Snow Persistence Dynamics in the Indian North Western Himalaya (2000– 2024): A MODIS-Based Trend Analysis

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Abstract

Snow persistence is a key indicator of cryospheric variability and strongly influences hydrological processes and water availability in mountainous regions. This study examines the spatio-temporal dynamics and long-term trends of snow persistence across the North-Western Himalaya (NWH), including Ladakh, Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, during 2000–2024 using MODIS-derived snow cover products (MOD10A1F and MYD10A1F). Annual snow persistence was estimated by aggregating daily cloud gap-filled snow cover data, while elevation-dependent variability was analyzed using SRTM DEM data. Temporal trends and their statistical significance were assessed using the non-parametric Mann–Kendall test. Results reveal a strong altitudinal influence on snow persistence. High-elevation regions (>4500 m) exhibit near-perennial snow cover exceeding 150 days annually, whereas mid- and low-elevation zones show lower persistence and greater spatial fragmentation. Approximately 29% of the NWH displays statistically significant trends, predominantly negative, indicating a widespread decline in snow persistence at an average rate of ~3.2 days per year. Regionally, Ladakh shows the highest proportion of declining trends, followed by Uttarakhand, Himachal Pradesh, and Jammu & Kashmir. Spatio-temporal analysis of Snow-Covered Area (SCA) indicates a consistent seasonal cycle but also highlights earlier snowmelt, reduced snow retention duration, and increased intra-seasonal variability in recent years. The findings emphasize the vulnerability of mid-elevation zones (2000–4000 m) to climate variability and their implications for downstream water resources and climate adaptation planning

1. Introduction

Seasonal snow cover is an important component of the cryosphere and plays a major role in regulating the Earth’s energy balance, hydrological processes, and regional climate systems. Changes in snow cover extent, duration, and persistence directly affect surface albedo, land–atmosphere interactions, and freshwater availability, especially in mountainous regions (Tsai et al., 2019; Desinayak et al., 2022). Because snow cover is highly sensitive to variations in temperature and precipitation, it is widely considered a key indicator of climate variability and climate change.

The Himalayan region, particularly the Northwestern Himalaya (NWH), acts as a crucial freshwater reservoir for major river systems such as the Indus and Ganga, supporting millions of people living downstream. Snowmelt contributes significantly to river discharge during dry seasons, making snow cover dynamics essential for water resource management and hydrological planning in the region (Naegeli et al., 2022). However, snow distribution in the Himalaya shows strong spatial and temporal variability due to the influence of complex topography, elevation differences, and climatic factors such as western disturbances.

Recent studies have highlighted noticeable changes in snow cover dynamics across the Hindu Kush Himalayan region under the influence of global warming. Long-term observations indicate considerable variability and declining trends in snow cover and snow persistence (Desinayak et al., 2022; Muhammad, 2025). Increasing temperatures and shifting precipitation patterns are altering snow accumulation and melting processes, which in turn impact seasonal snow persistence and regional hydrological regimes. Variations in snow persistence also influence ecological systems by affecting habitat conditions, species distribution, and winter ecosystem functioning (Keyser et al., 2023).

At local and regional scales, snow distribution and melt processes are strongly controlled by terrain and surface characteristics such as slope, aspect, canopy cover, and incoming solar radiation (Koutantou et al., 2023). In recent decades, advances in remote sensing technologies have greatly improved the monitoring of snow dynamics over large and inaccessible mountainous regions. Optical sensors such as MODIS provide long-term and high temporal resolution datasets for studying snow cover variability, while microwave sensors offer the advantage of monitoring under cloud-covered and low-light conditions (Tsai et al., 2019; Singh et al., 2024). In addition, SAR-based techniques have shown strong potential for mapping snow properties and snowmelt dynamics in rugged mountain terrains (Thakur et al., 2018; Li et al., 2025).

Although several studies have investigated snow cover variability across the broader Hindu Kush Himalayan region, comparatively less attention has been given to long-term snow persistence dynamics in the Northwestern Himalaya. Most previous studies mainly focused on snow cover extent and seasonal variability, with limited emphasis on persistence patterns and their long-term changes. Therefore, the present study aims to analyze annual snow persistence dynamics in the Northwestern Himalaya during the period 2000–2024 using MODIS-derived snow cover data. The study focuses on assessing spatial variability, identifying temporal trends, and examining changes in snow persistence patterns over time. Time-series analysis, including the non-parametric Mann–Kendall trend test, is used to evaluate the presence and significance of trends in snow persistence. The results indicate a significant decreasing trend in snow persistence across regions such as Uttarakhand, Himachal Pradesh, Ladakh, and Jammu & Kashmir. These findings provide important insights into ongoing cryospheric changes and can support improved hydrological planning and environmental management in this climatically sensitive region.

