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Received 17 December 2024
Revised 24 January 2025
Accepted 11 February 2025

Glacier retreat and morphological changes in the Suru Sub Basin of Ladakh region from 1992 to 2023

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Abstract

Purpose – The present study aims to develop glacier inventories for year 1992 and 2023 in Suru Sub Basin and classify them based on Global Land Ice Measurement from Space (GLIMS). The retreat analysis is carried out for 29 glaciers based on their snout positions.

Design/methodology/approach – Landsat TM/OLI sensors data were used along with ASTER DEM to identify and map glacier boundary which was further validated by Google Earth imagery. The retreat was calculated using centreline method for demarcating retreating snout based on elevation change. The field measurement was further used to validate the snout change in Parkachik Glacier.

Findings – In total, 214 glacier were identified in 2023 with 52.8% north facing glaciers. There is a significant decline of 24.9% area in 31 years. The average glaciers retreat is recorded to be 23.6% in all the glaciers between 1992 and 2023. Snout retreat of Glacier-18 shows highest retreat of 45.8 m/yr.

The authors would like to express their sincere gratitude to the United States Geological Survey (USGS) for providing free access to the Landsat satellite data, which was crucial for the completion of this study. We also extend our appreciation to all individuals and institutions that contributed to the research.

Conflicts of interest/competing interests: The authors declare that they have no conflicts of interest or competing interests.

Data availability: The data that support the findings of this study are available from the corresponding author, Rayees Ahmed, upon reasonable request.

Authors contributions: Sakshi Mankotia: Conceptualization, data collection, analysis, Writing – original draft. Masood Ahsan Siddiqui: Supervision, methodology, data validation, review and editing. Rayees Rashid*: Supervision, project administration, data interpretation, writing – review and editing. Tania Nasrin: Visualization, GIS analysis, data curation. Intikhab Ahmad: Statistical analysis, software application. Mohd Ramiz: Data acquisition, literature review.

Frontiers in Engineering and Built Environment
Vol. 5 No. 2, 2025
pp. 152-172
Emerald Publishing Limited
e-ISSN: 2634-2502
p-ISSN: 2634-2499
DOI 10.1108/FEBE-12-2024-0087

Originality/value – The study used a long-term data to calculate glacier retreat pattern with combination of satellite data and field measurement which adds ground truth and validate the study. Findings may help policymakers and stakeholders to understand climate adaptation strategies in the region.

Keywords Glacier morphology, GLIMS, Glacier classification, Retreat analysis, Suru river sub-basin

Paper type Research paper

1. Introduction

Glaciers are important part of earth cryosphere and are under consistent threat of melting due to global warming and climate change (Wang, 2024). Himalayan glaciers are rapidly receding due to climate change, posing significant challenges for communities dependent on their meltwater (Bolch *et al.*, 2019; Pritchard, 2019; Azam, 2021). The role of temperature is critical in the analysis of glacier health in Himalayas as there is a much greater influence of westerlies and Indian monsoon (Bookhagen and Burbank, 2010; Bolch *et al.*, 2012). These two phenomena gave rise to diverse pattern of glacier response in changing climatic condition (Fujita and Nuimura, 2011; Scherler *et al.*, 2011; Bolch *et al.*, 2012). Many researches on Himalayan glaciers indicates that there are diverse and inconsistent patterns of glaciers response across the Karakoram – Himalayan mountain region (Bolch *et al.*, 2012; Kääb *et al.*, 2012; Azam *et al.*, 2018) which create glaciers anomaly by increasing the glacier mass balance (Scherler *et al.*, 2011; Bolch *et al.*, 2012; Negi *et al.*, 2021). In the past century, the Himalayan region has undergone a warming trend (Bhutiyani, 2015) that surpasses the global average temperature increase of 0.85 °C, ranging from approximately 0.9 to 1.6 °C (Bolch *et al.*, 2012, 2019; Kääb *et al.*, 2012; Shukla and Ali, 2016).

The rate of warming in the Himalayas will exceed the global average 0.7 °C ± 0.18 in the next 100 years (Bindoff *et al.*, 2007). The projections indicated 0.5–1 °C by 2020 and 1–3°C by middle of the century (Christensn *et al.*, 2013) which significantly affect over 1.5 billion people in India who rely on glacier-fed rivers for water supply (Basnett *et al.*, 2013; Pandey *et al.*, 2013) particularly crucial for agriculture. The consequences are profound, as glacier melt supports hydro power needs (Bolch *et al.*, 2019; Frey *et al.*, 2014; Garg *et al.*, 2021), and sustains human populations, supports ecosystems and biodiversity. Globally numerous studies have shown the estimated glacier mass change to range between 0–38 and 0.6 m.w.e over the last decades (Jacob *et al.*, 2012; Chen *et al.*, 2013), whereas the Himalaya region has undergone mass loss between −0.14 and −0.21 m.w.e, indicating severe rate of mass loss in particular than global average (Kääb *et al.*, 2012). Several global initiatives, like the World Glacier Monitoring Service (Gärtner-Roer *et al.*, 2019) Global Land Ice Measurement from Space (GLIMS) (Bishop *et al.*, 2004; Rau *et al.*, 2005; Ali *et al.*, 2023), the GlobGlacier project (Rounce *et al.*, 2023; Berthier *et al.*, 2023), ICIMOD (Bajracharya and Shrestha, 2011; Romshoo *et al.*, 2021; Soheb *et al.*, 2022) and the Randolph Glacier Inventory (Mishra *et al.*, 2023), aim to catalog glaciers. However, they lack a consistent and complete inventory for the Himalaya region, creating an urgent need for a standardized database. Recently, a comprehensive glacier inventory suggests Himalayan glaciers are retreating more rapidly than those in the Hindu Kush and Karakoram, with area losses ranging from 5% to 55% over the past 3 decades (Bolch *et al.*, 2019).Thus regional understanding is required with multi-temporal glacier inventories paired with high-resolution climate data for assessing regional glacier changes.

There is a lack of database for the glaciers in the Ladakh region due to their inaccessibility and difficult terrain. Because of these challenges only a small number of glaciers in the region have been monitored on the ground (Fujita *et al.*, 2011; Scherler *et al.*, 2011; Bolch *et al.*, 2012; Azam *et al.*, 2018; Dobhal *et al.*, 2013). Thus there is a need of continous and close monitoring of glaciers to understand the dynamics of their retreat and predict future changes. During the exploration, researchers have created a timeline of previous glaciations records in the region to understand the behavior (Shukla *et al.*, 2018; Azam *et al.*, 2021) and impact on regional landscape (Zeitler *et al.*, 2001). This has decoded the formation of Himalayan glaciers and its response to changing climate ever since. Several glaciological investigations in this area concentrate either on individual glaciers or on compiling glacier inventories of smaller sub-basins (Fujita *et al.*, 2011;

Scherler *et al.*, 2011; Bolch *et al.*, 2012). Temporal analysis of 15 glaciers had been conducted between 1997 and 2016 explaining area reduction by 6.2% and increase retreat rate from 16 to 23 m/yr in Suru basin (Shukla *et al.*, 2020a, b). Similarly, consistent reduction in mass balance (-0.69 ± 0.28) m.w.e, has been reported in 75 glaciers of Suru basin between 1994 and 2018 (Garg *et al.*, 2021). Study over Parkachik Glacier in Suru basin showed average retreat of 20 ± 21 m/yr from 2015 to 2021 with decreased surface velocity of 28% (Rana *et al.*, 2023). Previous studies in the basin have primarily focused on selective glaciers. In this study, all ranges of small and large size glaciers have been identified and mapped, proving a holistic approach to glacier analysis to understand their morphology and behaviour in detail.

