Dynamics of Snow and Glacier Cover in the Upper Karnali Basin, Nepal: An Analysis of Its Relationship with Climatic and Topographic Parameters

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Abstract

Snow and glacier cover in the Upper Karnali Basin (UKB) are crucial freshwater reservoirs that support downstream ecosystems and human populations. This study uses remote sensing and GIS data from various sources, MODIS-derived land surface temperature, and ERA5 reanalysis climate datasets to analyze snow cover dynamics from 2002 to 2024. The results show a

significant decrease in snow-covered area (SCA), **with an annual decline of about 3.99 km².** Seasonal variations indicate the most significant reductions during the monsoon period (July–September), **where rising temperatures accelerate snowmelt**. The analysis also establishes a **strong negative correlation between snow cover and temperature (r = -0.59 to -0.77, p < 0.05),** with warming trends disproportionately affecting mid-to-high elevation zones (3000-5000 m a.s.l.). Glacier basins exhibit consistent retreat, **with the mean glacier area declining from 119.05 hectares in 2000 to 100.47 hectares in 2023,** highlighting the impact of climate change. Additionally, **snowline analysis demonstrates an upward migration, with the 10th percentile snowline increasing at a rate of approximately 5.16 m/year**, which indicates progressive snow loss at lower elevations. **Given the current warming trends (~0.0643°C/year above 5000 m a.s.l.), the UKB could experience a decline of glacier area by 47–69 % and snow-covered area by 19–30 %.** These findings emphasize the vulnerability of UKB's cryosphere to climate change, necessitating adaptive water resource management strategies. **This will help mitigate impacts on hydrology, agriculture, and regional water security.**

Keywords: Snow and Glacier, Karnali, Himalayas, Remote Sensing, Climate Change, Elevation-depended-warming, Snowline

1. Introduction

Snow and glaciers in the mountains act as freshwater towers. Their meltwater provides a consistent supply to rivers and downstream ecosystems (Immerzeel et al., 2020; Wester et al., 2019; Pritchard, 2019). The meltwater from Himalayan ice and snow supports the livelihoods of millions across Nepal, India, and China by supplying drinking water, irrigation, hydropower, and ecosystem services (Bolch, 2007; Bookhagen and Burbank, 2010). Therefore, a decline in snow and glacier extent threatens water availability, food security, and sustainable development in these regions (Krishnan et al., 2019).

Furthermore, snow and glacial ice regulate regional and global climates by reflecting solar radiation, thereby contributing to the Earth's energy balance and influencing local weather patterns (Xu et al., 2009). Seasonal meltwater sustains ecosystems that provide habitats for numerous animal and plant species in mountainous regions. Consequently, changes in snow cover and glaciers can disrupt these entirely (Wester et al., 2019). On both local and regional scales, variations in the amount of snow and ice can contribute to changes in sea level, affecting coastal areas (Forster et al., 2021; Mimura, 2013; NOAA, 2013)

Snow-covered peaks and glaciers are major hubs for adventure, religious, and nature-based tourism (Anup, 2017; Nyaupane and Chhetri, 2009). **Being sensitive to climate change, changes in their size and volume not only serve as visible indicators of broader climate trends but also directly threaten the tourism economy they support** (Elsasser and Bürki, 2002).

A comprehensive understanding of cryospheric transformations is essential for accurate hydrological forecasting, assessing cryospheric hazards, and developing effective adaptation

strategies. Historically, monitoring snow and glacier dynamics in the remote Himalayan regions was limited by a scarcity of in-situ observations. Since the 1970s, advances in satellite remote sensing have revolutionized large-scale cryospheric assessments (Kääb et al., 2012; Muhammad and Thapa, 2020). The synergistic integration of satellite-derived data with sophisticated climate models and targeted ground-based measurements has subsequently enabled improved understanding of snow and glacier mass balance changes, their resultant hydrological impacts, and spatiotemporal variability (Bajracharya et al., 2014; Bolch et al., 2012; Gurung et al., 2017; Kääb et al., 2012; Krishnan et al., 2019; Kulkarni et al., 2021). **Collectively, these studies demonstrate substantial snow and glacier loss across the Himalayas, altering river discharge seasonality and water resource availability**

Extensive research on glaciers, glacier lakes, and glacier lake outburst floods (GLOFs) in Nepal has been conducted (Bajracharya et al., 2008; Hall et al., 2002; Kääb et al., 2005; Shrestha et al., 2012; Zemp, 2006). However, these studies disproportionately focus on the central and eastern Himalayas. **The mid-western and far-western regions remain underrepresented due to their remoteness and limited accessibility** (Shrestha et al., 2019; Khadka et al., 2024). Although global and regional glacier inventories specifically addressing high-resolution (≤ 30 m) glacier cover remain limited (Bajracharya et al., 2014; Bolch et al., **Analyses of elevation-dependent warming (EDW) and trend analyses are also scarce in the Himalayas** (Pepin et al., 2015; Pepin et al., 2022; Desinayak et al., 2022)**. Furthermore, integrated studies linking glaciers, glacier basins, and snow cover to climate remain underexplored.**

Bridging this gap is crucial for understanding cryosphere dynamics and their impacts on hydrology, hazards, and livelihoods in western Nepal. The Karnali Basin, Nepal's largest river basin (~40,780 km² upstream of the Chisapani gauge station) **and home to approximately**

2.5 million people (CBS, 2021), exemplifies this need. Its rivers, fed by snow, **provide essential dry-season water for irrigation, drinking, and hydropower**. **Despite its ecological significance, the basin's cryospheric behavior remains poorly documented**.

Findings from studies conducted in the central and eastern Himalayas, the Indian Himalayas, and the Tibetan Plateau cannot be universally applied to the Karnali Basin due to differences in climatic regimes and geographical settings. Understanding the impacts of cryosphere changes on water resources requires studies specific to the Karnali Basin**.** **Integrating MODIS data, which offers high temporal resolution, with Landsat data, known for high spatial resolution, will improve our understanding of snow and glacier changes** and their relationships with topography, glacier basins, and climate.

Against this backdrop, the specific objectives of these study are to:

1. **Quantify spatial and temporal variations in snow and glacier cover in the Upper Karnali Basin (2000–2024) using multi-sensor remote-sensing datasets.**
2. **To determine the influence of climatic drivers (rising temperatures, precipitation shifts) and topography on the observed cryospheric dynamics, including the upward migration of the snowline.**

2. Study Area

he Upper Karnali Basin (UKB) is a transboundary catchment extending from 28.64° to 30.68° N latitude and 80.64° to 83.54° E longitude, covering 22,577 km². This region accounts for over 50% of the entire Karnali Basin above the Chisapani gauge station (225 m above sea level). It includes about **66% of the basin's glacierized area** (Bajracharya et al., 2011; Ghimire et al., 2024). The UKB comprises the Humla Karnali (partly within Tibet, China), Mugu Karnali, Kawari, and Tila Nadi sub-basins (see Fig. 1).

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The elevation ranges from 340 meters to 7,030 meters, with an alpine zone above 4,000 meters extending across the Middle Mountains, High Mountains, High Himalaya, and the Tibetan Plateau. **These regions encompass the geological units known as the Lesser Himalaya, Higher Himalaya, and Tethys Himalaya (LRMP 1986; Dhital 2015). This topographic and lithologic diversity significantly influences climatic gradients and cryospheric processes.**

The climate ranges from polar tundra in the glacier region to subtropical, temperate, and cold climates below 4,000 meters, with mean annual temperatures ranging from 27 °C to -12 °C and precipitation varying from **250 mm in rain-shadow areas to approximately 1,900 mm** annually on slopes. The cryosphere spans across both rainy and rain-shadow areas, which influences the distribution and mass balance of snow and glaciers.

The Upper Karnali Basin features a diverse landscape of snow-covered glaciers, valleys, permafrost, alpine meadows, and forests, supporting a rich variety of flora and fauna. It represents a cultural blend of Khas and Tibetan traditions and is an emerging tourist destination, including a stop on the Kailash Mansarovar pilgrimage route. The basin has an estimated population of approximately 816,941 people, with a density of 36.2 persons per square kilometer, residing in 4,395 settlements, primarily below 4,000 meters in elevation. The Human Development Index in the area is 0.49, which is below the national average.

Due to its climatic, geological, and cryospheric diversity, the Upper Karnali Basin represents the broader Himalayan environment. It serves as an ideal natural laboratory for studying spatial variations in snow- and glacier-covered areas, elevation-dependent warming, and hydro-cryospheric changes across far and mid-western Nepal.

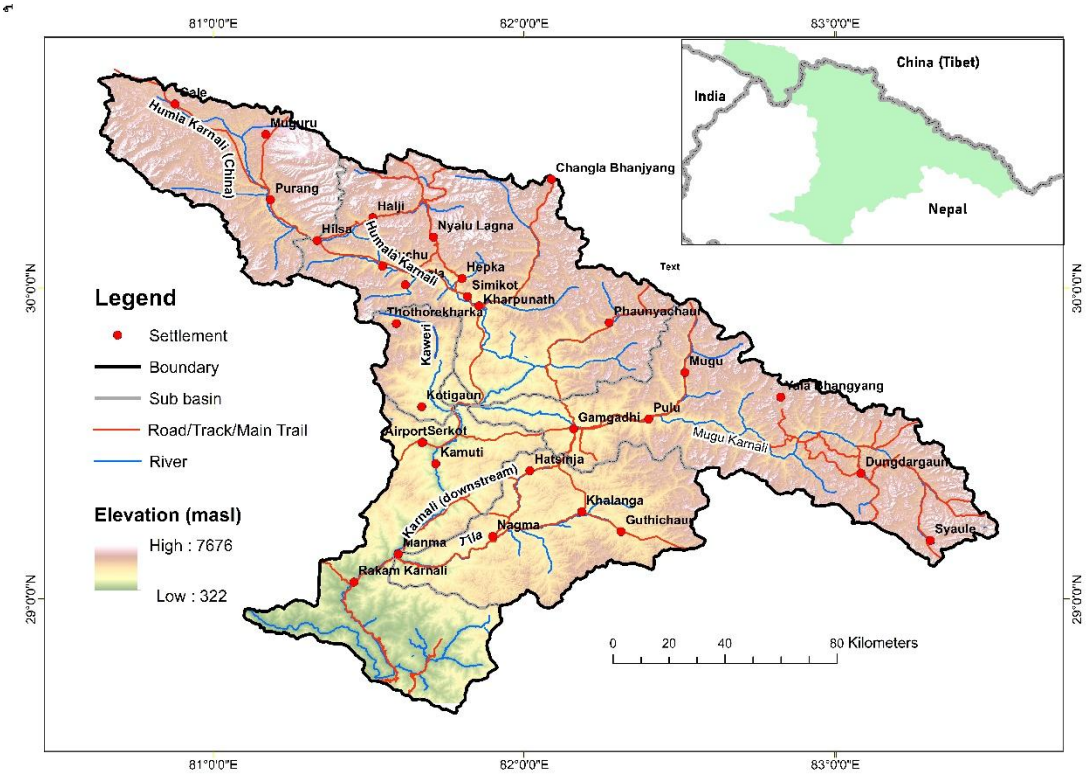

Figure 1. Location of the Upper Karnali Basin.

