https://doi.org/10.5194/essd-2023-522
Preprint. Discussion started: 5 February 2024

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A comprehensive rock glacier inventory for Jammu, Kashmir, and Ladakh, western Himalaya, India - Baseline for the permafrost research

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Abstract. The prevalent climate warming across the mountain regions worldwide has exacerbated the snow melt, glacier recession and permafrost thawing that is impacting the hydrological cycle. The rock glaciers, a manifestation of ice-rich permafrost, could be regionally important for sustaining the streamflow, especially in the lean season in the Himalaya. Several rock glacier inventories have been developed for high-mountain areas worldwide. However, there are sporadic studies that have characterized rock glaciers in the Himalaya. In this study, a comprehensive rock glacier inventory has been generated for the western Himalayan regions of Jammu-Kashmir and trans-Himalayan Ladakh spread over six mountain ranges utilizing optical satellite images from Google Earth and Sentinel 2A. The inventory has characterized each rock glacier with 22 attributes following the guidelines of the International Permafrost Association (IPA). The inventory contains 5492 rock glaciers (4973 intact and 519 relict) with a total area of 573 km^2 and an average area of 0.1 km^2. The highest number of rock glaciers (n=1772) were found in the Zanskar range and the lowest (n=311) were found in the Pir Panjal range. The majority of rock glaciers (~83%) have a talus origin, and the remaining ~17% have a glacier origin. The inventory reports 4756 tongue-shaped and 736 lobate rock glaciers. The average Potential Incoming Solar Radiation (PISR) was observed to be 511 (kWH m^{-2}). The rock glaciers are located between the elevation range of 3301 m asl and 5605 m asl with 63% of these having a north- or northeast- or northwest-facing aspect. The Mean Annual Air Temperature (MAAT) and precipitation of the rock glaciers range from -8 °C to 8 °C (mean -4°C) and 71 mm to 1135 mm (mean 328 mm), respectively. The rock glacier inventory provides direct evidence of the presence of permafrost in this ecologically sensitive region and provides a lower bound on the elevation of the permafrost. This inventory shall serve as a baseline for the future hydrological impacts of permafrost and its response to regional climate change. The rock glacier inventory is publicly available at https://doi.org/10.5281/zenodo.10559297 (Bhat et al., 2024).

https://doi.org/10.5194/essd-2023-522
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1. Introduction

Permafrost, the ground that remains at a temperature of 0 ˚C or below for at least two consecutive years, is an important component of the cryosphere (Dobiński, 2020; Jafarov et al., 2012; Romanovsky et al., 2010). It is tightly coupled with Earth's surface energy balance, and any change in this relationship can have serious implications for gaseous exchange and geomorphological processes (Stiegler et al., 2016; Stuenzi et al., 2021). Permafrost is a subsurface phenomenon and may not always be visible on the surface. However, rock glaciers, thermokarst characteristics, frost heave, patterned ground, and other traits indicate the presence of permafrost in various environments (Karlsson et al., 2012).

Rock glaciers, an important subset of permafrost, are cryo-conditioned landscapes or flowing bodies of coarse talus and the granular regolith with interstitial ice (Berthling and Etzelmüller, 2011). Morphologically, rock glaciers are lobate or tongue-shaped bodies with surface features, such as furrows, swales, and ridges, and show movement from a few centimetres to meters per year downslope by gravity-induced creep (Kääb et al., 2021; Groh et al., 2019). These are important components of high mountain systems and act as direct proxies and visual indicators of mountain permafrost (Barsch, 1996; Berthling and Etzelmüller, 2011; Haeberli, 1985). Rock glaciers define the lower limit of mountain permafrost in terms of the elevational distribution of landforms in glacial and periglacial environments (Haeberli et al., 2006; Lilleøren et al., 2013). The present or past climate plays an important role in the formation of rock glaciers, and their existence has been attributed to the continental climate (Haeberli, 1985). Consequently, rock glaciers are climatically and hydrologically important, contain valuable amounts of water (Bolch and Marchenko, 2009; Brighenti et al., 2021; Jones et al., 2018, 2021), and act as potential water reservoirs, particularly in semi-arid and arid mountains (Azócar and Brenning, 2010; Rangecroft et al., 2014). With anticipated climate change and warming temperatures, rock glaciers are expected to play a significant role in sustaining constant streamflow in the affected areas (Janke et al., 2015). Rock glaciers are classified as intact or relict: lack of vegetation on the surface, negative mean annual surface temperature (MAST), and increasing velocity distinguish intact rock glaciers from relict rock glaciers (Barsch, 2012; Ikeda and Matsuoka, 2002; Kofler et al., 2020). The rock glaciers are characterised by a 0.5 to 5 m thick, seasonally frozen active layer of clastic-blocky material (Jones, 2020). This active layer creates an insulating effect and slows the rate of ice melt within the rock glacier, thus thermally decoupling it from external micro- and meso-climates (Jones et al., 2019). Warming and thawing of rock glaciers due to increased temperatures can lead to thinning of the active layer and has the potential to change the sediment transfer systems, thus altering the frequency and magnitude of natural hazards, such as rock avalanches and debris flows (Beniston et al., 2018; Delaloye et al., 2013; Schmid et al., 2015a; Schoeneich et al., 2015). These mass movements have the potential to cause lake outbursts (Allen et al., 2009; Haeberli, 2013; Kääb, 2008). This also has the potential to change the land use and land cover (LULC) of these areas because LULC is connected to the presence of a water table perched on permafrost (Pandey et al., 2022).

Comprehensive research has been conducted to understand the spatial distribution of glaciers and snowfields in the western Himalayan region (Frey et al., 2012; Kulkarni et al., 2010). Conversely, very little research effort has been made to map and

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monitor the permafrost extent and spatial distribution of rock glaciers in the Himalayan region, particularly in the Western Himalaya. Information regarding the spatial distribution of rock glaciers and mountain permafrost could be an essential approach for paleoclimatic modelling (Colucci et al., 2016; Duguay et al., 2015). Therefore, it is necessary to understand the distribution and occurrence of these phenomena at a regional scale for targeted risk assessment and land-use planning (Haeberli et al., 2010).

The identification and compilation of rock glacier inventories using automated methods is challenging (Millar and Westfall, 2008). The complex terrain and varied topographic characteristics of rock glaciers make it difficult to develop a universal algorithm that can accurately map them in different mountain ranges with varying topography (Millar and Westfall, 2008). However, rock glaciers can be easily detected from high-resolution satellite images and used as first-order approximations for mapping and defining the distribution of mountain permafrost (Buckel et al., 2022). Several studies have been conducted on permafrost and rock glaciers in the Himalayan region (Khan et al., 2021; Schmid et al., 2015; Pandey et al.,2022). These studies have been sporadic, geographically dispersed, and limited in terms of long-term measurements and evidence of rock glaciers (Gruber et al., 2017).

