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High-resolution Mapping of Alpine Glaciers of Suru Basin: A 2022 Inventory Based on Sentinel-2 Satellite Data

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Original Research Article

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ABSTRACT

Alpine glaciers serve as critical indicators of climate change and play a vital role in regional and global hydrological cycles. This study focuses on the Suru basin in Ladakh, India, a region with a crucial network of alpine glaciers that serve as freshwater reservoirs. Utilizing high-resolution Sentinel-2 imagery and a Digital Elevation Model (DEM), we conducted a comprehensive mapping of 42 glaciers in the basin, covering 152.91 km². These glaciers were classified into five types: simple basin mountain glaciers, compound basin mountain glaciers, simple basin valley glaciers, compound basin valley glaciers, and ice aprons. Violin boxplot analyses revealed most glaciers have mean elevations between 5000-5400 meters and slopes between 10°-30°. Detailed analysis of glacier distribution by elevation, slope, and aspect highlighted the dominance of compound basin valley glaciers (70.27 km²) and compound basin mountain glaciers (46.18km²) in terms of area. Glaciers in the sub-basin are predominantly small to medium-sized, with the majority falling in the 1-2 km² size class. The slope analysis revealed that most glaciers fall within the 15-20° slope class, while aspect-wise, CB. Mountain Glaciers and SB. Mountain Glaciers were primarily found in the southern and southeastern aspects. Our inventory findings are comparable to the Randolph Glacier Inventory (RGI), underscoring the accuracy of our methodology. This study provides valuable insights into the distribution, extent, and characteristics of alpine glaciers in the Suru basin, contributing to our understanding of glaciological processes in this region. The high-resolution mapping serves as a crucial baseline for future monitoring of glacier changes and their implications for water resources and hazard assessment in the face of climate change.

Keywords: Glacier inventory; Sentinel-2; ALOS PALSAR DEM; violin boxplot; aspect; slope; elevation.

1. INTRODUCTION

Glacial inventory, a comprehensive analysis of the current state and changes occurring within glacial systems, has emerged as a valuable tool for monitoring and studying these transformations [1]. It involves detailed observations, measurements, and mapping of glaciers, providing invaluable information about their mass balance, surface area, and volume changes over time. By examining these parameters, researchers can gain insights into the rates of glacier retreat, the impacts of climate variability, and the potential consequences for water resources and downstream communities [2]. Glacier inventories are crucial for evaluating the representativeness of continuous measurements across various mountain regions, which are typically conducted on only a few selected glaciers. A climate signal derived from a single glacier often fails to adequately represent an entire mountain range. Therefore, comprehending the global impacts of climate change necessitates comparing the long-term behavior of glaciers across different mountain ranges [3]. Remote sensing technologies have emerged as indispensable tools for glacier mapping and monitoring, providing synoptic and high-resolution data that enable researchers to analyze changes in glacier extent, mass balance, and surface characteristics. In particular, the advent of open-access satellite missions like Sentinel-2, coupled with high-resolution Digital Elevation Models (DEMs), has revolutionized the field of glaciology [4].

Glaciers, being highly sensitive to temperature fluctuations and various climatic factors, have experienced significant alterations in their life cycles globally. Consequently, the ice and snow masses of glaciers are melting at an accelerated rate [5]. Meier [6] was the first to identify that mountain glaciers and ice caps, which comprise only 1% of the Earth's total ice volume, are substantial contributors to global sea-level rise. This is attributed to the extensive melting of these glaciers, driven by global warming. A projected escalation in glacial retreat across the globe is anticipated in the coming decades, with a potential for the complete disappearance of glaciers at lower and mid-latitudes [7-9]. Historical observations have unequivocally highlighted the vulnerability of alpine glaciers to climate change. Zemp et al. [10] reported that

Alpine glaciers lost about 35% of their area between 1850 and the 1970s and nearly 50% between 1850 and 2000. During this period approximately two-thirds of glacier ice was lost from Alpine glaciers. O'Neel et al. [11] reported significant retreat among glaciers in Alaska, which contains the majority of glaciers in the United States. Their study highlighted an accelerating rate of mass loss, with Alaskan glaciers losing approximately 30% of their total mass between 1950 and 2000, and the rate of loss nearly doubling from 1994 to 2013. Similarly, glaciers in the continental United States have also been retreating, though on a smaller scale. According to Hall et al. [12] the Grinnell Glacier has undergone significant retreat, losing over 85% of its ice volume from 1966 to 2016. Benn et al. [13] observed that the volume of glaciers in the Scottish Highlands decreased by 20% between 2006 and 2015, with an average annual loss rate of approximately 2%, which further increased 2.2 times higher than in the previous decade [14]. Glacier retreat and volume loss has been reported in the other parts of world, some exmaples of which include – Japan [15] Africa [16,17], etc.

As global temperatures rise, driven primarily by anthropogenic greenhouse gas emissions, recent studies have shown that Himalayan glaciers are retreating at an alarming rate [4,18-22]. Notably, glaciers in the Western Himalayas exhibit less shrinkage compared to those in the central and eastern regions [19,20,23]. In contrast, glaciers in the neighboring Karakoram region demonstrate long-term irregular behavior, characterized by frequent advances and surges with minimal shrinkage, a phenomenon “Karakoram anomaly” [24] that remains not fully understood [19,25,26]. Interestingly, the area of glaciers in the Karakoram region has increased since 2000, primarily due to the presence of surge-type glaciers. Like glaciers worldwide, Ladakh's glaciers have been experiencing accelerated rates of recession and retreat in recent decades [23,27,28], raising concerns about the future water availability and ecological stability of the region. Alpine glaciers are critical indicators of climate change [29,30], playing a crucial role in regional and global hydrological cycles [31]. In high-altitude arid regions like Ladakh, alpine glaciers are fundamental to the local economy, especially during periods of low winter precipitation when glacier melt becomes the primary water source [32]. The consequences of this phenomenon are far-reaching, including reduced water availability, increased risk of glacial lake outburst floods (GLOFs), and altered downstream ecosystems. This highlights the urgent need for accurate and up-to-date information on glacier extent and dynamics in regions such as the Suru sub-basin. The Suru sub-basin, nestled within the intricate expanse of the Ladakh region of India, harbors a crucial network of alpine glaciers. These glaciers serve as vital freshwater reservoirs, contributing significantly to the region's hydrological balance and supporting downstream ecosystems and communities [4,33- 35].

This study leverages the capabilities of Sentinel-2 imagery, along with DEM data, to conduct a comprehensive alpine glacier mapping of the Suru sub-basin. The high spatial and temporal resolution of Sentinel-2 data allows for detailed delineation of glacier boundaries, identification of supraglacial debris cover, and assessment of seasonal variations. Additionally, DEMs provide critical information on glacier topography, enabling the calculation of glacier volumes and the assessment of potential hazards like glacial lake outburst floods (GLOFs). By integrating these diverse datasets, this research aims to produce an accurate and up-to-date glacier inventory of the Suru sub-basin, quantifying glacier area, extent, and surface characteristics. The findings will contribute to a deeper understanding of the region's glaciological processes, enhance our knowledge of the impacts of climate change on alpine glaciers, and inform water resource management and hazard mitigation strategies in the region.

1.1 Study Area

The primary focus of this research study centres on the glaciers located in the Suru basin of Zanskar catchment of UT Ladakh in the western Himalayas region. Suru basin (Fig. 1) covers an area of 1276.68 km^2 occupying the Western part of the Zanskar catchment. It lies between 33.797º to 34.150º N latitude and 76.033º to 76.593º E longitude. The Suru River, which originates from the Pensilungpa glacier at an altitude of approximately 4675 meters above sea level (a.s.l.),is a tributary of the Indus sustained by meltwater from the glaciers of the Great Himalayan Range (GHR), including prominent ones such as Lalung, Dulung, Chilung, Shafat, and Kangriz/Parkachik [23]. The largest glacier in the region, Kangriz, originates from the Nun and Kun peaks and contributes significantly to the river's flow [36]. The Suru River meanders through the landscape, fed by multiple glaciers