2. Study Area and Data

The present study focuses on the Indian Northwestern Himalaya (NWH), encompassing parts of Jammu & Kashmir, Himachal Pradesh, Ladakh and Uttarakhand, a climatically and topographically complex region characterized by rugged terrain and pronounced elevation gradients ranging from below 1,000 m to above 8,000 m (Figure 1). Elevation plays a dominant role in controlling temperature lapse rates, precipitation phase, and snow accumulation–ablation processes, while terrain attributes such as slope and aspect further regulate solar radiation and snowmelt dynamics (Desinayak et al., 2022; Li et al., 2025). The region is strongly influenced by western disturbances, which contribute significantly to winter snowfall, making it a critical component of the Himalayan cryosphere and a major freshwater source for downstream river basins such as the Indus and Ganga (Muhammad, 2025). In addition to its hydrological importance, the NWH represents an ecologically sensitive zone with diverse forested and alpine ecosystems, where snow persistence plays a key role in regulating seasonal water availability and ecosystem functioning. The analysis utilizes daily snow cover products from MODIS Terra (MOD10A1F) and Aqua (MYD10A1F) datasets spanning 2000–2024, employing the cloud gap-filled layer to derive annual snow persistence at 500 m spatial resolution. The use of gap-filled products reduces cloud-induced data gaps and enhances the reliability of long-term snow cover monitoring in mountainous regions characterized by frequent cloud cover (Singh et al., 2024). Additionally, the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) at 30 m spatial resolution was incorporated to support elevation- dependent analysis, as topographic controls are fundamental in determining spatial variability and persistence of snow cover in complex Himalayan terrains (Thakur et al., 2018).

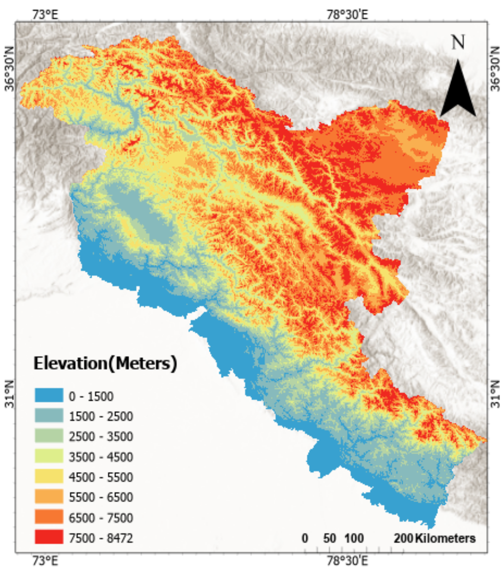

Figure 1. Elevation map of the study area in the North-Western Himalaya (NWH)

3. Methodology

3.1 Snow Persistence Estimation

The methodology adopted in this study involves the generation of annual snow persistence maps from MODIS-derived daily snow cover products. Daily MODIS Terra (MOD10A1F) and Aqua (MYD10A1F) snow cover datasets for the period 2000–2024 were processed to ensure spatial and temporal consistency. Initially, four MODIS tiles covering the study area were mosaicked for each day to generate seamless daily snow cover maps. These mosaicked datasets were subsequently clipped to the study area boundary to restrict the analysis to the Indian Northwestern Himalaya (NWH). The cloud gap-filled Snow_Cover layer was then reclassified to identify snow-covered pixels, where pixel values ranging from 50 to 100 were considered as snow-covered, while remaining values were treated as non-snow. Following reclassification, a temporal aggregation approach was applied by summing the number of snow-covered days for each pixel over a hydrological year, resulting in annual snow persistence maps with values ranging from 0 to 365/366 days (Figure 2). The processed outputs were stored in GeoTIFF format for further spatial analysis and visualization.