Rock glacier inventories have been compiled for various mountain ranges across the world. For example, inventories exist in the European Alps (Kellerer-Pirklbauer et al., 2012; Krainer and Ribis, 2012), Andes (Falaschi et al., 2015; Rangecroft et al., 2014), Rockies (Janke, 2007; Liu et al., 2013), and Hindukush Himalaya (Baral et al., 2020; Haq and Baral, 2019a; Hassan et al., 2021; Jones et al., 2018; Pandey, 2019). Therefore, the current study attempts to create an inventory of rock glaciers in the Himalayan and trans-Himalayan regions of Jammu-Kashmir and Ladakh, respectively. This investigation will be the first step in determining the distribution of rock glaciers in this ecologically fragile area. Moreover, it can help assess potential risks, such as rockfalls, landslides, and slope instability associated with permafrost degradation. These considerations hold utmost significance in guiding land utilisation strategies and the strategic development of infrastructure, which could ultimately contribute to the long-term wellness of the environment and local population.

2. Data and methods

2.1 Study area

The geographic domain of analysis, comprising of Jammu-Kashmir and trans-Himalayan Ladakh, which constitute the northwestern part of the Himalaya, is situated between 32° 28' - 37° 06' latitude and 72° 53' - 80° 32' longitude at an altitudinal range of 220 - 8611 m asl (Fig. 1).

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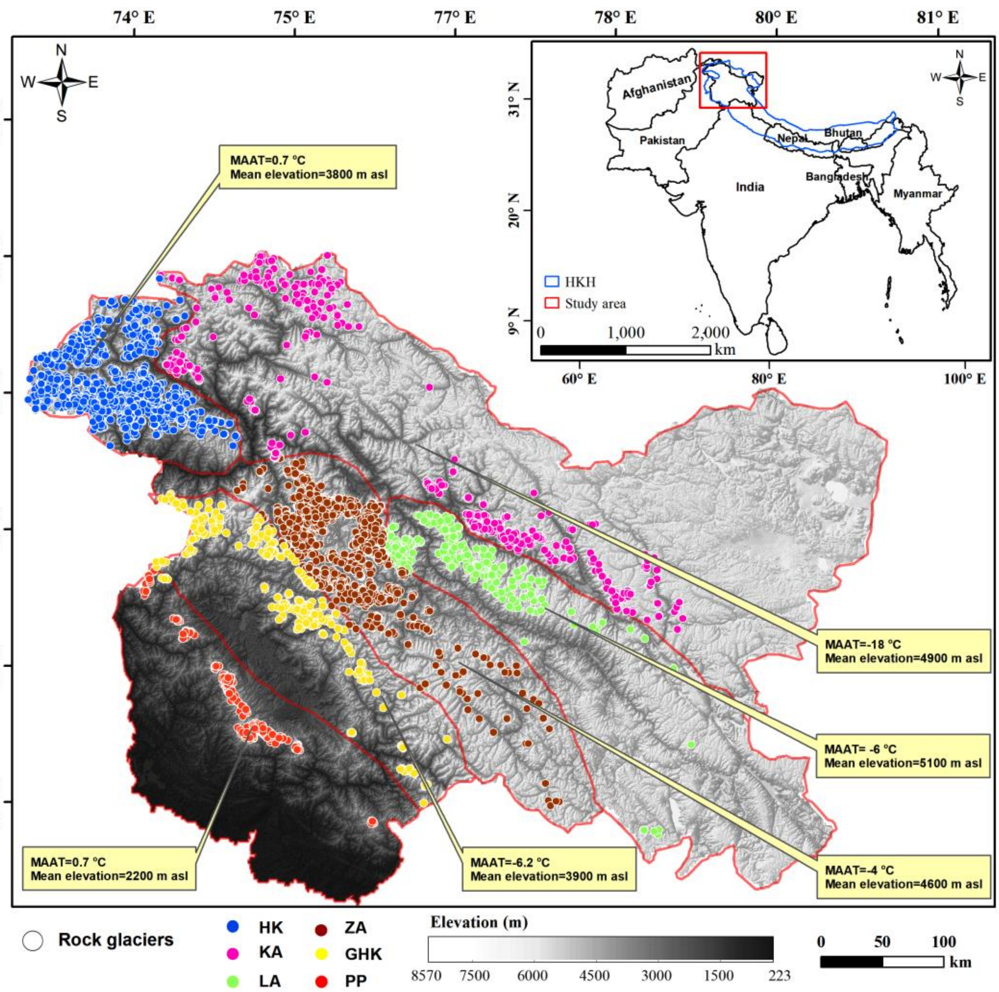

Figure 1. Depicts the study area and emphasizes the different mountain ranges and their climatic and topographic characteristics Hindukush (HK), Karakoram (KA), Ladakh (LA), Zanskar (ZA), Greater Himalaya of Kashmir (GH) and Pir Panjal (PP)

The study area is spread over 2,22,236 km^2 and is divided into three physiographic regions, Jammu, Kashmir, and Ladakh, with ~80% of the total area comprising mountains (Gupta, 2018). Approximately 75% of the study area falls under the alpine zone (>3300 m asl) while 25% of the area falls under the subalpine zone (Romshoo et al., 2020). In this study, rock glacier mapping was carried out above 3300 m asl elevation since this region is periglacial hosting 11436 glaciers (Bajracharya, 2011) with favourable environmental, topographic, and climatic conditions for permafrost occurrence. Meltwater from these glaciers and permafrost acts as the main source of water for rivers and streams in the region (Thayyen and Gergan, 2010). Geomorphic and climatic factors including cold, humid, and dry climates have a significant impact on the formation of these landscapes. Due to the location of part of this area in subtropical latitudes and small-scale altitudinal variation of relief, the climate found in most parts is similar to that of mountainous and continental temperate latitudes (Humlum, 1998). The climate type ranges

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from the cold, arid, and dry desert region of Ladakh in the north, the temperate zone of the Kashmir valley in the middle, and hot plains of Jammu in the south (Jee, 2020). The mountainous northern and central parts of this region receive annual precipitation in the form of rain and snow, whereas the southern plains receive precipitation from the monsoonal rain (Romshoo et al., 2020). This region has a highly heterogeneous lithology and contains some of the finest developments in stratigraphic succession from the Archaean Era to the present (Dhang, 2016).

