

Analysis of Snow Cover Dynamics in the Beas River Basin during 2019-2021

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Abstract

Snow is a key component of the Himalayan cryosphere and plays a significant role in water resource availability and hydrological processes. This study examines the characteristics of snow cover in the Beas River Basin using MODIS satellite imagery for the period 2019-2021, with particular emphasis on temporal variations in snow cover and its potential influence on the hydrological cycle. Snow Cover Area (SCA) was estimated for the basin using the improved 8-day snow-cover product (Version 6), Terra-Aqua (MOYDGL06), generated from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. In addition, snow-cover maps were developed from the MODIS observations to analyse the spatial distribution and temporal variability of snow cover across the Beas River Basin. During the study period, SCA in the region varied from 41% (November 2020) to 90% (February 2019). SCA and total precipitation showed declining trends at rates of 2.1 km² and 47.3 cm, respectively, while the average temperature increased from 2019 to 2021 at a rate of 0.14°C. However, during 2019-2021, SCA declined at a higher rate of 19.21 km² and total precipitation decreased at a rate of 28.6 cm. In contrast, the mean temperature increased at a higher rate of 0.40°C. The study indicates that SCA and precipitation declined more rapidly during 2019-2021. The findings suggest that climate change may be an important factor influencing the observed trends in SCA, precipitation, and mean temperature. The observed SCA trend was also found to be consistent with the climatic parameters. The study examines SCA variability from January to December.

Keywords: Beas River basin, MODIS product, Snow cover area.

1. Introduction

Climate change has brought considerable changes to the cryospheric regions of the Earth, particularly in snow cover and glaciers. Rising global temperatures have resulted in the reduction of snow cover and retreat of glaciers, which have further contributed to sea-level rise and changes in the global climate (Negi et al., 2017). A decline in snow cover and glaciers has been reported across different parts of the world, including the Arctic, Antarctic, and Himalayan regions. These changes have influenced the hydrological cycle and have also affected ecosystems and human populations dependent on snow and glacier resources. Snow Cover Area (SCA) is an important indicator of environmental change and is strongly associated with variations in climatic conditions. Changes in temperature and precipitation patterns can considerably influence the extent and persistence of snow cover, thereby affecting various ecological and socio-economic systems (Taloor et al., 2019). Seasonal SCA is therefore an important parameter for understanding and monitoring environmental processes and their influence on regional and

global climate. The extent and duration of snow cover can significantly affect the Earth's energy balance, water cycle, and hydrological processes (S. Singh et al., 2021; Sood et al., 2021)

The Himalaya are widely known as the "Water Tower of Asia" because several major river systems, including the Ganges, Brahmaputra, and Indus, originate from this region. Snow, ice, and glaciers of the Himalaya provide an important source of freshwater to a large population living across and downstream of the region. The Himalayan region also has considerable economic importance for India (Kulkarni et al., 2007). In addition, the Himalaya play an important role in sustaining agriculture in the region (Sharma et al., 2014). The extreme variations in altitude and weather conditions, together with the rugged terrain, make it difficult to obtain reliable information on Snow Cover Area (SCA) through conventional measurement techniques (Bisht et al., 2019). Traditionally, SCA has been monitored through ground observations and manual snow surveys, which are often time-consuming, costly, and difficult to conduct in the challenging terrain of the Himalaya. Satellite remote sensing has therefore emerged as an effective technology for monitoring SCA over extensive areas. Satellite-based observations have become an important means of assessing changes in SCA and estimating other snow-related parameters, including snow depth, snow water equivalent, and snow albedo.

In recent years, satellite images have been extensively used to examine snow cover variations in the Western Himalayan cryosphere (Barman & Bhattacharjya, 2015; Birajdar et al., 2014; Gurung et al., 2011, 2017; Jain et al., 2009; Kour et al., 2016b; Kulkarni et al., 2007; Negi et al., 2017; Shafiq et al., 2019; Sharma et al., 2012, 2014). Several studies have reported a declining trend in seasonal Snow Cover Area (SCA) across the Himalayan region, particularly during spring (Cherry et al., 2004; Kour et al., 2016a; Muntán et al., 2009; Sharma et al., 2014; Vikhama & Solberg, 2003; Zhao et al., 2009). A reduction in SCA has been documented in different sections of the Himalaya, including the Western, Central, and Eastern regions. This decline has mainly been associated with increasing temperatures and changes in precipitation patterns resulting from climate change. (Kour et al., 2016b; Kulkarni et al., 2007, 2010; Sharma et al., 2012) have (Moderate Resolution Imaging Spectroradiometer) used MODIS (Moderate Resolution Imaging Spectroradiometer) data, particularly the 8-day and 10-day snow products, to identify declining SCA trends in different river basins of the Indian Himalaya.