This study introduces a new multi-temporal glacier inventory for the Suru Sub Basin, India, spanning 31 years of changes from 1992 to 2023. This updated dataset and analysis of glacier distribution aims to enhance the understanding of glacier dynamics and the effects of climate change on glacier types, their elevation and area in the Ladakh region. However, it has been observed that there is a lack of comprehensive study, incorporating the types of glaciers being affected since 1992. Consequently, remote sensing satellite data, such as Landsat, have become crucial tools for conducting extensive and long-term glaciological studies (Bolch *et al.*, 2008; Raj, 2011; Basnett *et al.*, 2013; Raj *et al.*, 2017*)*. The inventories are entirely based on Landsat images, primarily acquired during Ablation period (September/October), with additional verification using Google Earth imagery. Hence, in this study, the objectives are (1) accurate glacier inventory for 1992 and 2023, (2) standardize illustration to classify glaciers (3) characteristics of glaciers within the region (4) their retreat rate.

2. Methods and materials

2.1 Study area

Suru basin is located in the southern part of District Kargil, Union territory of Ladakh. The geographical coordinates of the region are 33°94′ to 34°15 N to 75°66′ to 76°50 E. The region is drained by Suru river, which originates from Pensilungpa Glacier (Shukla *et al.*, 2020a, b; Garg *et al.*, 2021). The river passes through Parkachik Village and merges into river Indus at Nurla (Shukla *et al.*, 2020a, b, 2018; Garg *et al.*, 2018). The region falls between Ladakh range in the North and Zanskar range in the south in Figure 1. As winter precipitation extremes are brought on by mid latitude westerlies, the positioning of Suru sub basin allows to receive significant amount of moisture (Dimri *et al.*, 2018). The region experiences downpour brought by westerlies, brining snowfall in the basin. The mean annual precipitation and temperature recorded at Kargil weather station is 121 mm and −8.4 to 17.5 °C (Lone *et al.*, 2017), respectively. As per India Meteorological Department (IMD), during 1901–2002, the average annual temperature of Suru Sub-basin is −5.3 °C and average annual precipitation 588.77 mm at Kargil (Shukla *et al.*, 2020a, b).

The basin is a part of Indus river system; Previous studies suggests the presence of 18,495 glaciers (Bajracharya *et al.*, 2019). The estimated area of the basin is 4,511 km^2 covering 26.6% of glaciated area of the basin Table (S2). Suru Sub basin contains huge peaks such as Nun and Kun with estimated elevation (7,100–7,400 m). This study focuses on building an inventory by identifying and mapping the glaciers to further classifying them based of GLIMS classification. As the maximum concentration of the glaciers is located at the southern position of the basin, thus Suru Sub Basin has been selected as the study area.

2.2 Materials

For glacier mapping, there is a need for sophisticated data utilization. In this study, Landsat satellite data were adopted for the years 1992, 1998, 2009, 2020 and 2023. The data are downloaded from https://earthexplorer.usgs.gov/, with the low cloud cover preference (less than 7%). Landsat datasets have been proven to be highly effective for mapping clean glacier ice. The months were selected based on specific conditions like peak glacier melting period, i.e. the ablation period (August/September/October) which has little snow and cloud cover to

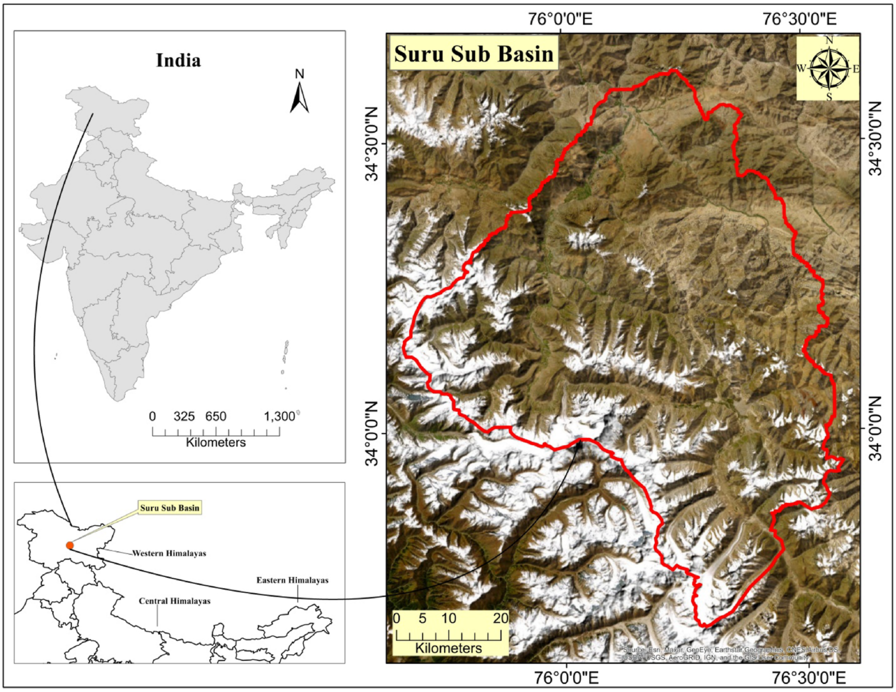

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Figure 1. Location map of Suru Sub Basin

understand the seasonal snow cover and help in drawing positive conclusion for glaciers boundaries demarcation (Bhambri *et al.*, 2012; Pandey *et al.*, 2013; Shukla and Ali, 2016) were carried out with the ArcGIS 10.8 software platform. Detailed information regarding the imagery employed in the research is provided in Table 1.

To effectively delineate individual glaciers along their drainage divides and calculate specific topographic parameters such as minimum, maximum, mean, and median elevation, mean slope and mean aspect, a digital elevation model (DEM) of suitable quality and resolution is necessary. Global elevation datasets, the ASTER Global Digital Elevation Model (GDEM), cover nearly the entire basin offer adequate accuracy for compiling topographic glacier inventory data (Frey *et al.*, 2012). GDEM version has been extensively used in various glaciological studies, particularly in assessing ice volume variations over time (Berthier *et al.*, 2007). The study utilized Advanced Spaceborne Thermal Emission and Reflection Radiometer global digital elevation model (ASTER GDEM) scenes for tasks such as basin delineation and the computation of slope, aspect and elevation for glaciers (Figure 2). These tasks, including glacier digitization, basin delineation, and area calculation have been done using four ASTER GDEM tiles with 1-degree coverage, downloaded and mosaic together in ENVI software. The ASTER GDEM, with a spatial resolution of 30 meters, is used to cover the entire study region. The methodology adopted in the present study is illustrated in Figure 3.