2.1.1 Datasets used

Currently, a lot of research literature is available that focuses on the automatic and semi-automated mapping of glaciers from satellite imagery (Baraka et al., 2020; Kaushik et al., 2019); however, these approaches make it difficult to map rock glaciers and debris-covered glaciers, because the debris cover that originates from surrounding valley rock results in the loss of distinctiveness in spectral signatures (Brenning, 2009). Therefore, the present rock glacier inventory was compiled by using the widely employed manual digitization from freely available Google Earth (version 7.3.4.8642). It is pertinent to mention that Google Earth imagery has been used in various previous studies (Majeed et al., 2022; Pandey, 2019; Schmid et al., 2015b) to compile rock glacier inventories. Google Earth provides multitemporal satellite data from the early 1990s, which provides an opportunity to obtain cloud-free, snow-free, and shadow-free images, thereby reducing the ambiguity (Johnson et al., 2021). Google Earth uses high-resolution SPOT images or digital globe products, such as IKONOS and Quick Bird, and provides several tools for the creation of databases and delineating features (points, lines, and polygons). Additionally, it supports the creation of shapefiles which can be exported as Keyhole Markup Language (KML) for further analysis in various GIS-based software. However, Google Earth imagery has limited temporal coverage for certain areas which limits the data selection. Sentinel-2A images with a ten-day revisit time and 10 m spatial resolution were used to address this issue. Sentinel-2A provides both the spectral and spatial details of the landscape and has been previously used in various cryosphere studies; however, it has rarely been employed in permafrost or rock glacier studies (Haq and Baral, 2019b). Therefore, cloud-free Sentinel-2A images of the summer months (usually snow-free periods) were used to delineate and validate the rock glacier inventory. Sentinel-2A imagery was downloaded from the Copernicus Scientific Data Hub website as a Level 1C product. The validation process of rock glaciers extracted from Google Earth imagery, as well as the subsequent manual digitisation of the remaining rock glaciers, was performed using ArcGIS 10.1 software.

2.1.2 Identification and classification of rock glaciers

The study area comprises a vast geographic expanse which presents a significant challenge to exhaustive mapping of rock glaciers. Rock glacier mapping is a subjective approach that relies heavily on the identification of geomorphic characteristics unique to these features, such as ridge and furrow topography, steepness of frontal and lateral slopes, swollen ground, and distinct textures (Roer and Nyenhuis, 2007) (Fig. 2). A thorough and comprehensive literature review was conducted to critically evaluate the previous studies on this topic (Table 1). In this study, the methodology of Jones et al. (2018) and IPA

(Delaloye et al., 2018) was adopted, which offers a solid and organized framework for the analysis of rock glaciers. The methodology enhances the reliability of findings and promoting consistency to address subjectivity-related identification and classification issues of rock glaciers. The 1 km grid was created on the entire study area in ArcMap 10.1 using the '*create fishnet*' tool. The fishnet was then overlaid on Google Earth and each grid cell was visually inspected on an individual basis. A scale of 1:2000 or better was used for the identification of rock glaciers, and the perimeter was delineated manually for each candidate on Google Earth. The nature of rock glaciers makes the delineated boundaries inherently uncertain. While this is an unavoidable problem, we performed a thorough analysis of the uncertainty involved, which is presented in section 2.1.4.

A total of 22 attributes were calculated for each rock glacier to provide quantitative information for further analysis and comparison of the inventory (Table 1). The rock glacier unit ID (RGUID) for each rock glacier was assigned automatically according to IPA guidelines. The RGUID consists of RGU (Rock Glacier Unit) followed by 12 to 15 digits, determined by the latitude and longitude values, with four digits consistently appearing after the degrees. The area of the rock glaciers was calculated in square kilometres using ArcMap10.1. Based on the extent of activity, the mapped rock glaciers were classified as intact or relict (Fig. 3). Intact rock glaciers contain active and inactive rock glaciers which are differentiated based on their ice content, variations in movement, and sedimentary contributions (Baral et al., 2020; Lilleøren and Etzelmüller, 2011). Because our mapping effort relied exclusively on visual inspection, distinguishing these features from visual cues is challenging. Therefore, following Scotti et al. (2013) active and inactive rock glaciers were placed under the intact group.

Table 1. Comprehensive review and evaluation of previous rock glacier inventories across different mountain ranges of the world

Region	Number of rock glaciers	Elevation range	Reference
Hindukush Himalaya	702	3500- 5500	Schmid et al. (2015)
Himachal Pradesh	516	3052-5503	Panday (2022)
Uttarakhand	1004	>4000	Baral et al. (2020)
Nepal Himalaya	6000	3225-5675	Jones et al. (2018)
Central Himalaya	370	4000-6000	Rastner et al. (2021)
Jhelum basin	231	3019-4633	Majeed et al. (2022)
Arid West Kunlun	413	3389-5541	Hu et al. (2023)
Hunza Basin	616	2800-5700	Hassan et al. (2021)
Daxue Shan	344	3860-5094	Cai et al. (2021)
Alaknanda Valley	198	4270-5200	Pandey et al. (2022)
Sikkim	185	2341-7878	Haq and Baral (2019)
Guokalariju	5053	4800-5400	Li et al. (2022)

Furthermore, the rock glaciers were classified as talus-derived or glacier-derived based on their source of sedimentary material (Fig. 4). Rock glaciers with source material talus slopes are classified as talus-derived, whereas rock glaciers with source material glacier moraine and glacial ice with associated sedimentary material are classified as glacier-derived (Humlum, 2000; Scotti et al., 2013).

The rock glaciers were classified as tongue-shaped or lobate based on their length-to-width ratio (Lw). Rock glaciers with $Lw < 1$ were classified as lobate, whereas those with $Lw \geq 1$ were classified as tongue-shaped. Lw was calculated both automatically and manually. In the automated method the length of rock glacier was calculated based on the maximum and minimum coordinates in both the X and Y dimensions and width were determined by the taking the ratio of area (A) to the length (L). In the manual method the length and width were calculated using the '*Measure*' tool in ArcGIS 10.1, the length in the direction of flow and width perpendicular to length (Fig. 5). However, the manual approach has been found to be the more robust method and was hence adopted in this study. When employing the automatic approach, it was revealed that 60 rock glaciers showed varying results compared to the manual approach (Fig. S1). A manual re-evaluation revealed that the manual approach produced more accurate results. For automatic calculations, the following equations were established using R programming:

$$L = \sqrt{(X_{max} - X_{min})^2 + (Y_{max} - Y_{min})^2} \qquad \ldots(1)$$

where X_{max} and X_{min} respectively represent the highest and lowest x-coordinate of the rock glacier, and Y_{max} and Y_{min} respectively represent the highest and lowest y-coordinate of the rock glacier.

$$W = A/L \qquad \ldots(2)$$

where W represents the width of a rock glacier

$$L_w = \mathrm{L/W} \qquad \ldots(3)$$

2.1.3 Extraction of topoclimatic parameters

The freely distributed Copernicus digital elevation model (GLO-30), with a spatial resolution of 30 m, was used for the analysis of topographic parameters. The topographic parameters of elevation, slope, and majority aspect, were calculated by using the raster functions in ArcGIS10.1 "*Spatial Analyst*" tool. Further, the GLO-30 DEM was also used for the determination of PISR using the tool "*Area Solar Radiation*". The concept of Sattler et al. (2016) was adopted, and the snow-free period from July to September was selected for PISR. PISR values were calculated in kilowatt-hours per square meter (kWH m^{-2}). The climatic characteristics of rock glaciers that include MAAT and precipitation were extracted from WorldClim version 2.1 climate data (Fick and Hijmans, 2017).

