


Monitoring and Mapping of Batura Glacier in Northern Pakistan's Gilgit Baltistan Region: A Geospatial Approach

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Abstract: Pakistan is home to some of the world's richest natural resources, including glaciers, which are among its most vital assets. To ensure their sustainable use, these resources require effective mapping, monitoring, and strategic planning. Modern geospatial technologies, including remote sensing and Geographic Information Systems (GIS), offer efficient and convenient methods for monitoring and mapping key natural resources. The Batura Glacier, one of the major glaciers in Pakistan's Himalayan region, plays a significant role in the region's hydrology. This study used remote sensing and GIS-based techniques to assess changes in the Batura Glacier's area following ice melt and to analyze the spatiotemporal dynamics of its snow cover area (SCA) over the past 25 years (1998–2023) during the winter season. By applying the Normalized Difference Snow Index (NDSI) to Landsat satellite imagery from December 1998 to November 2023, the study revealed that the lowest SCA was recorded in December 2008, covering 39.83%, while the highest SCA, 49.15%, was observed in November 2013. The overall changes in SCA from 1998 to 2023 is, 4.90%. In conclusion, the use of geospatial technology proved highly effective in assessing and monitoring the glaciated areas of the Batura Glacier. It can be applied to real-time monitoring efforts in similar regions.

Keywords: Geospatial Technology; Batura; Snow Covers Area; NDSI; Landsat; Himalayan Region

1. Introduction

The freshwater ecosystem of the Earth is mainly located in mountainous regions, where glaciated areas have substantial effects on the worldwide flow of downstream rivers [1, 2]. Glaciers play a crucial role as water supplies and are highly responsive indicators of climate change [3]. In particular, its water plays a significant role in the Indus Basin water due to glacier melt [4]. The upper Indus Basin (UIB) consists of the Hindukush, Karakoram, and Himalayan Mountains (HKH) [3] and has the most significant accumulation of glaciers beyond the Arctic zone [5]. There are 12,705 square kilometres of glaciers, and the Karakoram area accounts for more than 70% of the glaciated area [6]. However, estimations of the glaciated ice volume in the Karakoram area vary greatly, with estimates ranging from 1683 to 2827 km² using various methodologies [7]. In contrast to other glaciers in High Mountain Asia (HMA), Karakoram glaciers have remained relatively stable over the last 30 years despite atmospheric warming [8-10]. Hydrology, meteorology, and climatology depend heavily on precise mapping of areas covered with snow, particularly in cold weather [11]. For the majority of major rivers

that originate in high Asia, snowmelt comprises the majority of the runoff from most land surfaces at latitudes [12].

Mapping areas covered with snow is crucial for modelling snowmelt and reconstructing estimations of the snow water equivalent [13-15]. Snow-covered areas change quickly and in a complex manner in response to climate change [16,17], which is especially important for climate analyses. Accurate snow-covered areas also act as important inputs for numerical weather predictions [18,19] and land surface models [20,21]. Snow-covered mountain areas provide a steady supply of water for a range of purposes, including drinking, irrigation, electricity production, water storage in dams, and serving as life-saving buffers during dry spells [22]. Tall mountains with the highest frequency of glacier melts that impact water resources include the Hindu Kush Himalan (HKH) [2,23,24]. The largest mountainous region is the HKH region, which encompasses several Asian countries and Pakistan. Because the HKH area has large freshwater reserves that are not in the polar zone, it is also commonly termed the “third pole’ or” ash water tower of Asia’ [25]. Most of the main rivers in these countries have their base sources in the HKH area and are sustained by the melting of snow and glaciers [26]. Consequently, this area sustains the subsistence of those living downstream by providing water resources [27,28], which are crucial for agricultural output, energy generation, drinking purposes, and industrial development [29,30]. Nevertheless, as a consequence of changes in climatic conditions, glaciers and snow-covered regions face significant danger and undergo continual transformation [31].

