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Decadal Decline in Snow Cover and Upward Shift of Snowline in the Western Himalaya: A Remote Sensing-Based Assessment of the Baspa Basin.

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Abstract

Mountain snowpacks are critical components of the cryosphere–hydrosphere system, particularly in the Himalaya where they regulate seasonal water availability. This study investigates the spatio-temporal variability of snow cover and snowline elevation in the Baspa Basin (Western Himalaya) using multi-temporal Landsat data from 1994 to 2023. Snow cover was delineated using a refined Normalized Difference Snow Index (NDSI) approach integrated with spectral masking techniques to minimize classification uncertainty. Results reveal a statistically significant decline in snow cover during peak ablation periods, from 23.84% (1994) to 17.42% (2023), corresponding to a net loss of ~54 km². Concurrently, the mean snowline has shifted upward by ~97 m (3.23 m yr^{-1}), indicating a systematic elevation-dependent response to climatic forcing. Seasonal analysis demonstrates altered accumulation–ablation regimes, including delayed ablation phases and reduced peak snow extent (~85% compared to >95% in earlier studies). Spatial heterogeneity highlights strong topographic controls, with elevation, aspect, and basin orientation modulating snow persistence. These findings suggest an emerging signal of climatic warming in the basin and underscore the vulnerability of Himalayan cryosphere systems to ongoing environmental change.

1. Introduction

Snow cover variability in high mountain environments serves as a sensitive indicator of climate change and directly influences downstream hydrology. In the Himalaya, seasonal snow contributes substantially to river discharge, particularly during pre-monsoon periods when water demand peaks. Consequently, even subtle shifts in snow cover extent or snowline altitude can have disproportionate impacts on water availability, hazard regimes, and ecosystem stability.

Despite its importance, long-term snow cover monitoring in the Himalaya remains constrained by limited in-situ observations. Remote sensing has emerged as a robust alternative, enabling consistent, synoptic, and repeatable measurements across inaccessible terrains. Among various techniques, the Normalized Difference Snow Index (NDSI) has been widely adopted due to its ability to exploit spectral contrasts between visible and shortwave infrared bands.

While several studies have documented glacier retreat in the Himalaya, fewer have focused on snow cover dynamics and snowline variability, particularly at basin scales. Moreover, the interplay between topographic controls and climatic forcing remains insufficiently explored. This study addresses these gaps by providing a comprehensive assessment of snow cover dynamics in the Baspa Basin over two decades.

2. Study Area

The Baspa Basin, located in the Kinnaur district of Himachal Pradesh, represents a high-altitude Himalayan catchment characterized by complex topography and pronounced climatic gradients. Elevation ranges from ~2000 m to over 6000 m above mean sea level, creating strong altitudinal zonation in snow accumulation and melt processes.

A clear west–east elevation gradient exists, with higher elevations and extensive glacierization in the eastern sector. This gradient plays a decisive role in controlling snow distribution, accumulation persistence, and melt dynamics. The basin is influenced by both western disturbances (winter snowfall) and Indian summer monsoon, resulting in a hybrid precipitation regime.

3. Data and Methodology

3.1 Data Sources and Pre-processing

This study utilizes multi-temporal satellite datasets from the Landsat series, including Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI sensors, spanning the period from 1994 to 2023. All datasets were acquired from the United States Geological Survey (USGS) Earth Explorer platform. To ensure consistency and minimize radiometric discrepancies across sensors, only surface reflectance products were employed. These datasets are pre-processed for atmospheric correction, geometric rectification, and sensor calibration, thereby enabling reliable multi-temporal comparison.

Cloud-free or minimal cloud-cover scenes were carefully selected to represent both seasonal variability (hydrological year 2022–2023) and long-term temporal changes (1994–2023). The spatial resolution of all Landsat datasets used in this study is 30 meters, which provides an optimal balance between spatial detail and temporal coverage for basin-scale snow mapping.

In addition to optical imagery, a Digital Elevation Model (DEM) derived from ASTER GDEM Version 2 (30 m resolution) was used to extract topographic parameters and to support snowline elevation analysis. The DEM was projected to the Universal Transverse Mercator (UTM) coordinate system (WGS 84 datum) to maintain spatial consistency with the Landsat data.