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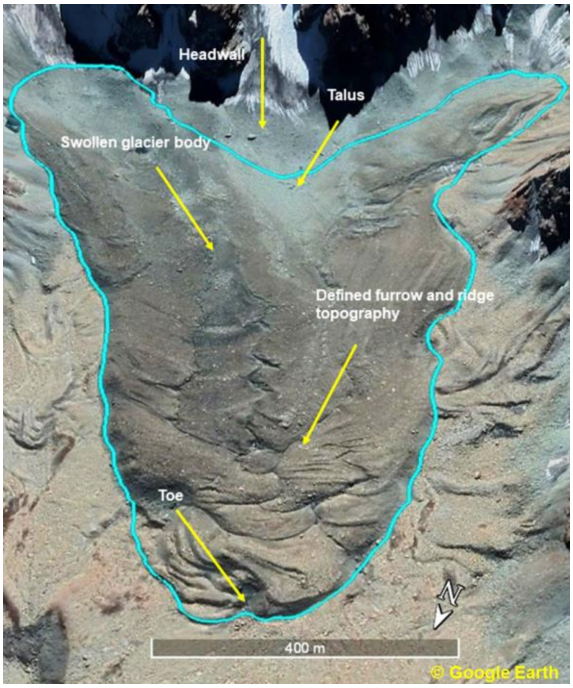

Figure 2. Illustrates the unique surface characteristics of rock glacier and challenges for identifying the boundary upper and lower end of the rock glacier due to its irregular flow patterns and adjacent landforms.

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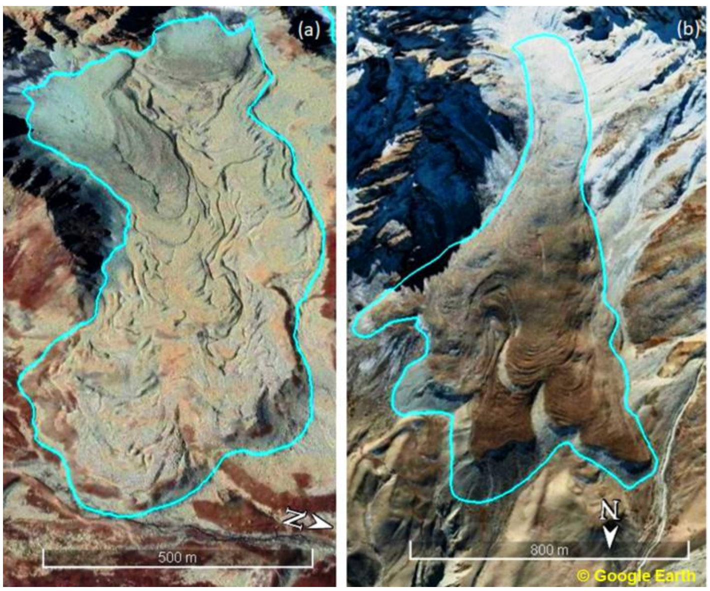

Figure 3. Visual representation of two types of the rock glaciers. (a) Intact rock glacier with RGID-RGU339410N744018E, (b) Relict rock glacier with RGID-RGU351133N763472E.

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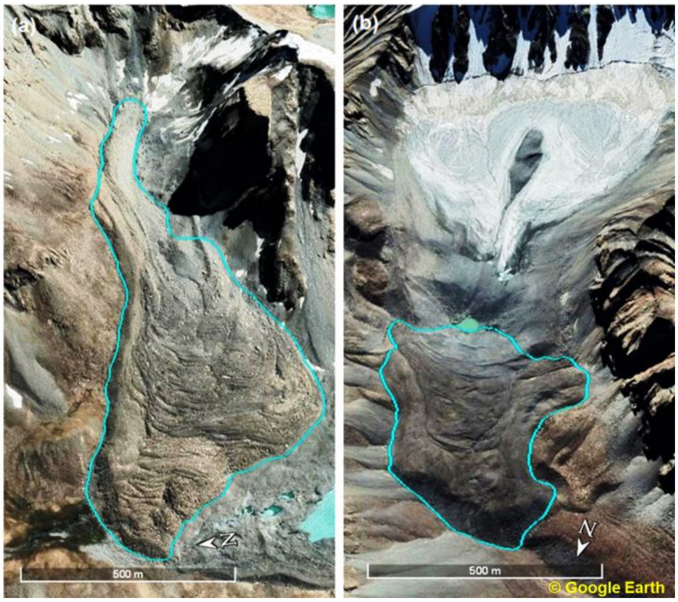

Figure 4. Classification of rock glaciers based on source (a) Talus-derived with RGIDRGU359030N730756E (b) Glacier-derived with RGID RGU359681N730191E. Satellite image credits: Google Earth.

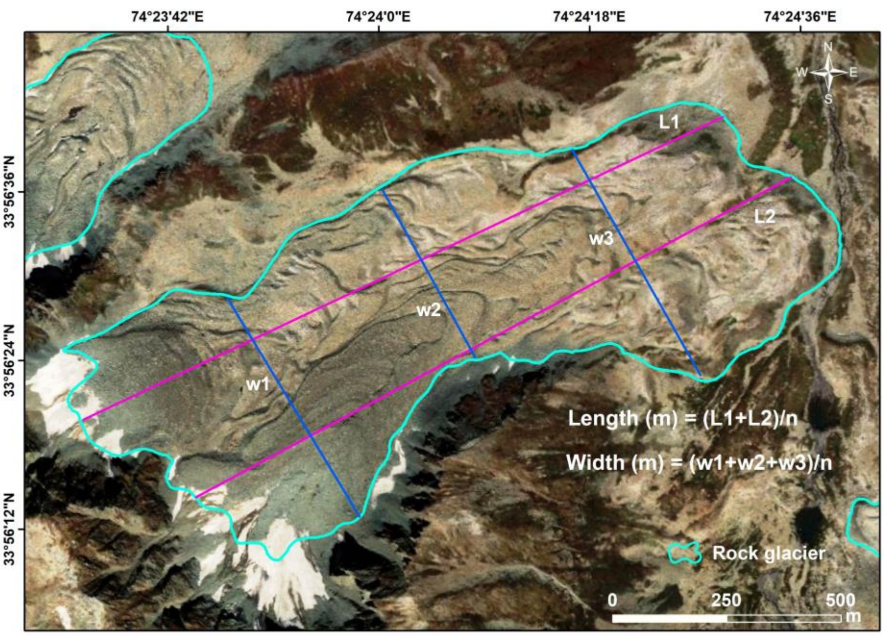

Figure 5. A conceptual representation of computing *Lw* for each rock glacier in ArcMap 10.1 by considering average measurements of two lengths and three widths. Satellite image credits: ESRI Basemap, ArcMap 10.1.