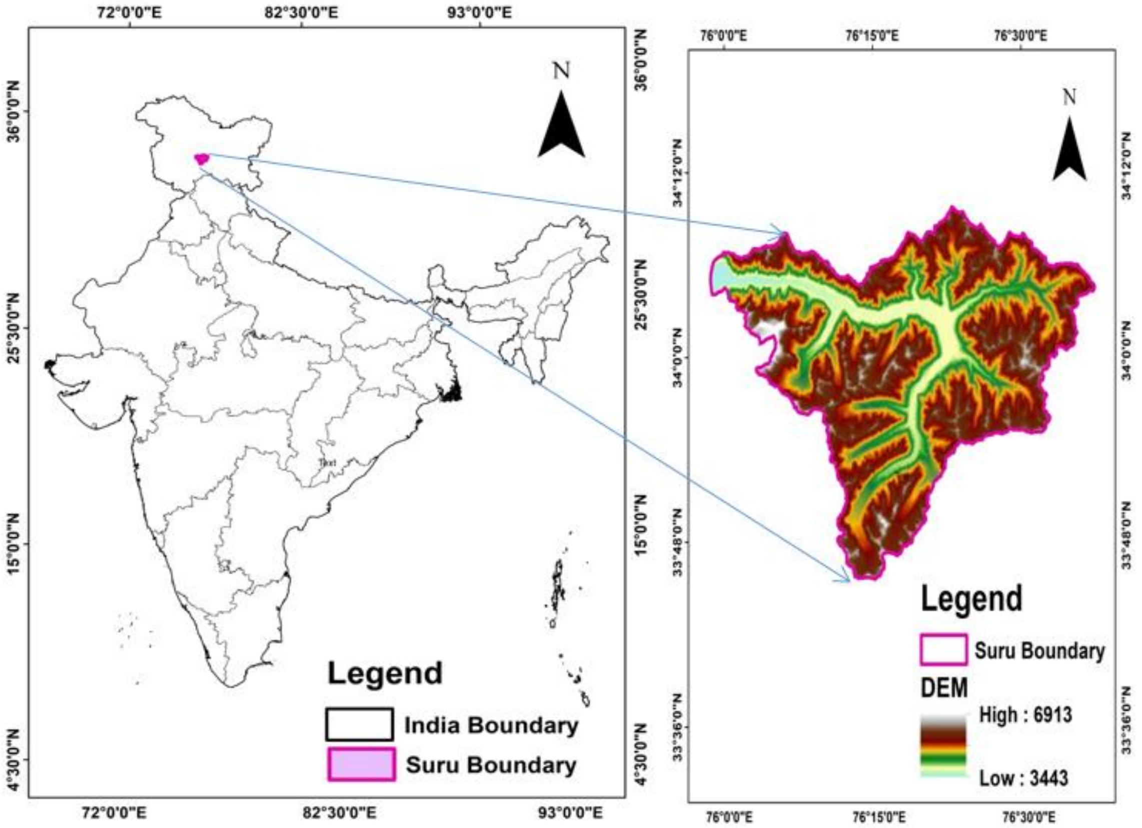

Fig. 1. Location Map of Suru Basin

along its course, before eventually joining the Indus River at Nurla.

The region's hydrology is heavily influenced by westerlies, which bring fluctuating snowfall patterns [37]. Precipitation varies substantially across the area, ranging from 2050 to 6840mm annually in Padum valley, with an average temperature of 4.3°C [38]. Long-term data for Kargil and Leh reveal average temperatures between 5.5°C and -2.04°C, and precipitation between 588.77mm and 278.65mm, respectively [39].

2. MATERIALS AND METHODS

2.1 Data Acquisition

To achieve high-resolution glacier mapping, this study utilized Sentinel-2 satellite imagery due to its high spatial resolution, multispectral capabilities, and frequent revisit times. The following datasets were acquired:

- **Sentinel-2 Imagery**: Free satellite images with high spatial resolution (Sentinel-2) are recognized for their sufficient radiometric and geometric accuracy, making them suitable for glacier monitoring [40-42]. High-resolution (10 m) multispectral images served as the primary data source for glacier identification and mapping. Sentinel-2 images were acquired from European Space Agency (ESA) web portal (www.earth.esa.int), specifically targeting the peak ablation period to capture the maximum extent of glacier ice. These images were selected for their multispectral capabilities and relatively high spatial resolution, which enabled precise delineation of glacier boundaries.
- **Digital Elevation Model (DEM)**: The Advanced Land Observing Satellite (ALOS) Phased Array Synthetic-Aperture Radar (PALSAR) radiometrically terrain corrected (RTC) Digital Elevation Model (DEM) was sourced from the Alaska Satellite Facility web portal (https://asf.alaska.edu/). This high-resolution DEM, with a spatial resolution of 12.5 meters, was instrumental in deriving topographic information like slope, aspect,

and elevation, aiding in the differentiation of glacier ice from snow. ALOS PALSAR DEMs are extensively used in hydrodynamic modeling to produce essential geometry data, including river centerlines, bank lines, flow lines, cross sections, and breach invert levels [43,44].

- **Ancillary Data**: Cloud-free images from Google Earth or other high-resolution sources were used for visual interpretation and validation. The Randolph Glacier was used for comparison and accuracy assessment.

2.2 Glacier Inventory Mapping

The comprehensive glacier inventory mapping was conducted for the year 2022 using a diverse approach, incorporating remote sensing data, digital elevation model, and ancillary information. This methodology was meticulously designed to ensure accurate, reliable glacier delineation, and attribute extraction.

The preprocessing of Sentinel-2 imagery involved several steps to ensure data quality and accuracy: radiometric correction to correct sensor-induced radiometric distortions and ensure consistency in pixel values across images; atmospheric correction using the Sen2Cor processor to remove atmospheric effects, including aerosols and water vapor, and to generate surface reflectance products; and geometric correction to align the images with the DEM and other geospatial datasets, ensuring accurate spatial referencing.

The glaciers were mapped employing a hybrid methodology, combining the Normalized Difference Snow Index (NDSI) to delineate snow–ice boundaries with manual digitization techniques for accurately identifying debris-covered areas [23]. Initially, digital algorithm technique like Normalized Difference Snow Index (NDSI) was employed to delineate glaciers [45,46]. This method is robust and time-effective for mapping clean glaciers and provides accurate results for debris-free ice [47]. The NDSI was calculated using the reflectance values of green (G) and shortwave infrared (SWIR) bands:

$$NDSI = \frac{G-SWIR}{G+SWIR}$$

Threshold of 0.4 for NDGI were applied to distinguish between glaciated and non-glaciated areas. Binary images were generated and converted into vector format for further analysis. The vector data often contained misclassified glacier areas such as water bodies, shadows, and isolated rocks. These were eliminated through manual post-processing to accurately delineate glaciers and ice divides. Debris-covered glaciers were delineated manually based on various indicators such as the origin of streams, glacier surface texture, and peri-glacial areas. Manual delineation is considered more accurate for debris-covered glaciers compared to automated methods [48].

DEM was used to correct glacier outlines through better visualization of glacier extents and ice divides. Visual inspection of glaciers and associated features on Google Earth (≤ 5 m resolution) provided additional information for mapping and helped eliminate any mismatches. Topographic parameters such as glacier size, elevation, length, slope, aspect, and hypsometry were determined using DEM. These parameters were essential for understanding the behavior and response of glaciers to climate change. Parameters like area and perimeter were calculated directly from glacier polygons in a GIS environment using “Calculate Geometry” option available. Other attributes like elevation, slope, and aspect were determined through statistical analysis of the DEM and other derived data [1], using “Zonal statistics as Table” tool available in ArcTool Box.

2.3 Accuracy Assessment

Uncertainty quantification is crucial for assessing the accuracy and significance of glacier mapping using multi-sensor and multi-temporal satellite data [9,49]. Mapping errors, often influenced by spatial resolution and meteorological conditions, can significantly affect results [1,50]. While meteorological factors were minimized in this study due to image acquisition timing, mapping uncertainties were addressed using a buffer method, correlating results with high-resolution data [51]. The buffer method, recommended by various studies, was employed to estimate errors in mapping glacier extents using Sentinel-2 (MSI) images [52,53]. High mapping errors were found in smaller glaciers, primarily due to the inclusion of more pixels at the edges of glacial polygons.

For debris-covered glaciers, a buffer size of 10 meters was used for Sentinel-2 imagery. For clean glaciers, a buffer size of 6 meters was used for Sentinel-2, resulting in average mapping uncertainties of 1.7%. These results are comparable to previously reported mapping uncertainties of around 2–5% [54,55, 47].

3. RESULTS AND DISCUSSION

This study encompassed the development of a glacier inventory for the year 2022 and the calculation of various glacier parameters.

3.1 Glacier Inventory

A study conducted in the region identified and mapped a total of 42 glaciers with a size greater than 0.1 km^2, covering an area of 152.91 km^2 (Fig. 2). The inventory was compared with the RGI inventory "Randolph Glacier Inventory (RGI) version 6.0″ and it was found that the area of the selected glaciers was 159.01 km^2, which is greater than the area we have calculated but is comparable to the value. Variability in these figures may stem from differences in mapping techniques, leading to an increased risk of systematic errors. Additionally, the involvement of different analysts could contribute to random errors, further affecting the results.