2.3 Methods

The Landsat data were preprocessed using ERDAS Imagine software. Initially, layer stacking was performed, and a mosaic was created from the satellite images. The basin was delineated from the ASTER Digital Elevation Model (DEM) and further clipped using the Spatial Analyst

Table 1. Details of the satellite data and digital elevation model (DEM) used in this study

Data set	Sensor	Spatial resolution	Date of acquisition	Path/row	Cloud cover (%)
Landsat (4–5)	TM	30	24-10-1992	148/036	1
				148/037	4
			09-10-1998	148/036	2
				148/037	4
			07-10-2009	148/036	3
				148/037	6
Landsat (8)	OLI/ TIRS	15	19-09-2020	148/037	2.93
				148/036	1.53
			28-9-2023	148/036	2.77
				148/037	2.79
ASTER GDEM		30	04-09-2000	33/75, 33/76, 34/75, 34/76	

Source(s): Table by authors

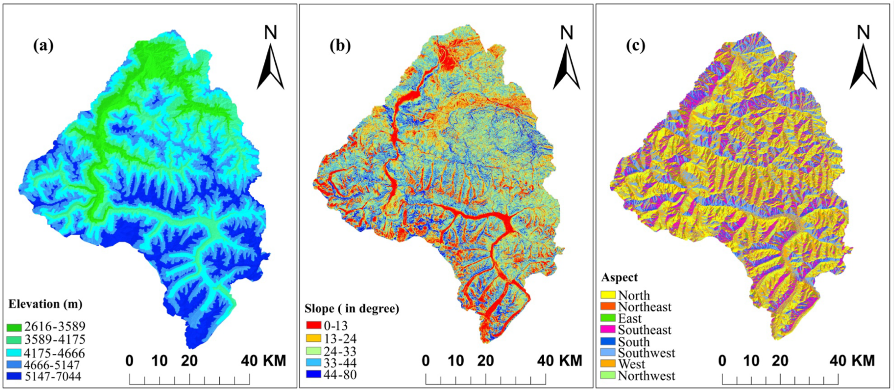

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Figure 2. Topographic thematic maps: (a) elevation, (b) slope, (c) aspect

tool in ArcGIS software. To get the accuracy, corrections were applied to minimize errors due to solar radiation, atmospheric conditions and topographic variations. Accuracy assessment was conducted through visual interpretation using Google Earth Pro. Field samples collected from the Parkachik Glacier in 2021 were also used for validation, with corresponding imagery for these years reviewed through Google Earth Pro. Various multispectral indices were employed to highlight specific features such as snow, ice, debris and terrain. Band ratio techniques were applied to enhance the identification and mapping of these features, providing a more detailed and accurate representation of the glacier characteristics.

2.3.1 Mapping of clean ice. Clean ice glaciers which is free of debris cover can be accurately mapped using band ratios (Racoviteanu *et al.*, 2008). The NDSI snow detection method, extensively utilized in assessing snow cover variability (Burns *et al.*, 2014; Man *et al.*, 2014; Mityók *et al.*, 2018; Zhang *et al.*, 2019), NDSI values were computed for each Landsat image NDSI pixel values using green and short-wave infrared bands. Here, green represents the reflectance degree in the green visible spectrum (band 2 in Landsat TM and band 3 in OLI), and swir denotes the short-wave infrared band—either 5 for TM or 6 for OLI. This resultant index, ranging from 0 to 100, signifies the degree of reflection in a pixel area corresponding to the electromagnetic spectrum associated with snow (i.e. the spectral signature of snow).

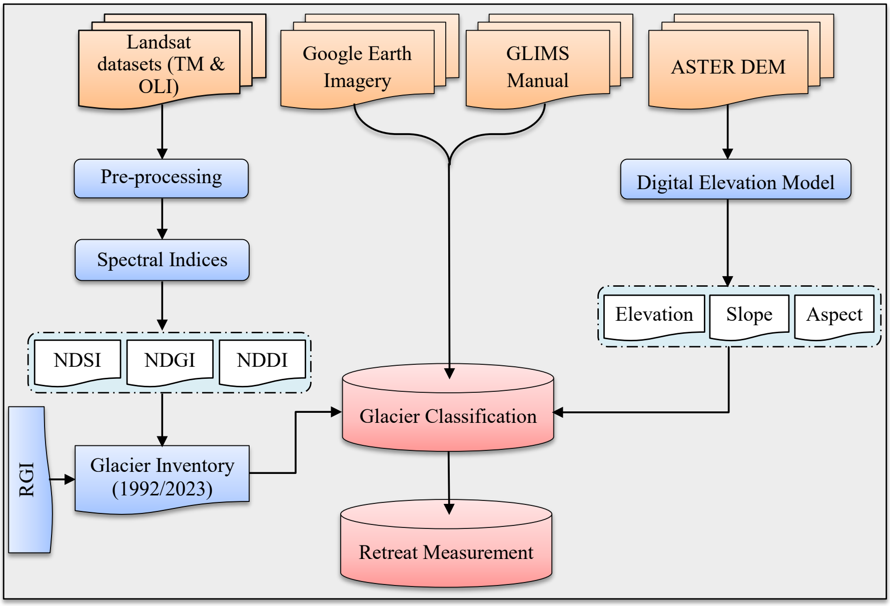

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Figure 3. The flowchart of identification, mapping and classification methodology

Normalized difference snow index (NDSI). NDSI primarily helps differentiate between snow/ice and non-snow/ice surfaces, making it valuable for identifying snow cover extent (Dozier, 1989).

$$\mathrm{NDSI} = \frac{GREEN - SWIR}{GREEN + SWIR} \tag{1}$$

2.3.2 Mapping of debris cover. Normalized difference debris index (NDDI): For mapping and differentiating between supraglacial debris and other surface materials (Shukla and Ali, 2016).

$$\mathrm{NDDI} = \frac{SWIR - TIRS}{SWIR - TIRS} \tag{2}$$

Normalized difference glacier index (NDGI): NDGI assists in distinguishing debris-covered areas from clean ice/snow surfaces, providing insights into glacier debris cover distribution (Keshri *et al.*, 2009)

$$\mathrm{NDGI} = \frac{GREEN - RED}{GREEN + RED} \tag{3}$$

Equations (1), (2) and (3) are used in establishing the inventory Figure 4 of both the years.

2.3.3 Glacier boundary demarcation. The glacier boundary delineation involves two ways Automatic Mapping of Clean Glacier Areas, utilizing a band ratio Equation (1, 2, 3) approach between Near Infrared (NIR) and Shortwave Infrared (SWIR) bands of Landsat OLI images. A threshold of 0.4 (NIR/SWIR) is applied to delineate the clean part of glaciers (Wang *et al.*, 2020; Singh *et al.*, 2021). This method helps distinguish glacier pixels from water features and is effective in areas with low snow/cloud cover. The manual correction of glacier outlines,