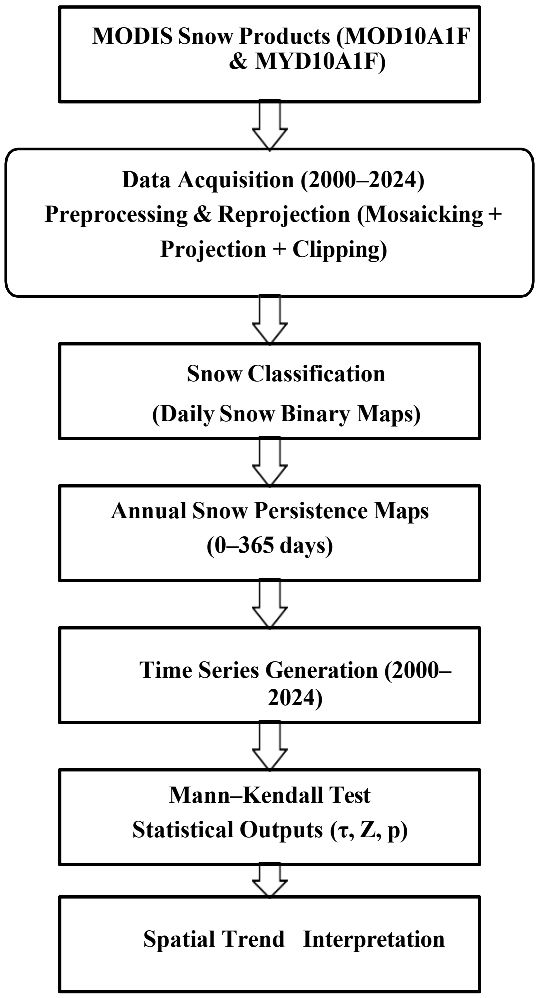

Figure 2. Flowchart of Methodology

3.2 Trend Analysis

To assess long-term temporal variations in snow persistence, a non-parametric Mann–Kendall (MK) test was applied on a pixel-wise basis to the annual snow persistence time series. The MK test is widely used in hydro-climatic studies due to its robustness against non-normal data distributions and missing values. The statistical parameters derived from the MK test include Kendall's Tau (τ), which indicates the strength and direction of the trend, the Z-statistic for determining trend direction, and the associated p-value to evaluate statistical significance at a 95% confidence level. Positive values of τ indicate an increasing trend, while negative values represent a decreasing trend in snow persistence.

All analyses were performed using Python-based libraries, including *pymannkendall*, *numpy*, and *rasterio*, while spatial visualization and mapping were carried out using QGIS and Python visualization tools. This approach enables the identification of spatially explicit trends in snow persistence across the study region.

4. Results and Discussion

4.1 Spatio-Temporal Analysis of Snow- Covered Area (SCA)

The Snow-Covered Area (SCA) across Ladakh, Jammu & Kashmir, and Uttarakhand shows a clear seasonal pattern that reflects the combined influence of climate and topography on snow accumulation and melting processes in the Himalayan region. In general, snow cover reaches its maximum extent during the winter months (January–March), followed by rapid melting during spring and early summer (April–June). The lowest snow cover is observed during the monsoon season (July–September), after which snow gradually begins to recover during autumn and early winter (October–December). This seasonal cycle is mainly controlled by winter precipitation associated with Western Disturbances, along with temperature-driven snowmelt and elevation-dependent climatic conditions. Among the three regions, Ladakh consistently records the highest Snow-Covered Area, with winter peak values reaching nearly 120,000 km². The region also exhibits relatively longer snow retention due to its high-altitude cold desert environment, low temperatures, and extensive mountainous terrain. Snow cover remains persistent over large areas for extended periods compared to the other Himalayan regions. However, observations for 2025 reveal a steeper decline in SCA during the melt season compared to the long-term average (2000–2025), indicating accelerated snowmelt and increased snow ablation in recent years. This trend suggests that the cryosphere in Ladakh may be becoming increasingly sensitive to rising temperatures and changing climatic conditions.

Jammu & Kashmir shows moderate snow cover, generally ranging between 25,000 and 30,000 km² during peak winter conditions. The 2025 seasonal pattern remains broadly similar to the long-term climatological average during winter, indicating relatively stable snow accumulation. However, the region experiences noticeable short-term fluctuations during late summer and autumn, which are likely linked to episodic snowfall events and localized weather variability. The complex terrain and varying climatic conditions across the region contribute to strong spatial and temporal differences in snow cover distribution.

In comparison, Uttarakhand records the lowest Snow-Covered Area among the three regions, with peak winter snow cover generally limited to around 14,000–15,000 km² (Figure 3). Snow cover in Uttarakhand also shows the fastest depletion during the melt season and frequently remains below the long-term average. This behavior indicates a greater sensitivity to temperature changes, elevation effects, and ongoing climatic variations. In this region, snow is mainly restricted to high-altitude ridges and glacierized areas, while lower and mid-elevation zones experience rapid snowmelt and limited snow retention.