Although Landsat surface reflectance products are pre-corrected, all images were co-registered to a reference scene (Landsat 8 OLI) to ensure sub-pixel alignment, which is critical for accurate change detection. This step minimizes positional errors that could otherwise introduce bias in multi-temporal snow cover estimation.

3.2 Basin Delineation and Base Map Preparation

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The Baspa Basin boundary was delineated using hydrological analysis tools within a GIS environment. The ASTER DEM served as the primary input for watershed extraction. Initially, the DEM was processed to remove spurious depressions through sink-filling algorithms, ensuring a hydrologically consistent surface. Flow direction and flow accumulation grids were subsequently generated to identify drainage patterns within the basin.

A pour point was defined at the confluence of the Baspa River with the Sutlej River, and this point was used to delineate the watershed boundary. The resulting basin polygon was then used to clip all satellite-derived products, ensuring that subsequent analyses were restricted strictly to the study area.

3.3 Snow Cover Mapping Using Spectral Indices

Snow cover was mapped using the Normalized Difference Snow Index (NDSI), which exploits the high reflectance of snow in the visible (green) band and its strong absorption in the shortwave infrared (SWIR) region.

$$NDSI = \frac{\rho Green + \rho SWIR}{\rho Green - \rho SWIR}$$

A threshold value of NDSI ≥ 0.4 was applied to classify snow-covered pixels. While this threshold is widely accepted in snow mapping studies, its application in mountainous terrain often leads to misclassification due to spectral similarities with clouds, water bodies, and shaded surfaces. Therefore, a multi-criteria masking framework was implemented to enhance classification accuracy.

3.4 Spectral Masking and Error Minimization

To address spectral confusion and improve the reliability of snow detection, additional indices and thresholds were incorporated into the classification workflow.

Cloud cover, which exhibits high reflectance in both visible and infrared wavelengths, was discriminated using SWIR band thresholds. Pixels with reflectance values exceeding 0.225 in the SWIR band were identified as clouds and excluded from snow classification. This approach leverages the contrasting spectral behaviour of snow (low SWIR reflectance) and clouds (high SWIR reflectance).

Water bodies, which can exhibit spectral characteristics like snow in certain conditions, were masked using the Normalized Difference Water Index (NDWI). A threshold value greater than 0.1 was used to identify and exclude water pixels, thereby preventing overestimation of snow cover during melt periods.

Vegetation presents another challenge, particularly in areas where snow is partially obscured by forest canopy. To account for snow under vegetation, the Normalized Difference Vegetation Index (NDVI) was used to identify forested areas. In these regions, the NDSI threshold was relaxed from 0.4 to 0.1, allowing the detection of mixed pixels representing snow beneath vegetation.

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Topographic shadows, common in high-relief terrain, can lead to underestimation of snow cover. This issue was mitigated using surface reflectance products and the inherent robustness of NDSI, which remains effective in shadowed conditions due to its ratio-based formulation.

3.5 Snow Cover Area Estimation

Following classification, binary snow maps were generated for each observation date, distinguishing snow, and non-snow pixels. The total snow cover area was calculated by summing all snow-classified pixels and converting pixel counts into area units (km^2). To ensure comprehensive estimation, snow detected under forest canopy was included in the final snow cover calculation.

All snow cover maps were clipped to the Baspa Basin boundary, ensuring spatial consistency across temporal datasets. These maps formed the basis for both seasonal and long-term trend analysis.