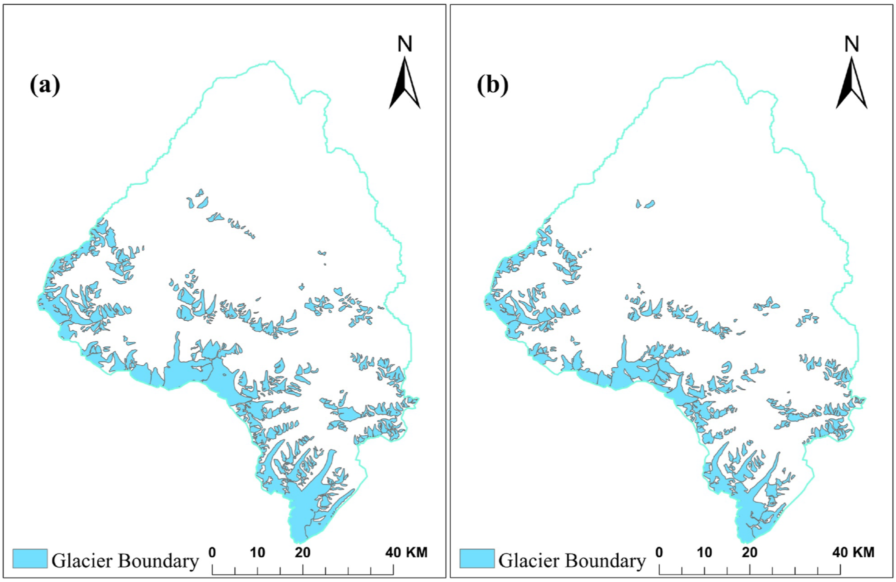

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Figure 4. Glacier inventory (a) 1992 and (b) 2023

especially focusing on areas with debris cover. The glacier is delineation according to the guidelines outlined in the GLIMS manual (http://www.glims.org/MapsAndDocs/guides.html). Randolph Glacier Inventory (RGI) version 6.0 from 2002 as the baseline for glacier outlines. These outlines were then refined and modified using cloud-free Landsat 4/8 (TM/OLI/TIRS) satellite images spanning the period from 1992 to 2023. This process involves digitizing on standard false-color composites (FCC) generated from Landsat TM/ETM+/OLI imagery. While this method has proven effective, it also minimizes human error, as recognition of glacier terrain features (Albert, 2002). The method's accuracy is instrumental in discerning characteristics such as seasonal snow, clouds and shadows. It relies on a standardized combination of spectral bands, often complemented by image enhancement techniques and DEM-derived parameters, facilitating the differentiation between glacial and non-glaciated surfaces. Geomorphic features such as moraine-dammed lakes and steep ice walls at terminus play a pivotal role in precisely delineating glacier terminus and extent. Satellite imagery from the ablation period is considered particularly suitable for this purpose.

2.3.4 Glacier classification. Glacier classification in this study followed the GLIMS Classification Manual Table (S1) provides standardized methods for categorizing glaciers based on size, shape and type. By employing the GLIMS classification system, the study systematically categorized glaciers in the region based on attributes such as shape, presence of debris cover and movement pattern. This approach ensures consistency and accuracy across different glacier studies, facilitating global comparison and analysis of glacier data.

3. Results

3.1 Glacier inventory

Glacier inventory is the first step in understanding the nature of glaciers in a region. The glaciers were mapped, and inventory was prepared for 1992 and 2023. The glacier indices such as Normalized Difference Debris Index (NDDI), Normalized Difference Glacier Index

(NDGI) and Normalized Difference Snow Index (NDSI) were used to enhance the identification of glaciers in the basin. In study area, about 317 glaciers were recorded which covers an area of about 811 km^2 shown (Figure 4). Moving to 2023, the number of glacier have dropped to 214, with a significantly reduction in area of 608.6 km^2. This represents a staggering decline of 202.4 km^2 marking a 24.9% reduction in glaciated area in just 3 decades.

3.2 Distribution of glaciers

3.2.1 Distribution based on size. The examination of glacier changes in the region from 1992 to 2023, shown in Table 2, demonstrates considerable changes across different glacier size categories, emphasizing the continued impact of climate change and other environmental factors on glacial retreat and degradation. The general trend indicates a significant loss in the number of glaciers, with the total number falling from 317 in 1992 to 214 in 2023, representing a 24.9% decrease. The number of glacierets and snow fields (less than 0.1 km^2) increased from 23 to 33, representing a 16% area change. This could imply glacier fragmentation or the emergence of new snow fields due to changing climate conditions. Mountain glaciers in the 0.1–1 and 1–5 km^2 size ranges decreased dramatically from 143 to 77 (30.6% drop) and 119 to 79 (11.1% decrease), indicating considerable glacial retreat caused by rising temperatures and changing precipitation patterns. The number of valley and mountain glaciers in the 5–10 km^2 category declined by 41.4%, indicating significant ice loss in these larger and more stable glaciers. The greatest glaciers (above 10 km^2) experienced a smaller number fall from 12 to 10 but a 29.1% area change, indicating significant surface area reduction due to thinning and retreat at glacier snouts. The widespread loss in glacier numbers and area across all size categories demonstrates the pervasive influence of climate change on glacial environments. The disproportionate decline in smaller glaciers suggests their greater vulnerability to climatic changes, whilst the significant area reduction in larger glaciers highlights their susceptibility to long-term warming. These changes have far-reaching ramifications for water resources, as glaciers are important suppliers of freshwater. The loss of glacial mass can result in decreased water availability during dry spells, affecting agriculture, drinking water supply and overall ecosystem stability in the region.

3.2.2 Distribution based on aspect. The study reveals that the north-western and eastern glaciers are experiencing the highest retreat rates between 1992 and 2023 i.e. 31.9 and 31.7%, respectively. North facing glaciers have reduced by 23.9% between 1992 and 2023. The south facing glaciers are losing their area by 21.8%. South-western and north-eastern glaciers have been retreating with moderate rates of 19.5 and 17.3%, respectively. South east and west facing glaciers demonstrated relative stable retreat, i.e. 8.1 and 2.6%. The varying retreat rates between orientations emphasize the complex interaction of factors impacting glacial dynamics, with north-western and eastern glaciers being more vulnerable to climate change. Understanding these orientation-specific dynamics is critical for forecasting future

Table 2. Changes in glacier numbers and area by size categories from 1992 to 2023

Based on size (Km^2)	Number of glaciers 1992	2023	Area change (%)	Type of glacier
Less than 0.1	23	33	−16	Glacierets and snow-field
0.1–1	143	77	−30.6	Mountain glaciers
1–5	119	79	−11.1	Mountain glaciers
5–10	20	15	−41.4	Valley and mountain glaciers
Above 10	12	10	−29.1	Valley glaciers
Total	317	214		

Source(s): Table by authors

glacier changes and managing water resources, necessitating additional research into local meteorological conditions, topography and other environmental factors.