In contrast, Tahir et al. (2015) observed an increasing trend in SCA over the Indian Himalaya and adjoining Karakoram region using the MODIS images. Similarly, (Shafiq et al., 2019) examined snow cover variability in the Kashmir Himalaya using eight day MODIS data for 2002–2018 and reported an increasing trend in SCA, consistent with the inferences drawn by (Tahir et al., 2015). (D. K. Singh et al., 2018) investigated the variability of SCA in the Indian Himalayan climatic zones making use of MODIS sensor images to generate a 10-day snow cover product from 2001 to 2016. Another study also detected post-2010 changes in SCA. This study also showed that the rate of change in snow cover may vary across time and that climate change can impact the dynamics of snow cover in a highly complex manner. There are however large variations in time periods analyzed and topography which have prevented a strong agreement on SCA trends throughout the Himalayas. The Indian Himalayan region is also very important with relatively little research on SCA within this region. Clouds can also impact SCA analyses as they can mask the land surface and complicate the identification of snow cover from remote sensing data. In addition, uncertainties can also exist due to differences in the capabilities and constraints of the remote sensing sensors used.

Muhammad & Thapa (2020) proposed a snow cover product uncertainty reduction technique for enhancing the accuracy of snow cover products generated by MODIS data from Terra-Aqua.

Uncertainties in the snow cover products were reduced using spatial, temporal and seasonal filtering and combining several MODIS snow cover products (MOYDGL06* being the primary one used). The technique greatly enhanced the quality of the snow cover product by eliminating outliers and reducing errors. The product was shown to be 10% more accurate than Landsat-8 data.

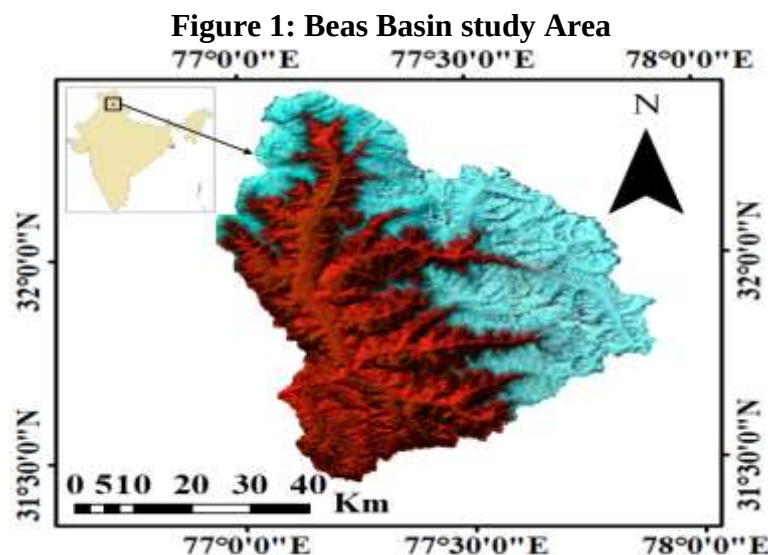
In the current research the enhanced Terra-Aqua MODIS (MOYDGL06*) snow product is employed for assessing snow cover variability over Beas River Basin. This research aims at studying the dynamics of snow over Beas River Basin using MODIS data from years 2019 to 2021 and also studying the snow cover variability and its implications to the hydrological cycle over the area using enhanced 8 Day snow cover product (Version 6) from Terra-Aqua (MOYDGL06) over MODIS sensor. Trends in SCA time series are detected and quantified using statistical methods. Mann-Kendall non-parametric test and Sen's slope estimator are employed to estimate trend existence and magnitude in the time series data.