2.1.4 Uncertainty Analysis

Accurately identifying the upper and lower boundaries of rock glaciers poses a significant challenge due to irregular surface morphology, variable flow dynamics and gradual transitions with surrounding terrain (Fig. 2). These challenges underscore the need for more comprehensive approaches to identify the rock glacier boundaries precisely (Pandey; 2019). In this study a robust approach was employed to quantify the uncertainty associated with the cognitive aspects of delineating rock glacier inventory outlines. This approach allowed us to capture potential variations and subjectivity in delineating the extent of rock glaciers. To achieve this, we selected a representative dataset comprising 20 rock glaciers and distributed their centroids among 6 proficient remote sensing experts with glacier mapping experience to delineate rock glacier extents to account for cognitive error in our mapping (Table. S1).

The following equations were employed for the calculation of cognition and digitisation errors:

$$\varepsilon_c = \frac{\sigma}{\mu} \times 100 \qquad \ldots(4)$$

where ε_c is the cognition error, σ is the standard deviation in area, and μ is the mean area.

$$\varepsilon_d = n \times \frac{\lambda^2}{2} \qquad \ldots(5)$$

where ε_d is the digitisation error, n is the number of pixels on which the rock glacier outline falls, and λ is the spatial resolution of the data.

The total error (ε_t) was calculated by adding the cognitive error and digitisation error as:

$$\varepsilon_t = (\varepsilon_c + \varepsilon_c) \qquad \ldots(6)$$

3 Results

3.1 Overall distribution

We identified 5492 rock glaciers distributed across different mountain ranges in the study area. The identified rock glaciers comprise 4973 intact rock glaciers and 519 relict rock glaciers covering an area of 573 km^2 (average=0.10 km^2). A total of 4582 rock glaciers (83%) have talus origin, while the remaining 910 rock glaciers (17%) have glacier origin. The *Lw* of 4756 rock glaciers is greater than 1 and classified as tongue-shaped, while the *Lw* of 736 rock glaciers was found to be less than 1 and classified as lobate type. Topographically, the rock glaciers are located between elevations of 3300 m asl and 5605 m asl (average = 4476 m asl), with an average slope of 15.79. Climatically the Mean Annual Air Temperature (MAAT) and

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precipitation of the rock glaciers were ranging from -8 ˚C to 8 ˚C (mean -4˚C) and 71 mm to 1135 mm (mean 328 mm), respectively. The analysis reports that the highest and lowest values of PISR for rock glaciers are 748 kWh m^{-2} and 0.0014 kWh m^{-2} respectively, with an average of 511 kWh m^{-2}. The study further revealed that the overall aspect of rock glaciers is predominantly north facing. Overall, ~64% (3500) of rock glaciers have a north-facing aspect, with 30% (1673) facing north, 17% (937) northwest, and 16% (890) northeast. On contrary, 36% (1992) of rock glaciers exhibit a non-northerly orientation, among which 5% (254) face southeast, followed by 6% (345) east, 10% (581) west, 7% (363) south, and 8% (449) southwest.

3.1.1 Range-wise distribution

The largest number of rock glaciers were found in the ZA range and the lowest in the PP range. The decreasing order of rock glaciers in different mountain ranges is ZA> HK>LA>KA>GH>PP. The precipitation followed increasing trend from north to south: LH (192 mm) < ZA (275 mm) < KA (376 mm) < HK (389 mm) < GH (460 mm) < PP (573 mm). MAAT showed a similar increase: LH (-5.7 ˚C) < KA (-4.9 ˚C) < ZA (-4.5 ˚C) < HK (3.2 ˚C) < GH (-2.3 ˚C) < PP (-2.5 ˚C).

In the ZA Range, 1772 rock glaciers were found (intact=1606 and relict=166), of which 1472 rock glaciers have a talus origin, while 300 rock glaciers have a glacier origin (Fig. 6b). The rock glaciers cover an area of 162 km^2 (mean 0.10 km^2). Based on *Lw*, 1497 rock glaciers were classified as tongue-shaped, while 275 rock glaciers were classified as lobate (Fig. 6b). The average elevation of the rock glaciers in this range is 4518 m asl, the average slope is 15.6˚, average *Lw* is 2.4, and the average PISR is 524 kWh m^{-2} (Fig. 7). Climatically MAAT and precipitation of the rock glaciers were ranging from -9 ˚C to 3 ˚C (mean -4.5˚C) and 80 mm to 1106 mm (mean 275 mm), respectively (Fig. 7). In the ZA range, the majority 66% (1180) of the observed rock glaciers exhibit a north-facing aspect. Among this subset, 30% (535) were oriented directly towards the north, followed by 17% (311) northeast, and 19% (334) northwest. The remaining 34% 592 of rock glaciers displayed southerly orientation, with 12% (210) facing west, 7% (128) southwest, 5% (88) south, 6% (108) east, and 3% (58) southeast.

In HK, 1750 rock glaciers were found (intact=1606 and relict=166), of which 1461 rock glaciers have a talus origin, whereas 289 rock glaciers have a glacier origin (Fig. 6a). The rock glaciers cover an area of 162 km^2 (mean 0.10 km^2). Based on *Lw*, 1518 rock glaciers were classified as tongue-shaped, whereas 232 rock glaciers were classified as lobate (Fig. 6a). The average elevation of rock glaciers in HK is 4399 m asl, the average slope is 15˚, the average *Lw* is 2.7 m and the average PISR is 523 kWh m^{-2} (Fig. 7). Climatically MAAT and precipitation of the rock glaciers were ranging from -9 ˚C to 5 ˚C (mean -3˚C) and 79 mm to 1063 mm (mean 389 mm), respectively (Fig. 7). In the HK range, most rock glaciers 67% (1178) exhibit a north-facing aspect Among this subset, 34% (591) were oriented toward the north (N), followed by 17% (306) northeast, and 16% (281) northwest. The remaining 33% (572) of the rock glaciers have a non-northerly aspect, with 9% (167) west, followed by 8% (135) southwest, 5% (90) south, 6% (104) east, and 4% (76) southeast.

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In the LA Range, 684 rock glaciers were found (intact=616 and relict=68), of which 601 rock glaciers have a talus origin, whereas 83 rock glaciers have a glacier origin (Fig. 6c). The rock glaciers are spread over an area of 80 km^2 (mean 0.11 km^2). Based on *Lw*, 563 rock glaciers were classified as tongue-shaped, whereas 121 rock glaciers were classified as lobate (Fig. 6c). The average elevation of rock glaciers in LA range is 4864 m asl, the average slope is 15˚, the average *Lw* is 2.6 m and the average PISR is 530 kWh m^{-2} (Fig. 7). Climatically MAAT and precipitation of the rock glaciers were ranging from -10 ˚C to 3 ˚C (mean -5˚C) and 75 mm to 1060 mm (mean 197 mm), respectively (Fig. 7). In this range, most rock glaciers 61% (415) exhibit a north-facing aspect. Among this subset, 29% (199) are oriented toward the north, followed by 16% (109) northeast, and 16% (107) northwest. The remaining 39% (269) of the rock glaciers exhibit a non-northerly orientation, with 9% (64) facing west, followed by 7% (49) southwest, 6% (43) south, 8% (58) east, and 8% (55) southeast.