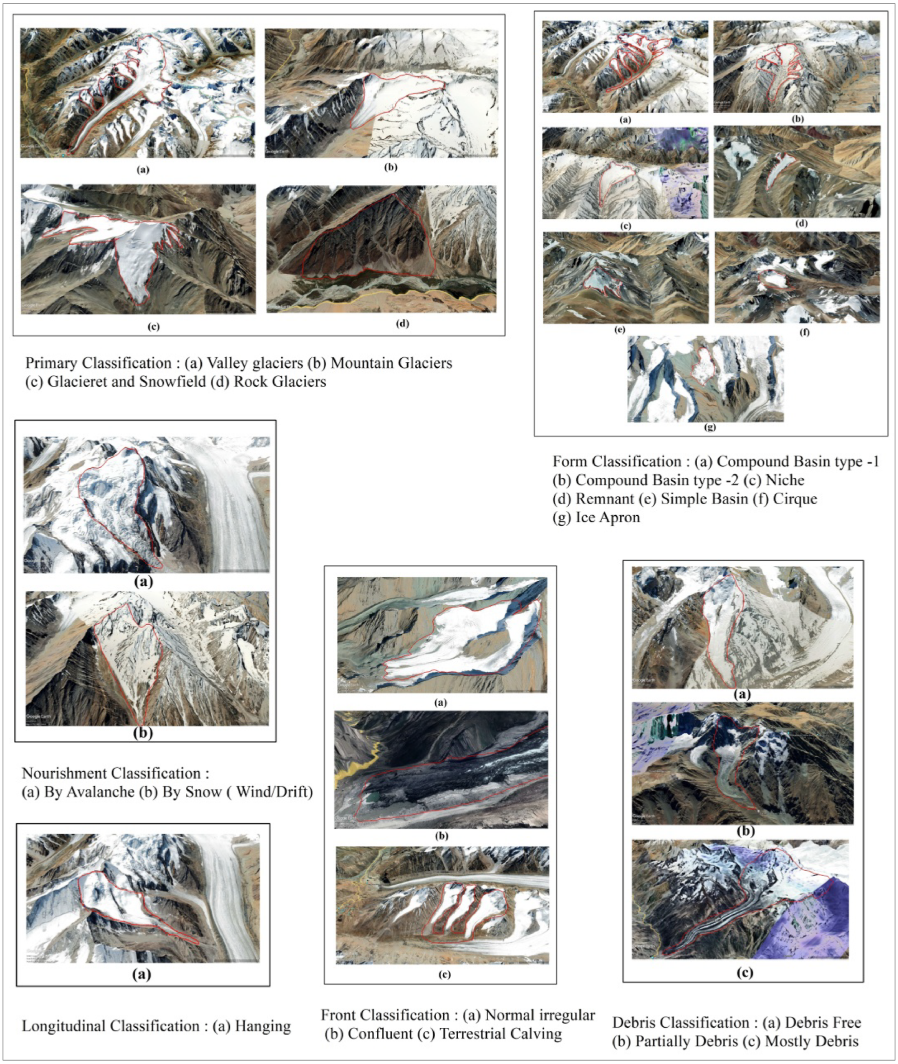
3.2.3 Distribution based on elevation. The distribution of glacier elevations was categorized into four distinct groups. Glaciers located at elevations of 6,000 m and above accounted for 2.3% of the total glaciers. In the range of 5,500–6,000 m, glaciers covered 47.6% of the area, indicating a significant portion of high-altitude glacier coverage. Glaciers positioned between 5,000 and 5,500 m represented 45.3% while those within the 4,500–5,000 m range contributed 4.6% of the overall glacier coverage, highlighting the diverse distribution of glaciers across different altitude zones. The analysis of the distribution of glacier elevations reveals several key insights into the geographical characteristics of the study area. Firstly, the data show a clear trend of decreasing glacier number as elevation increases, i.e. 75% loss of glaciers above 6,000 m. Glaciers located at higher elevations, specifically between 5,500–5,000 m, account for a significant decrease by 37.8%. Secondly above 5,000 meters, there is combine coverage of 92.5% of glaciers. This indicates the prevalence of large, high-altitude glaciers in the region, which are typically associated with colder climates and greater snow accumulation. Conversely, glaciers situated at lower elevations, particularly those below 4,500 m, represent a smaller proportion of the total glaciers over the study area. However, it is noteworthy that glaciers within the 5,000–5,500 m range contribute the second-largest percentage (45.3%) to the total glacier area, suggesting a significant presence of glaciers in this elevation band.

3.3 Classification of glaciers

3.3.1 Primary classification. The primary classification system classifies glaciers based on morphology for the identification of various glacier types shown in Figure 5. In 1992, 317 glaciers were categorized as primary glaciers, but by 2023, this number increased to 454. The surge was primarily due to valley glaciers fragmenting into mountain glaciers, leading to a 31.8% reduction in valley glacier area. Additionally, glacierets and snowfields experienced a drop of 7.2% in area. Valley glaciers saw a significant decrease in area by 403 km^2, whereas mountain glaciers witnessed a slight rise by 4.3 km^2 despite a decrease in their number from 128 to 90. However, the number of glacierets and snowfields increased from 155 to 304, although their total area shrunk by 10 km^2 during the study period. Notably, rock glaciers showed a substantial decrease in both number and area, reducing from 25 to 32 by −25%. These findings highlight the dynamic changes occurring within glacier systems over time.

3.3.2 Form classification. The form classification categorizes glaciers based on their shape, extent such as Ice aprons, Cirque and Niche etc. Compound basin (Type-1) consists of more than two basins resulting from the combination of multiple valley glaciers as tributaries shown in Table (S2). Five glaciers were identified in 1992 covering an area of 276 km^2 which reduced to three glaciers by 2023, marking a striking reduction of 75% in the area of these basins. Compound basin (Type-II) carries multiple accumulation basins that feed to a singular glacier system. Here 10 such glaciers were identified occupying 233.4 km^2 in 1992 which further showed drop of 12.5% in 2023. Simple basin forms from single defined catchment. In 1992, these glaciers covered 355.4 km^2, and the area reduced by 18% in 2023. Cirques are bowl depression on or near mountains nourished by snowfall. 26 glaciers were identified covering 50 km^2 initially and by 2023 their number dropped to 20 with 49.2% decline in area. Niche glaciers are mostly mountain glaciers associated with calving. Their presence in 1992 was 32 and by 2023 were reduced by 54.8%. Ice aprons are subjected to massive fragmentation as their number increased from 233 to 282. Remnants are small ice fragments left behind by retreated glaciers. 22 ice masses which further disintegrated to 6 in 2023, showed a decline of 67%.

3.3.3 Frontal classification. Terrestrial calving is a process in which ice separates from glaciers, mainly occurring at the frontal area leading towards the formation by crevasses, ice cliffs and interactions with the surrounding shown in Figure 5. The number of glaciers



Primary Classification : (a) Valley glaciers (b) Mountain Glaciers (c) Glacieret and Snowfield (d) Rock Glaciers

Form Classification : (a) Compound Basin type -1 (b) Compound Basin type -2 (c) Niche (d) Remnant (e) Simple Basin (f) Cirque (g) Ice Apron

Nourishment Classification : (a) By Avalanche (b) By Snow (Wind/Drift)

Longitudinal Classification : (a) Hanging

Front Classification : (a) Normal irregular (b) Confluent (c) Terrestrial Calving

Debris Classification : (a) Debris Free (b) Partially Debris (c) Mostly Debris

Source(s): Figure by authors

Figure 5. Google Earth images of the glacier classification

increased from 117 in 1992 to 129 in 2023, but Figure 6 illustrates a 17.3% decrease. Confluent glaciers are formed when two glacier tongues merge, there is a significant decrease in area by 49.3%. Also, three glaciers with irregular fronts showed a reduction of 11.2% in area. These trends reflect changes in glacier dynamics influenced by environmental factors like slope, avalanches and interactions with surrounding terrain.