2. Study area

Study was conducted in Beas River up to Pandoh Hydropower Project Dam. Beas is one of the major Himalayan rivers which starts from Beas Glacier at Rohtang Pass in Himalayas and receives inputs from several major tributaries during its transit. The study area is spread over a large area of about 3900 m elevation which characterizes the Himalayan mountain region. The river starts from Beas Glacier at Rohtang Pass and flows in a north–south direction till Larji Hydropower project. After Larji, Beas River shifts to a southwest direction and follows the same until Pandoh Dam.

Beas river provides irrigation, hydropower, and drinking water to the region. It is also a tributary of one of the major drainage systems of India – Indus River system. The river is about 116 km long from source to Pandoh Dam. Parbati and Sainj Khad rivers are glacier tributaries, which have a significant contribution to the flow of Beas River. The catchment area size up to Pandoh Dam is about 5406 km².

There are several tributaries that join Beas River at various points along its length. Parbati river joins Beas at Bhuntar, Sabari Nala joins at Kullu, Tirthan and Sainj rivers join at Larji and Bakhli joins at Pandoh Dam. Pandoh Hydropower project is part of the water resources development in the area. This project takes water from Beas and conveys it to Satluj for hydropower production. This water can further be used for power production at Dehar Power house on the right bank of Satluj River. Location and size of the study area is shown in Figure 1.



3. Satellite Dataset

Snow Cover Area (SCA) for the years 2019-2021 was analyzed using the MODIS snow product (Version 6) that utilizes both Terra and Aqua MODIS data (MOYDGL06*). This product depicts the maximum amount of snow that exists during a period that includes snowfall on one or more days. It is provided as an 8-day composite dataset, with each tile covering an area of $1200 \times 1200 \text{ km}^2$. The data are projected using the Sinusoidal map projection and have a spatial resolution of 500 m. (Riggs et al., 2006)

The MODIS sensor is carried by NASA's two Earth-observing satellites, Terra, launched in 1999, and Aqua, launched in 2002. It collects information on land surface conditions and clouds across the electromagnetic spectrum from 0.4 to $14.4 \mu\text{m}$ using 36 spectral bands. The MODIS snow product is available at spatial resolutions of 500 m and 5 km and at different temporal scales, including regular, 8-day, and monthly products. In the present study, the 8-day maximum snow extent product was used to analyse snow cover during 2019-2021. Compared with Version 5, Version 6 provides improved snow detection by reducing both omission and commission errors, particularly under clear-sky conditions. (Riggs et al., 2016)

MODIS is a whiskbroom-type multispectral sensor that operates across 36 spectral bands, covering wavelengths from the visible region to the thermal infrared, ranging from 0.412 to $14.235 \mu\text{m}$. Among these 36 bands, two provide a spatial resolution of 250 m, five have a resolution of 500 m, and the remaining 29 bands have a spatial resolution of 1000 m (Table 1). In high-elevation regions, MODIS has demonstrated better performance than IRS (AWiFS) and NOAA sensors for observing and monitoring surface conditions. (Jain et al., 2008).

Figure 2 a. ASTER GDEM of Beas Basin, b. Slope of Beas Basin, c. Aspect of Beas basin