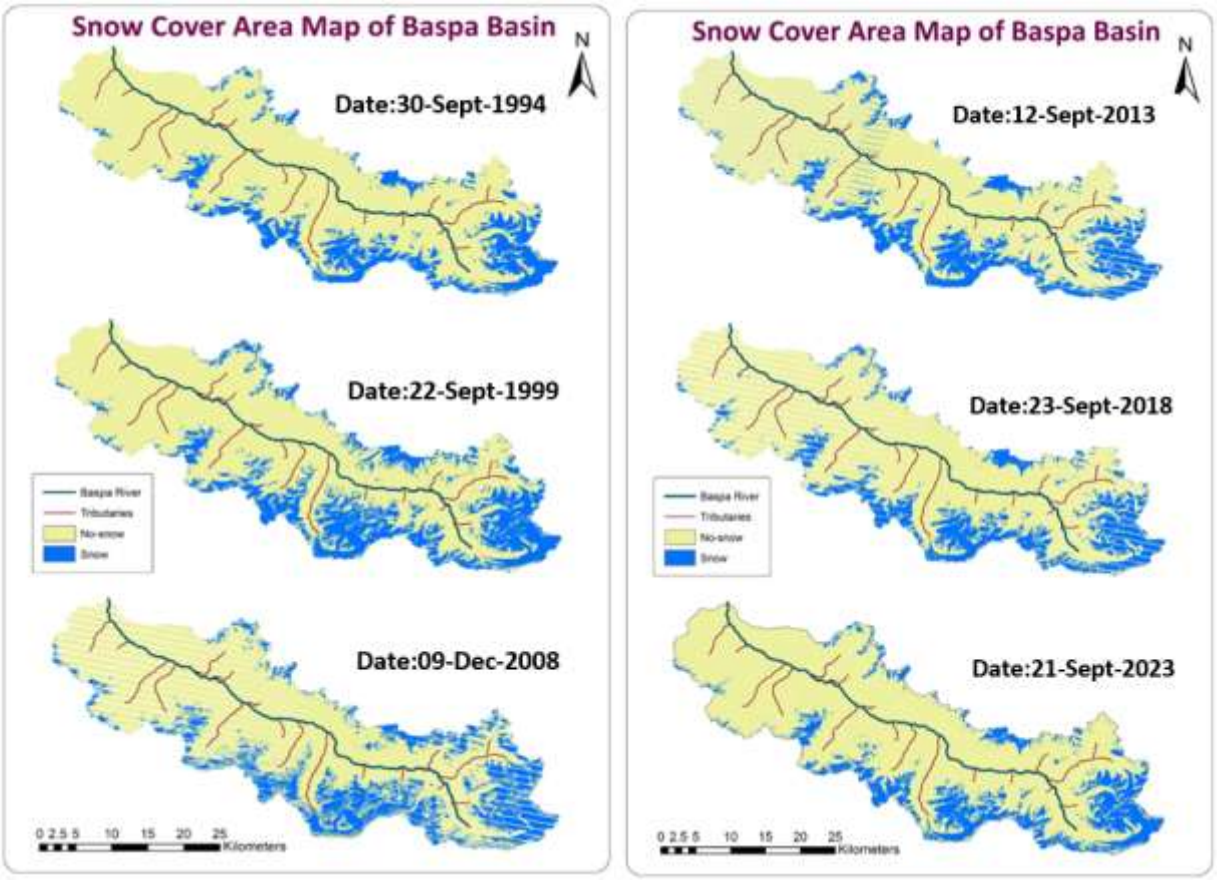

Figure: Temporal distribution of snow cover area from 1994 to 2023 in the Baspa Basin.

3.6 Snowline Extraction and Elevation Analysis

Snowline delineation was performed using the boundary between snow-covered and snow-free areas derived from binary classification. Contour extraction techniques were applied to identify the transition zone between these classes, effectively representing the snowline.

Given the inherent irregularity of snow distribution in mountainous terrain, multiple snowline segments were averaged to derive a representative snowline for each observation date. This approach reduces the influence of localized anomalies caused by topography or microclimatic conditions.

The extracted snowlines were subsequently integrated with the DEM to derive elevation attributes, including minimum, maximum, and mean snowline altitude. This integration enables a more comprehensive understanding of snowline dynamics by linking spatial patterns with elevation gradients.

3.7 Temporal and Seasonal Analysis Framework

The study adopts a dual analytical framework, incorporating both seasonal and temporal perspectives. Seasonal analysis focuses on the hydrological year (October–September) to capture accumulation and ablation cycles, while temporal analysis examines long-term trends during peak ablation periods across multiple years.

This combined approach allows for the identification of short-term variability as well as long-term trends, providing a more nuanced understanding of snow cover dynamics. Linear regression analysis was employed to quantify trends in snow cover extent and snowline elevation, enabling the assessment of statistical significance and rate of change over time.