These glaciers were categorized into different types- Simple basin mountain glacier, Compound basin mountain glacier, Simple basin valley glacier, Compound basin valley glacier and Ice apron. These glaciers contribute around 11.98% of the total basin area. The glaciers were categorized into five size classes: 1–2, 2–3, 3-4, >4 km^2 (Table 1, Fig. 3). There are 15 compound basin mountain glaciers in the central basin, collectively covering an area of 46.18 km^2. These glaciers are predominantly found in the mountainous regions of the central basin and fall in each area size class ranging from 1 km^2 to over 4 km^2. There are 8 compound basin valley glaciers in the central basin, with a total area of 70.27 km^2. These glaciers are located in the valley regions of the central basin. The majority of these glaciers are larger than 4 km^2, indicating significant glacial activity and influence in these valley areas. There are 2 ice aprons, covering an area of 2.39 km^2, each falling within the 1-2 km^2 size range. Ice aprons are smaller glacier formations often found on steep inclines [56]. Their limited size and number reflect their specialized formation conditions and localized impact. The sub-basin contains 16 simple basin mountain glaciers, totaling 32.16 km^2 in area. The simple basin mountain glaciers are primarily small to medium-sized, with the majority being in the 1-2 km^2 range. There is only one valley glacier in the sub-basins, covering an area of 1.91 km^2.

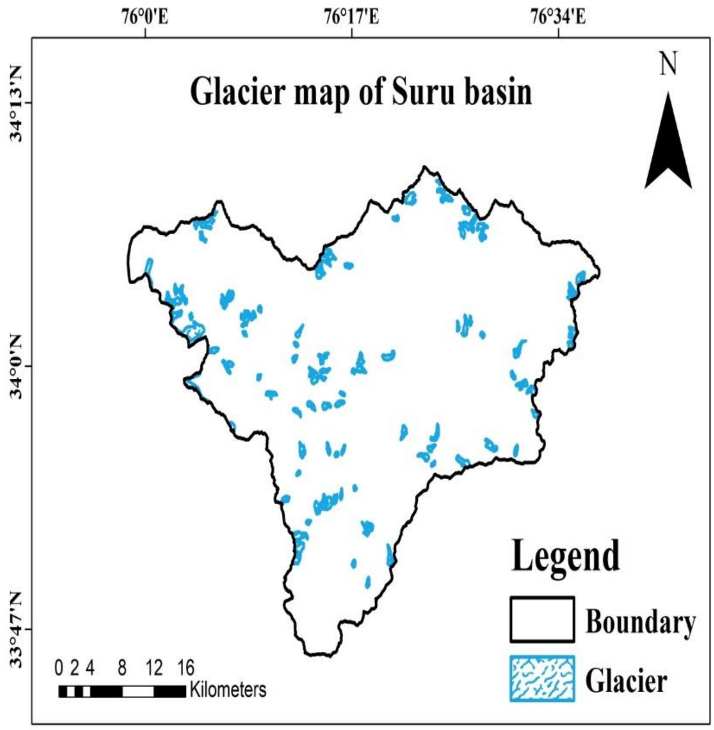

Fig. 2. Glacier map of Suru basin

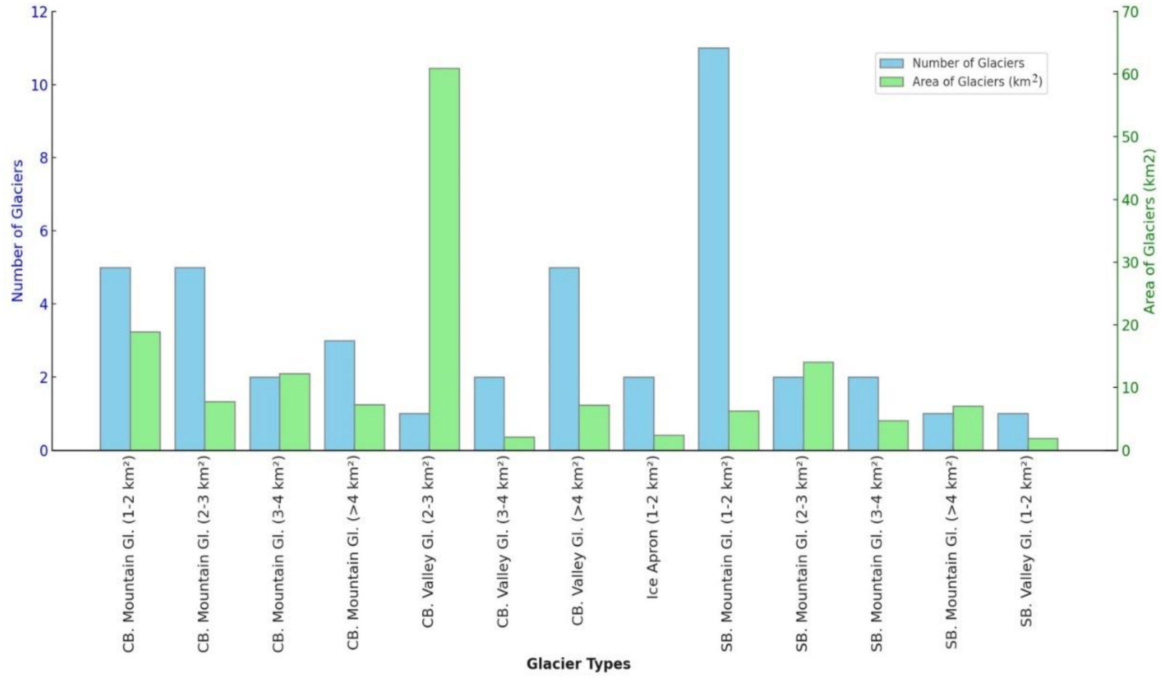

Fig. 3. Distribution and areal extent of glacier types in the Suru basin

Table 1. Distribution and areal extent of glacier types in the Suru basin

Glacier Type	Number of glaciers	Area of glaciers (km^2)
CB. Mountain Gl.	**15**	**46.18**
1-2	5	18.91
2-3	5	7.77
3-4	2	12.22
>4	3	7.28
CB. Valley Gl.	**8**	**70.27**
2-3	1	60.95
3-4	2	2.14
>4	5	7.17
Ice Apron	**2**	**2.39**
1-2	2	2.39
SB. Mountain Gl.	**16**	**32.16**
1-2	11	6.28
2-3	2	14.05
3-4	2	4.75
>4	1	7.08
SB. Valley Gl.	**1**	1.91
1-2	1	1.91
Grand Total	**42**	**152.91**

Note: CB.-Compound Basin, SB.-Simple Basin, Gl.-Glacier

This detailed categorization of glacier types and their respective areas provides valuable insights into the glacial characteristics of the Suru basin. Understanding the distribution and size of these glaciers is crucial for glaciological research, water resource management, and assessing the impacts of climate change in this mountainous region.

A heat map is a visual representation of data that simultaneously displays the hierarchical cluster structure of both rows and columns within a data matrix [57]. Heat maps convert data into a color-coded summary, allowing for the clear visualization of data distribution and characteristics at a glance, thus facilitating the identification and summarization of anomalies. Additionally, data points can be grouped according to their corresponding heat map colors [57,58]. Overall, heat maps effectively present complex data in a concise and comprehensive manner, making it easily interpretable in a single view [59]. The heatmap presented in Fig. 4 illustrates the distribution of glacier areas across different types and size categories within the Suru sub-basin. This visualization provides a clear understanding of how glacier areas vary among different glacier types and their respective size categories. The key observations from the heat map are as:

Key Observations:

- **CB Mountain Glaciers:**
  - There are significant numbers of glaciers in the "1-2 km²" and "2-3 km²" categories.
  - Larger glaciers (>4 km²) are also present but in fewer numbers.
- **CB Valley Glaciers:**
  - Most of these glaciers fall into the ">4 km²" category, indicating that CB valley glaciers tend to be larger.
- **Ice Aprons:**
  - These are relatively small glaciers, with all instances falling into the "1-2 km²" category.
- **SB. Mountain Glaciers:**
  - A high concentration of these glaciers is in the "1-2 km²" category, showing a prevalence of smaller glaciers.
- **SB. Valley Glaciers:**
  - Only one glacier is present in the "1-2 km²" category, indicating limited glacier formation of simple basin valley glaciers.