Recent developments in Himalayan glacier changes, remote sensing, and climate modelling have significantly enhanced our understanding of the cryosphere dynamics in the study area. Based on recent studies [54-56] this combination integrates post-2020 research to deliver a brief summary of current improvements and technological novelties. Bhat et al. [54] analyzed snow resources and climatic variations in Jammu and Kashmir, India. Their research underscores the understanding of snow cover in relation to climate change and the consequences for water resources in the study area. Azam et al. [55] present a reanalysis of the extensive mass balance sequence in the Himalayas, employing a nonlinear model to reveal refined observations of glacier changes. Their results highlight the difficulty of glacier mass balance and the need for progressive modelling approaches to capture these changes precisely. Zaho et al. [56] discovered the application of UAV technology in glaciology studies in the third-pole region. Their study emphasized the benefits of UAVs in obtaining high-resolution spatial and temporal images, providing a greater understanding of glacier changes.

Khadka et al. [57] examined the influence of climate dynamics on glaciers and glacier lakes in the Nepal Himalayas. Their study focused on the increasing retreat of glaciers and the associated risks to water resources in the research area. Gao et al. [58] provided experimental evidence of the Karakorum anomaly, representing the post-20th century near the steady state of the Batura Glacier. This process differs from the extensive global glacier retreat, indicating regional changes in glacier activity. Biswas et al. [59] focused on the preservation problem and adaptation plan for Indian Himalayan biological diversity in the context of climate change. This research focused on the need for a technology-driven data system to support informed decision-making in preservation efforts. Mishra et al. [60] conducted a comprehensive glacier inventory and assessed glacier dynamics from 1994 to 2020 in the central Himalayas' upper Alaknanda basin. Their output showed a considerable decrease in glacier area, with an observable pace of retreat over the study duration. This research highlights the sensitivity of glaciers in the context of climate change and the importance of regular studies in understanding their evolving dynamics. Chowdhury et al. [61] emphasized the Chhoombo Chhu Watershed of the Tista Basin in the Sikkim Himalaya, monitoring glacier dynamics between 1975 and 2018. Their finding detects seventy-four glaciers, with a total area decrease of approximately 17.9 Km² over the 43 years, calculating an annual loss rate of approximately 0.42 Km². The research focused on clear glaciers being more

vulnerable to melting than debris-covered glaciers and the decreasing rates of change across different periods, with the most noticeable loss occurring between 2010 and 2018. This output focused on the current retreat of glaciers in the eastern Himalayas and the requirement for targeted preservation.

Pakistan is home to a large number of glaciers covering an area of approximately 13,680 km², and melted glacier water supplies water to its rivers is the melted glacier water [32]. Through ice flow, ablation, and movement, a Chinese study team found that the Batura glacier stopped moving between 1997 and 1999, while it was expected to move 180–240 m before and within an area of 300 m on the Highway. Since the 1990s, scientists have predicted a decline in these glaciers over the next 20 to 30 years. However, the Batura glacier did not follow a similar temporal pattern; instead, it remained almost entirely stationary between 1885 and the 1940s, before retreating in the 1950s and 1960s. The subsequent advances, both actual and predicted, may be related to the overall large-scale dynamics of the local environment. Nevertheless, Chinese glaciologists [33] discovered their observations of the Batura Glacier and considered it a non-surging glacier. Moreover, they forecasted that the glacier terminus would advance and threaten HKH in the 1980s and the 1990s, respectively [34,35]. This glacier plays a significant role among the glaciers located in the Himalayan region of Pakistan. Hence, the goal of the present study was to assess changes in the Batura area after the melting of ice, as well as to spatiotemporally analyze this area over the past 25 years (1998-2023).

2. Materials and Methods

2.1 Study Area

Outside the polar region, Batura is one of the largest glaciers in the world. It is 57 km long and covers an area of 236 square kilometers. It is located north of Passu at an altitude of 7,500m above sea level [35]. Based on its geographical location, Batura Glacier lies between 36° 30' N-36° 40' N latitude and 74° 22' 33"E -74° 52' 30" E longitude, as shown in Figure 1. This glacier feeds the Hunza River and flows from west to east in northern Pakistan, below the northern face of the peaks of Batura Muztagh (7,795 m). The glacier has more than 20 minor subsidiary glaciers in addition to its five major ice flows. The Gilgit and Naltar Rivers join the Hunza River before it flows [35].

