



Spatiotemporal Trends of Snow Cover under Climate Change Using Landsat Imagery: A Case Study of the Astore Region, Western Himalaya, Pakistan

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Abstract: The Upper Indus Basin is a significant freshwater resource for Pakistan's irrigation system, with approximately half of its annual water resources are produced from glacier and snow nourished basin within the Himalaya, Karakorum, and Hindu Kush (HKH) region. The basin is increasingly vulnerable to climate change, making it important to study and assess the spatiotemporal changes of snow cover area (SCA) and their relationships with climatic factors for actual water resource management. This study is focused on the sub-basin of Upper Indus Basin Astore region, using Landsat imagery from 1998 to 2023 to calculate SCA during the summer season through the indices of the Normalized Difference Snow Index. Climatic variables, with precipitation and temperature were downloaded from NASA's Prediction of worldwide energy resources (POWER) dataset. Results illustrate a significant decline in SCA at a rate of -4.92 km^2 per year, which is associated with increasing mean annual temperature and decreasing precipitation. These findings confirm that increasing temperature and reduced precipitation are contributing to the reduction of snow cover in Astore. This study highlights the significance of regional scale studies to know the consequence of climate change on change in snow cover within the Upper Indus Basin.

Keywords: Snow Cover Area, Climate Change, Normalized Difference Snow Index, Landsat Imagery, Astore Basin, Precipitation, Temperature.

1. INTRODUCTION

The Astore Basin, a snow-fed sub-basin of the Upper Indus Basin located in the western Himalayas, was selected as the focus of this study. The freshwater ecosystem of the earth is mostly located in mountainous regions, where glaciers have a substantial impact on the worldwide flow of streams and rivers [1, 2]. During drought periods, snow covered mountain regions act as continuous water sources and serve as a lifesaving buffer [3]. The Himalayas, Karakoram, and Hindukush (HKH) are among the highest mountain ranges where glaciers melt significantly and influence regional water supplies [2, 4, 5]. The HKH region comprises the most extensive mountainous areas, spanning many countries including Pakistan, Afghanistan, China,

India, Nepal, Bhutan, and Myanmar. These areas are renowned as the 'Third Pole' or 'Water Tower of Asia' due to their substantial freshwater reserves. A significant portion of the major river systems in these countries originate in the HKH region, and are sustained by glacier and snowmelt [6, 7]. Consequently, this area sustains the livelihoods of inhabitants in downstream areas by providing vital water resources, which are crucial for drinking, agricultural production, power generation, and industrial development [8-11].

Nevertheless, as a consequence of climate change, snow covered and glacier regions are facing significant threats and are undergoing continual transformation [12]. Pakistan is mostly agrarian nation that heavily relies on Indus River

system [13]. The main source of water in this river originates from glacier and snow melt [14, 15]. Snow-covered mountains remain largely unaffected by direct human activities, they are susceptible to climatic variability. Climate change is causing rising temperatures, shorter snowfall durations, and altered snowfall patterns. These factors influence river flow throughout summer and help to cause the snow cover to melt sooner [16-18], ultimately leading to water-shortage and other related natural disasters [19]. Temperature directly affects snowmelt development, whereas precipitation especially in solid form is the key source of snow accumulation [20]. Current studies underscore that the relationship between temperature, precipitation and snow cover area is unstable and intensifying under climate change. With increasing temperature foremost to previous spring melt and decreased snow perseverance in numerous mountain regions [21-22]. Despite advancements, a substantial research gap continuous in developing strong, spatially clear outlines that methodologically integrate Normalized Difference Snow Index (NDSI) obtained Snow Cover Area (SCA) with temporally corresponding temperature and precipitation data to improve the considerate of seasonal snowpack changing aspect and its sensitivity to climatic variables. Some existing analysis remain on description and coarse-resolution climatic datasets that inconsistency the spatial information of satellite-based SCA.