4. Results and Discussion

4.1 Seasonal Snow Dynamics and Regime Characteristics

The seasonal evolution of snow cover in the Baspa Basin reveals a well-defined accumulation–ablation cycle, but with notable deviations from conventional Himalayan patterns. Snow accumulation begins during late autumn and intensifies through the winter months, reaching its maximum spatial extent in February, when approximately 85% of the basin is covered by snow. This peak, however, is lower than values reported in earlier studies, where snow cover often exceeded 95%, suggesting a possible reduction in winter accumulation or increased mid-winter melt events.

An equally important observation is the timing of minimum snow cover, which occurs in December (~11%), rather than at the end of the hydrological year (September–October), as commonly expected. This indicates a shift in the ablation regime, where significant snow depletion occurs earlier, followed by intermittent accumulation phases. Such behaviour points toward increasing variability in seasonal snowfall patterns, potentially influenced by changing temperature regimes and altered precipitation timing. The observed seasonal asymmetry suggests that snow processes in the basin are becoming less predictable, reflecting broader climatic instability in high mountain environments.

4.2 Decadal Trends in Snow Cover Extent

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The temporal analysis of snow cover during peak ablation periods from 1994 to 2023 indicates a consistent declining trend, reflecting long-term changes in the basin's cryospheric conditions. Snow cover extent decreased from 23.84% of the basin area in 1994 to 17.42% in 2023, corresponding to an absolute loss of approximately 54 km² over three decades. This decline, although gradual, is statistically robust, as indicated by a high coefficient of determination (R^2 = 0.845), suggesting that the observed trend is not a result of random interannual variability but represents a systematic change.