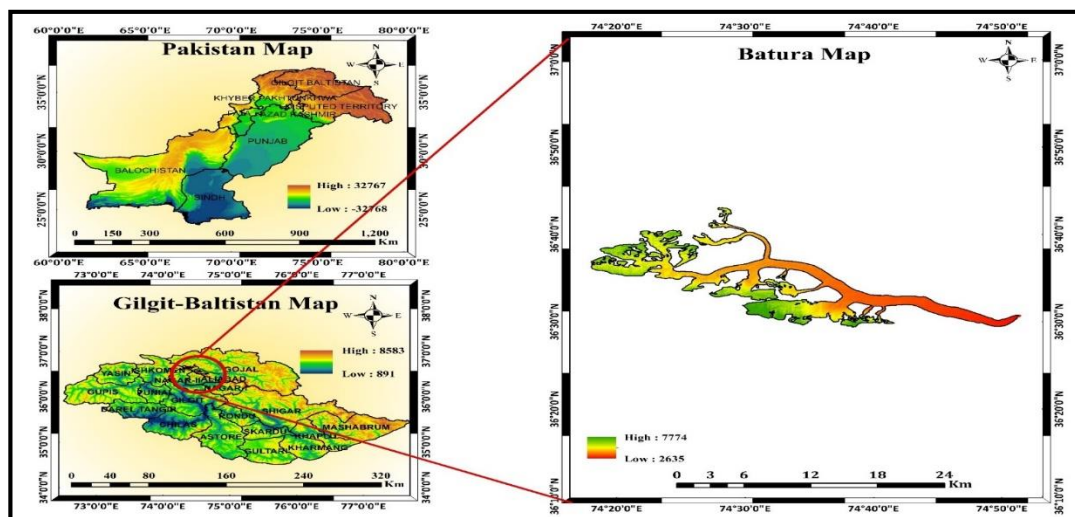


Figure 1: Location map of the study area.

2.2 Materials

Yearly Landsat data for the research region were obtained free from 1998 to 2023 from the USGS Earth Explorer [36]. When evaluating snow cover, Landsat offers the longest temporal data with multispectral and geographic resolution [37]. After 16 days, every Landsat satellite completed its orbit

around the planet. This research used data from Landsat 5 TM, Landsat 7 ETM, and Landsat 8 OLI/TIRS in this investigation. Table 1 lists the detailed parameters of Landsat images.

Table 1: Parameters of the Landsat images

Data type	Date	Spatial Resolution (m)	Cloud Cover (%)	Path	Row
Landsat 5 (TM)	Dec-1998	30	2	150	035
Landsat 7 (ETM)	Dec -2003	30	5	150	035
Landsat 7 (ETM)	Dec- 2008	30	2	149	035
Landsat 8 (ETM)	Nov -2013	30	3	149	035
Landsat 8 (OLI/TIRS)	Dec -2018	30	3	150	035
Landsat 7 (ETM)	Nov -2023	30	24	150	035

3. Methodology

Figure 2 shows the complete methodology used in this study. This study utilized modern satellite images, specifically Collection 2 Level 2 data, obtained from the USGS website, spanning the period from 1998 to 2023. The downloaded Landsat imagery was preprocessed [53]. We selected only satellite imagery with cloud cover of less than 10%. Top of the atmosphere (TOA) reflectance values were computed in keeping with the techniques delineated in Landsat's user handbook. Atmospheric alteration was not used, as this result permits a reliable contrast with various preceding studies in the literature that apply the normalized difference snow index for snow cover area mapping, particularly at high mountain altitudes, where atmospheric influence is minimum [62-64]. Fortunately, the images used in this research did not have cloud cover in the study area. This collection contains imagery-based data from Landsat 4-5 to (TM), Landsat 7 (ETM), and Landsat 8 (OLI/TIRS). These Landsat images were used for the Normalized Difference Snow index (NDSI) with a 30-m resolution. To determine the variation in SCA, this study used yearly (winter) satellite imagery.