The second heatmap (Fig. 5) focuses on the number of glaciers across different types and size categories within the Suru basin. This heatmap provides insights into the prevalence of glaciers of various sizes within each glacier type. The key observations from the heat map are as:

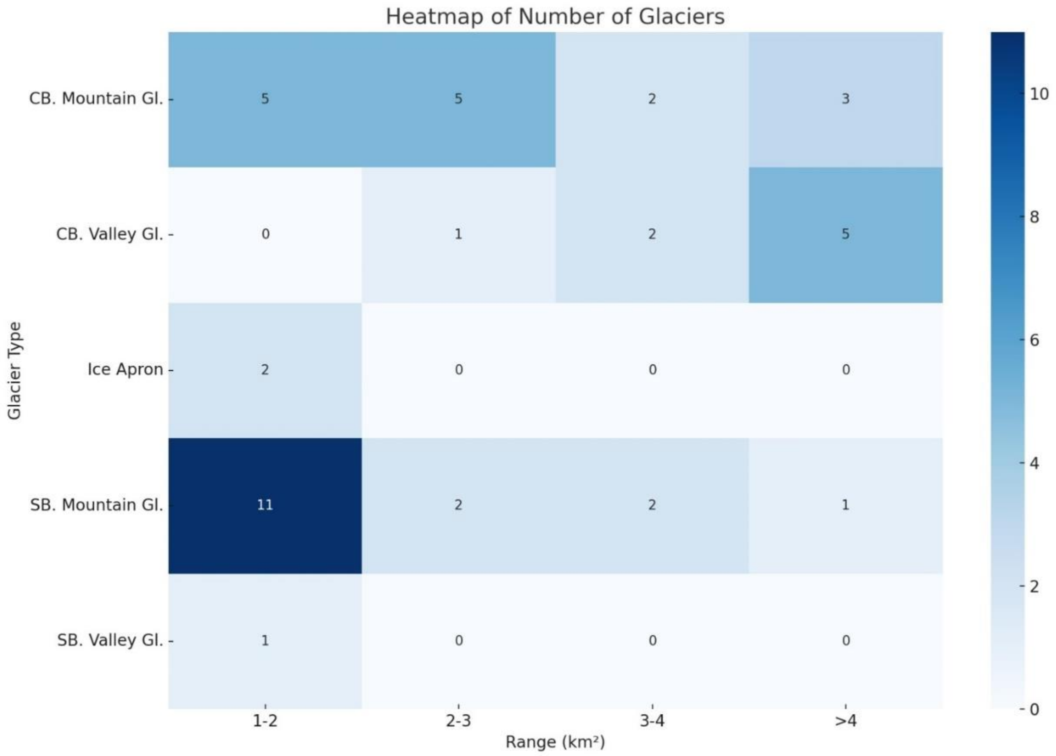

Fig. 4. Heat map of glacier sizes in the Suru basin

Key Observations:

- **CB. Mountain Glaciers:**
  - Significant glacier area is found in the "1-2 km²" and "2-3 km²" categories.
  - The largest area is in the ">4 km²" category, reflecting the presence of larger glaciers.
- **CB. Valley Glaciers:**
  - The majority of the glacier area is in the ">4 km²" category, indicating that these valley glaciers cover extensive areas.
- **Ice Aprons:**
  - These are relatively small in area, with all instances in the "1-2 km²" category.
- **SB. Mountain Glaciers:**
  - The "1-2 km²" category has the most significant area, indicating a high prevalence of smaller glaciers.
- **SB. Valley Glaciers:**
  - Only one glacier is present, and it falls within the "1-2 km²" category, indicating limited glacier area in simple basin valleys.

3.2 Distribution of Glacier Characteristics in the Suru Basin: Violin Boxplot Analysis

This section will present the detailed violin boxplot analysis of various glacier characteristics in the Suru Basin for the year 2022. The violin boxplots provide a detailed visual representation of various glacier characteristics in 2022. The characteristics considered here are- Aspect, Slope and Elevation. The mean elevation and slope show the typical altitudinal and angular distribution of glaciers, while the aspect ranking indicates their orientation. The glacier area plot highlights the predominance of smaller glaciers and the presence of a few significantly larger ones. This comprehensive view aids in understanding the distribution and variability of glacier properties within the study area. Fig. 6 consists of four violin boxplots, each representing different characteristics of glaciers for the year 2022. Violin plots combine aspects of box plots and kernel density plots. They show the distribution of the data, its probability density, and the interquartile range (IQR) with an embedded box plot.

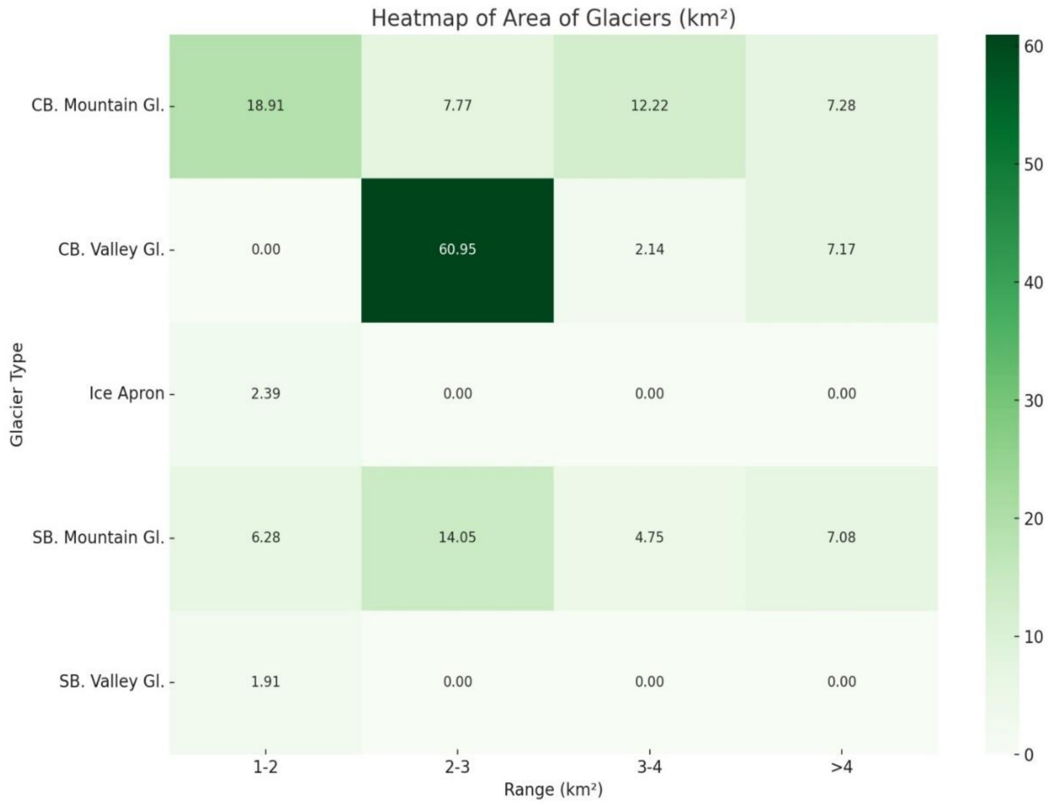

Fig. 5. Heatmap of glacier areas in the Suru basin

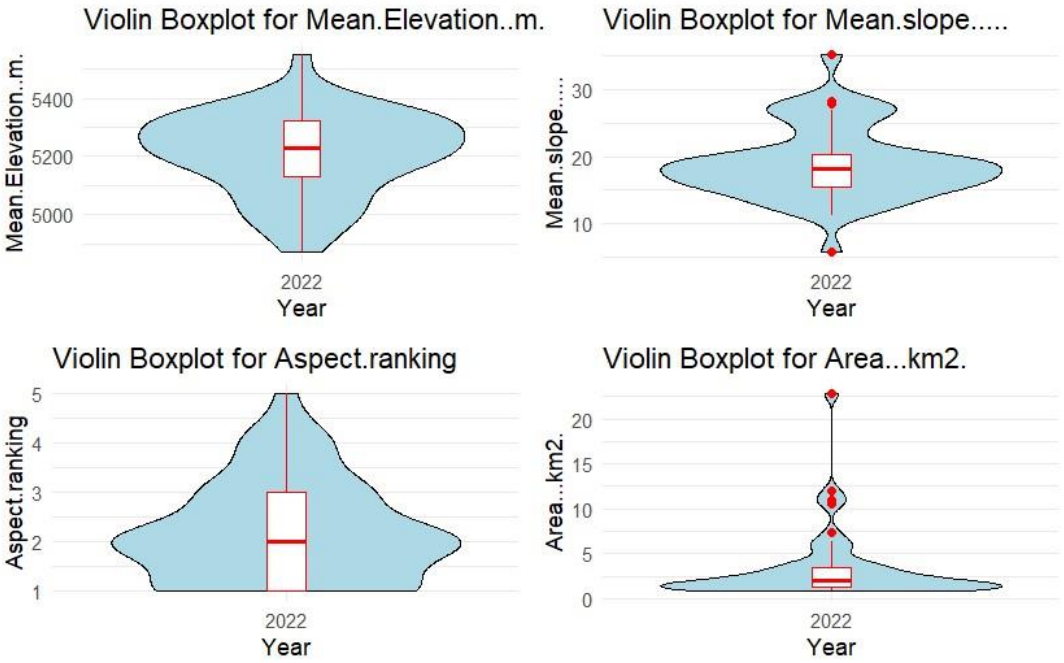

Fig. 6. Violin box plot for mean elevation (m), mean slope (⁰), aspect and area of glaciers for year 2022

3.2.1 Violin Boxplot for Mean Elevation (m)

- **Y-Axis:** Mean Elevation (m)
- **X-Axis:** Year (2022)

The plot shows the distribution of mean elevations of glaciers. The width of the violin plot indicates the density of glaciers at different elevation levels. The embedded box plot shows the median elevation, interquartile range, and possible outliers. The distribution suggests that most glaciers have mean elevations between 5000 and 5400 meters, with a median around 5100 meters.