3.3.4 Longitudinal classification. The longitudinal classifications include hanging glaciers, which are formed when a valley glacier is retreated and results in small valleys and further leads to hanging as shown in Figure 6. The longitudinal characteristics often give us the insight of surface profile and ice thickness. The number of hanging glaciers increased from 275 in 1992 to 319 in 2023, despite a decrease in area by 27 km^2. This is attributed to large glaciers

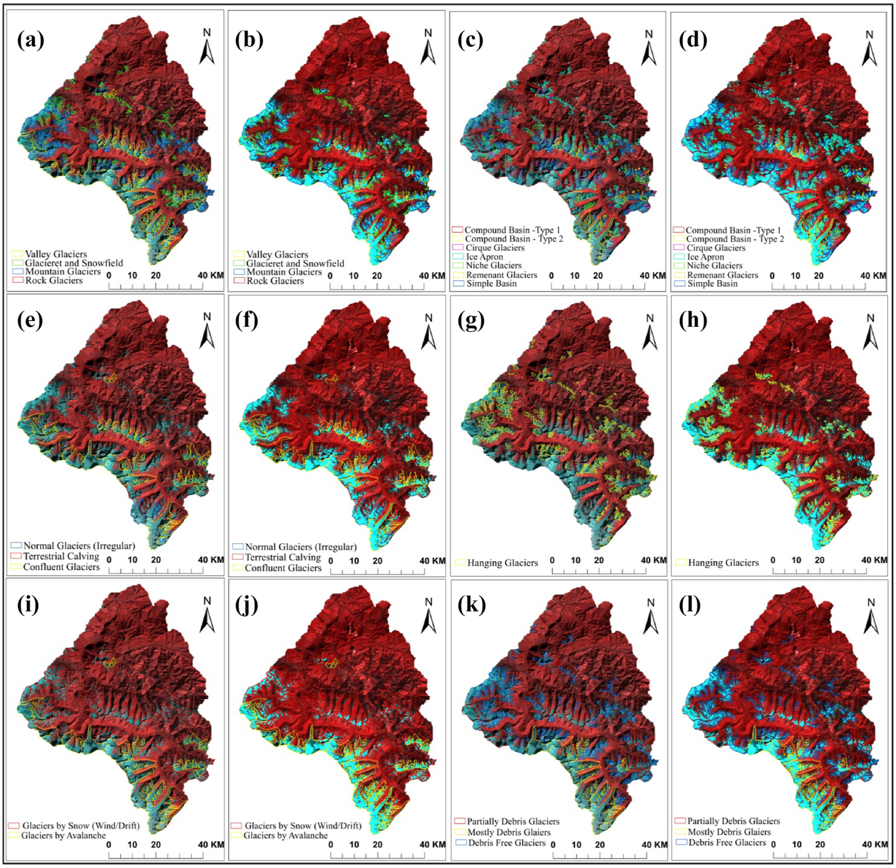


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Figure 6. Six categories of glacier classification. Primary classification (a) 1992, (b) 2023; Form classification (c) 1992, (d) 2023; Front Classification (e) 1992, (f) 2023; Longitudinal classification (g) 1992, (h) 2023; Nourishment classification (i) 1992, (j) 2023; Debris classification (k) 1992, (l) 2023

fragmentation and new smaller ones forming at the slopes. Most of these glaciers are ice aprons, classified as glaciers and snowfields, nourished mainly by snowfall. Clean ice without debris cover characterizes hanging glaciers.

3.3.5 Nourishment classification. In this categorization, glaciers primarily associated with snowfall for their supply nourishment, as it compacts and forms into ice for the glacier formation. 317 snow-fed glaciers were discovered covering 578 km^2 in 1992, this number decreased to 232, with a 45.3% reduction in area. Avalanches are sudden pouring of snow due to wind or drift flows down slopes or cliffs, particularly on slopes exceeding 30°. In 1992, 23 glaciers were avalanche-fed, occupying 701 km^2, as given in Table (S2). By 2023, this number increased to 40 glaciers, yet their area reduced by 226 km^2, resulting in an overall loss of 32.2%. Most avalanche-fed glaciers are valley glaciers with compound basins, mainly nourished by both snowfall and avalanches.

3.3.6 Debris coverage tongue classification. Debris-free glaciers carry less than 10% debris cover. From 1992 to 2023, they were decreased from 280 to 193, with a 20.7% loss in area. Partly debris-covered glaciers have 10–50% debris cover; they remained stable at 19 but saw a

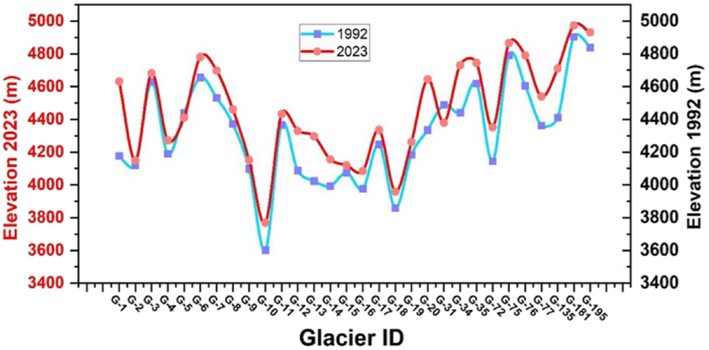
42.1% decrease in area. Mostly debris-covered glaciers have 50–90% of debris cover, they increased from 10 to 18, but area reduced by 31.1%. These glaciers primarily rely on snowfall for nourishment.

3.4 Spatio-temporal analysis

3.4.1 Retreat of glaciers. Glacier retreat has been calculated for 29 glaciers. The length of glaciers was determined using the central flow line corresponding to the longest flow distance. For glaciers with multiple accumulation areas, complex geometries, crevasses and debris coverage changes in glacier length were calculated using two established methods: (1) measuring along the central flow line (Lopez *et al.*, 2010; Machguth and Huss, 2014) and (2) calculating the mean length change using 50-m horizontal strip lines (Koblet *et al.*, 2010; Bhambri *et al.*, 2012; Schmidt and Nüsser, 2012; Thakuri *et al.*, 2014). Total frontal recession is calculated by plotting points on the glacier terminum position and measured with the points taken on snout of glacier 2023. The average is taken as total recession.

Table (S3) provides a comprehensive analysis of glacier changes from 1992 to 2023, including area reduction, mean elevation, snout elevation and total snout retreat for various glaciers. The results show reduction accompanied by substantial snout retreats, like G-18 with total retreat of 1,420 m, G-75 with 1,230 m and G-20 with 1,147 m, G-8 (Dalung) and G-14, which saw snout retreats of 982 meters and 1,271 meters, respectively, indicating accelerated melting and mass loss. G-35 has lost 71.43% of area, whereas G-20 (67.35%) and G-34 (64.71%) reported to be the highest area to lose glaciers. G-20 and G-35 exhibit more stable retreat at snout. G-9 (Shafat) has almost lost its major portion by 2023 as it reported highest area loss, 45.71% and significant snout retreat of 862.5 m. The G-2, G-10 have longer length and showed lower percentage of area change. G-72 and G-76 exhibit average recession of 33 m/year. The mean elevation and snout elevation data show a general trend of lowering snout elevations, such as G-10 (Parkachik) with a decrease from 3,769 meters to 3,602 meters, suggesting glaciers are retreating to higher altitudes. Several glaciers such as G-20 reported to increase in elevation of the snout from 4,335 m (1992) to 4,645 m (2023), suggesting that the glacier snout are retreating to higher elevation due to their melting at lower elevations. The average recession rates per year indicate rapid glacier retreat for some glaciers, such as G-8 (Dalung) at 31.6 meters per year and G-14 at 41 meters per year, while others like G-3 (Pensilungpa) and G-7 have more moderate recession rates of 9 meters and 18 meters per year. Both large glaciers and small glaciers are experiencing retreat, for example, G-2, G-9 and G-10 have shown moderate to large increase in snout elevation. Therefore, G-20, G-34 and G-135 indicate that glaciers at lower altitude are more vulnerable to rapid melting, thus lower elevation terminus are losing more mass rapidly. Overall, the data suggest a clear trend of glacier retreat and area reduction, with significant implications for water resources, ecosystem stability and local communities dependent on glacial meltwater. The retreat of glacier snouts to higher elevations and the consistent reduction in glacier areas highlight the urgent need for continuous monitoring and comprehensive studies to understand the drivers of these changes and develop effective mitigation strategies, underscoring the critical impact of climate change on glacial regions (see Figure 7).