The NDSI was used to find the snow-covered area by leveraging distinctive snow optical features, such as its high reflectance in the visible spectrum and low reflectance in the shortwave infrared (SWIR) region. The NDSI was calculated as the ratio of the digital values from the green and SWIR bands [65]. The values of the NDSI range from -1 to +1, with values higher than 0 usually representing the occurrence of snow. Generally used threshold for snow categorization in optical satellite imagery is $NDSI \geq 0.4$ [66-69]. In the outdated NDSI approach, a threshold of ≥ 0.4 was used in the Landsat Imagery series to categorize snow pixels. The bands used for Landsat 5 TM and Landsat 7 ETM+ were green band -2 and shortwave infrared band (SWIR) -5, while the Landsat 8 Operational Land Imager (OLI) bands, green band 3 and SWIR band 6, were used to calculate the normalized difference snow index.

The NDSI was used to calculate the snow cover area and calculate SCA using the pixel value; then, it was reclassified into two categories, 0 and 1, with 0 for snow-free areas and 1 for snow-covered areas, using the "Reclassify" tool. Subsequently, we calculated the SCA of this region, specifically the region of interest (ROI), using a field calculator, as it is efficient for calculating areas based on pixel values. Subsequently, these image data were reclassified into snow and non-snow pixels, and finally, the SCA (year-wise) was calculated using snow pixels as follows:

$$(1) \quad \text{NDSI} = \frac{\text{GREEN} - \text{SWIR}}{\text{GREEN} + \text{SWIR}}$$

