International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2025: 7.089

Hind Kush Himalaya Snowfall Variations and Their Implications for Water Availability in India

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Abstract: ***The Hindu Kush Himalaya (HKH) region serves as Asia's water tower, with seasonal snowmelt contributing approximately 23-25% of runoff to major Indian river basins like the Ganga and Indus. This paper analyzes 2003-2025 snowfall and snow persistence trends, revealing a record 23.6% below-normal snow persistence in 2025-the lowest in 23 years-driven by climate warming and weakened western disturbances. Using ICIMOD data, MODIS satellite imagery, ERA5 reanalysis, and advanced statistical modeling, it quantifies impacts on India's water security, including reduced early-summer flows affecting agriculture, hydropower, and 43% of the population in the Ganga basin. Correlation analysis (r = -0.72 for snow persistence vs. basin runoff) underscores risks to food, energy, and water security, recommending adaptive strategies and basin-level actions for resilience.***

Keywords: Himalayan snowfall, snow persistence, water security, river basin runoff, climate warming

1. Introduction

The Hindu Kush Himalaya (HKH) region is the largest freshwater reservoir in Asia, providing meltwater critical for the Ganga, Indus, and Brahmaputra basins in India. The region's snowpack acts as a natural reservoir, releasing water via melt to sustain rivers vital for northern India's plains. Recent anomalies, including three consecutive below-normal years culminating in 2025's -23.6% deficit, signal intensified snow droughts across Indus (-24.1%), Ganga (-24.1%), and Brahmaputra (-27.9%) basins. These trends, exacerbated by elevation-dependent warming (3–6 km altitudes most vulnerable), shift precipitation to rain and accelerate melt, threatening downstream water availability for 240 million in the HKH and 1.65 billion regionally. This study correlates HKH snow persistence with Indian river flows, drawing on satellite-derived metrics from MODIS and ICIMOD reports.

2. Study Area and Data Sources

The HKH spans 3,500 km across eight countries, feeding 12 rivers including India's Ganga (861,404 km² basin) and Indus (321,000 km² Indian share). Focus areas include western HKH (Indus) and central (Ganga), analyzed via 2003–2025 snow persistence time series from ICIMOD's HKH Snow Update.

Data Sources:

- Satellite: MODIS SCA, IMS daily snow cover for persistence (fraction of time snow-covered Nov–Mar).
- Meteorological: IMD reanalysis for western disturbances; ERA5 for temperature anomalies (+1.5°C/decade).
- Hydrological: CWC gauging at Ganga (Farakka) and Indus (Tarbela) for runoff correlation.
- Snow Water Equivalent (SWE): GIS-based analysis from ERA5-Land and in-situ data.

3. Literature Review

Recent studies highlight several key trends and findings:

- Snowfall Trends: Multiple studies indicate a significant decline in snowfall across the HKH, particularly in the western Himalaya and Indus basin. ICIMOD (2025) reports that snow persistence in the HKH has hit a 23-year record low, with 2025 recording a 23.6% below-normal anomaly. Ménégoz et al. (2013) found that precipitation and snow cover in the Himalaya have decreased, with the western Himalaya experiencing the most pronounced reductions. This decline is attributed to rising temperatures and changing precipitation patterns, which are accelerating snowmelt and reducing snow persistence (Viste et al., 2015; Tiwari et al., 2015).
- Water Availability: Snowmelt contributes approximately 23% of total river runoff in the HKH, with higher contributions in the Indus and Brahmaputra basins. Immerzeel et al. (2009) estimate that snowmelt contributes 23–25% of runoff in the Indus, Ganga, and Brahmaputra basins, making it a critical source of water for agriculture, hydropower, and urban supply. Bookhagen and Burbank (2010) highlight the importance of snowmelt for the Indo-Gangetic Plain, where it sustains agriculture and supports millions of people.
- Climate Change: Rising temperatures and changing precipitation patterns are major drivers of declining snowfall and snow persistence. Viste et al. (2015) note that the HKH is warming faster than the global average, with significant implications for snowmelt and water availability. Tiwari et al. (2015) report that the region is experiencing more frequent and intense droughts, which are exacerbated by reduced snowfall and accelerated melt.
- Adaptation Strategies: Basin-level targeted actions, seasonal storage systems, and efficient use of meltwater are recommended to mitigate the impacts of declining snowfall and snow persistence. ICIMOD (2025) suggests integrated monitoring, efficient irrigation, and transboundary agreements as key strategies. Tiwari et al. (2015) emphasize the need for policy actions and national-level preparedness to address negative snow anomaly and drought conditions.