3.2.2 Violin Boxplot for Mean Slope (°)

- **Y-Axis:** Mean Slope (°)
- **X-Axis:** Year (2022)

This plot illustrates the distribution of mean slopes of glaciers. The density distribution shows that most glaciers have mean slopes between 10° and 30°. The median slope is around 20°, with a wider spread and some potential outliers at higher slope values.

3.2.3 Violin Boxplot for Aspect Ranking

- **Y-Axis:** Aspect Ranking
- **X-Axis:** Year (2022)

Aspect ranking indicates the orientation or direction of the glacier slopes. The violin plot shows a relatively uniform distribution of aspect rankings. The median aspect ranking is around 3, with values ranging from 1 to 5. The density distribution suggests some variability in glacier orientation.

3.2.4 Violin Boxplot for Area (km²)

- **Y-Axis:** Area (km²)
- **X-Axis:** Year (2022)

This plot depicts the distribution of glacier areas. The density distribution indicates that most glaciers have areas less than 5 km², with a few glaciers having significantly larger areas. The median glacier area is around 2 km², with a notable outlier around 20 km². The box plot within the violin indicates a skewed distribution with some larger glaciers pulling the mean higher.

3.3 Elevation-Wise Distribution

The Table 2 and Figs (7, 8 and 9) present a detailed analysis of glacier distribution categorized by elevation class and glacier type. The data includes the number of glaciers and the cumulative area of these glaciers (in km²).

Table 2. Distribution of number and area of glaciers by elevation class and glacier type

Elevation Class	Number of glaciers	Area (km²)
4500-5000m	**3**	**14.27**
CB. Valley Gl.	2	12.66
SB. Mountain Gl.	1	1.60
5000-5500m	**38**	**136.44**
CB. Mountain Gl.	15	46.18
CB. Valley Gl.	6	57.60
Ice Apron	2	2.39
SB. Mountain Gl.	14	28.35
SB. Valley Gl.	1	1.91
5500-6000m	**1**	**2.21**
SB. Mountain Gl.	1	2.21
Grand Total	**42**	**152.91**

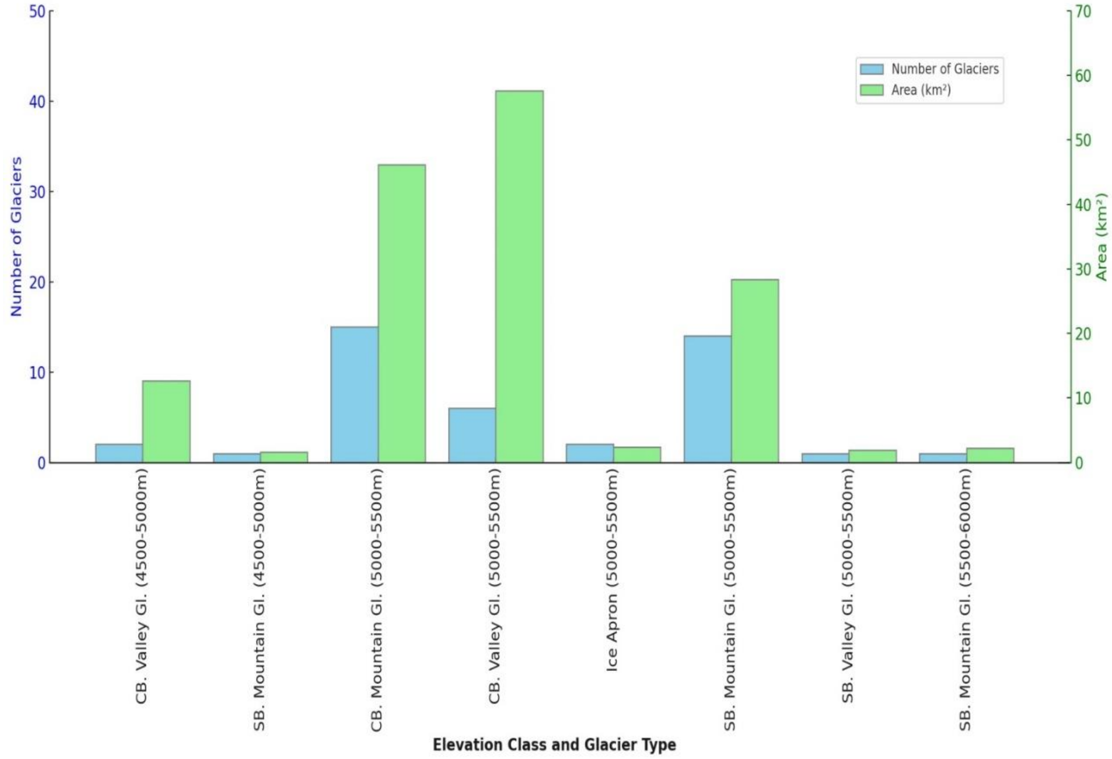

Fig. 7. Distribution of number and area of glaciers by elevation class and glacier type

In the 4500-5000m elevation class, there are a total of 3 glaciers covering an area of 14.26698 km². Specifically, CB. Valley Glaciers account for 2 glaciers with a combined area of 12.66492 km², and SB. Mountain Glaciers account for 1 glacier with an area of 1.60 km². In the 5000-5500m elevation class, the number of glaciers significantly increases to 38, with a combined area of 136.44 km². Within this elevation class, CB. Mountain Glaciers contribute 15 glaciers with a total area of 46.18 km², CB. Valley Glaciers contribute 6 glaciers with a combined area of 57.60 km², Ice Aprons account for 2 glaciers covering 2.39 km², SB. Mountain Glaciers contribute 14 glaciers with an area of 28.35 km², and SB. Valley Glaciers contribute 1 glacier with an area of 1.91 km². The 5500-6000m elevation class has the least number of glaciers, with only 1 glacier covering an area of 2.21 km², specifically an SB. Mountain Glacier.

Overall, the grand total for the region includes 42 glaciers with a combined area of 152.91 km². The 5000-5500m elevation class contains the majority of glaciers, accounting for 38 glaciers and a substantial portion of the total glacier area. This contrasts with the 4500-5000m and 5500-6000m elevation classes, which contain fewer glaciers and smaller areas.

The data reveals that CB. Valley Glaciers and CB. Mountain Glaciers are significant contributors to the total glacier area within their respective elevation classes. In contrast, SB. Mountain Glaciers are present across all three elevation classes but are fewer in number and cover a smaller total area compared to CB glacier types. Notably, CB. Valley Glaciers in the 5000-5500m range possess the largest combined area of 57.60 km², while SB. Mountain Glaciers also have a considerable presence in this range, with 14 glaciers covering 28.35 km².