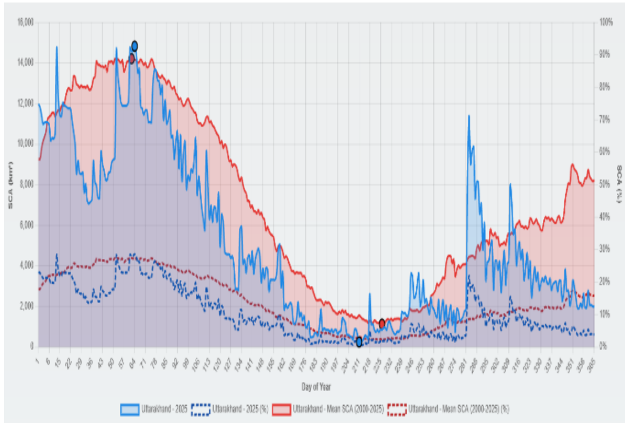

Figure 3. Seasonal variation of Snow-Covered Area (SCA) and Snow Cover Area percentage in Uttarakhand, showing the comparison between 2025 observations and the long-term mean (2000–2025).

A comparison between the 2025 observations and the long-term mean indicates that although winter snow accumulation remains close to normal conditions, snowmelt is beginning earlier and progressing more rapidly across all regions. In addition, snow recovery during autumn appears more irregular and spatially inconsistent. During winter, snow cover reaches nearly 80–95% of its seasonal maximum, but declines sharply afterward, suggesting reduced snow persistence and shorter snow retention periods. Abrupt increases in SCA during the middle and later parts of the year, particularly in Jammu & Kashmir and Uttarakhand (Figure 3), further indicate enhanced intra-seasonal variability and the occurrence of temporary snowfall events outside the primary winter season. These irregular fluctuations point toward increasing climatic variability and instability in snowfall patterns across the Himalayan region. Overall, the observed changes suggest a transition toward earlier snowmelt, faster snow depletion, reduced snow retention, and greater temporal variability in snow cover dynamics. Such changes may significantly affect regional hydrology, glacier-fed river systems, seasonal water availability, hydropower production, agriculture, and downstream water resource management. The increasing variability and declining persistence of snow cover also highlight the growing vulnerability of the Himalayan cryosphere to ongoing climate change.

4.2 Spatio-Temporal Snow Persistence Patterns

The results show that mean snow persistence across the Indian North-Western Himalayas (NWH), including Ladakh, Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, follows a clear spatial and elevation-dependent pattern. Snow persistence is strongly influenced by elevation and regional topographic conditions, with higher-altitude regions generally experiencing longer snow retention compared to lower elevations.

The spatial distribution maps indicate that regions located above 4500 m altitude experience the highest snow persistence, often exceeding 150 days per year. These high-altitude zones form extensive and relatively continuous snow-covered areas, particularly across Ladakh and the northern mountainous parts of Jammu & Kashmir and Himachal Pradesh. The longer persistence of snow in these regions is mainly associated with lower temperatures, reduced melting, and prolonged winter snow accumulation. In Ladakh, the cold desert climate, combined with extremely high elevations and low atmospheric temperatures, results in highly stable and near-perennial snow persistence across several areas. In comparison, mid-elevation regions between 2000 and 4000 m show moderate snow persistence, generally ranging from 100 to 150 days annually. These zones are widely distributed across Himachal Pradesh and Uttarakhand and display more fragmented and discontinuous snow cover patterns. Snow persistence in these elevation ranges is strongly controlled by local terrain characteristics such as slope, aspect, terrain orientation, and exposure to solar radiation. South-facing slopes tend to experience faster snowmelt and lower persistence due to higher solar exposure, whereas north-facing slopes retain snow for longer durations. The fragmented snow distribution in these regions also reflects their greater sensitivity to climatic variability and changing temperature conditions.