In this study snow cover area generally shows a decline, however some studies [23-25] reported a rising trend in SCA due to increase in winter precipitation and reduced summer temperatures. Subsequent research anticipated that the HKH region would experience increased precipitation from 1901 to 2099; however, temperature trends show strong interannual variability. According to other studies [26, 27], there would be a notable rising trend in precipitation in Gilgit-Baltistan throughout the midcentury (2021-2060). In the Northwest Himalayan area, Negi and Kanda [28] also noted a rising tendency in SCA due to a slowing rate of warming. These variations in climate thus suggest variations in SCA. Therefore, it's important to keep an eye on how the snow cover is changing. Nonetheless, a sizable portion of the HKH region is vulnerable, and there is little information available on the geographic variability of SCA overall. The high altitude and challenging terrain of the SCA made mapping extremely challenging in the

past [29, 30]. Since the 1960s, various geospatial techniques have been developed to facilitate snow cover mapping [31]. Khan *et al.* [32] studied snow characteristic in Astore sub-basin using MODIS satellite data, showing robust seasonal spread and spatial changes in snow water correspondent, snow depth, and SCA, with winter snow cover area up to 94% and summer as noted low as 20%. Snowmelt was affected by local basin and metrological factors. Ali *et al.* [33] projected future hydrological responses using CMIP6 models, showing that rising temperatures and variable precipitation could alter streamflow and reduce snowmelt contributions, despite some scenarios indicating increased precipitation. Regionally, Dar and Sarif [34] reported negative glacier mass balance and glacial area loss in the Kashmir Himalayas and UIB, though some Karakoram glaciers show slower loss (Karakoram anomaly). Almagioni *et al.* [35] identify complex, spatially diverse trends over Karakoram, Western Himalaya, and Kunlun Mountain ranges, with change in snow season during connected with temperature and precipitation changes. Hydrological response and snow cover change in Astore are formed by connection among climate, topography, and atmospheric forcing, highlighting the need for combined climate modeling, remote sensing and hydrological assessment.

Currently, geospatial communities use a variety of indices and techniques for SCA mapping, as well as image-classification methods. These indices including normalized difference debris index (NDDI), normalized difference principal component index (NDPSCI), normalized difference water index (NDWI), normalized difference snow thermal index (NDSTI) and normalized difference snow index (NDSI). In this study, NDSI is used for monitoring as it produces good results in mountain terrain and is one of the most famous indices for SCA calculation. Present SCA analysis based on NDSI frequently lack integration with main regulatory climatic variables, temperature and precipitation, restricting the ability to assess the contributing factors behind observed snow cover patterns, trends and anomalies, especially in data-scare mountain regions.

The main purpose of this study is to determine the snow-covered area in Astore with application of normalized difference snow index (NDSI) from 1998-2023. Temperature and precipitation, two

climatic parameters, were analyzed in relation to SCA. Understanding the SCA's relationship to temperature and rainfall was crucial for those who depend on glaciers in mountainous and low-lying locations. The past study elaborated the glacier cover in Astore, Hunza and Gilgit [36]. The western Himalaya region shows exceptional patterns of topographic complexity, erosion, and exposure [37]. The Astore basin, located in the western Himalayas, is a snow-fed system characterized by low- to mid-elevation glaciers and predominantly north-facing slopes. Due to its relatively low elevation, Astore is mostly reliant on precipitation particularly in winter season. These fundamental characteristics give Astore its unique geographic settings. Accordingly, the objectives of this study are to: (1) Monitor the spatial and temporal fluctuation of SCA in the Astore region, and (2) analyze the relationship between climatic variables and SCA to assess climate-change impacts on snow cover dynamics.

2. MATERIALS AND METHODS

2.1. Study Area

The study area is located between $34^{\circ} 16' - 37^{\circ} 06' N$ latitude and $72^{\circ} 03' - 77^{\circ} 44' E$ longitude, defining the boundary between greater Himalaya and Karakorum ranges [38]. The Indus River starts from the Tibetan Plateau, flow through northern Pakistan, and provide water to the Tarbela Dam [39,

40]. For this study, the Astore region was selected, which lies in the dangerous western Himalayas of northern Pakistan. Farhan *et al.* [39] described that annual mean temperature in Astore range from $-2.9^{\circ}C$ to $9.9^{\circ}C$, however annual precipitation changes between 500 mm and 870 mm. Significant precipitation expected (75%) during the spring and winter season due to westerly distribution, although the residual 25% occurs during the summer and autumn seasons, mainly “affected by local jet streams” and the south Asian monsoon. Both winter rainfall and solid precipitation driven by westerlies meaningfully effect the discharge of the Astore River [41]. Figure 1 shows that Astore is bounded to the North by Gilgit, South by Khyber Pakhtunkhwa, and Neelum valley, East by Skardu, and West by Diamer district with total cover area about 5200 km^2 [42].