3.4.2 Field insights. A field visit to Parkachik has been done on 21/09/2021. GPS points were taken over front and snout position shown in Figure 8. Ice thickness was calculated of the central right side of glacier, where most of the melting is happening. Table (S4) presents detailed GPS measurements of various points on the Parkachik Glacier, including their latitude, longitude, altitude, horizontal root mean square (HRMS), vertical root mean square (VRMS) and position dilution of precision (PDOP). These measurements provide insights into the accuracy and reliability of the data, with lower PDOP values indicating stronger satellite geometry and better positional accuracy. The altitudes of the points range from approximately 3551.3–3569.3 m, showing minor elevation variations across the glacier. Table (S3) also includes measurements of snout thickness, ranging from 15 inches (38 cm) to 130 inches



Source(s): Figure by authors

Figure 7. Snout retreat of glaciers

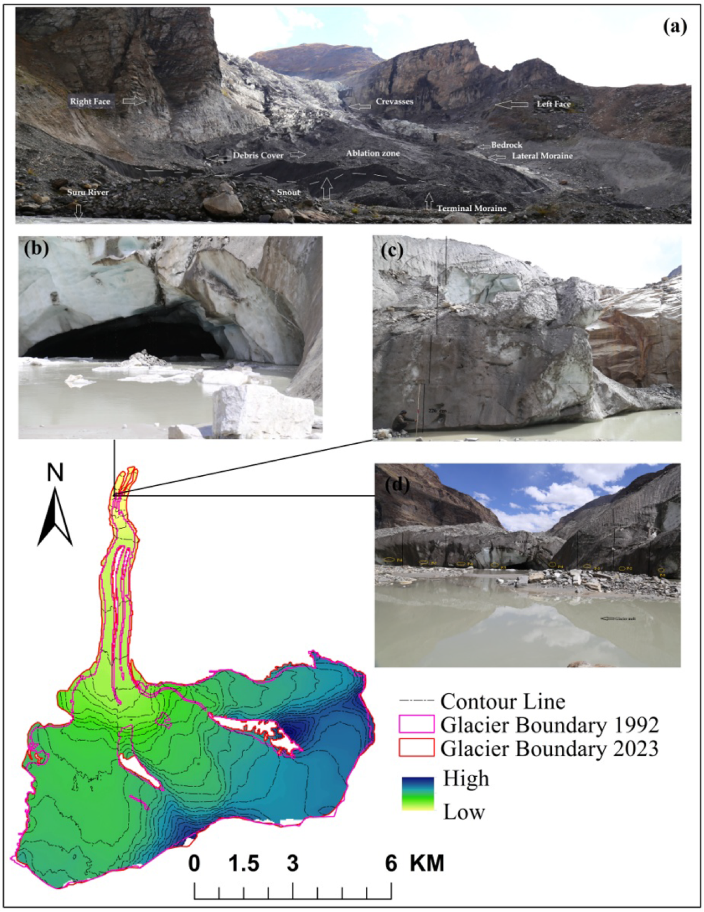
(330 cm), obtained using a 101-inch wooden rod. These data are crucial for understanding the glacier's dynamics, particularly changes in snout positions and thickness over time, which are essential for assessing glacier retreat and its implications on the surrounding environment.

4. Discussion

The considerable retreat and decline in glacier areas observed in the study region over the last 3 decades clearly demonstrate the influence of climate change on glacial environments. The general trend of glacier shrinking is consistent with worldwide patterns, which show that rising temperatures and shifting precipitation patterns are causing glacial retreat. As the outcome of this phenomenon, the regions rely on meltwater for their day to day needs like agriculture, commercial requirements and overall ecosystem equilibrium. The findings underscore glaciers' vulnerability to climate change, particularly those of smaller size and lower elevation. The study shows that glacial retreat is not uniform and differs depending on glacier size, orientation and elevation. Smaller glaciers and those at lower elevations are more vulnerable to melting, but larger, higher-altitude glaciers tend to be more resilient, though still decreasing. Furthermore, glaciers with specific orientations, particularly those facing north and northwest, exhibit faster rates of retreat, most likely due to increased solar exposure and local meteorological conditions. This asymmetrical retreat highlights the intricate connections between climate conditions and glacier dynamics, prompting more focused research and conservation efforts.

In this study, the area change, classification and retreat is observed from 1992 to 2023. Comparing to previous studies in the Himalayas and other regions, there is a presence of both coherence and inconsistency in glacier behaviour. Basin is investigated in year 1992 with 317 glaciers covering 811 km^2 area and in 2023, 214 glaciers were identified with area of 608.6 km^2 which is varying from the study of Shukla *et al.* (2020a, b) with 240 glaciers and 496 km^2. Study shows a loss of 24.9% in glacier area in 31 years, comparatively higher than the findings of Rai *et al.* (2013) who noted a loss of 0.71%, Chudley *et al.* (2017) who noted a loss of 0.56%, and Nabi *et al.* (2022) who noted a loss of 0.33% glacier area in suru basin. For instance, factors such as topography, local climate and glacier characteristics are the founding causes of the glacier area change variability across Ladakh, Zanskar and Karakoram regions. Whereas some regions presented with small changes, like the current research region, show considerable loss of glacier area.

We also examined the glaciers under their classification, where it has been observed that valley glaciers had experienced drastic reduction of 45% and compound basin type 1 glaciers exhibit highest percentage loss of 75%. Unlike previous researches, this method of



Source(s): Figure by authors

Figure 8. Field photograph of Parkachik glacier (a) frontal degradation of glacier, debris cover and ice cover, Suru river (b) calving from right side of glacier tongue, (c) right lateral ice thickness and (d) high melting at front position (DGPS) points taken during field visit

classification brings out a novel perspective providing granular understanding of glacier across all classification types. The study distributed glaciers in five classes mainly to understand the size factor for their respective nature against climate change. It has been observed that glacier between 5 and 10 km^2 exhibit −41.4% of area loss since 1992, and contribute higher percentage of total glaciers in the basin, whereas there is a variability in study by Shukla *et al.* (2020a, b) which revealed 15% of their total area is under 7–15 km^2 glaciers.

The average retreat is found to be between 9 and 45.8 m/yr in the glaciers of the basin, which implies greater variability in the corresponding studies such as Shukla *et al.* (2020a, b) and Garg *et al.* (2021). This scenario leads to the understanding that heterogeneity exists in the nature of glacial responses to climate change across different geographic and climatic contexts. Other Himalayan studies have found that glacier area loss and snout retreat occur at variable rates. Such as in the Tista Basin, there is a significant glacier loss, along with the Western Himalayas have undergone much minor changes over time. Whereas the Karakoram region has stated much stability in glacier areas, possibly due to their unique climatic and topographic conditions, which may act as a buffer against rapid melting. Therefore, these differences predominately underscore the need for localized research to better understand the individual drivers and consequences of glacier change in different places. The implications of glacial retreat go beyond the immediate geographic area, influencing water supplies, agriculture and hydroelectric power generation. The decline in glacier mass causes decreased water flow during dry spells, jeopardizing water security for millions of people. Furthermore, changes in glacier dynamics can disrupt river flows and sediment transport, affecting downstream ecosystems and human infrastructure. Understanding and minimizing the effects of glacial retreat is crucial for long-term development and climate resilience. This work emphasizes the need for ongoing monitoring and new research approaches, like as remote sensing and field surveys, to capture the intricate dynamics of glacier change. The integration of geomorphological mapping, climate data analysis and hydrological modelling is critical for generating complete management plans. Policymakers and conservationists must prioritize efforts to reduce the negative effects of glacier retreat, with an emphasis on both short- and long-term adaptation measures to maintain water security and ecosystem stability in glacier-dependent areas.