3. Data Sources, Method, and Limitations

This study considers snow and glacier cover as a unified cryospheric component, given their analogous functional roles. This study analyzed cryospheric dynamics using remote sensing. Satellite imagery was processed to generate time-series data on snow and ice cover, derive land-surface temperatures, and map glacier basins.

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3.1.Snow Cover Mapping

We mapped snow cover in the Upper Karnali Basin using Google Earth Engine (GEE) and imagery from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI. For the period preceding the Scan Line Corrector (SLC) failure, we used only Landsat 7 ETM+ images (2002–2003). For subsequent years, we utilized data from Landsat 5 TM and Landsat 8 OLI. To ensure high data quality, we selected only scenes with less than 30% cloud cover (Appendx A)

We preprocessed all Landsat images by masking clouds using the Quality Assessment (QA) bands–pixel_qa for Landsat 5 and 7, and QA_PIXEL for Landsat 8. Next, we calculated the Normalized Difference Snow Index (NDSI) using the green and short-wave infrared (SWIR) bands (Hall et al., 2002; Gorelick et al., 2017) and applied a threshold of NDSI > 0.4 to identify snow pixels. **To reduce confusion between snow and vegetation in mixed or forested terrain, we also calculated the Normalized Difference Vegetation Index (NDVI) and excluded pixels with NDVI > 0.2 from the snow classification, following the approach of Rittger et al. (2013). Finally, we exported the resulting snow cover maps as GeoTIFF files for overlay and sub basin and micro-basin analyses.**

To supplement the Landsat observations, we processed MODIS 8-day composite snow-cover products (MOD10A2) using Google Earth Engine (GEE). The MOD10A2 algorithm applies a maximum snow-extent compositing method over each 8-day period (Parajka and Blöschl, 2008), which minimizes cloud contamination and produces a spatially continuous dataset for analyzing seasonal and interannual snow-cover variability. Although it loses

daily temporal resolution, the 8-day composite effectively smooths out short-lived cloud effects, providing a more stable dataset for trend analysis.

After processing the imagery, we executed a Python script within the Google Earth Engine (GEE) environment to automate the download and organization of snow cover data. The script aggregated MODIS-derived snow extent by season, sub-basin, and elevation band (derived from the SRTM DEM).

The year was divided into four distinct three-month periods—January–March (Peak Accumulation), April–June (Major Ablation), July–September (Monsoon Ablation), and October–December (Early Accumulation). This division was explicitly chosen to capture the hydrological phases of snow accumulation and melting while minimizing cloud contamination during the monsoon season(Hunt et al., 2025; Khatiwada et al., 2016; Kulkarni et al., 2017). The resulting structured snow dataset was used as the main input for analyzing snow cover trends, elevation-dependent variability, and hydrological differences among sub-basins.

We describe the methods for spatial resolution harmonization and accuracy assessment between Landsat and MODIS datasets in Appendix B. Despite these refinements, persistent monsoon cloud cover continues to limit optical remote sensing in the Himalayas, often resulting in underestimation of snow-covered areas and uncertainties in seasonal trends.

Elevation bands were defined using the SRTM DEM and categorized into 200-meter intervals, ranging from ≤2000 m to ≥6500 m. Zonal statistics were applied to extract the frequency of snow cover for each elevation band and subbasin. Snow-covered area was calculated using a threshold-based binary mask. The results were aggregated into a structured dataset, revealing

seasonal snow distribution and variations across elevation zones and watersheds, thereby facilitating hydrological analysis.

3.2. Land Surface Temperature Data and Validation

We also downloaded the land surface temperature (LST) 1 km resolution from the Application for Extracting and Exploring Analysis Ready Sample (AppEEARS) platform. AppEEARS is a NASA-supported platform developed to easily access, subset into specified areas, and analyze climate and environmental data(Wan et al., 2015). MODIS Land Surface Temperature (LST) data have been reliably used to determine surface temperature patterns in areas where ground observations are scarce, especially in rugged mountainous regions. Several studies have confirmed their accuracy, showing average biases of less than 1.5 K and high correlations ($R^2 > 0.9$) with on-site measurements (Duan et al., 2019; Yu et al., 2011; Zhao et al., 2019), demonstrating their appropriateness for analyzing elevation-related warming trends in the Himalayas. We also obtained temperature and precipitation records, including maximum and minimum values, from the Department of Hydrology and Meteorology (DHM), Government of Nepal, and open-access reanalysis datasets such as ERA5. The temperature data (2 m above ground) obtained from various meteorological stations in the study area, were compared with MODIS LST; the results of this comparison are discussed in Section 4. Due to the 1 km spatial resolution of the MODIS product, the analysis of time series data reflects area-averaged temperature trends rather than in situ measurements at individual stations.

3.3. Delineation of the Glacier Basin and Glacier Data

The boundaries of glacier basins were **delineated to assess changes in glaciers and snow cover fractions within glacier-drained areas**. **Glacier basins include trunk glaciers, tributary glaciers, and surrounding slopes nourished by moving ice and snow. Their boundaries are topographically defined, with the lower boundary terminating at the terminus of the main glacier. This delineation process involved multiple steps to ensure accuracy.**

Initially, the Glacier Inventory map referenced earlier served as a fundamental resource. High-resolution imagery and ESRI's topographic maps in ArcGIS 10+ and later versions provided detailed spatial data. A 12.5 meter DEM was used to extract drainage networks, produce contour lines, and generate hillshade maps, enhancing the visualization of divides between glacier basins. **These components were essential for accurately identifying glacier termini and delineating glacier head basins**. **This integrated approach,** combining topographic analysis, remote sensing, and geospatial techniques, enabled precise delineation of glacier basins for comprehensive evaluations of snow cover fraction.

The time series glacier data compiled by Ghimire et al. (2025), were included in this study. The lead author of the current manuscript was also responsible for that research paper. In summary, we mapped glacier polygons for the years 2000, 2010, and 2023 using high-resolution imagery from Google Earth, Bing Maps, and RapidEye 2023 to maintain temporal consistency. Snow and glaciers were identified based on their bright characteristics, features, smooth textures, and shadows cast by adjacent terrain. Landsat composites (both true and false color) and the Normalized Difference Snow Index (NDSI) enhanced and improved the visibility of snow and ice, while altitude and topographic data derived DEM highlighted potential glacier regions. Outlines from the Randolph Glacier (RGI)(Pfeffer et al., 2014) and ICIMOD (Bajracharya et al.)

served as reference, while ground-truth and additional data helped validate the findings. This comprehensive approach ensured precise delineation.

3.4.Limitations and Validation

A key limitation of this research is that optical remote sensing is significantly affected by cloud cover, particularly during the monsoon season (Hall et al., 2002; Gafurov and Bárdossy, 2009). Frequent cloudiness often restricts the availability of clear Landsat images, leading to an underestimation of snow cover and potential inaccuracies in the spatial and seasonal assessment of snow patterns. In this study, cloud-free images were primarily available from January to March and October to December in most Upper Karnali sub-basins. Nevertheless, all four seasons were analyzed for microglacier basins where **suitable data existed.**

To address these issues, we used MODIS MOD10A2 data, **which provide higher temporal resolution (8-day composites at 500 m) compared to Landsat's 16-day revisit cycle and 30 m spatial resolution. This multi-sensor strategy enhances temporal continuity and minimizes data gaps caused by clouds; however, results should still be interpreted cautiously (Maskey et al., 2011; Parajka and Blöschl, 2008).**

The scarcity of high-altitude temperature stations necessitated the use of MODIS land surface temperature (LST) data at a 1 km resolution, representing daytime skin temperature at approximately 10:30 A.M. local time. This skin temperature was compared with in situ air temperature measurements taken at 2 meters above ground from four stations: Jumla (2,300 m), Simkot (2,800 m), Guthi Chaur (3,080 m), and Rara (3,048 m). Correlations varied by site and season–strongest at Jumla (up to 0.85), moderate at Guthi Chaur, and weakest at high-altitude, snow-covered sites such as Simkot and Rara (−0.18).

MODIS LST performs well in clear, snow-free areas but requires adjustments at higher elevations. Differences arise from factors including resolution, spatial averaging, land-cover heterogeneity, and surface–air temperature contrasts.

Validation studies further confirm its reliability for analyzing high-mountain temperatures in regions where in situ data are limited (see Duan et al., 2019; Yu et al., 2011; Zhao et al., 2019).

4. Result

4.1. Snow or Ice cover Trend and Variability: Annual and Seasonal

The total snow cover across the Upper Karnali Basin (22,546 km²) from 2002–2024 averages 872 km², with a standard deviation of 147 km², indicating moderate variability (Table 1 and Figure 2). The minimum recorded snow cover is 514 km²; about 25% of the recorded snow cover observations are at or below 777 km². The average snow covered area from January–March is 1528 ±333 km^2, followed by April-June (881 ± 212 km^2) and October–December (862±373 km^2), respectively. July–September witnessed the lowest snow cover area, i.e., 169 ±38.3 km^2 .

Snow cover data highlight significant year-to-year changes in every quarterly season with varying directions and magnitudes of trends, evidenced by correlation, the Kendall tau test, and Sen's slope. The annual average SCA shows, although not significant, a decreasing trend (p = 0.535), with Sen's Slope estimating a loss of ~3.99 km^2/year, which indicates a gradual decline in snowpack over two decades. Seasonally, the July–September period exhibits a gentler trend line compared to October–December; however, because of its much lower inter-annual variability, this period exhibits the statistically significant steepest drop in snow cover (Sen's Slope = -2.87, p = **0.001) (Table 1).** This period is charactersied by snow ablation, where the summer monsoon

brings warmer temperatures. In mid-latitude regions, the precipitation occurs more as rain than snow, resulting in accelerated snowmelt. While January–March shows a decline (Sen's slope =-8.63 km/year), it lacks statistical significance ($p = 0.523$), suggesting year-to-year winter variability in snowfall or early melt. Similarly, no significant trends were detected in April–June. Interannual variability is evident with peaks and lows of snow and ice coverage (Figure 2). Episodic snow coverage was observed in 2015, 2020, and 2022 (January–March), 2015 and 2019 (April–June), 2009, and 2021 (October–December), **indicating anomolous years of high episodic** heavy snowfall events. However, these anomalies do not counterbalance long-term declines. Compared to seasons, annual snow coverage's inter-annual variability is relatively low, i.e., with a 16% coefficient of variation (CoV)–ratio of the standard deviation to the mean.