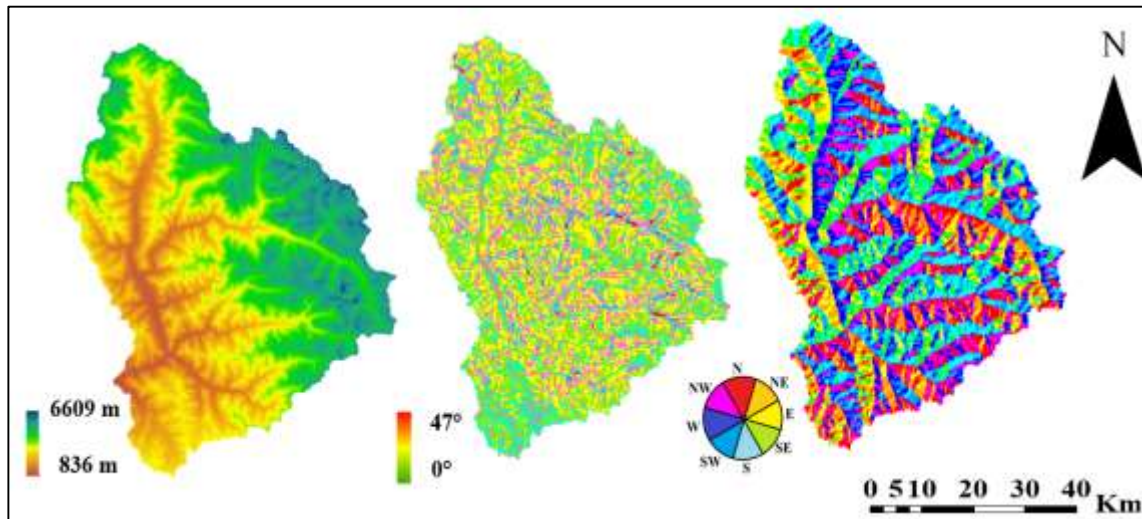


Table 1: MODIS Data Specifications

No. of bands	36
Swath	2330 km
Quantization	12 bits
Wavelength Range	$0.4\mu\text{m}$ - $14.4\mu\text{m}$
Orbit elevation	705 km

Global Coverage	1-2 days
MODIS Band	Spatial Resolution (m)
1-2	250
3-7	500
8-36	1000

3.1 ASTER DEM

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM), obtained from the USGS Earth Explorer platform, was used to derive elevation, slope, and aspect information for the study area. The DEM was resampled to a spatial resolution of 500 m to maintain consistency with the MODIS snow cover data. Using the processed DEM, slope and aspect maps were generated, as shown in Figure 2(b) and Figure 2(c), respectively.

3.2 Precipitation and Temperature Data

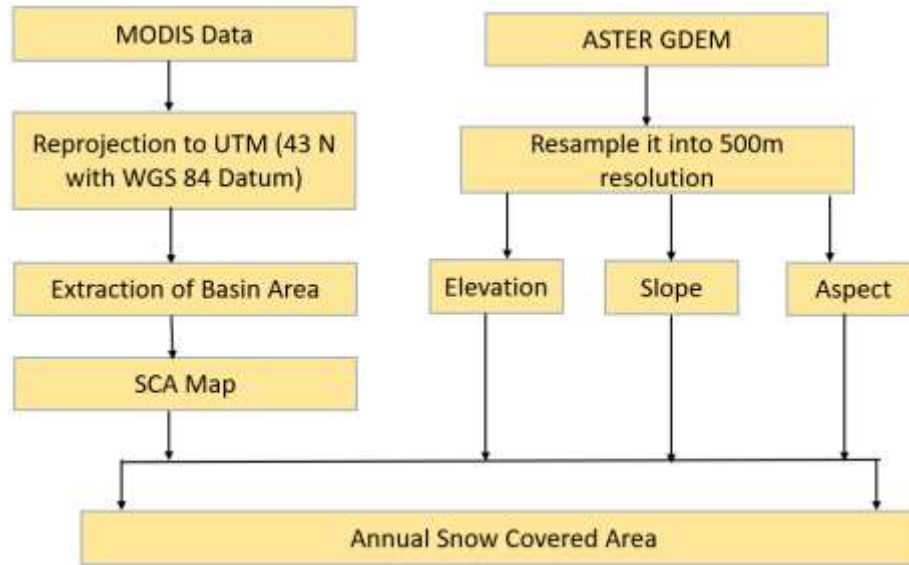
To examine the trends and their relationship with Snow Cover Area (SCA), climatic data from the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA5) was used. ERA5 data are produced by the Copernicus Climate Change Service (C3S) in collaboration with ECMWF. The dataset provides climate information from 1979 to the present at a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. For the present study, monthly temperature and precipitation data for the period 2019-2021 were obtained from the ERA5 monthly mean single-level dataset available through the Copernicus Climate Data Store (CDS).