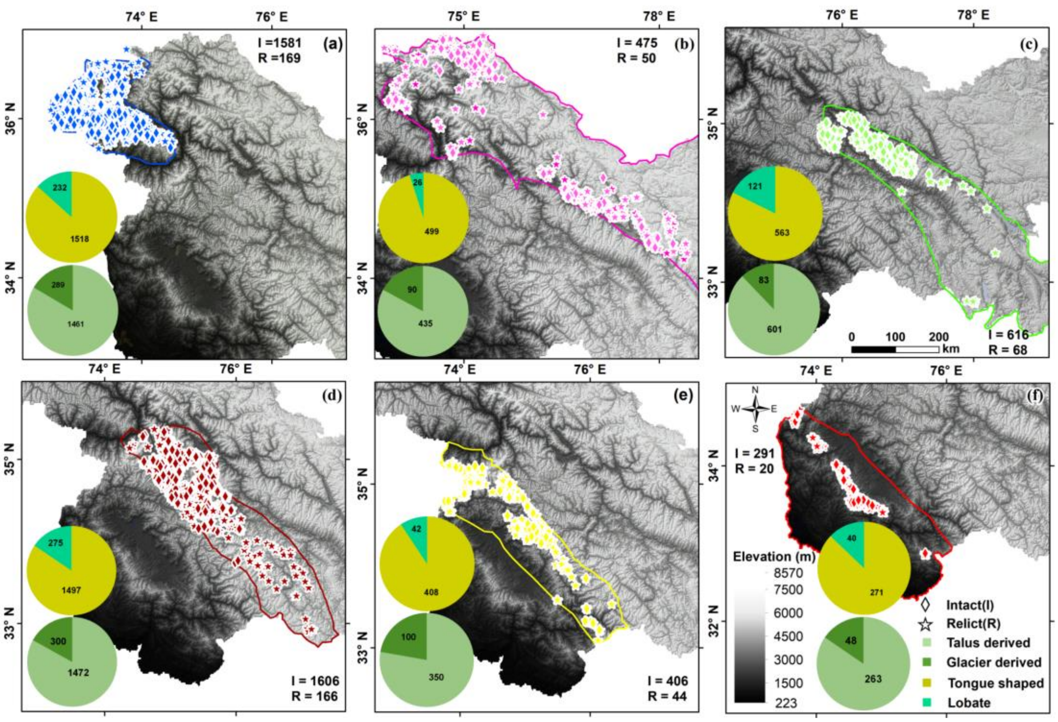

Figure 6. Geographical distribution and current status of rock glaciers in various mountain ranges: (a) HK - Hindukush, (b) ZA - Zanskar range, (c) LA - Ladakh range, (d) KA - Karakorum range, (e) GH - Greater Himalaya Kashmir, and (f) PP-Pir Panjal range

In the KA Range, 525 rock glaciers were found (intact=475 and relict=50), of which 435 rock glaciers have a talus origin, whereas 90 rock glaciers have glacier origin (Fig. 6d). The rock glaciers cover an area of 91 km^2 (mean 0.11 km^2). Based on *Lw*, 499 rock glaciers were classified as tongue-shaped, whereas 26 were classified as lobate (Fig. 6d). The average elevation of rock glaciers in this range is 4656 m asl, the average slope is 17˚, the average *Lw* is 3.6 m, and the average PISR is 474 kWh

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m^{-2} (Fig. 7). Climatically MAAT and precipitation of the rock glaciers were ranging from -11.5 ˚C to 3.5 ˚C (mean -5˚C) and 71 mm to 1135 mm (mean 228 mm), respectively (Fig. 7). Most rock glaciers 45% (339) in this range exhibit a south-facing aspect. Among this subset, 21% (111) are south-oriented, followed by 14% (76) southwest, and 10% (52) southeast. The remaining 55% (186) of rock glaciers exhibit a non-southerly orientation, with 16% (86) facing north, followed by 11% (60) northeast, 10% (54) west, 9% (46) east, and 8% (40) northwest.

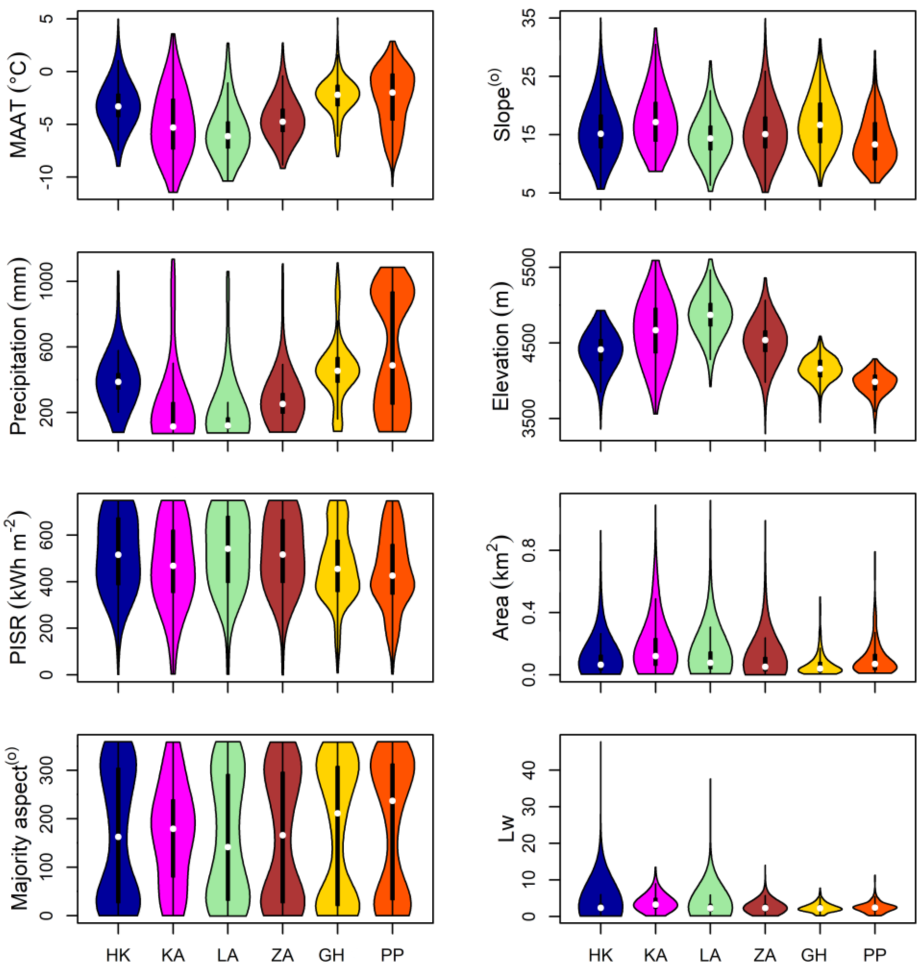

Figure 7. Geographic, topographic, and climatic characteristics of the rock glaciers across different mountain ranges in the study area.