Table 1. Snow cover descriptors and changes by seasons

Descriptor	**Jan–Mar**	**Apr–Jun**	**Jul–Sep**	**Oct–Dec**	**Annual avg.**
Mean (km²)	1 528.00	881.00	217.00	862.00	872.00
Median (km²)	1 569.00	858.00	210.00	739.00	886.00
Std. dev. (km²)	333.00	212.00	38.30	373.00	147.00
Minimum (km²)	1 025.00	503.00	169.00	340.00	514.00
Maximum (km²)	2 167.00	1 358.00	298.00	1 737.00	1 055.00
Skewness	0.21	0.47	0.94	0.51	−0.87
25th percentile (km²)	1 270.00	751.00	191.00	538.00	777.00
50th percentile (km²)	1 569.00	858.00	210.00	739.00	886.00
75th percentile (km²)	1 689.00	1 025.00	229.00	1 126.00	991.00
Correlation (r)	**−0.09**	**−0.07**	**−0.61**	**−0.25**	**−0.27**
Kendall's τ	**−0.09**	**0.01**	**−0.54**	**−0.13**	**−0.10**
p-value	0.523	0.950	0.000	0.398	0.535
Sen's slope (km² yr⁻¹)	−8.63	−3.14	−2.87	−13.21	−3.99

Note: Sen's slope represents the median of all possible pairwise slopes, quantifying trend (here snow cover) over time (Sen, 1968). It gives a more reliable long-term trend of snow cover loss without being skewed by short-term anomalies (Gilbert, 1987; Yue and Wang, 2004)

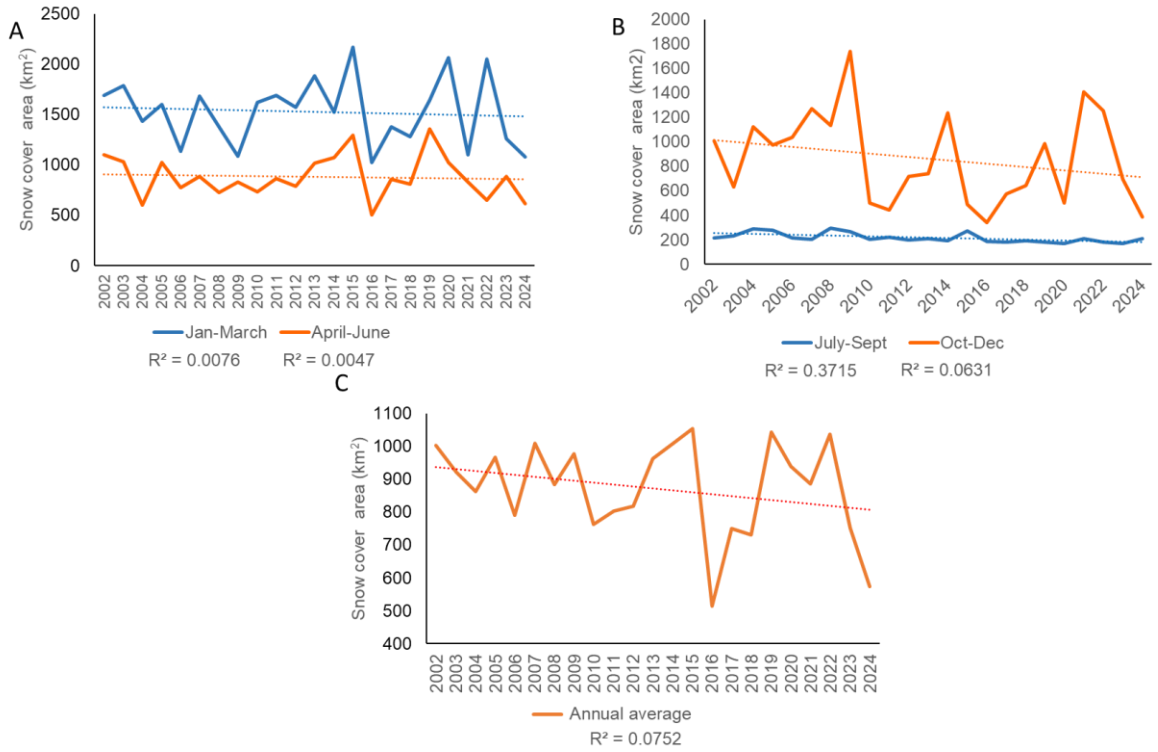


Figure 2. Temporal variation and trends in seasonal and annual snow-covered area (SCA) in the Upper Karnali Basin (2002–2024).a) Time series of SCA for January–March (orange) and April–June (orange); (b) SCA for July–September (blue) and October–December (orange); (c) average annual SCA (orange).

4.2. The Relation among Snow Cover, Temperature, and Precipitation

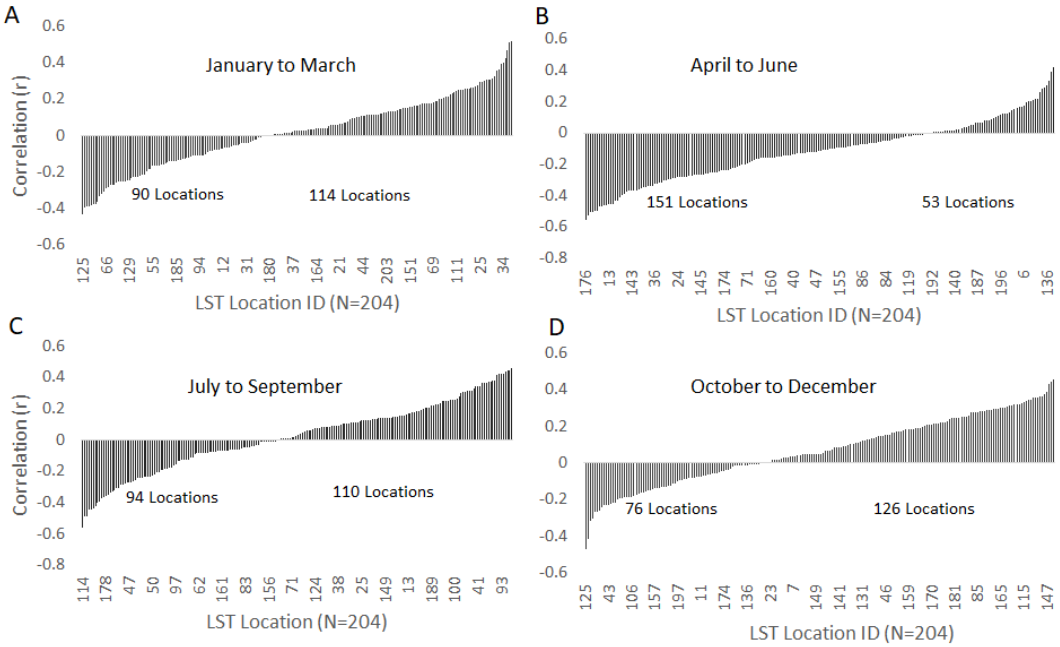
We derived land surface temperature (LST) data for 204 locations from MODIS Terra (MOD11A1) and Aqua (MYD11A2) (1 km resolution), which were processed through AppEEARS. Precipitation data were obtained from the ERA5-Land reanalysis (~9 km resolution) by ECMWF (Hersbach et al., 2020). These datasets, covering four different seasons, were used to examine temperature and precipitation trends, as well as their relationship with snow cover trends (Figures 3, 4, and 5).

Using correlation statistics, we found that among the 204 sampled sites, 143 locations (approximately 70%) exhibit a positive annual temperature trend, indicating a general warming pattern throughout the study region (Figure 3). However, statistically significant trends ($p \leq 0.1$) were identified in only a subset of these sites, highlighting that not all observed warming trends are statistically robust. Moreover, the warming pattern is not consistent across all seasons. Notably, during the April–June interval, the temperature trend tends to be weaker or, in some cases, negative. Several subsites across different seasons also demonstrate negative trends, although the majority of locations show a positive trend (Figure 3). Elevation-related variability in these trends is further analyzed in Figures 7–9 and Table 3.

Seasonal rainfall trends from 2000 to 2024 indicate weak to moderate increases across all seasons, with the exception of winter (January–March), which exhibits a slight downward trend (R^2= 0.0144) (Figure 4). Pre-monsoon (April–June) rainfall shows a slight upward trend (R^2 = 0.0119). All these seasons display high variability, suggesting a limited impact on snow accumulation. Monsoon rainfall (July–September) demonstrates a more noticeable increase (R^2 = 0.0975), primarily contributing to rainfall rather than snowfall. Post-monsoon (October–December) precipitation remains low and stable. When combined with rising temperatures, these trends indicate a shift toward rainfall-dominated precipitation, reduced snowfall, and earlier snowmelt, contributing to declining snow cover and altered hydrological regimes.

The snow-covered area shows a strong to moderate negative correlation ($r = -0.59$ to -0.77, $p < 0.05$) with temperature across all seasons (Figure 5). Conversely, precipitation has a positive correlation ($r = 0.55$ to 0.59, $p < 0.05$) with snow cover for January–March and October–

December, while during the remaining seasons, it shows a moderate negative correlation. **Precipitation and temperature are negatively correlated in winter (Oct-March) and positively in the summer (April-September) half-year.**



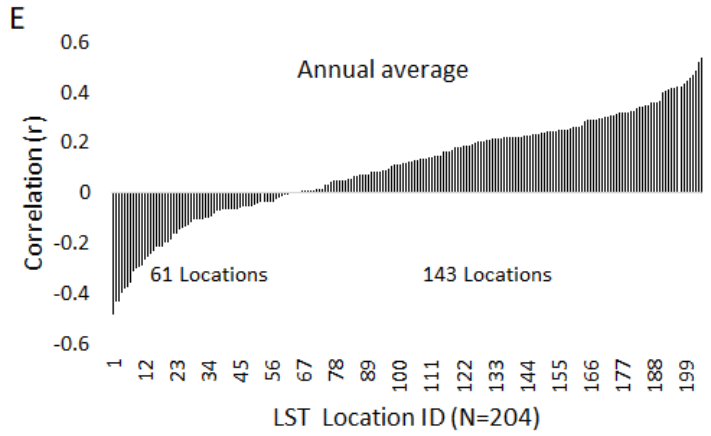


Figure 3. The correlation illustrates the season wise (A-E) temperature trend directions at various sites between 2000 and 2024 (Source: MODIS Terra and Aqua MOD11A2, MYD11A1, AppEEARS). Significant correlations at a 90 % confidence level are observed at r= ±0.364.

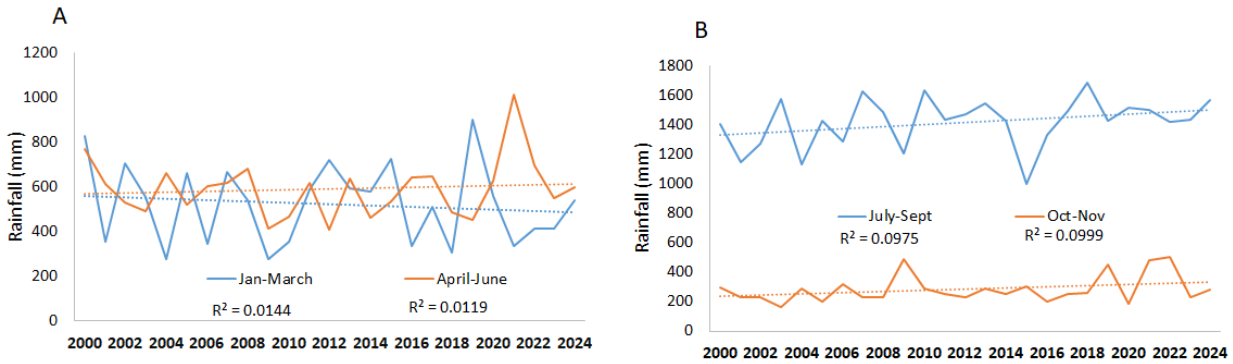


Figure 4. Yearly rainfall trends across various periods. Precipitation data was collected from the ERA5-Land reanalysis by ECMWF (Hersbach et al., 2020) from 204 locations across four different periods.