4. Methodology

The procedure followed for the estimation of Snow Cover Area (SCA) is illustrated in Figure 3. For the 2019-2021 period, cloud-free satellite observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra platform, together with the integrated Terra-Aqua MODIS snow product (MOYDGL06*, Version 6), were acquired through the NASA LAADS data portal. The downloaded datasets were processed using ERDAS IMAGINE and reprojected to the Universal Transverse Mercator (UTM) coordinate system based on the World Geodetic System 1984 (WGS 84) datum. Following preprocessing, the study-area boundary was delineated and the required portion was extracted from the processed satellite imagery.

An improved final snow product was used to estimate SCA, with different flag values representing changes between snow and non-snow conditions within individual pixels. Six classes of flag values were used. 0 means non-snow. 200 means snow in both the initial and final product. -200 means a change from snow to non-snow. 210 means snow in the cloud corrected product. In the snow product, a pixel value of 240 represents debris-covered surfaces, whereas a value of 250 indicates debris-free ice. Snow-covered pixels were then identified and extracted from the processed snow product to prepare snow cover maps and facilitate subsequent Snow Cover Area (SCA) analysis. The generated binary snow cover maps effectively differentiate between snow-covered and snow-free regions, providing useful information for applications such as water resource management and climate modelling.

Figure 3: The methodology flowchart for computing the trend analysis of snow cover.



4.1 Meteorological Data

The study considered four climatic parameters: maximum temperature, minimum temperature, mean temperature (calculated as the average of the maximum and minimum temperatures), and precipitation. Statistical analyses were carried out on both the climatic variables and the satellite-derived Snow Cover Area (SCA) data to identify trends during the winter season.

4.2 Statistical Analysis

The Mann–Kendall (MK) test was applied to examine the significance and direction of trends between Snow Cover Area and the selected climatic parameters (Mann, 1945). The Mann-Kendall test is a non-parametric statistical approach commonly used to assess whether a systematic trend exists in a time-series dataset. A statistically significant p -value indicates the presence of a trend, whereas a non-significant p -value suggests that the observed changes are not statistically meaningful. The MK test statistic (Z_s) was calculated using Eq. (1)

$$\text{if } |z| > z_{\alpha/2} \quad (1)$$

A significance level (alpha) of 5% was considered in the present study. For a two-tailed test at this significance level, the corresponding critical value is ± 1.96 . Therefore, when the calculated (Z_s) value is greater than 1.96 or lower than -1.96 , the null hypothesis is rejected.

In addition to the Mann-Kendall test, Sen's slope estimator (Kumar Sen, 1968) was used to quantify the magnitude and direction of the identified trend. Sen's slope is a non-parametric method that estimates the slope of a time series without assuming a particular probability distribution of the data

$$Q_i = \text{median} \left(\frac{x_j - x_i}{t_j - t_i} \right) \quad (2)$$

where x_j and x_i represent the observed data values corresponding to times (j) and (i), respectively, and (N) denotes the total number of observations. The Sen's slope is calculated for all possible pairs of observations, and the median of these slopes is taken as the final estimate. A positive Sen's slope indicates an increasing trend, while a negative value represents a decreasing trend. In this study, the trend significance was evaluated at a 95% confidence level the data values at time t_j and t_i , respectively.

5. Results and Discussion

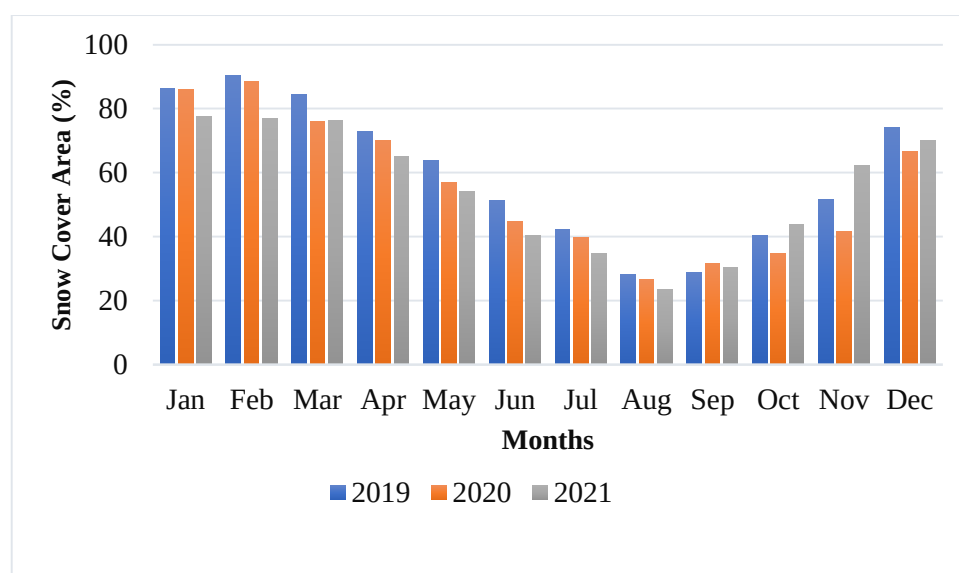
The MODIS snow product was used to assess the spatial and temporal variation of Snow Cover Area (SCA) in the Beas River Basin during 2019-2021. The results obtained from the analysis are discussed below. Monthly evolution of SCA over the three study years (January to December) overland and between years is shown in figure 4. Over-all the greatest area of snow cover tended to be in January and February.