2.2. Methods

This study used a temporal satellite imagery spanning from 1998 to 2023. “Satellite data (Collection 2 level-2) were downloaded from USGS website.” Only images with less than 10% cloud coverage were selected to confirm precision and accuracy. All downloaded images underwent standard preprocessing process as delineated in preceding literature [43]. To continue consistency with previous studies and to enable accurate assessment, atmospheric correction was omitted intentionally; this method is mainly valid in high

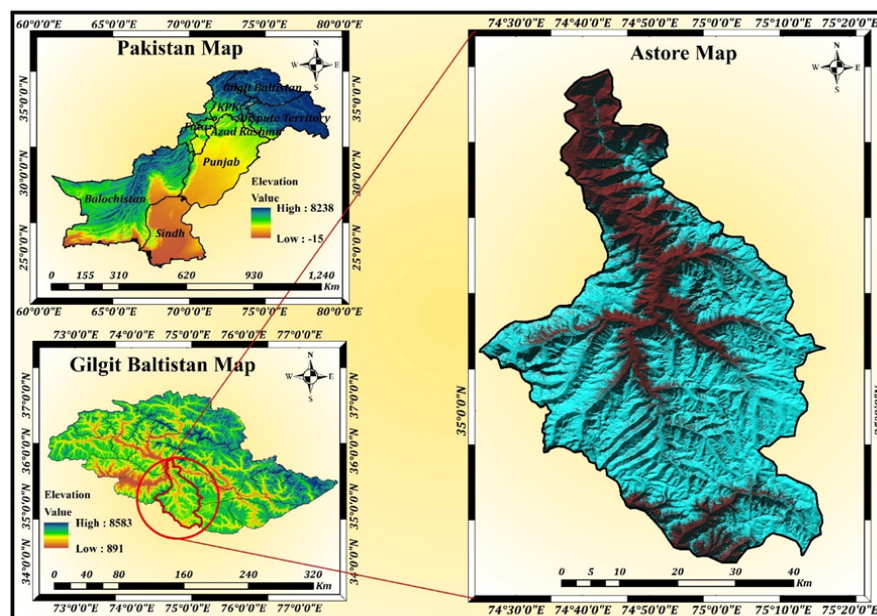


Fig. 1. Geographical location of study area.

altitude mountainous region where atmospheric effect is minimum and do not meaningfully effect snow detection [44-46]. The dataset comprised imagery from different generation of Landsat satellite particularly, Landsat 4-5 TM, Landsat 7 ETM+, and Landsat OLI/TIRS. “All satellite images used had a spatial resolution of 30 m. and were analyzed mainly for the summer season. The NDSI was employed to find and define snow covered areas. This index takes benefit of snow spectral signature, especially its robust reflectance in the visible band (green) and low reflectance in the shortwave infrared (SWIR) band. The NDSI is calculated using below formula, as defined by Hall *et al.* [47]:

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

NDSI value ranges from -1 to +1, with values above 0 representing the presence of snow. A most common threshold of $NDSI \geq 0.4$ was used to categorized snow pixels in the satellite imagery, as suggested in various literature studies [48-51]. The optimal threshold should be determined based on the study area, atmospheric and sensor description to minimize misclassification. For the calculation: Landsat 5 TM and 7 ETM+ used band 2 (Green with spectral range 0.52-0.60 μm) and Band 5 (SWIR with spectral range 1.55-1.75 μm). For Landsat 8

OLI used band 3 (Green with spectral range 0.53-0.59 μm) and band 6 (SWIR spectral range 1.57-1.65 μm). Once the NDSI was calculated, the snow cover area (SCA) was extracted by reclassifying the NDSI values into two classes, for instance 1 for snow covered area and 0 for snow free areas. This classification was performed using the reclassify tool. Following classification, the entire snow-covered area within the study area was computed. “This was computed using the field calculator tool” which allowed for efficient conversion of pixel based into area measurements. Resultantly, the SCA was calculated on an annual basis (for summer season) by totaling up the classified snow pixels, allowing for the evaluation of temporal changes in snow distribution over the 25 years of study period. In addition to satellite imagery, climatic data on precipitation and temperature were acquired from NASA website perdition of worldwide energy resources database (<https://www.earthdata.nasa.gov/data/projects/power>) for the time period (1998-2023). These data were particularly extracted for the study area to examine the connection between climatic factors and variation in SCA. The correlation between annual snow cover level and corresponding climate variables such as rainfall and temperature were analyzed to evaluate the impact of climate change on snow dynamics in the region. Figure 2 shows the overall methodology of the study area.