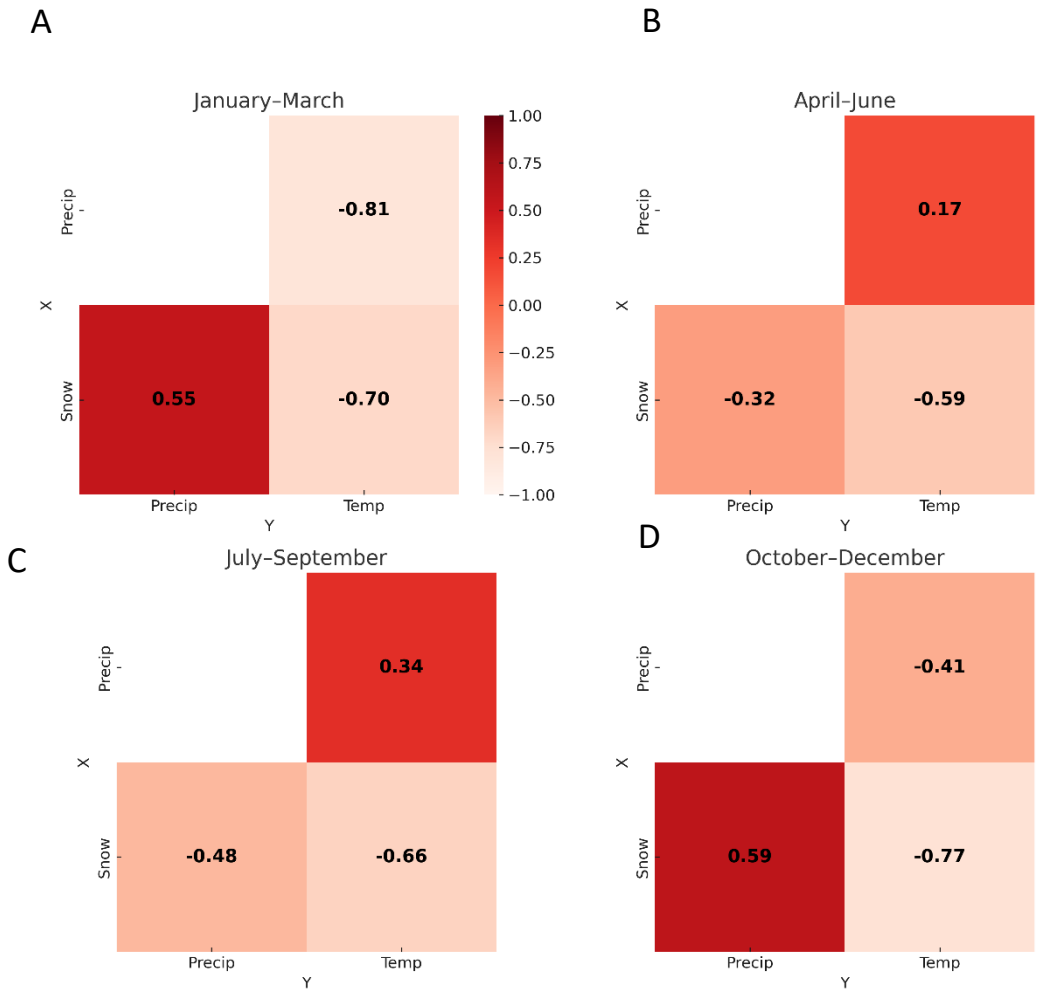


Figure 5. Seasonal correlation patterns among snow cover, temperature, and precipitation across a 22-year period, shown separately for each season (A–D).

4.3. Snow Cover Changes in Sub-Basins Using Landsat Series Data

Landsat-derived reliable snow and ice data were unavailable for the pre-monsoon and monsoon seasons due to significant cloud coverage (**as mentioned in Section 3.4)**. Therefore, only two seasons, January–March and October–December, were considered. These seasons are characterized by snowfall as precipitation, which contributes to snow accumulation.

Examining snow cover patterns in the sub-basins of the Upper Karnali Basin (UKB) for two seasons (January–March and October–December) reveals notable seasonal and spatial

differences (Table 2). During January–March, Humla Karnali has the largest average snow cover (3,336 km²), followed by Mugu Karnali (1,864 km²) **and Humla Karnali (China)** (1,478 km²), while areas downstream like Tila and Kawari have very little coverage (less than 350 km²). Significant variability in the snow cover trend is observed, particularly in Tila and Downstream Karnali, which have a coefficient of **variation (CoV) above** 50%. **This high CoV indicates inconsistent snow cover from year to year during January–March. Furthermore, this variability is associated with a significant negative correlation i.e., $r \geq -0.37$ ($p<0.1$). Figure 6 also graphically shows the temporal trends with the correlation coefficient (r) and fluctuations in Landsat-derived snow cover for the two seasons mentioned above.** The **moderately** negative skewness of the temporal distribution does not affect the correlation, which is negative for all basins, indicating a declining trend.

Conversely, the October–December season has a lower average snow cover (823 km²) and exhibits strong fluctuations (e.g., a range of 227–1570 km² and a CoV of 55%). Strong variability is observed for all basins, particularly Humla Karnali (China), Tila, and Downstream Karnali. The skewness is moderate, except for Downstream Karnali. Correlation values are reliable and indicate a declining trend. However, Downstream Karnali, in spite of high variability, indicates a statistically significant negative r value, i.e., -0.47 ($p<0.05$) (Figure 6).

Table 2. Descriptive statistics of snow cover across sub-basins for two seasons (January-March and October-December) and the time series correlation from 2002 to 2024.

Descriptor	January - March							October-December						
	Humla Karnali (China)	Humla Karnali	Mugu Karnali	Tila	Kaweri	Down stream	Seasonal average	Humla Karnali (China)	Humla Karnali	Mugu Karnali	Tila	Kaweri	Karnali (Down stream)	Seasonal average
Mean	1478	3336	1864	351	294	41.9	1227	854	2057	1442	332	204	48.1	823
Median	1420	3667	1827	346	308	39	1239	754	2159	1301	288	190	40.2	781
Standard deviation	501	597	645	184	86.2	24	311	622	1163	862	227	112	44.7	457
Coefficient of variation (CoV in %)	33.90	17.90	34.60	52.42	29.32	57.28	25.35	72.83	56.54	59.78	68.37	54.90	92.93	55.53
Minimum	552	1904	887	50.1	121	5.74	612	67.2	166	226	44.3	35.2	3.28	227
Maximum	2317	4009	3056	691	420	93.5	1642	2092	4074	2868	716	434	185	1570
Skewness	-0.707	-0.488	-1.29	-0.69	-0.469	-0.763	-1.1	0.533	-0.016	0.231	0.347	0.204	1.43	0.202
Temporal correlation (r<-0.44 and r>0.44, p<0.05	-0.16	-0.18	-0.10	0.12	-0.37	-0.41	-0.14	-0.16	-0.07	-0.23	-0.17	-0.13	-0.47	-0.17

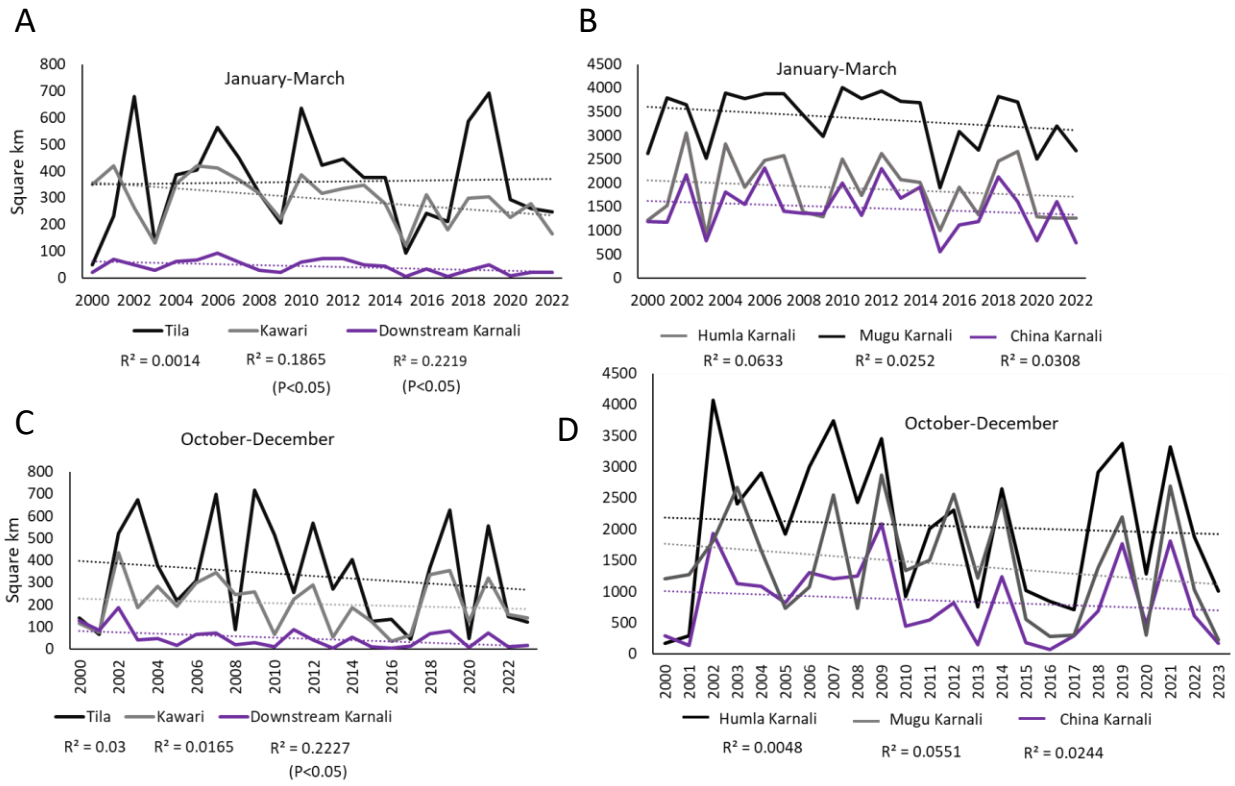


Figure 6. The snow cover trend in the Upper Karnali Basin varies across different sub-basins from January–March and from October–December (A-D).