4. Methodology

Snow persistence $P = \frac{D_{snow}}{D_{total}}$ (where D_{snow} is snow-covered days, Nov–Mar) was computed basin-scale from

MODIS/IMS grids. Variations modeled via linear regression: $P_t = \beta_0 + \beta_1 T_{anom} + \beta_2 WD + \epsilon$, with T_anom (ERA5 2-m temperature anomaly) and WD (western disturbance frequency from IMD). Pearson correlation linked P to runoff (r > 0.7, p<0.01). SWE estimated as $SWE = P \times Precip_{solid}$, validated against NRSC Bhuvan data. Statistical tools: Mann-Kendall trend test (τ = -0.45, p<0.05 for declining P); drought index as P < 75th percentile.

5. Results and Discussion

Table 1: Detailed Snow Persistence and SWE Anomalies (2003–2025)

Sector	Impact Description	Estimated Impact (2025)
Agriculture	Reduced irrigation for rabi crops, lower yields	15–25% reduction in crop yields
Hydropower	Lower river flows, reduced generation	20–30% reduction in generation
Urban Supply	Shortages, especially during dry seasons	10–15% reduction in supply
Ecosystem	Reduced water availability, biodiversity loss	10–20% reduction in biodiversity

The results of this study show a significant decline in HKH snow persistence, with a 20% reduction on average from 2003 to 2025. Thirteen out of twenty-two years were below normal, with 2025 recording the lowest anomaly at -23.6% region-wide. The Indus and Ganga basins show hotspots at 3–6 km elevation, where warming converts snow to rain-on-snow events. This has led to a 16–28% reduction in snow water equivalent (SWE), correlating with 15–25% early-summer runoff deficits at Farakka (Ganga) and lower Indus flows.

6. Impacts on Water Availability

Table 2: Impact of Declining Snowfall on Water Resources (2025)

Basin	2025 Snow Persistence Anomaly (%)	2025 SWE Anomaly (%)	Historical Mean SWE (mm)	2025 SWE (mm)	Contribution to India Runoff (%)
Indus	-24.1	-28	320	232	25
Ganga	-24.1	-26	280	207	23
Brahmaputra	-27.9	-30	250	175	15

Declining snowfall and snow persistence have severe implications for water availability in India. Reduced early-summer flows affect irrigation for rabi crops, leading to lower yields and food insecurity. Lower river flows reduce hydropower generation, impacting energy security. Cities dependent on river water face shortages, especially during dry seasons. Reduced water availability affects biodiversity and ecosystem health, with potential cascading effects on regional ecosystems.

7. Case Studies: Ganga, Indus, and Brahmaputra Basins

Table 3: Basin-Wise Case Study Impacts (2025)

Basin	Key Impact	Estimated Impact (2025)
Ganga	Irrigation shortfalls, hydropower dips, urban water shortages	15–25% reduction in flows
Indus	Increased drought, groundwater stress	20–30% reduction in flows
Brahmaputra	Declining snow cover, reduced SWE, food security concerns	25–30% reduction in flows

- Ganga Basin: Home to 43% of India's population, faces irrigation shortfalls and hydropower dips.
- Indus Basin: Experiences increased drought frequency and groundwater stress.
- Brahmaputra Basin: Shows declining snow cover and reduced SWE, affecting agriculture and hydropower.

8. Climate Change and Future Projections

Table 4: Projected Snowfall Loss by 2050 (SSP2-4.5 Scenario)

Basin	Projected Snowfall Loss (%)	Projected SWE Loss (%)	Implications
Indus	30–70	35–75	Severe water and food insecurity
Ganga	30–70	35–75	Hydropower and agriculture risk
Brahmaputra	30–70	35–75	Ecosystem and food security risk

Future projections under SSP2-4.5 indicate 30–70% snowfall loss by 2050, with severe implications for water, food, and energy security. Adaptation strategies, such as reservoir optimization and efficient irrigation, are crucial.

9. Adaptation Strategies and Policy Recommendations

- Integrated Monitoring: IMD-NRSC collaboration for real-time SWE modeling.
- Efficient Irrigation: Promote water-saving technologies and practices.
- Transboundary Agreements: Enhance regional cooperation for water management.
- Policy Actions: National-level preparedness and response plans for negative snow anomaly and drought conditions.

10. Conclusion

Declining HKH snowfall imperils India's water availability, demanding integrated monitoring, efficient irrigation, and transboundary agreements. Early drought strategies, like reservoir optimization, can mitigate impacts for Ganga-Indus dependent agriculture and 300 million users. Future research should assimilate GPM data for real-time SWE modeling.

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