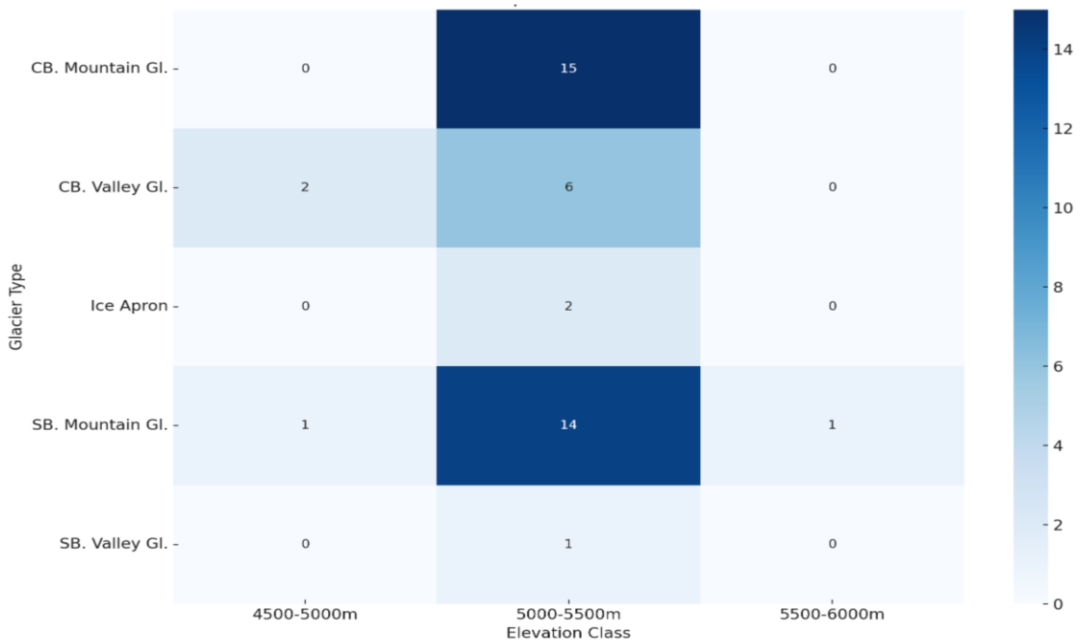

Fig. 8. Heatmap of number of glaciers by elevation class and glacier type

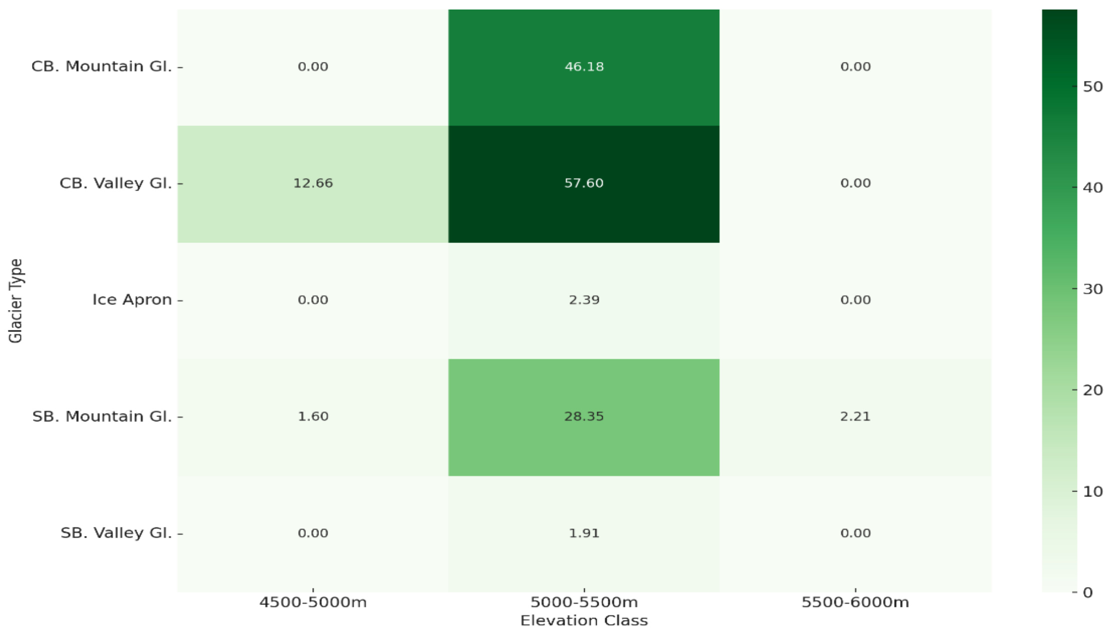

Fig. 9. Heatmap of area of glaciers (km²) by elevation class and glacier type

The variability in glacier count and area across different elevation classes and glacier types may be attributed to climatic conditions, topography, and other environmental influences that affect glacier formation and persistence. The data suggests that certain glacier types are more prevalent in specific elevation ranges, indicating adaptation to altitude-related climatic conditions. This comprehensive dataset provides valuable insights into the distribution and characteristics of glaciers within the studied region. Future research should consider the potential impact of mapping techniques and the involvement of different analysts, as these factors could introduce systematic and random errors into the results.

3.4 Slope-wise Distribution

The Table 3 and Figs. (10, 11 and 12) present an analysis of the distribution of glaciers categorized by slope class and glacier type. The analysis is supported by a bar graph and two heatmaps, providing a comprehensive view of the number and area of glaciers across different slope classes. Fig. 10 illustrates the relationship between the number of glaciers and their area across different slope classes and glacier types. In the slope class of 11-15°, CB. Valley Glaciers are predominant, with 3 glaciers covering an area of 38.53 km². Similarly, SB. Mountain Glaciers also have a notable presence with 3 glaciers covering an area of 6 km². The total number of glaciers in this slope class is 8, accounting for a combined area of 53.53 km².

The slope class of 15-20° exhibits the highest number of glaciers, totaling 22 glaciers and covering an area of 64.16 km². Within this class, CB. Mountain Glaciers are the most significant, with 11 glaciers covering 23.93 km². CB. Valley Glaciers and SB. Mountain Glaciers follow, with 4 glaciers (28.33 km²) and 5 glaciers (8.61 km²), respectively. This class also includes Ice Apron and SB. Valley Glaciers, contributing a smaller number of glaciers and areas.

In the slope class of 20-25°, there are 5 glaciers with a combined area of 18.05 km². SB. Mountain Glaciers are predominant in this class, with 3 glaciers covering 8.69 km². CB. Mountain Glaciers and CB. Valley Glaciers have 1 glacier each, covering areas of 5.95 km² and 3.41 km², respectively. The slope class greater than 25° comprises 7 glaciers with a total area of 17.18 km². SB. Mountain Glaciers are again prominent, with 5 glaciers covering 8.86 km². CB. Mountain Glaciers and Ice Aprons contribute 1 glacier each, covering areas of 7.30 km² and 1.02 km², respectively.

The heatmaps (Figs. 11 and 12) provide a detailed visual representation of the distribution of glaciers by slope class and glacier type. Fig. 11 displays the number of glaciers within each slope class for different glacier types. The color intensity reflects the number of glaciers, with darker shades indicating a higher count. The 15-20° slope class shows the highest concentration of glaciers, particularly for CB. Mountain Glaciers and CB. Valley Glaciers. This suggests that these glacier types are more prevalent in moderate slope ranges. The 11-15° and >25° slope classes also show significant numbers for CB. Valley Glaciers and SB. Mountain Glaciers, indicating their adaptability to varying slope conditions.

Fig. 12 illustrates the total area covered by glaciers in each slope class for different glacier types. The color intensity in this heatmap corresponds to the area, with darker shades representing larger areas. The 15-20° slope class again stands out with the largest total area covered by glaciers, especially for CB. Valley Glaciers and CB. Mountain Glaciers. The 11-15° slope class shows a significant area for CB. Valley Glaciers, while the >25° slope class highlights SB. Mountain Glaciers as covering a notable area.

3.5 Aspect-wise Distribution

Table 4 and Figs. (13, 14 and 15) present an analysis of glacier distribution categorized by aspect and glacier type, illustrated through a bar graph and two heat maps.

Fig. 13 illustrates the relationship between the number of glaciers and their respective areas. The data reveals that CB. Mountain Glaciers are primarily found in the southern and southeastern aspects, with 8 glaciers covering 23.89 km² in the south and 4 glaciers covering 15.71 km² in the southeast. CB. Valley Glaciers show a significant presence in the south and southeast as well, with 2 glaciers covering 33.32 km² and 4 glaciers covering 31.4 km², respectively. Ice Apron glaciers are less widespread, mainly found in the northwest and southeast aspects. SB. Mountain Glaciers exhibit notable adaptability, being distributed across the east, south, southeast, and southwest aspects, with the highest concentration in the southeast. SB. Valley Glaciers are limited to the southeast aspect.

Table 3. Distribution of number and area of glaciers by slope class and glacier type

Slope Class (º)	Number of glaciers	Area (km²)
11-15	**8**	**53.53**
CB. Mountain Gl.	2	9.00
CB. Valley Gl.	3	38.53
SB. Mountain Gl.	3	6.00
15-20	**22**	**64.16**
CB. Mountain Gl.	11	23.93
CB. Valley Gl.	4	28.33
Ice Apron	1	1.37
SB. Mountain Gl.	5	8.61
SB. Valley Gl.	1	1.91
20-25	**5**	**18.05**
CB. Mountain Gl.	1	5.95
CB. Valley Gl.	1	3.41
SB. Mountain Gl.	3	8.69
>25	7	**17.18**
CB. Mountain Gl.	1	7.30
Ice Apron	1	1.02
SB. Mountain Gl.	5	8.86
Grand Total	**42**	**152.91**

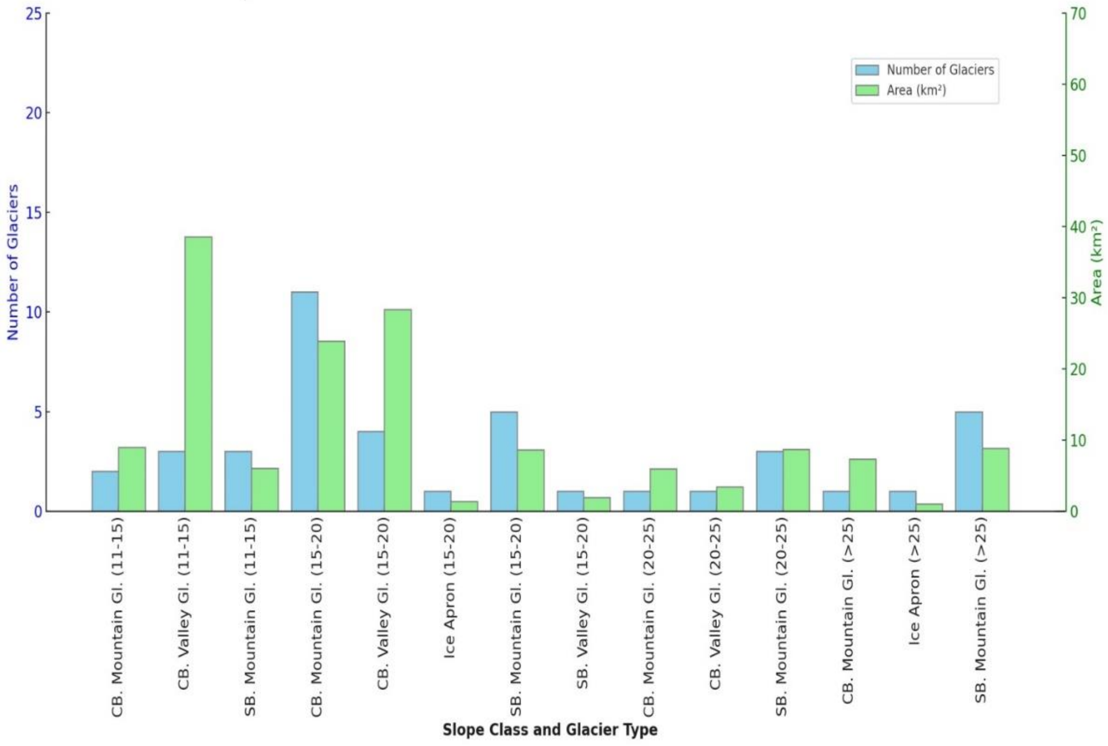

Fig. 10. Distribution of number and area of glaciers by slope class and glacier type