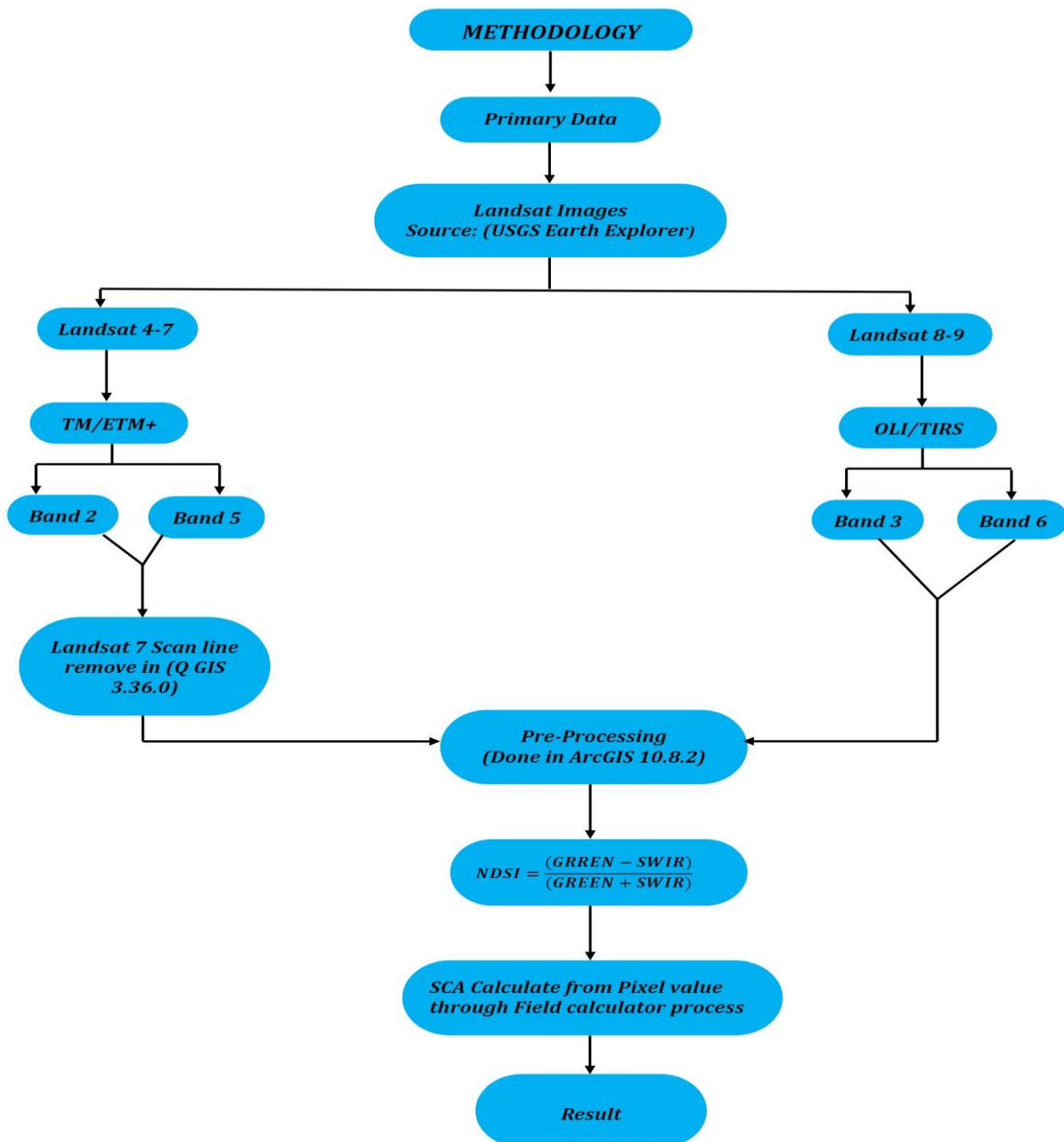


Figure 2: Methodology flowchart.

4. Results and Discussion

Using temporal Landsat satellite imagery (1998–2023) to monitor changes in specific glaciers over time in northern Pakistan revealed that the glaciers in the research area are receding. The findings of this study are consistent with those of related studies conducted in other parts of the world, including the Himalayas, the Alps, Alaska, Alberta, and Canada [38-43]. The retreat of glaciers in South Asia is the result of global warming [41]. Global warming has led to extensive glacial contraction, particularly in the eastern Himalayas and Tibetan Plateau [70-71]. The primary cause of the spatial alteration observed in the Himalayas and Karakorum glaciers is regional variations in the spreading of supra-glacial debris cover, which shields glaciers from direct sunlight [44,45]. Although clean glaciers melt more quickly, dense layers of glacial debris advance. Similar results were found for the study glacier,

where the melting rate of the Passu glacier was higher than that of the Batura glacier. The glacier melts as a result of rising global temperatures [46]. The studies of [72-73] demonstrated that the Batura Glacier retreat is visible. The rate of alteration is steady in contrast to glaciers in the Himalayas, which are observed to undergo quicker and more extreme reduction due to higher temperatures [74]. This slow retreat in the Karakoram region is known as the Karakorum Anomaly, in comparison to the extensive global glacial contraction observed in regions such as the Andes and Alps [75]. The melting water of the Batura Glacier is a vital resource for the local population, similar to glaciers in the Himalayas and the Andes, which also face water scarcity due to declining ice masses [76-77]. Although the status in the Karakorum is diverse because it is crucial for agriculture and irrigation in isolated areas, it is distinct from the glacier in the Andes that provides water to urban areas [78]. In addition, the retreat of the Batura glacier led to the creation of glacial lakes that are vulnerable to flood risks, such as those produced by retreating glaciers in the Hindu Kush Himalayas and the Andes [79]. The 2010 GLOF in upper Hunza produced damages similar to those in 2010 in Nepal, highlighting the susceptibility of the population living near these glaciers [80].