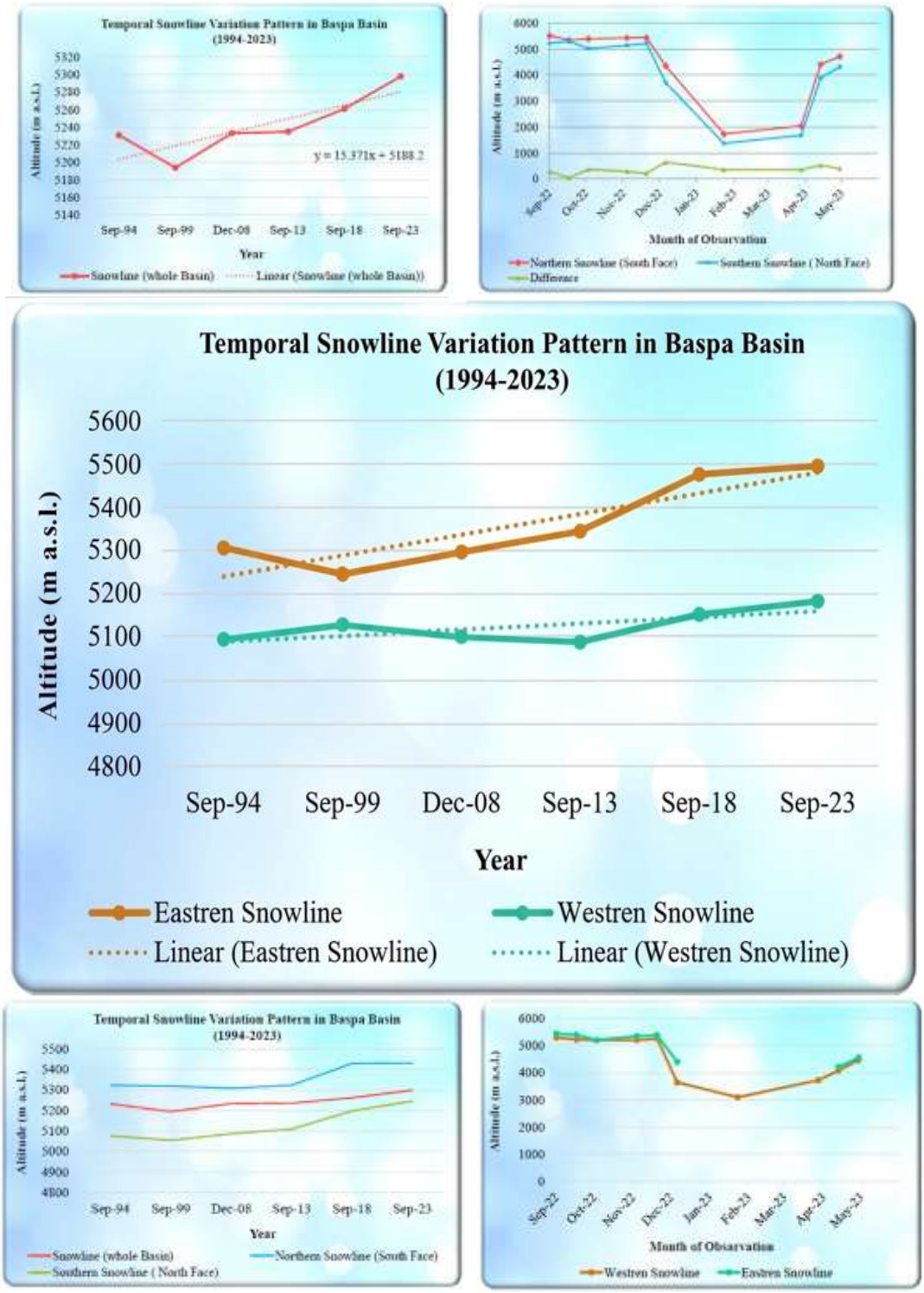

Figure: Snowline- seasonal and Temporal variation in Baspa basin.

Interestingly, the decline is not strictly linear, as short-term fluctuations are evident within the time series. For instance, the relatively higher snow cover observed in 1999 reflects a period of enhanced accumulation, likely associated with stronger monsoonal influence, or intensified western disturbances. However, beyond such episodic variations, the overall trajectory remains negative, pointing toward a long-term reduction in snow storage capacity within the basin. This reduction has significant implications for downstream hydrology, particularly in terms of reduced meltwater availability during critical pre-monsoon periods.

4.3 Snowline Dynamics and Elevation-Dependent Response

The analysis of snowline elevation provides further insight into the changing cryospheric conditions of the Baspa Basin. Over the study period, the average snowline altitude has shifted upward by approximately 97 meters, at a rate of 3.23 meters per year. This upward migration is closely linked to the observed reduction in snow cover extent, as diminished snow accumulation and enhanced melting lead to a contraction of snow-covered areas toward higher elevations.

The upward shift in snowline is a strong indicator of elevation-dependent warming, a phenomenon widely reported in mountainous regions where temperature increases are amplified at higher altitudes. The data reveal that years with relatively higher snow cover (e.g., 1999) correspond to lower snowline elevations, while years with reduced snow cover (e.g., 2023) exhibit elevated snowlines. This inverse relationship reinforces the sensitivity of snowline position to climatic variability and underscores its utility as a proxy indicator for environmental change.

Moreover, the increasing rate of snowline rise observed in recent years suggests an acceleration of warming impacts, which could have cascading effects on glacier health, runoff regimes, and slope stability in the basin.

4.4 Influence of Topography on Snow Distribution

The spatial distribution of snow cover in the Baspa Basin exhibits a strong dependence on topographic factors, particularly elevation, aspect, and basin orientation. A clear west-to-east gradient is observed, with snow cover increasing progressively toward the eastern part of the basin. This pattern closely corresponds with the elevation profile, as the eastern sector is characterized by higher altitudes and extensive glacierized terrain, which Favor snow accumulation and persistence.

Aspect plays a similarly important role in modulating snow dynamics. North-facing slopes, which receive relatively less solar radiation, tend to retain snow for longer durations and exhibit lower snowline elevations. In contrast, south-facing slopes experience higher insolation, leading to accelerated melting and consequently higher snowline positions. This differential behaviour highlights the influence of microclimatic conditions on snow retention and melt processes.

An interesting spatial anomaly is observed in the eastern region, where despite having greater snow cover, the snowline elevation remains relatively high. This suggests that while accumulation is significant in this region, melt processes are also more intense, possibly due to higher exposure or localized climatic conditions. Such patterns indicate a complex interplay between accumulation and ablation processes, governed by both regional climate and local topography.