The heatmaps provide a detailed visual representation of the glacier distribution by aspect and glacier type. Fig. 14 shows the number of glaciers within each aspect for different glacier types. The color intensity reflects the number of glaciers, with darker shades indicating higher counts. This heatmap reveals that CB. Mountain Glaciers are predominantly found in the southern and southeastern aspects, while SB. Mountain Glaciers show a significant presence in the southeast aspect. Fig. 15 displays the total area covered by glaciers in each aspect. The color intensity corresponds to the area, with darker shades representing larger areas. This heatmap highlights that CB. Valley Glaciers cover the largest areas, especially in the south and southeast aspects, indicating a significant concentration of glacier mass in these directions.

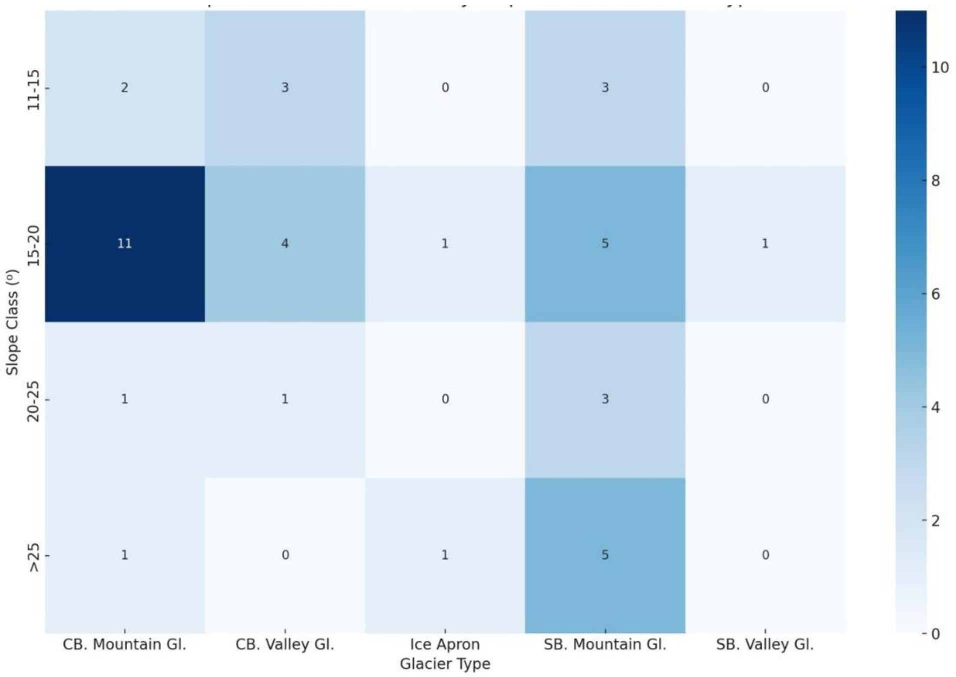

Fig. 11. Heatmap of number of glaciers by slope class and glacier type

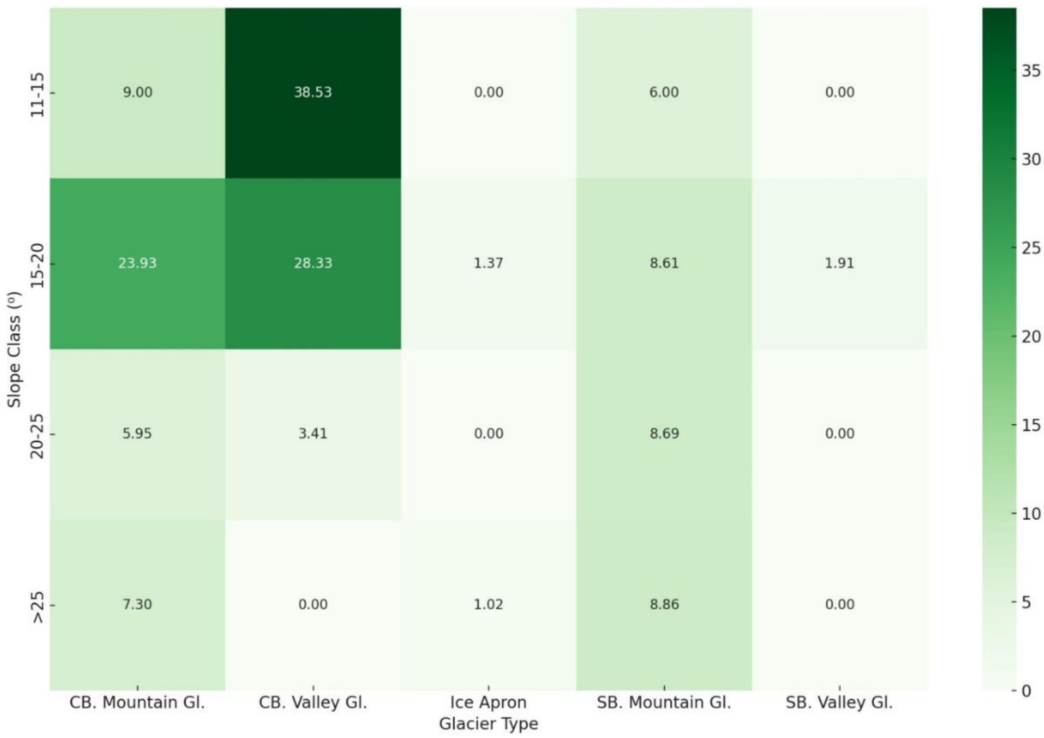

Fig. 12. Heatmap of area of glaciers (km²) by slope class and glacier type

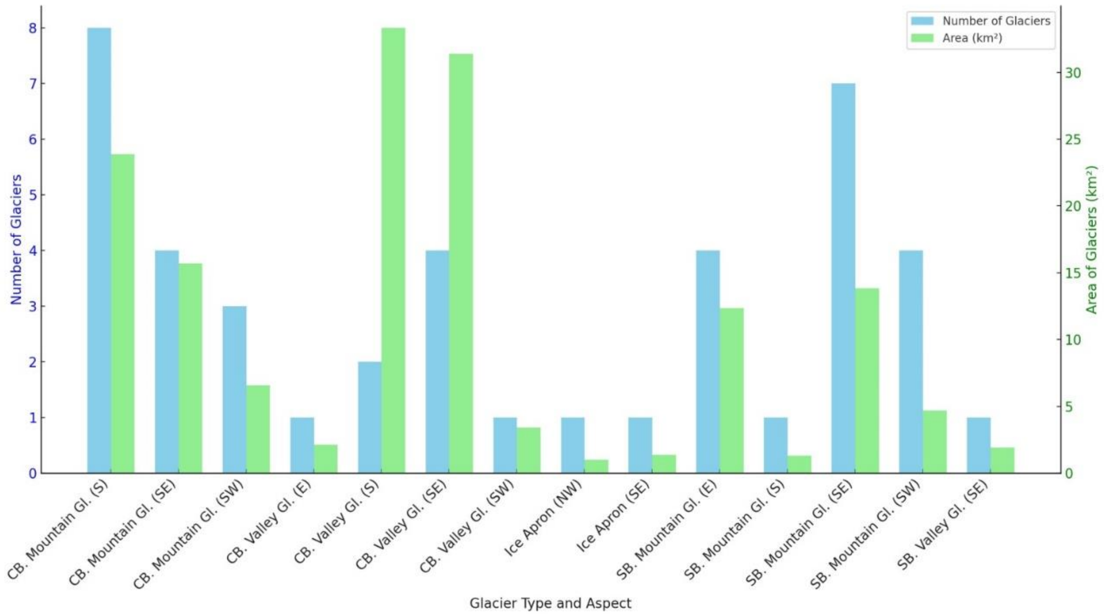

Fig. 13. Distribution of number and area of glaciers by aspect and glacier type

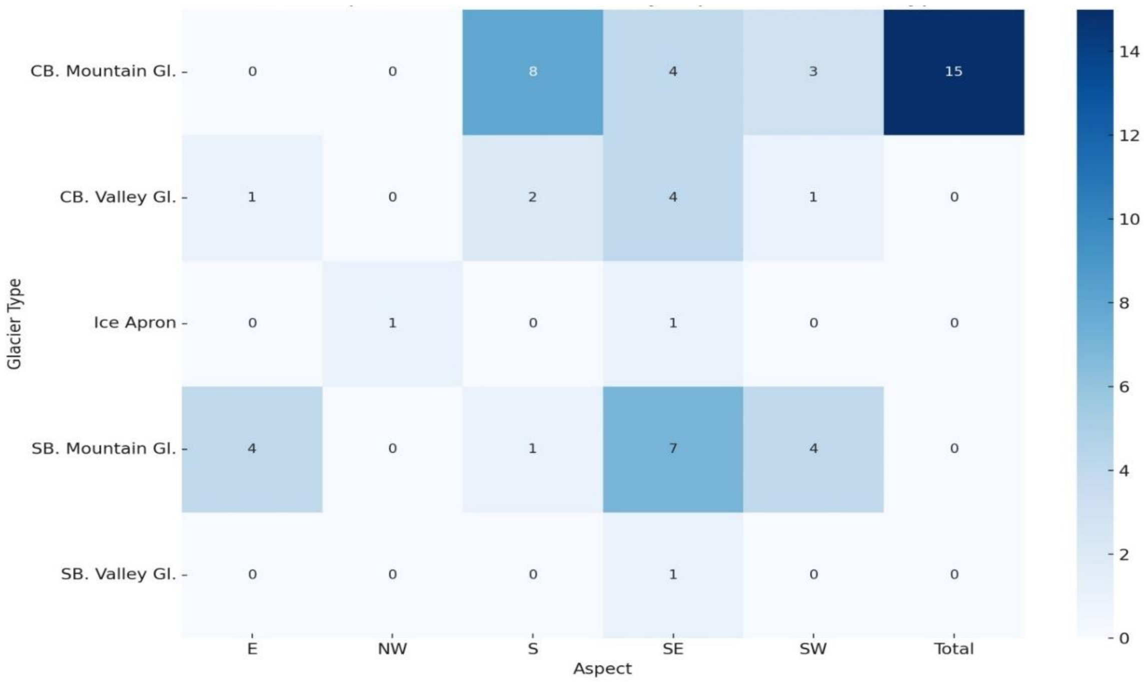

Fig. 14. Heatmap of number of glaciers by aspect and glacier type

Combining insights from the bar graph and heatmaps provides a comprehensive understanding of glacier distribution by aspect and glacier type. The data suggests that certain glacier types are more prevalent in specific aspects, influenced by environmental factors such as sunlight exposure, wind patterns, and topographical features. CB. Valley Glaciers and SB. Mountain Glaciers show significant adaptability across various aspects, while CB. Mountain Glaciers are predominantly found in the southern and southeastern aspects. Ice Apron glaciers are less widespread, mainly found in the northwest and southeast aspects. These visualizations enhance our understanding of glacier dynamics in relation to aspect and provide valuable insights for further research in glaciology. The distribution patterns observed can help in predicting glacier behavior and response to climatic changes, contributing to more effective conservation and management strategies. Overall, this study underscores the importance of considering both the number and area of glaciers when assessing their impact on the environment and their response to climatic variations.

Table 4. Distribution of number and area of glaciers by aspect and glacier type

S.No.	Aspect	Number of glaciers	Area (km^2)
1.	**CB. Mountain Gl.**	**15**	**46.18**
	S	8	23.89
	SE	4	15.71
	SW	3	6.58
2.	**CB. Valley Gl.**	**8**	**70.27**
	E	1	2.14
	S	2	33.32
	SE	4	31.40
	SW	1	3.41
3.	**Ice Apron**	**2**	**2.39**
	NW	1	1.02
	SE	1	1.37
4.	**SB. Mountain Gl.**	**16**	**32.16**
	E	4	12.34
	S	1	1.30
	SE	7	13.83
	SW	4	4.68
5.	**SB. Valley Gl.**	**1**	**1.91**