4.1 Comparative analysis

The research in the domain of glacier area change has been observed thoroughly in the Himalayas, as they uncover spatial and temporal variability. In Ladakh, an analysis of 657 glaciers from 1991 to 2014 showed a relatively minor area change of 0.56%, as reported by Chudley *et al.* (2017), using Landsat TM/OLI data. On the other hand Zanskar has experienced more considerable changes, with different studies showing a range of area reductions. Rai *et al.* (2013) found that 13 glaciers experienced area changes between 2.47 and 30.48% from 1962 to 2001, using LISS III and Landsat TM data. Furthermore, a study by Shukla and Ali (2016) noted a 0.42% change for five glaciers between 1977 and 2013 using Landsat MSS/OLI data, while Ghosh *et al.* (2014) reported a 2% change for 212 glaciers from 1962 to 2001 using IRS, LISS III and Landsat TM data (see Table 3). In the Suru Basin, many studies have shown differential rates of glacier change like Shukla *et al.* (2020a, b) who observed a minimal change of 0.13% across 240 glaciers from 1971 to 2017 using Corona and Landsat OLI datasets. Kasturirangan and Navalgund (2011) has reported changes of 0.49 and 0.82% for 215 glaciers during the periods 1962–2005 and 1989–2007, respectively, using LISS III data in Suru basin. Kamp *et al.* (2011) demonstrated more significant area changes for specific glaciers, with Drang Drung, Parkachik and Shafat glaciers showing changes of 9.4, 13 and 16.9%, respectively, between 1975 and 2008, using Landsat TM/ETM data. In the Suru region, different studies have reported varying rates of glacier area change. Shukla *et al.* (2020a, b) observed a minimal change of 0.13% across 240 glaciers from 1971 to 2017 using Corona and Landsat OLI data. Another study in the Suru Basin by Kasturirangan and Navalgund (2011) identified changes of 0.49 and 0.82% for 215 glaciers during the periods 1962–2005 and 1989–2007, respectively, using LISS III data. Kamp *et al.* (2011) noted more significant area changes for specific glaciers, with Drang Drung, Parkachik and Shafat glaciers showing changes of 9.4, 13 and 16.9%, respectively, between 1975 and 2008, using Landsat TM/ETM data. In the Kashmir region, Romshoo *et al.* (2020) documented area change of 28.2% for 147 glaciers from 1980 to 2018, based on Landsat TM/OLI data. The Parkachik glacier saw a reduction of 1.13% between 1971 and 2021, according to a study by Rana *et al.* (2023) using Corona, Landsat OLI and Sentinel data. The insights come from the work of Garg *et al.* (2018) observed a reduction of 1.42% for the Kangriz glacier between 2015 and 2017, using MODIS data. The present study focuses on the Suru sub Basin, where 214 glaciers showed an area change of 24.9% from 1992 to 2023, and using Landsat TM/ETM/OLI data. This significant change highlights the ever increasing impact of climate change on the glacier health in the region, compared to other regions within the Himalayas. The comparative analysis across

Table 3. Detail of glacier area change in the Western Himalayas

Study area	Glacier number	Period of study	Area change (%)	Data set used	Reference
Ladakh	657	1991–2014	0.56	Landsat TM/OLI	Chudley *et al.* (2017)
Zanskar	13	1962–2001	2.47–30.48	LISS III, Landsat TM	Rai *et al.* (2013)
Zanskar	5	1977–2013	0.42	Landsat MSS/OLI	Shukla *et al.* (2016)
Suru	240	1971–2017	0.13	Corona Landsat OLI	Shukla *et al.* (2020a, b)
Zanskar	212	1962–2001	2	IRS,LISS III,Landsat TM	Ghosh *et al.* (2014)
Kashmir	147	1980–2018	28.2	Landsat TM/OLI	Romshoo *et al.* (2020)
Parkachik	1	1971–2021	−1.13	Corona/Landsat OLI/Sentinel	Rana *et al.* (2023)
Kangriz		2015–2017	−1.42	Modis	Garg *et al.* (2018)
Suru Basin	215	1962–2005	0.49	LISS III	Kasturirangan and Navalgund (2011)
		1989–2007	0.82		
Drang Drung		1975–2008	9.4	Landsat TM/ETM	Kamp *et al.* (2011)
Parkachik		1979–1990	13		
Shafat		1990–2005	16.9		
Suru Basin	214	1992–2023	24.9	Landsat TM/ETM/ OLI	Present study

Source(s): Table by authors

these studies highlights the diverse responses of glaciers to climatic factors, emphasizing the need for localized and comprehensive monitoring efforts to better understand and mitigate the impacts of glacier retreat.

5. Conclusions

Suru sub basin presents a concerning picture of glacier modification between 1992 and 2023, indicating a notable decline of 24.9% loss in glacier area throughout the period studied. Since 1992, the basin has experienced fragmentation of large area glacieret into numerous snowfield and glacierets, rising up to 16% of total area. The valley glaciers have declined by 41.1% in area. It is anticipated that the observed glacier retreat would have a major impact on water supplies, affecting the frequency and amount of meltwater flow. As a consequence, the generation of hydropower will be effected alongside agriculture practices in the plains. The highest concentration of glaciers are concentrated between 5,500 and 6,000 m elevation which have witnessed a decline of about 75% area by 2023. Thus, there is a need for significant adaptive approaches to manage this crisis. The retreat measurement revealed approximately between 1,147 and 1,420 m area in G-18,75 and 20, whereas G-35 have undergone 71.45% of area loss between 1992 and 2023. The findings emphasize the significance of ongoing monitoring to better understand glacier dynamics and future trajectories. There is a need to investigate the individual glaciers with long term climatic data to understand their process of fragmentation and predict their future behaviour. Future studies may focus on precise assessments of glacier mass balance and ice thickness in order to improve glacier behaviour forecasts. Through the amalgamation of remote sensing and field based data, the accuracy and interpretation of glaciers in the region may be improved. Advance research techniques are required to evaluate the assessment of debris cover on glacier melting rates. Additionally, the role of the sub-glacial hydrology factor may offer insight into elements influencing glacier stability. Addressing these research gaps is critical for creating effective strategies to mitigate the effects of glacial retreat. The study area poses significant challenge due to the complex terrain, harsh climate conditions and limited cloud free satellite data during the period studied. These factors introduce uncertainties in the measurement of the glacier parameters. During the field visit, it has been observed that near the snout of Parkachik glaciers, there is a existence of glacier lake indicating a potential risk. To address these concerns, a thorough investigation and early warning system is required for safety of nearby settlement and downstream population in the region against GLOF and glacier-related hazards. Understanding the interaction of climatic conditions and glacier dynamics may aid in projecting future changes and reducing their impact on water supplies, agriculture and energy production.

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Supplementary Material

The supplementary material for this article can be found online.

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