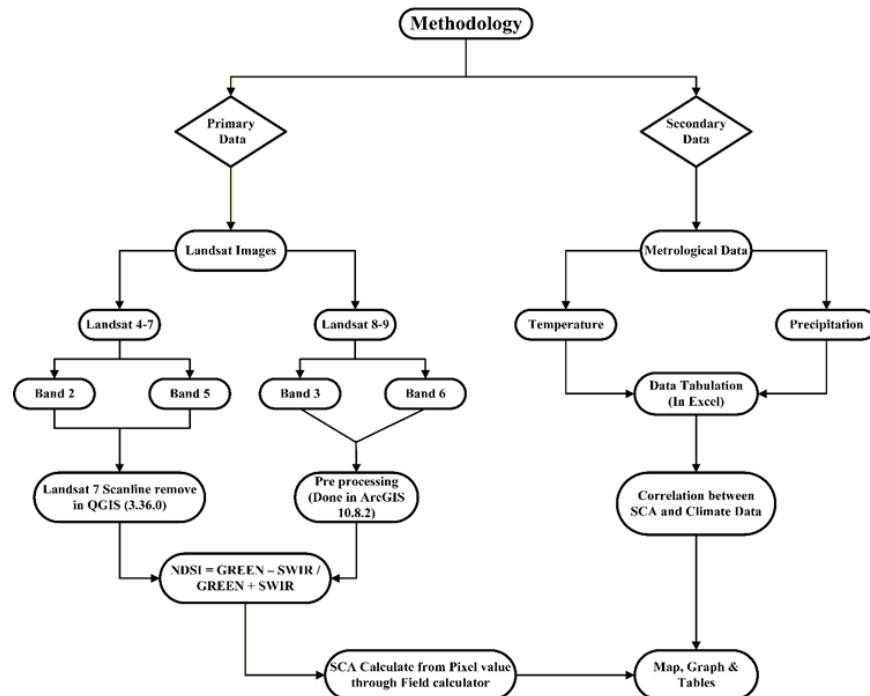


Fig. 2. Layout of the research methodology.

2.3. Landsat Data

Landsat data are easily available, annual Landsat imagery for the study region was freely acquired from USGS website for the period 1998 to 2019 [51]. Rastner *et al.* [52] explained that Landsat delivers extensive time series data with multispectral and spatial resolution, which is especially useful for snow cover area. Every Landsat satellite completes a full orbit cycle particularly every sixteen days. In this research, data from Landsat 5 Thematic Mapper TM, Landsat 7 ETM+, and Landsat 8 OLI were used. The detailed parameters of the satellite sensors are provided in Table 1.

2.4. Predication of Worldwide Energy Resources (POWER) Database (Rainfall and Temperature)

Climate data, with temperature and precipitation, were used to examine change in snow covered area (SCA) in the Astore region. For this drive, climatic data for the study period from 1998 to 2023 were downloaded from NASA Powered portal data. The effect of climate changes on SCA was examined using this dataset. Table 2 illustrated in detailed parameters of the climatic data.

3. RESULTS

The yearly snow cover area (SCA) of Astore was computed applying Landsat data from 1998 to 2023 in ArcGIS 10.8.2. This study shows significant changes in the Astore region due to variation in temperature and precipitation [33, 53]. In July 1998, the SCA of Astore was 6.32%, whereas in July 2008, it reduced to 2.27%. The significant discharge of the Astore River indicates distinguished variations within the regional snow cover. [54] noted, annual and seasonal changes in snow cover considerably effect the flow of the Astore River. Our results show a declining trend in SCA in Astore at a rate of -4.92% per year, determined by changing precipitation and temperature dynamics. In contrast, rise in SCA have been detected in Karakoram and western Himalaya regions [33]. The Upper Indus Basin (UIB) depend heavily on water from snow cover and glacier melt. With the detected decrease in snow cover, the Astore River is probable to be importantly impacted. Warmer summer and low precipitation (increasing summer temperatures and declining precipitation tendencies) accelerate snowmelt in the mountains, potentially leading to water scarcity in the Astore River and rising the risk of glacier lake outburst (GLOFs). Figure 3

Table 1. Detail parameters of Landsat data.