	SE	1	1.91
	Grand Total	42	152.91

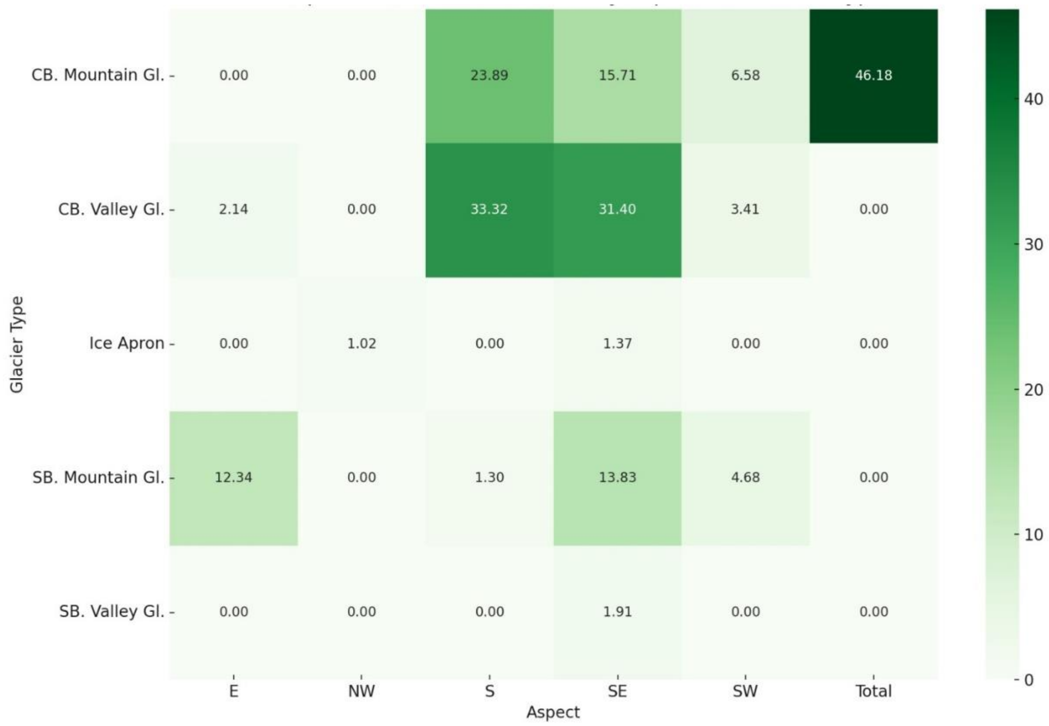

Fig. 15. Heatmap of area of glaciers (km²) by aspect and glacier type

4. CONCLUSIONS

This study aimed to create a detailed glacier inventory and analyze glacier characteristics in the Suru basin using high-resolution Sentinel-2 data and DEM. By leveraging remote sensing technologies, we accurately mapped the extent and surface characteristics of 43 glaciers, covering a total area of 153.91 km². The glaciers were categorized into compound basin mountain glaciers, compound basin valley glaciers, simple basin mountain glaciers, simple basin valley glaciers, and ice aprons. The majority of glaciers in the Suru basin are small to medium-sized, with significant variability in elevation, slope, and aspect.

Our findings indicate that compound basin valley glaciers tend to be larger, with most falling into the ">4 km²" category, while simple basin glaciers are predominantly smaller. The violin boxplot analysis revealed that most glaciers have mean elevations between 5000 and 5400 meters, mean slopes between 10° and 30°, and a median aspect ranking of around 3. The glacier area distribution showed a predominance of smaller glaciers, with a few significantly larger ones influencing the overall area metrics.

The heatmap analyses of glacier size and area by elevation, slope, and aspect classes provided additional insights into the distribution patterns of these glaciers. CB. Valley Glaciers and CB. Mountain Glaciers were significant contributors to the total glacier area within their respective elevation classes. In contrast, SB. Mountain Glaciers were present across all elevation classes but covered a smaller total area. The slope analysis revealed that most glaciers fall within the 15-20° slope class, with CB. Valley Glaciers showing a notable presence in the 11-15° class. Aspect-wise, CB. Mountain Glaciers and SB. Mountain Glaciers were primarily found in the southern and southeastern aspects.

5. FUTURE WORK

Future research should focus on long-term monitoring of glacier changes in the Suru basin to understand temporal dynamics and their implications for water resources and ecological stability. Integrating additional remote sensing data from various satellite missions and incorporating ground-based measurements will enhance the accuracy and reliability of glacier inventories. Furthermore, studies should investigate the socio-economic impacts of glacier retreat on local communities and develop adaptive strategies for sustainable water resource management in response to ongoing climatic changes. This study underscores the importance of considering both the number and area of glaciers when assessing their environmental impact and response to climatic variations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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