Lower elevation areas below 2000 m, especially the foothills and valley regions of Uttarakhand and parts of Jammu & Kashmir, exhibit very low snow persistence, generally remaining below 50 days per year. Snow cover in these areas is highly seasonal and short-lived, occurring mainly during winter and melting rapidly with the onset of spring. Instead of continuous snow cover, these regions mostly contain isolated and scattered snow patches, indicating limited snow retention capacity. The state- and UT-wise analysis further highlights noticeable regional differences in snow persistence patterns. Ladakh shows the most extensive and stable high-persistence snow zones because of its high-altitude terrain and cold climatic conditions. Jammu & Kashmir exhibits a mixed pattern, with higher snow persistence concentrated in the northeastern mountainous regions and relatively lower persistence in the southwestern areas. Himachal Pradesh demonstrates considerable spatial variability, with a strong transition from persistent snow cover at higher elevations to fragmented snow zones at lower altitudes. Uttarakhand records the lowest overall snow persistence among the four regions, where snow cover is mainly restricted to high-altitude ridges and glacierized areas(Figure 4).

Overall, the results clearly demonstrate that snow persistence decreases systematically with decreasing elevation and becomes increasingly fragmented toward lower altitudes. The observed spatial patterns emphasize the dominant role of elevation, slope, aspect, and regional topography in controlling snow accumulation, retention, and melting processes across the North-Western Himalayas. The results show that mean snow persistence across the Indian North-Western Himalayas (NWH), including Ladakh, Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, follows a clear spatial and elevation-dependent pattern. Snow persistence is strongly influenced by elevation and regional topographic conditions, with higher-altitude regions generally experiencing longer snow retention compared to lower elevations. spatial patterns emphasize the dominant role of elevation, slope, aspect, and regional topography in controlling snow accumulation, retention, and melting processes across the North-Western Himalayas.

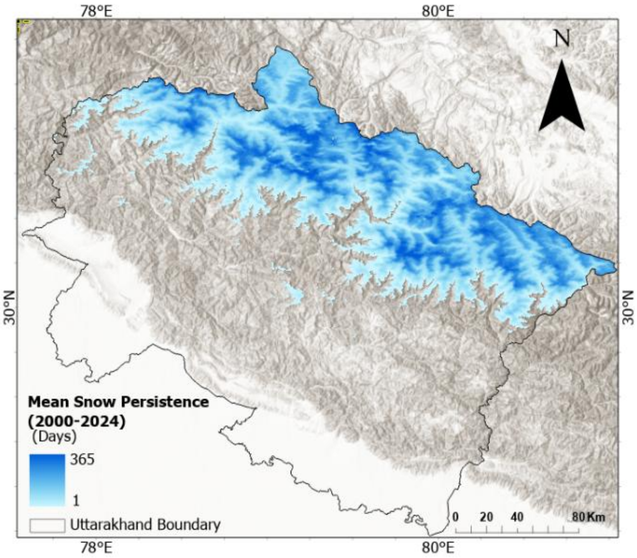

Figure 4. Spatio-Temporal Snow Persistence Maps of Uttarakhand

4.2 Mann-Kendall Trend Test and Statistical Analysis

The Mann–Kendall trend test is a commonly used non-parametric statistical method for identifying monotonic trends in time-series data without requiring the dataset to follow a normal distribution. The method works by comparing each observation in the time series with all subsequent observations and determining whether the later values are higher or lower than the earlier ones. These pairwise comparisons are then summed to calculate the test statistic (S), which is further standardized to obtain Kendall's Tau (τ), a normalized coefficient ranging from −1 to +1. Positive τ values indicate increasing trends, whereas negative values represent decreasing trends. The statistical significance of the detected trend is evaluated using the p-value, with $p < 0.05$ generally considered statistically significant. Due to its robustness against outliers and missing values, the Mann–Kendall test is widely applied in hydro-climatic studies, including the analysis of snow persistence.

The application of the Mann–Kendall test to snow persistence across the North-Western Himalayas (NWH), including Ladakh, Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, reveals that nearly 29% of the study area shows statistically significant trends ($p < 0.05$). The calculated Kendall's Tau (τ) values range from −0.42 to 0.18, with most of the significant values being negative, indicating an overall decline in snow persistence across the region. The average annual rate of change is estimated to be around −3.2 days per year, suggesting a gradual but continuous reduction in snow cover duration over time. Spatially, the strongest negative trends ($\tau < -0.3$) are mainly concentrated along the Pir Panjal and Garhwal mountain ranges, indicating that these regions are particularly vulnerable to changing climatic conditions and are experiencing accelerated reductions in snow persistence.

The analysis of long-term mean conditions further shows that the average snow persistence across the NWH during the 25-year study period is approximately 180 days per year.