SCA was obtained from the MODIS snow cover product at 8 -day intervals across the entire basin (about 5384 km²). Monthly mean SCA products were created for the years 2019-2021 and are shown in Figure 5. There was a large range of snow cover area from 26% to 90% over the duration of the study period. The mean SCA was estimated to be 3314.82 km² in 2019, 2974.87 km² in 2020, and 2938 km² in 2021. Maximum SCA was recorded in February with about 90% of the basin snow covered. The minimum SCA of 23% was recorded in August.

January to March experienced relatively high snow cover. This was mainly owing to precipitation from western disturbances. SCA for January, February and March was around 90%, 88% and 86% respectively. April through to end of the study period there was a gradual snow ablation. This ablation appears to be related to rising air temperatures causing melting of existing snow.

A gradual decrease in mean precipitation and mean SCA and an increase in mean temperature was also found over the duration of the study period. A t-test was run at 95% confidence and the results showed that no significance was found for the trend over the duration of the study period. Between 2019 and 2021, SCA decreased at a rate of 2.2 km², while total precipitation declined at a rate of 48.5 cm. In contrast, the mean temperature showed an increasing trend of approximately 0.12°C.

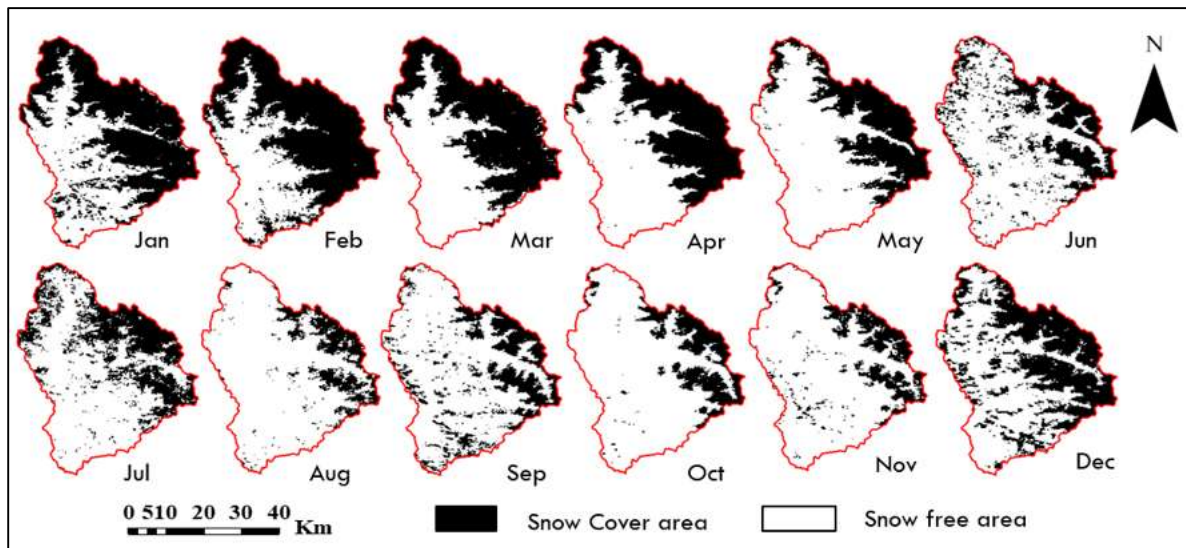
Figure 4: Annual variation of snow cover area (SCA) in the Beas River basin from January to December for the period 2019 to 2021, examining both intra- and inter- temporal changes.