4.5 Climatic Implications and Regional Context

The combined evidence from declining snow cover extent and rising snowline elevation points toward a broader climatic signal influencing the Baspa Basin. The reduction in snow cover suggests either a decrease in snowfall, an increase in temperature, or a shift in precipitation phase from snow to rain. Simultaneously, the upward migration of the snowline reflects enhanced melting conditions, consistent with warming trends reported across the Himalayan region.

The variability observed in certain years, such as the peak snow cover in 1999, indicates the continued influence of large-scale atmospheric systems, including the Indian summer monsoon and western disturbances. However, the dominance of a long-term declining trend suggests that these episodic events are increasingly overshadowed by persistent climatic changes.

Taken together, these findings highlight the sensitivity of Himalayan snow systems to climatic variability and reinforce the role of remote sensing as a powerful tool for detecting and quantifying such changes. The observed trends have important implications for water resource management, as reduced snow storage and earlier melt onset could alter the timing and magnitude of river discharge in downstream regions.

5. Conclusion

The present study provides a comprehensive assessment of snow cover dynamics and snowline variability in the Baspa Basin over a three-decade period using multi-temporal satellite observations. The results clearly indicate a persistent decline in snow cover extent during peak ablation periods, accompanied by a measurable upward shift in snowline elevation. These changes reflect a systematic alteration in the cryospheric regime of the basin, likely driven by evolving climatic conditions, including rising temperatures and potential shifts in precipitation patterns.

The seasonal analysis further reveals modifications in the accumulation–ablation cycle, particularly in the timing and magnitude of snow cover, suggesting increasing variability in snow processes. Such deviations from established seasonal norms highlight the sensitivity of high-altitude snow systems to even subtle climatic fluctuations. Additionally, the strong influence of topographic factors—such as elevation, aspect, and basin orientation—emphasizes that snow distribution in mountainous regions is governed by a complex interaction between local geomorphology and broader atmospheric processes.

The observed decline in snow cover and concurrent rise in snowline elevation have important implications for regional hydrology, particularly in terms of reduced snow storage and altered meltwater regimes. These changes may affect the timing and availability of water resources downstream, especially during critical pre-monsoon periods. Furthermore, the shifting snowline may contribute to increased exposure of slopes, potentially enhancing the susceptibility of the region to geohazards such as landslides and debris flows.

Overall, the study demonstrates that satellite-based remote sensing, when integrated with GIS and elevation data, provides a robust framework for monitoring and analysing snow dynamics in data-scarce mountainous environments. The findings contribute to a growing body of evidence indicating that Himalayan cryospheric systems are undergoing measurable changes, underscoring the need for continuous monitoring and adaptive management strategies in the face of ongoing climate change.

6. Novel Contributions

This study makes several important contributions to the understanding of snow dynamics in the Himalayan region by combining methodological rigor with long-term spatio-temporal analysis. A key contribution lies in the development and application of an integrated multi-index framework for snow mapping, which incorporates NDSI along with NDVI- and NDWI-based masking techniques to address common sources of spectral confusion such as clouds, water bodies, and vegetation. This approach enhances the accuracy and reliability of snow cover estimation in complex mountainous terrain, where conventional single-index methods often fall short.

Another significant contribution is the coupling of snow cover mapping with digital elevation data to derive snowline characteristics, enabling a detailed analysis of elevation-dependent snow dynamics. By distinguishing between spatially irregular “actual snowlines” and their averaged representations, the study improves the interpretability of snowline behaviour and its relationship with climatic variability. The quantification of long-term snowline shifts provides valuable evidence of elevation-dependent responses to environmental change, a topic of growing importance in mountain climatology.

The study also contributes empirically by documenting a consistent decline in snow cover and a corresponding upward migration of the snowline over a 30-year period in the Baspa Basin. This dataset adds to the limited pool of basin-scale cryospheric studies in the western Himalaya and provides a useful reference for comparative regional assessments. Furthermore, the identification of strong topographic controls on snow distribution, including aspect-driven differences and west–east asymmetry, offers new insights into the interaction between terrain and climate in shaping snow dynamics.

Taken together, these contributions advance both the methodological and empirical understanding of snow cover processes in high mountain environments and provide a scalable framework that can be applied to other Himalayan basins for climate impact assessment and water resource planning.

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