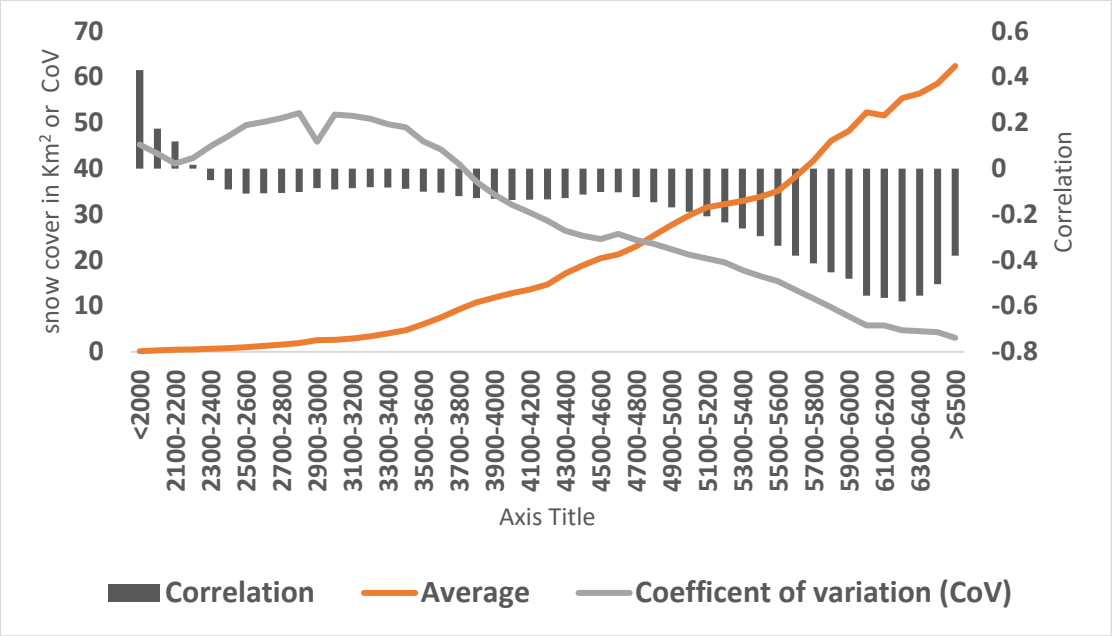
4.4. Snow Cover Dynamics across Elevation Zones

The dynamics of snow cover across elevation zones, categorized in 100-meter intervals from ≤2000 m to ≥6500 m, reveal remarkable elevation-dependent patterns in correlation and variability (Figure 7) with time (2002-2024). Snow cover in the lowest elevation zones shows a weak positive correlation (0.12-0.43), suggesting a marginal increase. However, pronounced

interannual variability (CoV ~ 41-43%) is likely driven by fluctuating temperature and precipitation regimes (Pendergrass, 2020).

Above 2300 m a.s.l., correlations shift to weak negative values (up to 5000 m a.s.l., r = -0.05 to -0.17, reaching peak negativity at 6100-6200 m a.s.l. (r = -0.56), indicating a significant decline in snow cover (Figure 7). This trend aligns with the impacts of global warming, where rising temperatures disproportionately affect higher elevations, accelerating snowmelt and reducing accumulation (Naegeli et al., 2019; Ren et al., 2023; Shen et al., 2021). The mean snow cover increases with elevation, showing a marked rise from 3300 to 6500 m a.s.l. or above, except between 5000-5200 m a.s.l, which exhibits a gradual rise in snow cover.

Above this elevation, the mean snow cover area rises sharply, coinciding with glaciers and permanent snow zones. In contrast, the CoV increases with elevation up to 3100 m a.s.l. and then trends sharply downward from 3100 m a.s.l. to 6500 m a.s.l. and beyond. This pattern indicates a decline in interannual variability alongside increased negative correlations. The low inter-variability reinforces the reliability of the declining trend in snow cover.

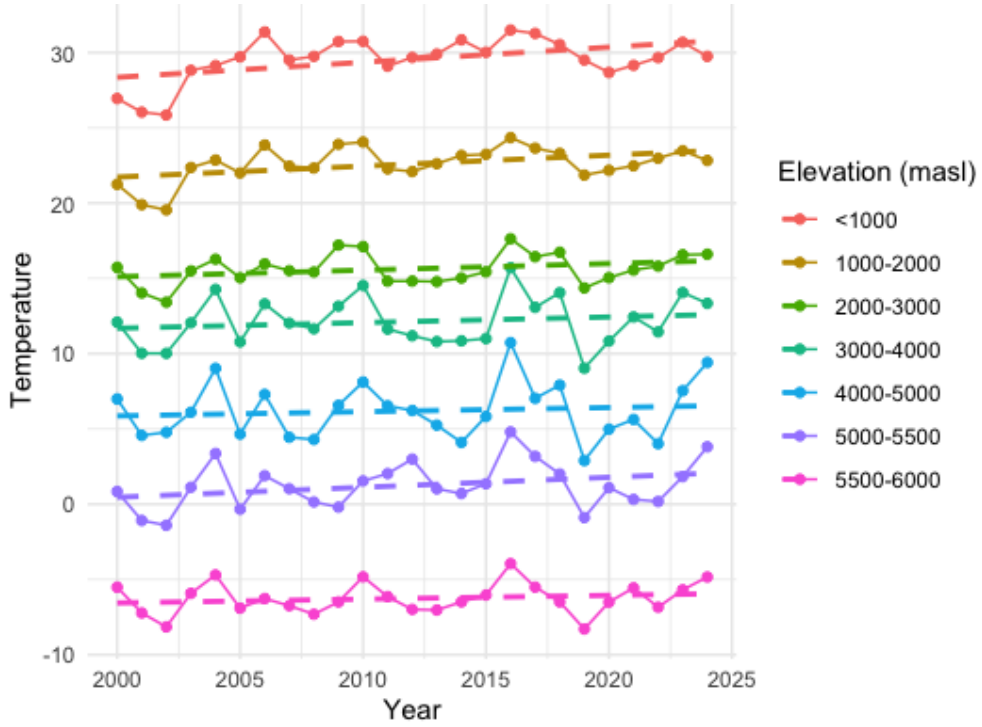


399

400 **Figure 7.** The average, coefficient of variation, and correlation of snow cover area (Source :
401 MODIS) across various elevation bands **with time (2002-2024).**

402 To examine the relation between temperature and snow cover, the elevation bands were
403 regrouped into seven broader bands: **<1000, 1000–2000,** 2000–3000, 3000–4000, 4000–5000,
404 5000–5500, 5500–6000, and above 6000 m a.s.l. The temperature trend from 2002 to 2024
405 across elevation bands in the Upper Karnali Basin, as evidenced by Sen's slope (Figure 8, Table
406 3), shows a general increase. The highest rate of change is observed at lower elevations (<1000
407 m: 0.0765°C/year). Mid-elevations (1000-2000m: 0.0576°C/year) and high elevations (5000–
408 5500 m: 0.0643°C/year) also **exhibit significant** warming. However, statistical significance (P-
409 value) weakens at higher elevations. This warming accelerates glacier retreat, reducing snow
410 cover and impacting the **hydrology of the Upper Karnali Basin by altering river flow**
411 **patterns and** leading to a declining glacier-fed water supply.

412



413

414 **Figure 8.** Temperature (source: MODIS) trend between 2002 and 2024 for different elevation

415 bands

416

Table 3. Rate of temperature change in different elevation between 2000–2024)

Elevation bands (m a.s.l.)	Sen's slope(Sen, 1968)	P Value
<1000	0.0765	0.052
1000–2000	0.0576	0.058
2000–3000	0.0390	0.168
3000–4000	0.0410	0.528
4000–5000	0.0198	0.833
5000–5500	0.0643	0.154
5500–6000	0.0287	0.414

Figure 9 shows a strong negative correlation between land surface temperature and snow cover across elevation bands in the Upper Karnali Basin. Tau values range from -0.43 to -0.79. The correlation is strongest between 3000–5000 m a.s.l. (Tau = -0.77 to -0.79) and 5000–5500 m a.s.l. (Tau = -0.75), with all p-values <0.01, confirming statistical significance. Even at 5500–6000 m a.s.l. (Tau = -0.43, p = 0.00353), snow cover continues to decline. **The impact is most severe at mid-to-high elevations, where warming accelerates snowmelt and glacier retreat, highlighting the vulnerability of the Upper Karnali Basin's hydrological balance to climate change.**

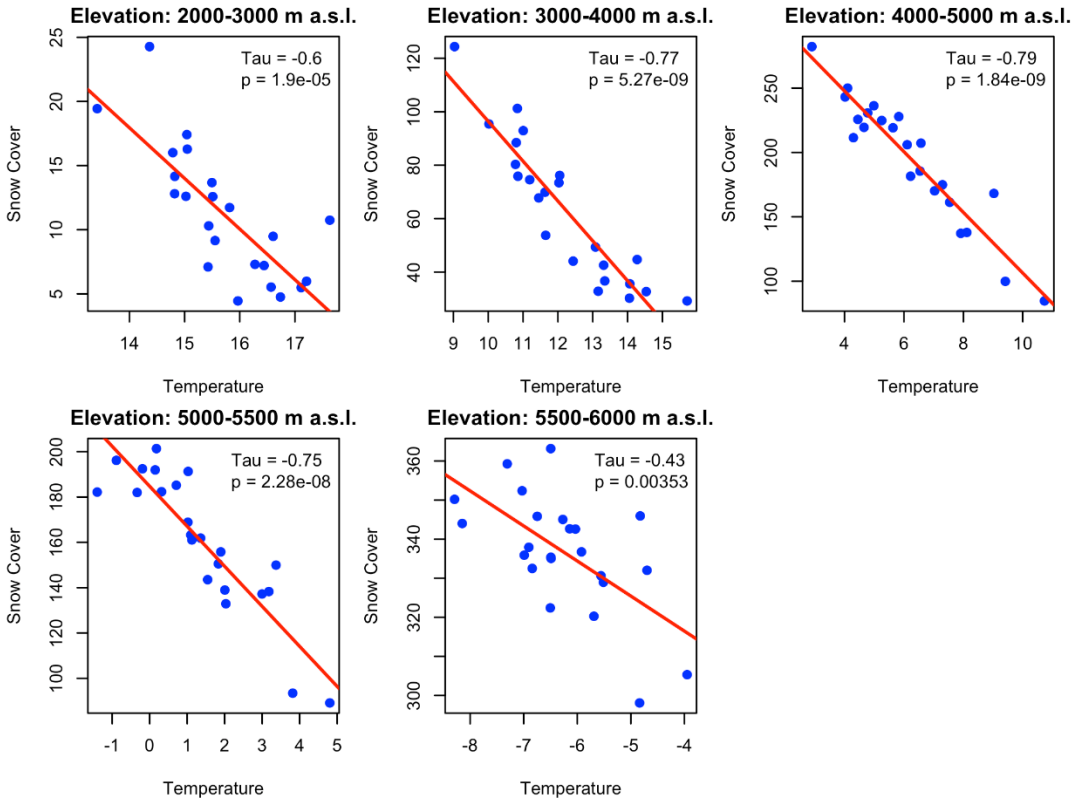


Figure 9. Relationship between snow cover and temperature (°C) across elevation zones in the Upper Karnali Basin (2002–2024). The correlation (Kendall's Tau) shows a strong negative association across all elevations, especially between 3000–5500 m a.s.l., where warming has significantly reduced snow cover.

Note: Elevation bands below 2000 m are excluded due to minimal snow presence, high interannual variability, and limited data reliability.

4.5. Snow Cover Trend in Glacier Basins (Landsat Data).

We examined using Landsat data snow cover trends in 735 glacier basins, each containing at least one glacier in 2000 that was greater than 10 hectares, which are crucial for assessing glacial status, water security, and climate change impacts (Table 4). The minimum altitude of the glacier basin where all tributary glaciers meet was considered the outlet of the glacier basin. **In these basins, snowfall restocks ice lost to melting, contributing to glacier stability.** Reduced snow

cover in the glacier basins accelerates negative mass balance, leading to glacier retreat. These glacier basins are at a minimum altitude above 4000 m a.s.l. with an average of ~5100 m a.s.l. Twenty-five and 75 % lie below 4800 and 5330 m a.s.l., respectively. Besides other meteorological parameters, current temperature trends and albedo patterns play a critical role in glacier mass balance (Dowson et al., 2020; Ye & Tian, 2022). Higher temperatures directly increase the snow melting rate, and a decrease in reflectivity of solar radiation leads to more solar radiation being absorbed by the glacier surface, leading to accelerated melting. Declining permanent snow cover in the glacier basin disrupts the glacier mass balance, affecting glacier persistence, altering water availability, and accentuating climate-driven environmental changes.