Similarly, over the past 40 years, Pakistan's average temperature has increased by 0.76°C , leading to the melting of glaciers [47]. The northern region of Pakistan is experiencing a rise in temperature and a decrease in precipitation [48,49]. The accumulation region in Batura is smaller than that in the ablation zone. Because the region has steep, high rock walls that serve as snow barriers and retain more snow, more snow accumulates, and the area may reach a high elevation, displaying the glacier's side at different elevations, and the percentage of its area that changed between 1998 and 2023.

Figure 3 shows the annual variations in snow extent across various years obtained by applying the above methods to all Landsat TM, ETM+, and OLI/TIRS images captured between 1998 and 2023. Based on the statistical analysis of Figure 4, Figure 4 shows the snow cover area (SCA) for December 1998 is 102 km^2 . SCA increased to 106 km^2 in December 2003, an increase of 4 km^2 . However, in December 2008, it decreased to 94 km^2 , indicating a significant change in SCA. It displays SCA's looseness. It grew to 116 km^2 in November 2013. The area decreased to 115 km^2 in December 2018. In November 2023, the area decreased by 107 km^2 .

In summary, SCA exhibited a declining trend. According to the percentage of the study area, the results showed that the maximum SCA of 49.15% was recorded in November 2013. In contrast, the lowest amount of snowfall was recorded in December 2008, with an area covered of 39.83%. It was deduced that there was a sinusoidal variation/trend in Batura Glacier snow coverage, as shown in the graph below. One of the major contributors to power generation in Pakistan is the Batura Glacier, and it has also been observed that the Batura Glacier has an increasing trend in snow cover area [50,51]. A growing trend in the stability of the SCA in the western Himalayas and central Karakoram regions was also found. This increasing trend in SCA can significantly contribute to the perspective of the Hunza River, owing to its dependency on SCA and glaciers.

Moreover, this increase in SCA enriches the glaciated area, significantly contributing to the mass balance of the glaciers in the Karakoram region. A growing SCA suggests that the study region's agricultural activities and reliance on water resources will benefit from increased water availability in the future. More in-depth research has been conducted at the micro-level to understand why the growing amount of snow cover in this area differs from the present global level of warming and climate change. Enhancing knowledge and comprehension of water resource management is possible using this approach. This study reveals the overall melt of specific glaciers from 1998 to 2023, attributed to the rise in regional temperatures and decline in precipitation, which is consistent with the findings of [52] for the Hunza Valley area during 2007 and 2011. Because the Landsat database of temporal images, which extends temporal recordings, is freely available and has global coverage, it is a

significant data source for tracking changes in glaciers to minimize topography changes and atmospheric errors. The NDSI efficiently detected clean glaciers. The normalized difference snow index application in debris-covered glaciers is insufficient due to their similar spectral response. Glaciers are the primary freshwater source for rivers and freshwater in Pakistan. Thus, a nation's water resource system is significantly affected by glacier melting. Climate variables, such as temperature and precipitation, influence the study of future glacier movement and climate variability [41].

