin. The centre-right inset photograph shows the DGPS rover and camera setup, with a prominent hanging glacier visible across the valley. **b**–**d** Close-range field photographs of hanging glaciers in proximity to Badrinath township, Mana village, and highway (NH-7). The upper boundary of the hanging mass is marked by a red dashed line, while crevasses are indicated by black-dashed lines. Black arrows indicate the glaciers' flow direction. *Base layer / image sources: ALOS PALSAR DEM; field photographs by N. Krishnan (2024).*

Conservative avalanche scenarios are considered by assuming complete detachment of the mapped hanging glacier masses. Accordingly, the release volume is defined as the total estimated hanging mass volume of each hanging glacier. The rheological behaviour of the flowing mass is parameterized using the basal friction angle (φ) and the internal friction angle (δ), which govern momentum transfer and resistance during flow propagation. For the initial stage of the process chain, which is predominantly controlled by the solid phase (ice avalanche), the parameters are set to $\varphi = 25°$ and $\delta = 10°$. The density of the moving mass is assumed to be 900 kg m^{-3}, representing glacier ice.

The computational domain is delineated to encompass the avalanche source zones and the nearest downstream settlements potentially affected by the simulated events. Model outputs, including maximum flow depth and runout distance, are subsequently analysed to quantify potential exposure of population, infrastructure, and LULC classes.

Data availability

The data used in this study are obtained from remote sensing analyses and field observations. Sentinel-2 optical imageries are accessible via the Sentinel Hub API (https://www.sentinel-hub.com/). ALOS PALSAR DEMs can be acquired from NASA's ASF Vertex portal (https://search.asf.alaska.edu/). LULC and GHSL datasets are available at https://collections.sentinel-hub.com/impact-observatory-lulc-map/ and https://human-settlement.emergency.copernicus.eu/, respectively. Glacier outlines from RGI can be accessed at https://www.glims.org/RGI/. The datasets generated in this study are available from the second author upon reasonable request.

Code availability

The GlabTop2-py codes used for ice-thickness estimation are freely available at https://glabtop2-py.readthedocs.io/en/latest/index.html. The python scripts for delineating glacier longitudinal profiles, slope breaks, and orientations are available at https://doi.org/10.5281/zenodo.15181743, https://doi.org/10.5281/zenodo.18789400, and https://doi.org/10.5281/zenodo.15182179.

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Author contributions

N.K. designed the study, performed formal analysis, data curation and methodology development, implemented software, conducted validation and visualization, and prepared the manuscript. A.S. contributed to study design, formal analysis, methodology development, validation, manuscript revision, and provided supervision. A.V.K. contributed to study design, data curation, analysis, funding acquisition, methodology development, and oversaw project administration, supervision and manuscript revision. H.S.N. contributed to the conception of the idea, funding acquisition, project administration and manuscript review. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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