The data reveal a significant decline in glacier area across 735 glacier basins between 2000 and 2023. The mean glacier area decreased from **119.0 ha in 2000 to 100.5 ha** in 2023, reflecting an average loss of **18.6 ha per basin**. The total glacier area shrank **by 13,633.2** ha, indicating widespread glacier retreat. The percent of glacier area to total basin area declined from 53.23% in 2000 to 44.93% in 2023. Statistical tests show high skewness (>3.9), suggesting that a few large glaciers dominate the dataset. The Shapiro-Wilk test ($p < .001$) confirms a non-normal distribution.

Table 4. Change in glacier area between 2000 and 2023.

Glacier basin count (N=735)	Glacier basin Area (hectares)	Glacier area (hectares)		Difference in glacier area (hectares)
		2000	2023	
Median	101.4	52.8	39.7	-10.0
Mean	223.6	119.0	100.5	-18.6
Std. Dev	368.1	187.1	169.9	27.2

Skewness	4.6	4.0	4.0	-4.0
Sum	164140.9	87379.9	73746.8	-13633.2

The glacier area has declined significantly across all basin directions from 2000 to 2023, with the basins oriented toward North, Northwest, and Northeast experiencing the largest losses, totaling 6,126.9 hectares (Figure 10). The glaciers oriented towards North-east, East, and South slopes show the highest relative loss (%). The consistent loss across all directions highlights the ongoing effects of climate change on the region's glacier-fed water resources.

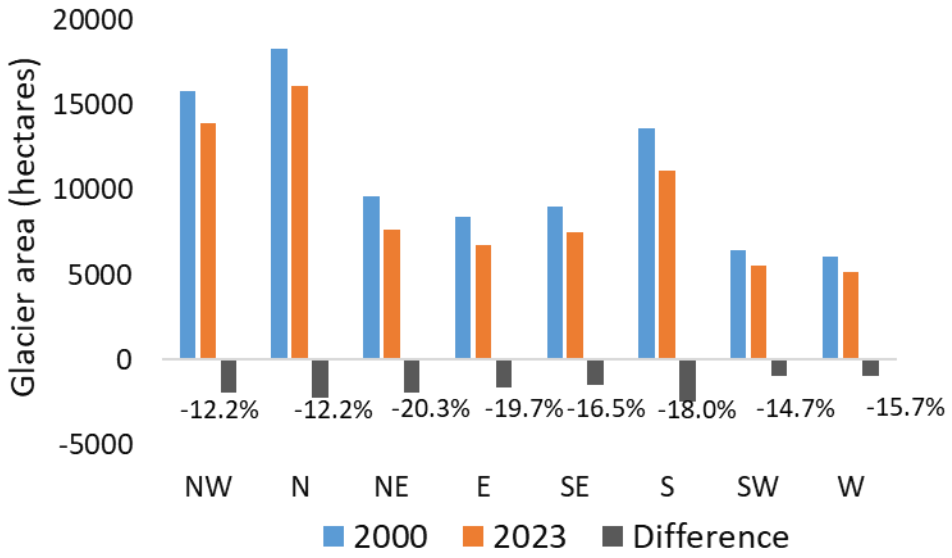


Figure 10. Change in glacier area in glacier basins by directions between 2000 and 2023.

Analysis of snow cover trends indicates that around 59% of glacier basins (n=735) demonstrate statistically significant negative correlations ($p<0.05$) from January to March. Among these, glacier basins with a correlation (r) value less than -0.44 represent 16.3% of the total (Figure 11, 12, and 13). Basins with moderate negative correlations, ranging from -0.44 to -0.30, constitute approximately 19% of the overall total. Additionally, 36% of basins show a positive correlation,

with 3% being statistically significant and 13% displaying a moderate correlation. The numerous glacier basins that exhibit negative correlations suggest a broader regional trend of declining snow cover over time during winter (January to March).

Similarly, during May–July, all 15 cloud-free glacier basins demonstrate a declining trend in snow cover from 2002 to 2024. Twelve of these basins exhibit a moderate negative correlation ($r < -0.30$). The trend in snow cover during July–September and October–December also indicates a decline. **Sixty two percent of the 70 glacier basins show a statistically significant negative correlation ($p<0.05$)**

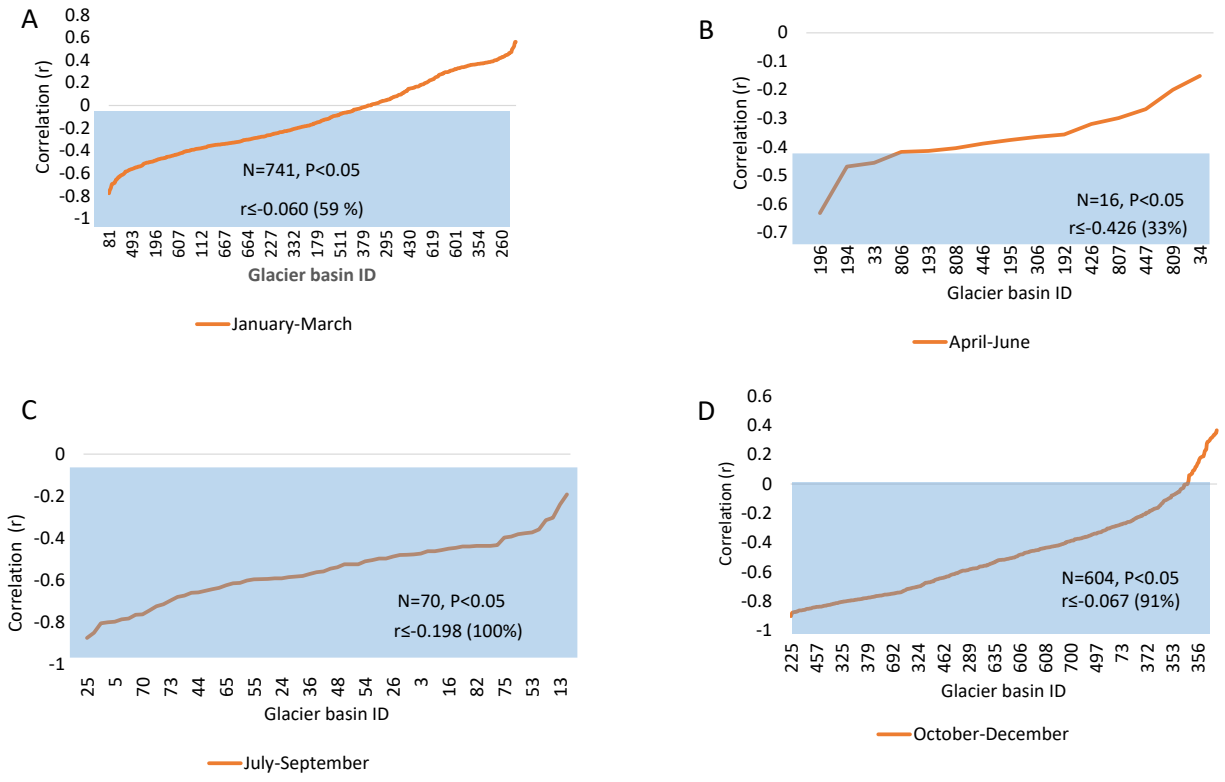


Figure 11. The correlation showing the snow cover change between 2002 and 2024 in different glacier basins.

The snow cover trend between July–September and October–December for 22 years also demonstrated a consistent decline in all glacier basins. Out of 604 basins selected for the analysis, **about 91%** have shown a statistically significant negative correlation ($p<0.05$), and 15 % of glacier basins showed a moderate negative correlation, i.e., r= -0.47 to -0.30 (Figure 10). The snow cover in the remaining basins exhibits a poor negative correlation yet indicates a decline in snow cover over the period.

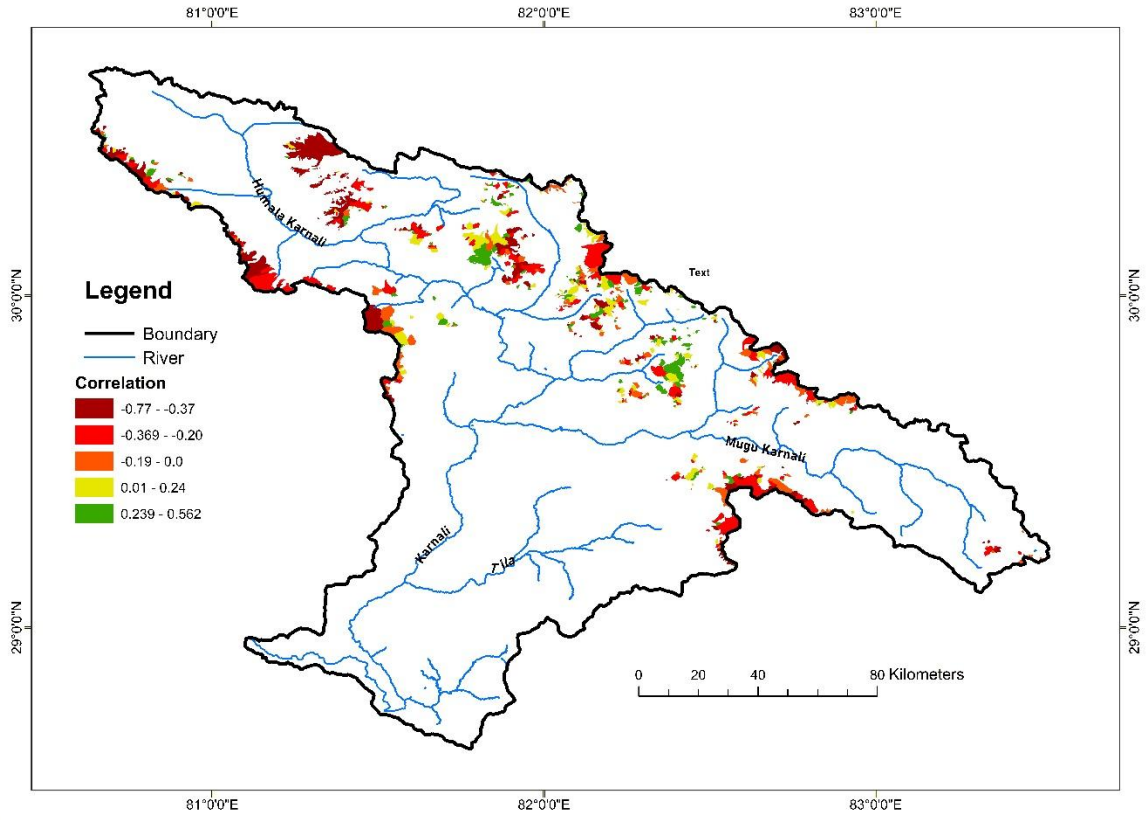


Figure 12. Snow cover trend on the Glacier Basins for January–March between 2000–2023 (Landsat 5, 7, and 8).