However, this average conceals substantial spatial variability, with a standard deviation of about 28.4 days. The highest variability, exceeding 40 days, is mainly observed within the mid-elevation range of 2000–4000 m, particularly across Himachal Pradesh and Uttarakhand. These mid-altitude regions represent transitional climatic zones where snow cover is highly sensitive to even small variations in temperature and precipitation, resulting in large year-to-year fluctuations in snow persistence.
In contrast, high-altitude regions, especially in Ladakh and northern Jammu & Kashmir, exhibit relatively stable and consistently high snow persistence due to colder climatic conditions and prolonged snow retention. Lower elevation regions, on the other hand, show minimal and rapidly declining snow cover. Overall, the results demonstrate a clear elevation-dependent pattern in both the magnitude and variability of snow persistence. The Mann–Kendall analysis further confirms that declining trends are most pronounced in climatically sensitive mid-altitude zones. The combination of decreasing snow persistence and increasing variability in these regions may have important implications for regional hydrology, as these areas play a crucial role in controlling seasonal snowmelt and sustaining downstream water availability.

5. Conclusion

The analysis of snow persistence across the North- Western Himalayas (NWH) reveals a pronounced elevation-dependent pattern and significant declining trends over the 25-year study period. Overall, approximately 29% of the study area exhibits statistically significant trends, with most showing negative values, indicating a widespread reduction in snow persistence. State- and union territory-wise, the proportion of area experiencing negative trends varies considerably: Ladakh shows the highest decline with 34.5%, Uttarakhand has 23.5%, Himachal Pradesh has 17.6%, and Jammu & Kashmir the lowest with 15.6%. (Figure 5) High-elevation zones (>4500 m), particularly in Ladakh and the northern mountainous belts of Jammu & Kashmir and Himachal Pradesh, maintain relatively stable and near-perennial snow cover. In contrast, mid- to low-elevation regions (2000–4000 m and <2000 m), especially in Himachal Pradesh, Uttarakhand, and southern Jammu & Kashmir, show moderate to low persistence and are experiencing the most pronounced declines. These patterns underscore the strong altitudinal sensitivity of snow cover to climate variability, with transitional mid-elevation zones being particularly vulnerable. In addition, the spatio-temporal analysis of Snow- Covered Area (SCA) indicates a consistent seasonal regime characterized by peak snow extent during winter and rapid depletion during spring, but with a noticeable shift toward earlier snowmelt, reduced snow retention duration, and increased intra-seasonal variability in recent years. While winter snow cover remains close to the long-term average, accelerated ablation during the melt season and irregular recovery during autumn suggest evolving snow dynamics across the region. Uttarakhand demonstrates higher sensitivity to warming with faster snow depletion, whereas Ladakh retains relatively greater persistence despite showing signs of accelerated melt.

The decreasing snow persistence, coupled with increasing variability and earlier melt onset, has important implications for regional hydrology, including altered timing of snowmelt, reduced water availability during critical periods, and potential impacts on downstream ecosystems and water resource management. Overall, the study highlights an ongoing shift in snow dynamics across the NWH, with higher-elevation areas remaining relatively stable while lower and mid-elevation zones show significant. declines in snow persistence, reflecting the growing influence of climate variability on the Himalayan cryosphere.

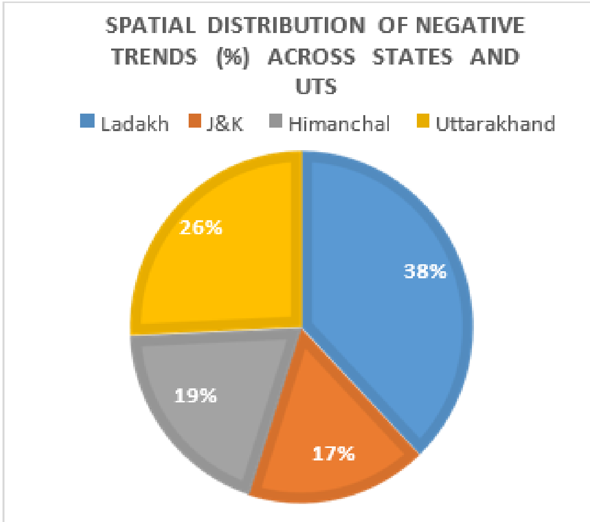

Figure 5. Percentage of area showing negative snow persistence trends (2000–2024) across Ladakh, Jammu & Kashmir, Himachal Pradesh, and Uttarakhand derived using the Mann–Kendall test.

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