Data type	Date	Spatial resolution (m)	Cloud cover (%)	Path	Row
Landsat 4-5 (TM)	July-1998	30	25	149	035
Landsat 7 (ETM)	July -2003	30	30	149	035
Landsat 7 (ETM)	July- 2008	30	1	149	035
Landsat 7 (ETM)	July -2013	30	1	149	035
Landsat 8 (OLI/TIRS)	Aug -2018	30	2	149	035
Landsat 8 (OLI/TIRS)	Aug -2023	30	4	149	035

Table 2. Detail parameters of climate data.

Date	Minimum temp.	Maximum temp.	Means temp.	Precipitation (mm)
Jul-1998	19.06	26.80	18.93	12.6
Jul-2003	17.88	22.91	20.39	28
Jul-2008	17.15	22.04	19.59	25.1
Jul-2013	15.15	21.32	18.23	35.8
Aug-2018	17.66	22.86	20.26	37.3
Aug-2023	16.79	21.88	19.34	15

illustrates the annual SCA, while Figure 4 presents a graphical description of Astore SCA.

Figure 4 shows a time series analysis of annual temperature, precipitation, and SCA from 1998 to 2023 at five-year gaps. The data show a clear rising trend in precipitation, increasing from 12.6 mm in 1998 to 37.3 mm in 2018 previously decreasing to 15 mm in 2023. This overall positive however weak linear connection is counted by the regression equation $y = 0.2891x - 555.65$ ($R^2 = 0.0692$). In, comparison, mean annual temperature showed minimal inconsistency across the study period, with values shifting narrowly between 18.2 °C and 20.4 °C, subsequent in a near- flat trend line defined by $y = 0.0017x + 16.01$ ($R^2 = 0.0004$). SCA confirmed

the most distinct and clear trend, considered by a long-term decline as defined by the equation $y = -28.237x + 57501$, which consider for a reasonable amount of the change ($R^2 = 0.4829$). The interannual changeability in snow cover, connecting successive increase and decrease, therefore, overlaid upon a substantial negative secular trend.

The linear data displayed in Figure 4 (1998-2023) share different and statistically diverse trends for three main climatic variables, temperature, precipitation and snow cover area (SCA). A relative analysis highlights the complex topography of mountain or high-latitude ecosystem responses to climatic changes, where SCA acts as a serious integrators' variable with a more sensitive and

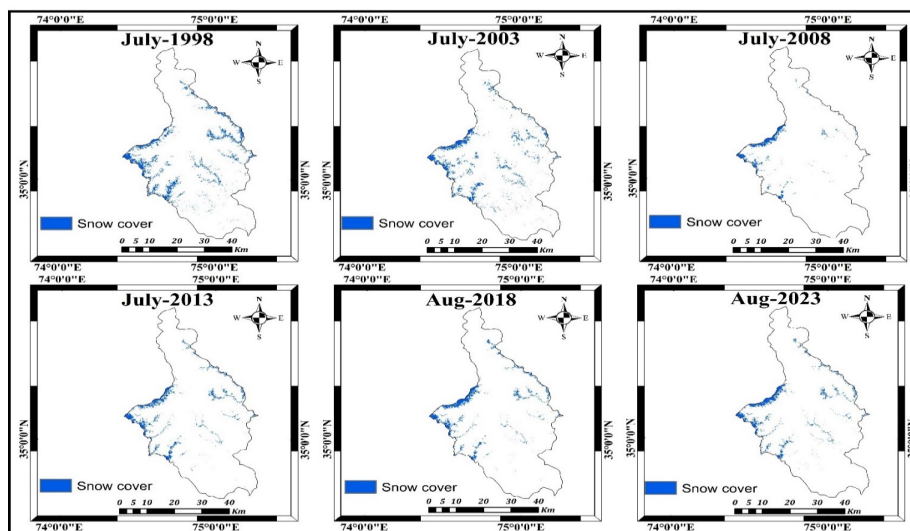


Fig. 3. Annual snow cover of Astore for the period (1998-2023).