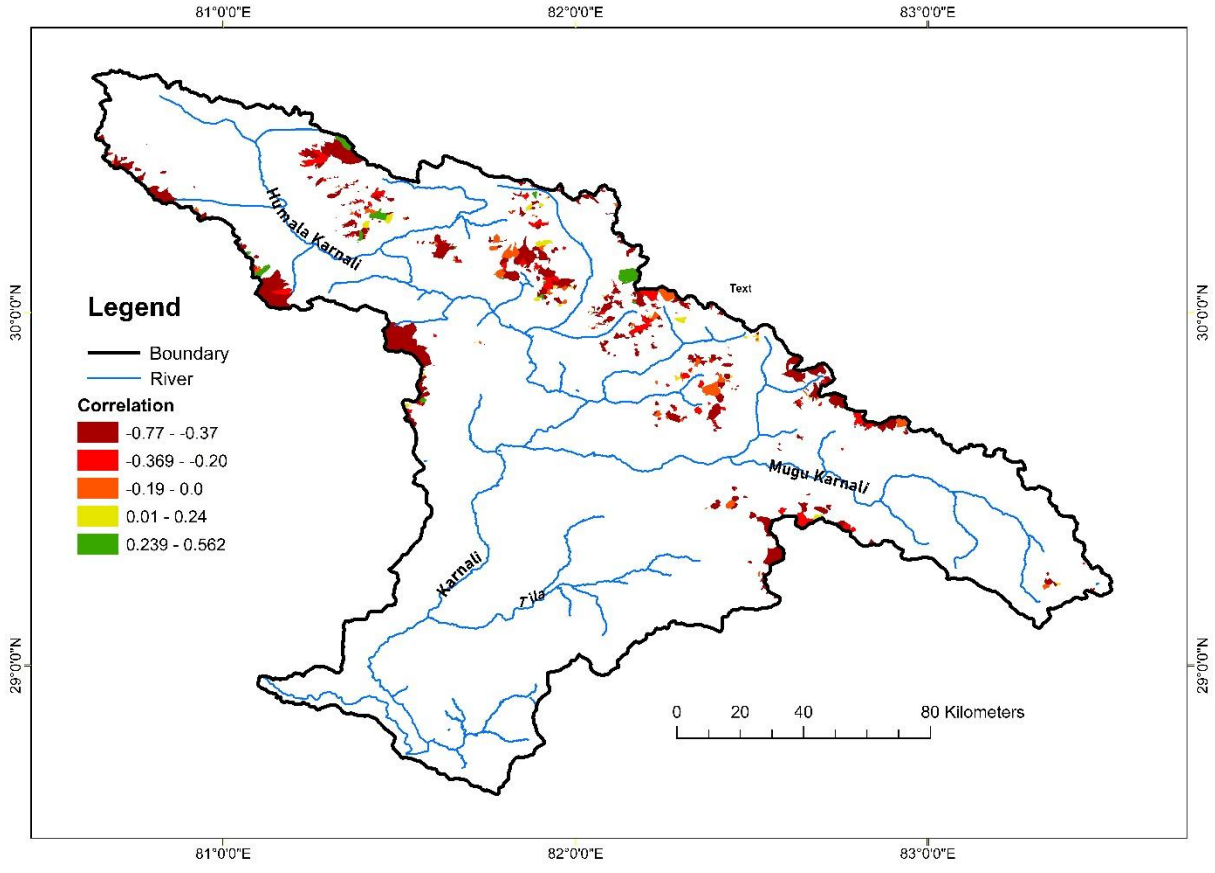


Figure 13. Snow cover trend on the glacier basins for October–December between 2000–2023 (Landsat 5, 7, and 8).

4.6. Snowline Shift across Elevations

Snow-covered areas were derived from the Landsat series 7, 8, and 9 by classifying snow using the Normalized Difference Snow Index (NDSI) algorithm to analyze changes in the snowline. This analysis was performed on the Google Earth Engine (GEE) platform. Snow pixels were identified with an NDSI threshold of > 0.4. The elevation-wise distribution of snow pixels

was then calculated. To determine the snowline's minimum elevation and its shift from 2002 to 2024, three statistical thresholds were applied: the 10th, 25th, and 50th percentiles of the snow cover distribution across various elevations.

The analysis of snowline altitude data from 2002 to 2024 reveals a significant upward trend across all percentiles (Figure 14). The 10th percentile shows the largest increase, with a Kendall's tau of 0.2662 and a Sen's slope of approximately 5.16 m/year, indicating that the lower snowline is rising quickly (Table 5). The 25th percentile presents a moderate yet statistically significant trend, with a Kendall's tau of 0.1938 and a Sen's slope of about 2.91 m/year. In contrast, the 50th percentile displays a gentler trend, with a Kendall's tau of 0.1483 and a Sen's slope of around 1.54 m/yr, which remains statistically significant ($p<0.05$). Collectively, these findings suggest that the snowline is moving to higher elevations, reflecting broader climatic changes that affect lower elevations more intensively than the median snowline altitude.

Table 5. Statistical analysis of snow line altitude trends using Kendall's Tau and Sen's slope.

Snow Line Percentile	Kendall's Tau	p-value	Sen's Slope (m/year)	Significance
10th Percentile (SLA_10P)	0.2662	0.00042	5.16	Significant ($p < 0.001$)
25th Percentile (SLA_25P)	0.1938	0.01022	2.91	Significant ($p < 0.05$)
50th Percentile (SLA_50P)	0.1483	0.04942	1.54	Significant ($p < 0.05$)

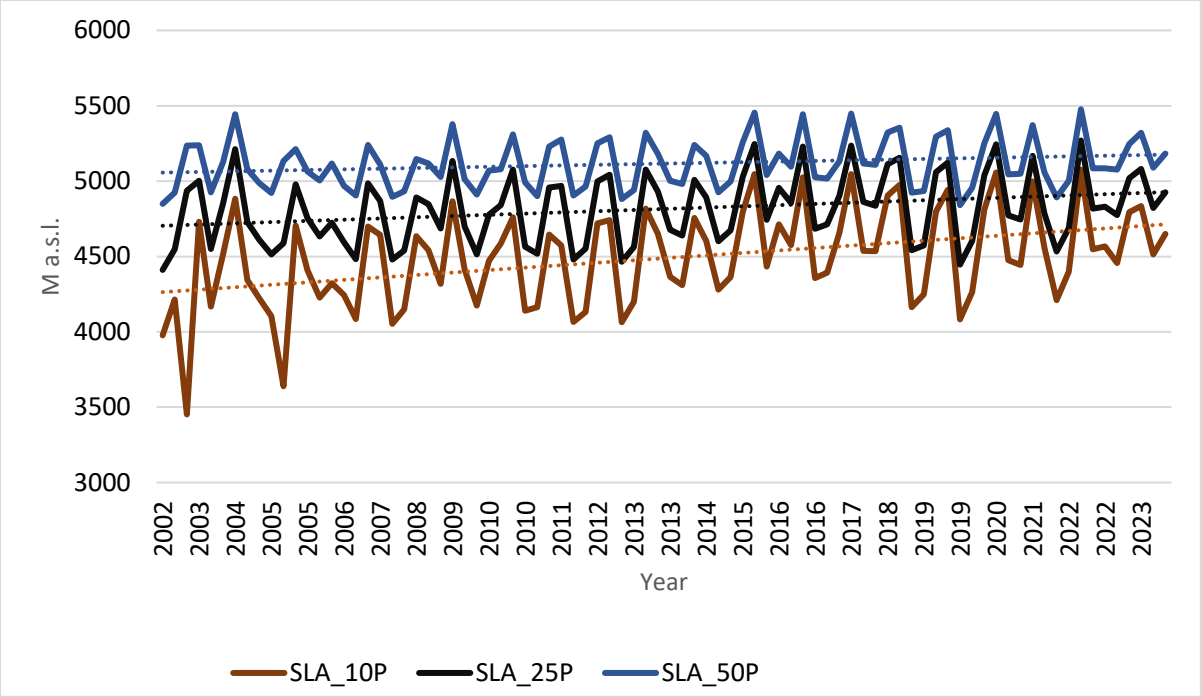


Figure 14. Snowline shift using snow line of elevation of 10, 25 and 50 percentile

5.0. Discussions

This study offers important insights into the interactions between snow and ice cover in the Upper Karnali Basin (UKB) and climatic and topographic factors. The results reveal notable trends and fluctuations in snow cover, glacial retreat, and the elevation of the snowline, aligning with the wider patterns of climate change seen in the Himalayan region. We will discuss the key findings below in relation to existing literature and their impact on water resources, ecosystems, and local communities.

The study on the Upper Karnali Basin from 2002 to 2024 reveals significant insights into the relationship between snow cover area (SCA), temperature, and precipitation. The annual average SCA is 872 km², with the highest snow cover occurring from January to March (1528 ± 333 km²)

and the lowest from July to September (169 ± 38.3 km²). The findings reveal a gradual decline in snow cover across the Upper Karnali Basin (UKB) from 2002 to 2024, with an average loss of ~3.99 km²/year.

There is a strong to moderate negative correlation between snow cover and temperature across all seasons ($r = -0.59$ to -0.77, $p < 0.05$), signifying that higher temperatures lead to reduced snow cover. In contrast, precipitation exhibits a positive correlation with snow cover in winter (January to March and October to December). The reduction in snow cover during winter months (January–March) indicates a potential shift in precipitation patterns, with more falling as rain instead of snow. **The winter and pre-monsoon snowpack in the western Himalayas is heavily influenced by the Westerly wind system, which is a key source of snowfall in the UKB (Syed et al., 2006; Dimri & Dash, 2012). Consequently, the decline in winter snow cover may be due not only to temperature-induced changes in precipitation but also to a possible weakening or changing of the Westerlies, which needs to be further investigated. Such changes could lead to a decrease in overall moisture inflow (Yadav et al., 2009).**

This shift is temperature-dependent and thus elevation-dependent, resulting in increased snowmelt, aligning with global warming trends (Wester et al., 2019). During the summer months (April to September), however, precipitation negatively correlates with snow cover, falling predominantly as rain, thus further enhancing snowmelt. Particularly, the period from July to September reveals a statistically significant decrease in snow cover (Sen's Slope = -2.87, $p<0.05$), primarily driven by warmer temperatures and higher rainfall during the summer monsoon, accelerating snowmelt.

Examining snow cover patterns in the UKB sub basins reveals notable seasonal and spatial differences. The Humla Karnali sub basin has the largest average snow cover during January–March, while downstream areas like Tila and Kawari **exhibit less snow cover.**

The interannual variability in snow cover highlights the sensitivity of snowpack to changing temperature and precipitation patterns. This variability significantly impacts water availability, as the observed reduction in snow cover could worsen water scarcity during the dry season, affecting millions who depend on snowmelt for irrigation, drinking water, **and hydropower generation** (Immerzeel et al., 2020; Pritchard, 2019). The strong negative correlation in Downstream Karnali ($r = -0.47$, $p < 0.05$) reinforces the declining trend in snow cover, which threatens water availability and ecosystem services in the region (Wester et al., 2019).

The outcomes emphasize the vulnerability of the UKB to climate change, with rising temperatures and shifting precipitation patterns leading to reduced snow cover. Adaptive water management strategies are essential to mitigate the impacts on water resources and local communities.