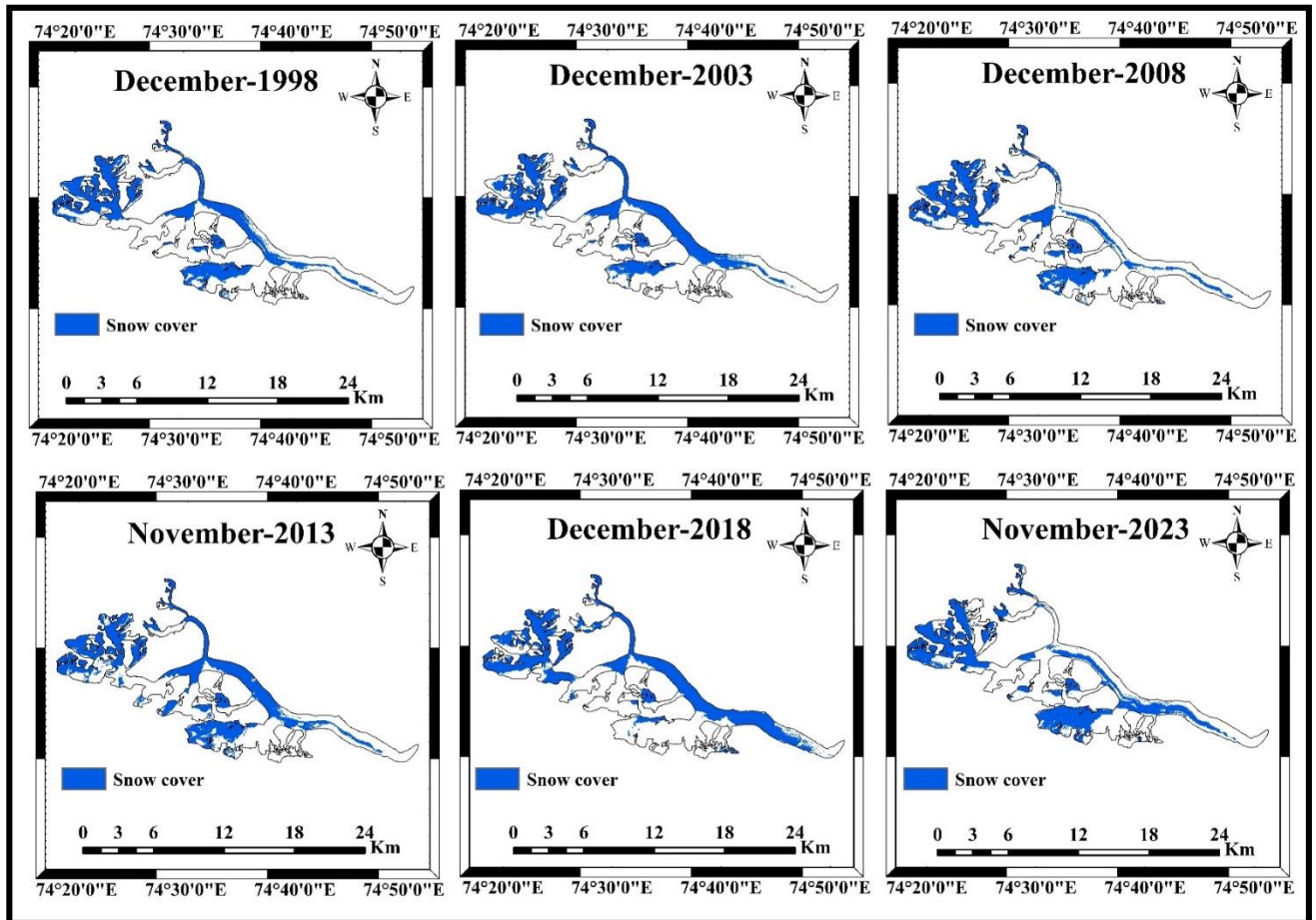


Figure 3: Annual SCA of Batura Glacier.