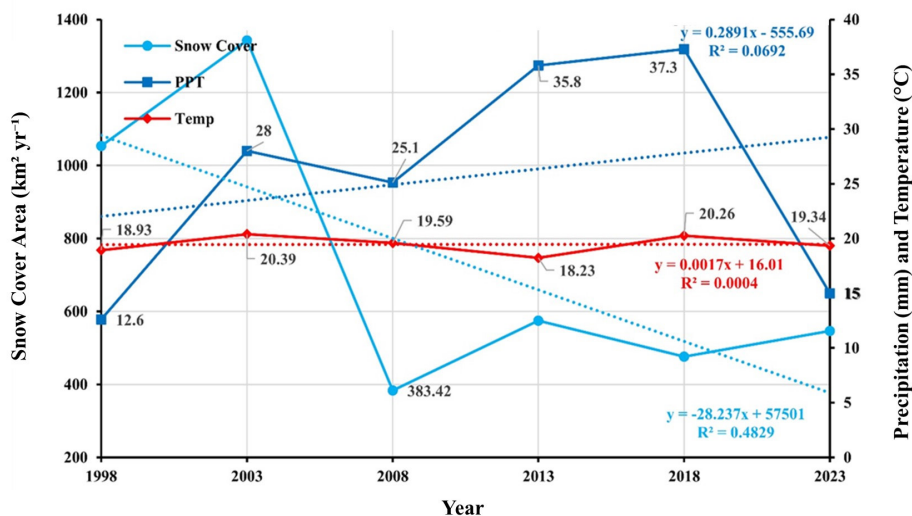


Fig. 4. SCA annual rainfall and temperature of Astore.

distinct trend than the primary climatic variables in this dataset. The main climatic drivers including precipitation, temperature displayed remarkable weak linear trends over the 25-year period in the study area. The precipitation trend, while showing a clear increase ($y = 0.2891 - 555.69$), is considered by high interannual instability, as proved by the peak of 37.3 mm in 2018 and following sharp decline to 15.0 in 2023. The very low coefficient of determination ($R^2 = 0.0692$) confirms that this mountain slope describes less than 7% of the variance in the data, signifying that precipitation is influence by stochastic, short-term changeability rather than a strong, deterministic trend. In contracts, mean annual temperature shows negligible variation no linear warming or cooling trend visible at this temporal and interval. The differentiate between those two weak trends (temperature stable and precipitation slightly increasing) is a serious starting point for analyzing the climatic response.

In sharp difference to the vague climatic sign, the snow cover area (SCA) shows a robust, coherent negative decline trend. The regression equation ($y = -28.237x + 57501$) shows a considerable rate of decline, which is endorse by the strongest statistical connection in the dataset ($R^2 = 0.4829$). This reveals that almost 50% of the changes in SCA can be described by the linear way of time, a convincing sign of determined loss. The narrative report “increase, decrease, again increase, again decreased and decreasing trend” precisely define the interannual changes overlaid upon this leading negative route. These year-to-year changes are likely assigned to the instable precipitation patterns that is high snow years in 2013 and 2018 consistent to high precipitation), but the basic secular decline is unique.

The Mann–Kendall test indicates a weak and statistically non-significant decreasing tendency in snow-covered area during 1998-2023. Sen’s slope estimator suggests an average decline of approximately 20.3 km² per year. Mean precipitation exhibits a weak increasing tendency, whereas land surface temperature shows no consistent monotonic trend in Table 3. Pearson correlation analysis reveals weak and statistically insignificant relationships between snow cover and both precipitation and temperature, indicating that snow-cover variability is likely influenced by multiple interacting climatic and topographic factors rather than individual climatic variables alone is illustrated in Table 4.

3.1. Climatic Variable and Snow Cover

To improve our considerate of snow cover dynamics, the SCA results were linked with other climate variable, such as precipitation and mean annual temperature. The analysis covered the period from 1998 to 2023. This study linked climatic data to notice changes in SCA and to evaluate the effect of climate variation toward snow cover. By calculating the precipitation and mean annual temperature for Astore, we found that the mean annual temperature is rising while precipitation is declining. Moazzam *et al.* [27] stated a positive trend in summer precipitation, they also observed increasing temperature trend. In this study, we detected an increase in mean temperature follow by a decreasing trend in precipitation, which accelerates snowmelt.

4. DISCUSSION

During this analysis, we evaluated variations in snow cover area in Astore region utilize Landsat data for

Table 3. Showing Mann–Kendall test analysis.

Variable	Z (MK)	Trend direction	Sen’s slope (Q)
Snow cover area	-0.75	Decreasing	-20.27 km ² yr ⁻¹
Mean precipitation (PPT)	0.75	Increasing	+0.62 mm yr ⁻¹
Mean LST	0	No clear trend	-0.009 °C yr ⁻¹

Table 4. Pearson analysis showing comparison of SCA, LST and PPT.