The findings on snow cover dynamics across elevation zones in the Upper Karnali Basin reveal significant elevation-dependent patterns, reflecting the influence of temperature fluctuations and global warming. At lower elevations (≤2000 m a.s.l.), snow cover exhibits a weak positive correlation (0.12–0.43), **likely caused by occasional snowfall during short cold spells and a shift between rain and snow (Pendergrass, 2020). These zones experience high year-to-year variability (CoV ~41–43%), making trends less reliable, which should be interpreted with caution. Similar elevation-sensitive variability has also been reported in other Himalayan basins** (Pepin et al., 2015).

The transition from weak negative correlations **(snow cover by elevation and year**) above 2300 m a.s.l. to the strongest negative correlation at 6100–6200 m a.s.l. (r = -0.56) corresponds with evidence of elevation-dependent warming (EDW), where higher altitudes experience accelerated warming, leading to reduced snow accumulation and increased melt rates. The sharp rise in mean snow cover above 5000 m a.s.l. coincides with permanent snow and glacier zones, but the decline in inter-annual variability (CoV) suggests a consistent reduction in snow cover, particularly at mid-to-high elevations (3000–5000 m a.s.l.).

The nonlinear relationship between elevation and inter-annual snow cover variability (CoV) proves particularly insightful. At 3000 m a.s.l. or below, the CoV reaches 41–43%, reflecting transitional zones where slight temperature fluctuations determine the precipitation phase (rain vs. snow). Above 3,000 m a.s.l., CoV drops to 25–30% as conditions remain persistently below freezing, but the dominant driver shifts to insolation and temperature-modulated melt rates. This aligns with Ren et al.'s (2023) findings on Tibetan Plateau glaciers, where albedo feedbacks dominate mass balance above 5000 m a.s.l.

The strong negative correlation between land surface temperature and snow cover (Tau = -0.43 to -0.79) highlights the impact of rising temperatures on snowpack. The most severe declines occur between 3000–5000 m a.s.l., where warming accelerates snowmelt and glacier retreat, threatening water availability for river flows, agriculture, and hydropower (**Immerzeel et al., 2020; Bolch et al., 2012).**

Between 2000 and 2023, glacier basins in the Upper Karnali Basin experienced significant ice and snow loss. The mean glacier area per basin declined from 119.04 to 100.47 hectares with an average loss of 18.6 hectares. While retreat was consistent across all aspects, north-facing basins (N, NW, NE) saw the largest total area decline. This trend, driven by rising

temperatures and reduced snowfall that create a negative mass balance (Pepin et al., 2022; Ren et al., 2024; Ye & Tian, 2022), threatens the persistence of glaciers and alters critical water resources.

Snow cover trends in glacier basins reveal a consistent decline across all seasons. **From January to March, a majority (59%) of the 735 basins analyzed exhibit a statistically significant negative correlation ($p < 0.05$), with 16.3% of all basins showing a strong decline ($r < -0.44$). The trend is even more pronounced in the post-monsoon and ablation seasons (October–December). From July to September, 62% of basins (n=70) show a significant negative correlation, and in October–December, this figure rises to 91% (n=604). This widespread reduction in snow cover is linked to rising temperatures, which increase snowmelt rates and reduce albedo, further** accelerating glacier retreat (Dowson et al., 2020). These trends underscore the vulnerability of the region's cryosphere to climate change, with serious implications for water security and regional hydrology.

The snowline in the Upper Karnali Basin is rising steadily, with rates of 5.6 m per year (10th percentile), 2.91 m per year (25th), and 1.54 m per year (50th). Although these are more conservative than many regional estimates, our findings align with the broader Himalayan trend of snowline elevation. Recent research reports faster increases, such as approximately 6.7–7.3 m per year in the Ganga–Brahmaputra basins (Dixit et al., 2024) and roughly 8–14 m per year in several Nepalese catchments (Sasaki et al., 2024), while the Langtang Basin shows a similar increase of about 2.2 m per year (Pradhananga et al., 2025). This suggests a consistent retreat of seasonal snow cover to higher elevations, which reduces the potential for snow accumulation to sustain glacier mass balance.

5.1. Feedback mechanisms and future projections

The correlation between temperature and snow cover (τ ranging from −0.43 to −0.79 across different elevations) confirms the presence of a reinforcing snow–albedo feedback in the Upper Karnali Basin (UKB). Increasing land surface temperatures reduces snow cover, lowering surface albedo and increasing shortwave radiation absorption. This process causes localized warming of about 0.8 to 1.2 °C, as estimated through Sen's slope analysis, further promoting melting and accelerating the feedback loop. Comparable snow–albedo feedback mechanisms have been observed across the central and eastern Himalayas (Kääb et al., 2015; Bolch et al., 2019; Bhattacharya et al., 2021; Salerno et al., 2021), underscoring the regional consistency of cryospheric amplification.

In addition to snow cover analysis, glacier change data (Ghimire, 2025) were integrated with long-term temperature and precipitation records to assess cryospheric variability. Relationships among temperature, snow cover, and glacier extent across elevation bands were quantified using Kendall's τ and Sen's slope, providing estimates of warming trends and snowline responsiveness. Future cryospheric conditions were simulated using a degree-day, elevation-band glacio-hydrological model forced with bias-corrected CMIP6 (NEX-GDDP) climate projections under the SSP1-2.6 and SSP2-4.5 scenarios, enabling projections of glacier and snow cover evolution through 2100 (Ghimire et al., 2025b)

Above 5,000 m a.s.l., Sen's slope analysis indicates a mean warming rate of +0.064 °C per year, comparable to the rates observed at mid-elevations (approximately +0.058 °C per year between 1,000 and 2,000 m). This elevation-dependent warming accelerates glacier thinning and shifts the snow–rain boundary upward, thereby reducing accumulation periods and causing earlier melt onset (Ghimire et. al., 2025). Similar warming trends, with

mean annual temperature increases of 0.05–0.07 °C per year and glacier thinning rates of 0.3–1.0 m per year since 2000, have been documented in the central Himalayas (Kääb et al., 2015; Bolch et al., 2019).

Under low-emission scenarios such as SSP1-2.6, high-altitude temperatures are projected to increase by approximately 1 °C by 2100. Under the moderate SSP2-4.5 scenario, temperature increases could reach 2 °C or more. Consequently, glacier areas are expected to decrease by 47–69%. Snow-covered areas are projected to decline by 19–30%. (Ghimire et al., 2025b). This would transform the basin's hydrology from nival (snowmelt-dominated) to pluvial (rain-dominated), increasing flood risks during monsoons and drought susceptibility in dry seasons.

These projections align with other studies of Himalayan basins, which forecast reductions in glacier area of 40–60% by mid-century (Bhattacharya et al., 2021; Salerno et al., 2021; Hock et al., 2019). Comparable amplification mechanisms are also evident in the Andes and Alps, where rapid glacier retreat and albedo-induced warming mirror trends observed in the Himalayas (Rabatel et al., 2013; Vuille et al., 2018; Dussaillant et al., 2019; Beniston & Stoffel, 2014; Zemp et al., 2019; Zekollari et al., 2019).

6.0. Conclusions

The study of snow and glacier cover dynamics in the Upper Karnali Basin from 2002 to 2024 reveals a persistent decline in snow cover, glacier area, and snowline elevation, driven by rising temperatures and altered precipitation patterns.

The annual snow-covered area (SCA) has decreased by approximately 3.99 km² per year, with the most significant reductions observed during the July-September monsoon period. The decline

in snow cover is statistically correlated with increasing temperatures, demonstrating the impact of climate change on seasonal snow accumulation and melt cycles. The winter snow cover variability suggests changes in snowfall patterns rather than a uniform decrease.

Notable seasonal and spatial differences in snow cover patterns are observed in the Sub basins of UKB for two seasons, January–March and October–December. The upstream sub basins experience less inconsistent snowfall than the downstream basins. During October–December, snowfall is inconsistent in all basins, but more inconsistent in particularly China Karnali, Tila and Downstream Karnali.

Elevation-dependent trend analysis confirms that snow cover at lower elevations (<2000 m a.s.l.) exhibits high interannual variability, while higher elevations (>3000 m a.s.l.) show a significant long-term decline. The strongest reductions occur between 3000–5000 m a.s.l., where warming accelerates snowmelt and glacier retreat. The observed negative correlation between snow cover and rising temperatures confirms the climate-driven reduction in snowpack, exacerbating the risk of water shortages.

The study of glacier basins shows widespread retreat, with the mean glacier area declining from 119.05 hectares in 2000 to 100.47 hectares in 2023. Glacier retreat is most pronounced in north-facing basins (N, NW, NE), where melting exceeds accumulation. The continuous decline in snow cover across glacier basins indicates an ongoing negative mass balance, threatening long-term glacier persistence.

Additionally, the snow line is gradually shifting upward, with the 10th, 25th, and 50th percentiles rising by approximately 5.16, 2.91, and 1.54 meters per year, respectively, indicating a consistent loss of seasonal snow accumulation.

Given the current warming trends (~0.0643°C/year above 5000 m a.s.l.), the UKB could experience a decline of glacier area by 47–69 % and snow-covered area by 19–30 %. This would transform the hydrology from snowmelt-dominated (nival) to rainfall-dominated (pluvial), increasing the frequency of extreme weather events and altering regional water security dynamics. The findings emphasize the need for proactive water resource management, improved climate resilience strategies, and continuous monitoring of cryospheric changes to mitigate future risks. Policymakers must prioritize adaptation measures, such as improved water storage infrastructure and sustainable land-use practices, to ensure long-term water security in the Upper Karnali Basin and beyond.

Author contributions

MG conceptualized the research, designed the methodology, conducted fieldwork, analyzed the data, and drafted the manuscript. DS. and RC assisted in proposal writing, research design, fieldwork, and data analysis. AT, TPPS, KPS, SBG, and SD contributed to procuring remote sensing and climate data. PB and SK were responsible for procuring and updating MODIS data. WY reviewed the manuscript and provided feedback to enhance its quality. NT and JK assisted in GIS analysis. All authors contributed to revising the manuscript and provided input before submission.

Competing Interests

The authors declare that they have no conflict of interest.

Data availability

MODIS, Landsat, Sentinel, ERA5 renalysis climate datasets, and NEX-GDDP data are publicly available.

Acknowledgments

We express our gratitude to the Director of Tribhuvan University's Research Coordination and Development Council (RCDC) for supporting the project titled "State and Dynamics of the Cryosphere of the Upper Karnali Basin, Associated Hazards and Implications for Water Resources and Livelihood" (Project Code TU-NPAR-077/78-ERG-15). This paper is a product of that project. We appreciate the Evaluation and Monitoring Committee of RCDC for their insightful feedback and suggestions, which greatly enhanced the manuscript. We also thank the University Grants Commission for providing research funding. Authors would also like to sincerely acknowledge the Sichuan Science and Technology Program (2024YFHZ0248) for partial support. We also acknowledge the contributions of Google Earth Engine, ERA5, ESRI, and other open-access resources for providing satellite imagery and data.

Financial support

This research was funded by the University Grants Commission (UGC), Kathmandu, through Tribhuvan University's Research Coordination and Development Council (RCDC) under the National Policy Area Research program. The Sichuan Science and Technology Program (2024YFHZ0248) also provided partial funding for this research.

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