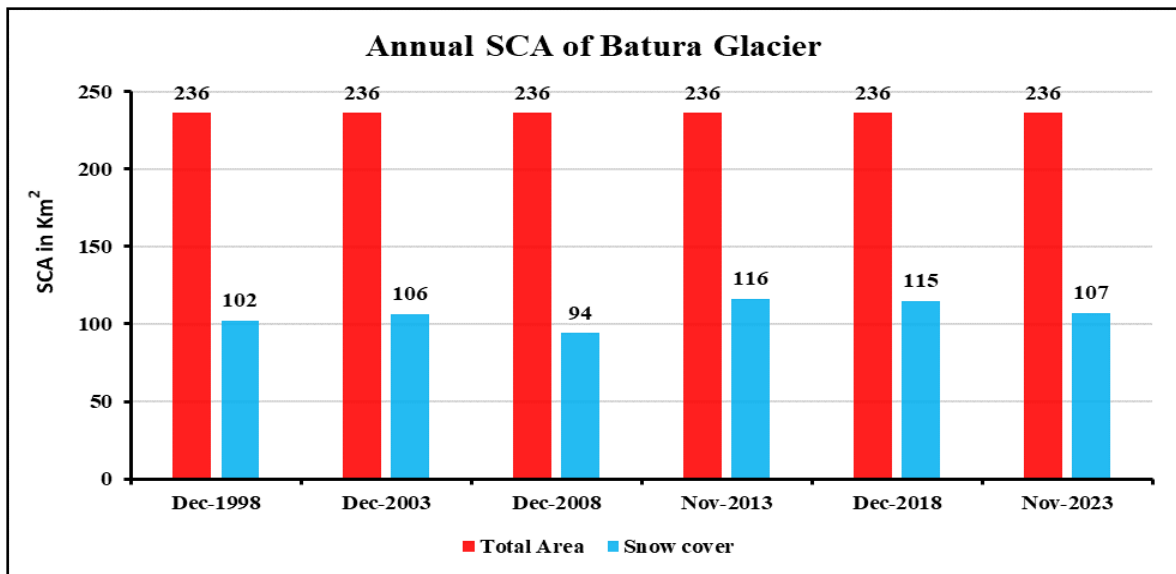


Figure 4: Temporal Changes of Snow Cover in Batura Glacier.

5. Conclusions

Based on Landsat multi-temporal images, this study evaluated the health of the preferred glacier and its decadal development from 1998 to 2023 in northern Pakistan. Landsat data were successfully utilized to monitor the temporal evolution of glaciers. The NDSI was helpful in detecting clean, debris-free glaciers; however, it produced erroneous results when identifying glaciers coated with debris. The rate of the Batura glacier retreat varies in both space and time. The thickness and distribution of debris in the supraglacial area provide information on the spatial diversity of the retreat pace. The annual temperature and precipitation records were used to calculate the temporal rate of retreat. Conversely, the pace at which glacial melt occurs increases with increasing annual temperature. Similarly, as annual precipitation increases, so does the area covered by glaciers. In proportion to the debris-covered area, the clear glaciers in the region are more susceptible to climate change.

The SCA of Batura Glacier with the approach of spatial and temporal change-based assessment for the period 1998-2023 of the winter seasons through Landsat data revealed an increasing trend of SCA in Batura during the winter period. The findings further demonstrated that the SCA in Batura is increasing (0.2 km²/ year) from 1998 to 2023. In December 1998, it covered 43.22%; in December 2003, 44.92%, in December 2008, it covered 39.83%, and in November 2013, it covered 49.15%; in 2018, 48.73%; and in 2023, 45.34% SCA. The overall increase in SCA is an anticipatory and sustainable indicator of water supply for agricultural activities in the study area, as well as the areas reliant on the water resources of the Hunza River. Moreover, this increasing trend of SCA in the focus area is in contrast to the present global climate warming, which requires further assessment at specific and micro levels.

Additionally, to obtain a more comprehensive understanding of the snow cover trend, it is essential to conduct a time-series analysis that considers existing historical statistics. A thorough investigation of the Batura Glacier is necessary, employing Microwave and hyperspectral imaging techniques, to address the differences observed in optical imaging caused by weather conditions, shadowing effects, and limitations in multispectral imaging signatures. Hyperspectral satellite imagery has finer spectral resolution than multispectral sensors, allowing enhanced differentiation between snow, debris, ice, and rocks. This improved the precision of snow cover mapping in rugged topographic terrain, where NDSI may mis detect the Earth's surface. Future research that combines the NDSI with a regional climate model would help connect perceived snow cover variations with climatic variables, such as temperature and precipitation. In addition, using a machine learning approach can enhance snow

categorization by studying multispectral and temporal characteristics, thereby increasing the validity of snow cover analysis (SCA). A comparison of the findings from related studies would benefit from the availability of ground-based data, such as snowmelt, water discharge, velocity, snowfall, and snow depth. Conclusively, this research may contribute to developing thought-provoking guidelines and enhancing understanding of water resource management.

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