The study investigated monthly variations in Snow Cover Area (SCA) and climatic parameters in the Beas River Basin from January to December. The Mann-Kendall test and Sen's slope estimator were applied at a 95% confidence level to identify the direction and magnitude of trends. SCA generally increased from November to December, with a decline observed in February; however, these trends were statistically insignificant during the winter season.

Maximum temperature exhibited an upward trend from November through January, followed by another increase in April, whereas a decreasing trend was observed during February and March. An increase of 0.29°C was noted in November; however, this trend was statistically insignificant. Minimum temperature increased from November to February and declined from March to April, but these changes were also statistically insignificant. Total precipitation decreased from November to December and increased from January to April. Overall, none of the observed winter trends reached statistical significance at the 95% confidence level.

Figure 5: Beas Basin monthly average SCA maps during 2019-2021



6. Conclusions

The Terra MODIS Version 6 snow products were used to estimate Snow Cover Area (SCA) in the Beas River Basin during 2019-2021 at 8-day intervals over a total area of 5384 km^2 . Monthly SCA was calculated from the average of the available 8-day observations. The mean SCA during the study period was 3076 km^2 , representing 56.46% of the basin area. The highest annual SCA occurred in 2019 (59.56%), while the lowest was recorded in 2021 (54.57%). SCA was generally highest during January and February, with the maximum value of 90% observed in February, whereas the overall monthly variation ranged from 23% to 90%. These variations were mainly associated with changes in temperature, precipitation, and snow ablation.

The Mann-Kendall test and Sen's slope estimator were used to examine the trends in Snow Cover Area (SCA) and climatic variables during the winter season (November-April). The results showed that SCA generally increased from November to December and then decreased in February; however, these changes were not statistically significant. Maximum temperature showed an increasing trend from November to January and again in April, while a decreasing trend was observed during February and March. In November, the maximum temperature increased by approximately 0.22°C , although this trend was statistically insignificant. Minimum temperature increased from November to February but showed a declining trend from March to April. Precipitation decreased between November and December and subsequently increased from January through April. Overall, none of the observed trends in SCA, temperature, or precipitation during the winter period were statistically significant.

Table 2: Temperature and precipitation trend analysis

Month	Precipitation			Temperature		
	Z	Q (C/year)	Trend (95%)	Z	Q (C/year)	Trend (95%)
Nov	0.59*	1.42	Falling	1.78**	0.239	Rising
Dec	0.56*	5.59	Falling	1.47*	0.173	Rising
Jan	0.139*	3.79	Rising	0.431*	0.062	Rising
Feb	0.128*	0.95	Rising	0.049*	0.035	Falling
Mar	0.77*	5.73	Rising	1.343*	0.021	Falling
Apr	0.153*	1.27	Rising	0.041*	0.05	Rising

Q: Sen's slope, Z: Mann-Kendall test statistics

*Insignificant Trend

**Significant Trend

Pearson correlation analysis indicated a strong association between Snow Cover Area (SCA) and the climatic variables. SCA showed a declining trend with increasing temperature, whereas higher precipitation was associated with greater snow cover. The analysis further indicated that temperature had a stronger relationship with SCA than precipitation, suggesting that variations in temperature have a greater influence on snow cover in the Beas River Basin than changes in precipitation.

This research has been carried out to analyze the variations in snow cover area, temperature and precipitation over Beas River Basin for the period 2019-2021. It was found that the temperature has increased over the study period and precipitation has also changed over the period. At the same time, a declining trend was observed in SCA and total precipitation, while temperature showed an increasing trend. These changes may have important implications for the regional climate, ecosystems, and water resources. The findings can support policymakers and other stakeholders in developing suitable climate adaptation and mitigation measures for the Beas River Basin and other Himalayan regions experiencing similar climatic changes

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