In the GH Range, 450 rock glaciers were found (intact=406 and relict=90), of which 350 rock glaciers have a talus origin, whereas 101 rock glaciers have a glacier origin (Fig. 6e). The rock glaciers cover an area of 30 km^2 (mean 0.06 km^2). Based on *Lw*, 408 rock glaciers were classified as tongue-shaped, whereas 42 rock glaciers were classified as lobate (Fig. 6e). The

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average elevation of rock glaciers in this range is 4158 m asl, the average slope is 17.2°, the average *Lw* is 2.4 m and the average PISR is 470 kWh m^{-2} (Fig. 7). Climatically MAAT and precipitation of the rock glaciers were ranging from -8 °C to 8 °C (mean -2°C) and 85 mm to 1113 mm (mean 460 mm), respectively (Fig. 7). In the GHK range, most of the observed rock glaciers 71% (320) exhibited a north-facing aspect. Among this subset, 36% (163) were oriented towards the north, followed by 13% (57) northeast, and 22% (100) northwest. The remaining 29% (130) of rock glaciers exhibited other orientations, with 10% (46) facing west, followed by 8% (38) southwest, 5% (21) south, 4% (20) east, and 1% (5) southeast.

Table 2. Rock glacier inventory attribute data

Attribute name	Attribute Description	Attribute Unit
FID	Feature ID - Unique identifier for each feature assigned automatically.	Unitless
Shape	Spatial geometry of a feature	Unitless
RGID	The RGID for each rock glacier was calculated from latitude and longitude	Unitless
AREA	The total area of rock glacier	Square kilometres (km^2)
RG_CLASS	Rock glacier class	Intact or relict
SOURCE	Talus-derived or glacier-derived	Unitless
LW_m	Length-to-width ratio (Manual measurement)	Unitless
LW_a	Length-to-width ratio (Automatic measurement)	Unitless
RG_SHAPE	Tongue-shaped and lobate	Unitless
LAT	Latitude of the centroid of the glacier	WGS84 Decimal degrees
LONG	Longitude of the centroid of the glacier	WGS84 Decimal degrees
M_ASP	Mean aspect – Average orientation of slope surfaces	Degrees
ELEV	The mean elevation of a rock glacier	m asl
MAX_ELV	The maximum elevation of a rock glacier	m asl
MIN_ELV	The minimum elevation of a rock glacier	m asl
SLOPE	The mean slope of the glacier	Degrees
M_RANGE	Mountain ranges: HK, KA, LA, ZA, GHK, PP	Unitless
PISR	Potential incoming solar radiation	(kWH m^{-2})
MAAT	Mean annual air temperature	Degree Celsius
PPT	Annual Average precipitation	Millimetres
PERIM	The total boundary length of a rock glacier (perimeter)	Meters
ASP_CLASS	Major aspect classes of a rock glacier (N, NE, E, SE, S, SW, W, NW)	Unitless

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In the PP Range, 311 rock glaciers were found (intact=291 and relict=20), of which 263 rock glaciers have a talus origin, whereas 48 rock glaciers have a glacier origin (Fig. 6f). The rock glaciers cover an area of 33 km^2 (mean 0.10 km^2). Based on *Lw*, 271 rock glaciers were classified as tongue-shaped, whereas 40 were classified as lobate (Fig. 6f). The average elevation of the rock glaciers in this range is 3965 m asl, the average slope is 14˚, the average *Lw* is 2.5 m, and the average PISR is 444 kWh m^{-2} (Fig. 7). Climatically MAAT and precipitation of the rock glaciers were ranging from -11 ˚C to 3 ˚C (mean -2.5˚C) and 82 mm to 1086 mm (mean 570 mm), respectively. In the PP range, majority of the observed rock glaciers 70% (221) exhibited a north-facing aspect (Fig. 7). Among this subset, 31% (99) were north-oriented, followed by 15% (47) northeast, and 24% (75) northwest. The remaining 30% (90) of the rock glaciers displayed other non-northerly orientations, with 13% (40) facing west, 7% (10), 3% south, 3% (9) east, and 2% (8) southeast.

4 Discussion

The main aim of this study was to generate the first comprehensive rock glacier inventory for the study area and analyse their spatial distribution, morphometry, and potential influencing factors. These findings could contribute to a better understanding of rock glacier dynamics in the Himalayan region. The inventory consists of 5492 rock glaciers spread across diverse mountain ranges that exhibit varied geomorphic and climatic characteristics. The majority of rock glaciers (86%) were found to have talus origin, and the remaining rock glaciers (16 %) were glacier origin.

Rock glaciers were predominately found in the ZA mountain range, consisting of (32.2%), followed by HK (31.8%), LA (12.4%), KA (9.5%), GH (8.1%), and PP (6%). The HK and trans-Himalayan Mountain ranges (ZA, LA, and KA) are located at higher elevations (You et al., 2017; Schmidt and Nüsser, 2017) ensuring colder temperatures that favour the formation of rock glaciers. Dry climatic conditions with limited precipitation and low humidity preserve permafrost, prevent interstitial ice melting in rock glaciers, and maintain rock debris cohesion and rock glacier stability (Jorgenson et al., 2010). The trans-Himalayas possess a unique climatic phenomenon, as studied by Dahri et al. (2016), called rain shadowing, in which mountains act as barriers and intercept moisture-laden clouds, causing precipitation on the windward side. The leeward side experiences scanty precipitation, and the climate of these mountain ranges is cold and arid, which is favourable for the development of rock glaciers (Barsch, 1996). Similarly, other environmental factors, such as freeze-thaw cycles and steep slopes, enhance the weathering and disintegration of rocks into talus material, which in turn promotes the formation of talus rock glaciers. The results of our analysis show a definite and substantial link between lower MAAT values and the occurrence of rock glaciers in the study region. This indicates that cold temperatures play a crucial role in the formation and preservation of the rock glaciers. The average PISR values of the rock glaciers were highest in the ZA, followed by LA, HK, KA, GH, and PP. The lowest PISR values of GH and PP were due to the location of the majority of rock glaciers in the mountain valleys. The valleys receive little solar radiation, because the surrounding mountains shield sunlight for a significant portion of the day. Additionally, lower elevations in these ranges can lead to higher air pollution levels (Rashid et al., 2022), which further block sunlight and contribute to lower PISR values. Conversely, the high PISR in ZA and LA is primarily attributed to their high-

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altitude locations, clear skies, and lesser air pollution. These factors could be responsible for the higher PISR values of rock glaciers in these mountain ranges.