Relationship	Pearson r	p value	Strength
Snow cover vs PPT	-0.26	0.61	Weak negative
Snow cover vs LST	0.23	0.65	Weak positive

the period 1998-2023. It is confirmed that higher accuracy in shaded and mountainous region [55-57], the NDSI was used to extract snow cover in this study. The study findings confirm a clear declining trend in the SCA of Astore over the study period. The observed decline in SCA negatively affects glacier mass balance, determined by increasing mean temperature and decreasing precipitation in the region [58, 59]. This negative SCA trend prevent glaciers and contribute negatively to the glacier mass balance in the western Himalayas occur earlier recorded and comparing with Global glacial trend. This regional anomaly is links to local climatic trends of increasing temperature and decreasing precipitation trends [36, 39, 60]. The location of Astore in the western Himalayas, with a climate more identical to the southern Karakoram due to westerlies effect, results in varied climatic drivers [40]. A significant decline is snow cover area has been observed, especially at lower and mid elevations. The previous studies demonstrate a strong and persistent long-term warming trend throughout the Gilgit- Baltistan region including Astore [61-63]. While a significant increases in mean and extreme temperatures, especially since the late of 20th century. Although precipitation trends show different variation and complexity, growing evidence of change in precipitation patterns. Previous studies reveal an overall increase in total rainfall conveyed by a decline in snowfall, representing a change from solid to liquid precipitation, especially during winter and spring [64-66].

The results of previous studies [67, 68] show decreasing trend in SCA for the Astore region which aligned and support our results. This negative snow cover area trend stops glaciers and pay negatively to the glacier mass balance in the western Himalayas occur previously recorded and comparing with the global glacier trend. This regional anomaly is matches to local climatic trends of increasing temperature and decreasing precipitation trends [27, 38].

These results match with the previous literature studies relating a declining inclination of snow cover in the area [40, 69]. This changing aspect of snow cover area in the central Karakorum and western Himalayas are mainly governed by patterns of climatic changes, in Astore rising mean annual temperatures accompanied by declining

precipitation indicate that global warming is considerably affecting snow cover in northern Pakistan. This regional snow cover decline reflects global patterns of glacier retreat connected to current climate change phenomena. Additionally, the decrease in glacial accumulation has led to reduced flow in the Astore river basin, posing significant risks to agricultural efficiency in the downstream low-lying areas. Conclusively, this study highlights the critical effects of climatic changes on snow cover and glacier health in the Astore region, resultantly affect water resources and regional agriculture. The glacier in the study regions nourish the Indus River, an essential resource and infrequent hazard for about 220 million low-lying peoples. Decreasing glacier mass has diminish river flow in the Astore sub basin, a potentially negative development for downstream agriculture.

5. CONCLUSIONS

This study assessed the spatiotemporal variations in the snow cover area of the Astore area using Landsat data downloaded from USGS for the period 1998-2023. The study was further extended to evaluate the linkages between SCA and core climatic factors such as temperature and precipitation. Results demonstrate that a clear declining trend in SCA in the study area, primarily driven by increasing temperatures and decreasing precipitation during the study period. The SCA decreased at an average rate of approximately -4.92 km² per year between 1998 and 2023. The lowest annual SCA of 2.27% was detected in 2008, whereas the highest value of 6.32% was observed in 1998. These finding highlights the significant influence of temperature and precipitation on annual snow cover changes in the region. The detected decrease in average rainfall combined with the rise in mean temperature appears to be the main factor contributing to the declining trend of SCA in Astore. In conclusion, the decrease in snow cover raises serious concerns for future water availability, which may threaten agricultural production and other water-dependent activities in the region that depend on the Astore river. The continuing decrease in precipitation and increase in mean temperature in Astore contrasts with some global trends, highlighting the need for detailed localized studies. This study provides valuable insights to guide effective water resource management and planning under changing climatic conditions.

6. ETHICAL STATEMENT

This work does not include any studies involving human or animal subjects.

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8. CONFLICT OF INTEREST

The authors declare no conflict of interest.

9. FUNDING

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10. AUTHORSHIP CONTRIBUTION STATEMENT

Bahadar Khan: writing methodology, original draft writing, and investigation of data analysis; Abdur Raziq: supervision; writing-review and editing, resources and English correction, proofreading, original draft extensive editing and finalizing; Izhar Ullah: writing, methodology, review of the manuscript, and editing; Yasir Hanif: review and rewriting of the manuscript.

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