Previous research in the Hindukush Himalayan region has consistently revealed the uniform elevation distribution patterns of rock glaciers across different mountain ranges. In the neighbouring Himachal Himalaya, the elevation range of the rock glaciers has been reported to be 3052-5503 m asl (Pandey, 2019), whereas it is slightly higher (3225-5675 m asl) in the Nepalese Himalaya (Jones et al., 2018). In the Karakorum region, the elevation range (3500-5500 m asl), particularly the lower limit, is the highest (Schmid et al., 2015). The present study identifies the location of rock glaciers between the elevation of 3300 m asl and 5605 m asl. By comparing these studies, it is evident that the elevation range of rock glaciers is fairly consistent across the mountain ranges along the Himalayan arc. The findings imply that the rock glaciers are typically located between 3300 m and 5605 m asl, which closely aligns with the elevation ranges proclaimed in the aforementioned studies. The heterogeneity of the elevation distribution of rock glaciers across these diverse Himalayan regions suggests climatic, topographical, and geological control. Furthermore, the analysis revealed that a significant proportion (64%) of the rock glaciers are oriented towards the northern aspect. The northern slope aspects generally receive less direct sunlight than the southern slope aspects which helps preserve ice and maintain the stability of the rock glaciers. These findings are consistent with those of previous studies conducted in the Hindukush Himalayan region (Jones et al., 2018; Wang et al., 2017).

4.1. Inventory Validation

Field validation, ground-based surveys, and in situ measurements are valuable for validating the results to obtain more accurate measurements of rock glacier dimensions and internal structures, including length, width, and slope. However, it is extremely difficult to visit rock glaciers in remotely rugged topographic and climatic settings. Nevertheless, we performed an on-field validation of 10 rock glaciers in the PP range through extensive fieldwork campaigns (Fig. S3). The PP range lacks typical glaciers; instead, it hosts many rock glaciers, making it a crucial resource for downstream population. The inhabitants living in the lower regions rely on rock glaciers for the steady supply of water for drinking and irrigation. During field visits, the rock glaciers were physically examined, taking note of their morphological features such as the presence of ice, ice-mixed debris, and the overall shape and size of the landforms. This direct observation provides valuable insights and serves as a means of confirming the accuracy of the inventory. The comprehensive validation efforts undertaken through field visits and the use of satellite imagery have contributed to establishing the accuracy and reliability of the rock glacier inventory in the PP Range. The field observations were in close agreement with the digitised rock glaciers. This rigorous validation process ensures that the inventory is a robust resource for future research, management, and decision making related to rock glacier water reserves in the region. Further the error analysis revealed that the uncertainty associated with the cognitive aspects of delineating rock glacier inventory outlines is about 6% in the spatial extent of rock glaciers and digitisation error showed an error of 0.5%. According to the IPA Action Group (Delaloye et al., 2018), achieving 10% agreement is considered indicative of a strong

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consensus. Therefore, the attained 6% variability underscores high-level agreement and quantifies the effectiveness of our approach associated with the rock glacier inventory (Fig. S2).

4.2. Possible applications of the inventory

This comprehensive rock glacier inventory will provide a baseline data and first-hand knowledge regarding the distribution of permafrost to stakeholders, national and local disaster management authorities, border road organisation, and tourist development authorities. This will help them implement sustainable strategies and set up environment-friendly development and construction projects in fragile permafrost areas. Consequently, this proactive approach can play a significant role in preserving these periglacial environments, while promoting sustainable regional development by informing the policy makers about this less researched but important component of cryosphere. Integration of the rock glacier inventory of a region with environmental and climatic variables, such as precipitation, temperature, slope, aspect, and solar radiation, will enable the development of robust models for identifying and monitoring areas with potential permafrost (Boeckli et al., 2012). This inventory could also contribute to climate change research by providing data for modelling and simulations focused on assessing the impact of climate change on the distribution of permafrost. Furthermore, the inventory will provide valuable insights to water managers about the precise location and size of these features. This information could be important for the management of water resources, especially in arid and semi-arid regions, and could play a vital role in meeting the water demands of downstream areas and communities.

5 Data Availability

Data described in this manuscript can be accessed at Zenodo under https://doi.org/10.5281/zenodo.10559297 (Bhat et al., 2024).

6 Conclusion

We present the first comprehensive rock glacier inventory for the western Himalayan regions of Jammu-Kashmir and Ladakh as on year 2023. The inventory encompasses 5492 rock glaciers covering an area of 573 km^2 and an average area of 0.1 km^2. The rock glaciers are distributed across different mountain ranges with distinctive topographies and climatic conditions, with the highest proportion of rock glaciers in the ZA mountain range and the lowest in the PP range. It was found that 4973 rock glaciers are intact, and 511 are relict. The proportion of tongue-shaped rock glaciers is significantly higher (4756), whereas lobate-shaped are relatively less common accounting for 736 rock glaciers. The majority (83%) of rock glaciers have a talus origin, while the remaining (17%) rock glaciers have a glacial origin. Furthermore, the analysis revealed that 64% of the rock glaciers are oriented towards the northern aspect (N, NE, and NW). Topographically, rock glaciers are found within an elevation range of 3300-5606 m asl. It is pertinent to mention that the present study fills the research gap by providing information on the number, geographic distribution, and properties of rock glaciers in the western Himalaya, a region where

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such data have been lacking. Additionally, this inventory of rock glaciers will serve as a foundation for future research focusing on permafrost and/or rock glacier dynamics, particularly with reference to the prevalent climate warming over the region. In addition, the inventory is potentially significant for policymakers, especially in arid and semi-arid areas, where rock glaciers play a crucial role in supplying water for both drinking and irrigation to communities living downstream.

Supplementary information

The supplement related to this article is available online at:

Author Contributions

Imtiyaz Ahmad Bhat wrote the first draft of the manuscript, performed analysis and executed R scripts. Irfan Rashid conceptualized the study and wrote a large part of the manuscript along with the first author. RAAJ Ramsankaran, Argha Banerjee and Saurabh Vijay modified the draft manuscript and provided constructive suggestions to improve the quality of the work. Irfan Rashid and RAAJ Ramsankaran jointly supervised the first author in generating this knowledge product.

Competing Interests

The authors declare that they have no conflict of interest.

Acknowledgements

The research work was conducted as part of the Science and Engineering Research Board, Department of Science and Technology (SERB-DST), Government of India-sponsored Core Research Grant [CRG/2020/000053] titled "Permafrost distribution and dynamics over Jammu and Kashmir Himalaya from remote sensing, in-situ measurements and machine learning". The financial assistance received from the Department under the project to accomplish this research is gratefully acknowledged.

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Preprint. Discussion started: 5 February 2024

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