



Hydrological Dimension of Ladakh under Changing Climate

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Abstract: Ladakh, in the Trans-Himalayan region of northern India, hosts a distinctive high-altitude cold-arid hydrological system in which seasonal snow, glaciers, perched aquifers and a limited network of perennial rivers jointly determine water availability for ecological and human systems. This narrative review-synthesis combines literature analysis (80+ studies) with original trend assessment of IMD gridded rainfall/temperature data (1975–2024) using Modified Mann-Kendall tests and Sen’s slope estimation to comprehend the changes in climate and hydrological dimensions. The synthesis reveals significant warming ($+0.02^{\circ}\text{C y}^{-1}$, $p < 0.05$) across Ladakh with spatially variable precipitation trends, earlier snowmelt timing ($\sim 1.2 \text{ days y}^{-1}$), and glacier mass loss (-0.21 to $-0.37 \text{ m w.e. y}^{-1}$). Springs show declining perennial discharge while Indus tributaries maintain 62–72% cryospheric runoff contribution. Springs and shallow groundwater systems provide disproportionately important perennial supply where surface waters are strongly seasonal, and precipitation is sparse, and major rivers (notably the upper Indus and tributaries such as the Suru, Zaskar, Shyok, and Nubra) integrate cryospheric and groundwater signals at basin scales. Observational and modelling evidence indicate a system in warming drives earlier snowmelt and a transient increase in glacier runoff, followed by long-term declines in glacier melt contributions as ice volume diminishes; concomitant shifts in recharge reduce spring resilience and alter river seasonality. These dynamics increase exposure to both chronic water scarcity and abrupt hazards. To manage these interconnected risks, we recommend priorities: establishment of integrated high-altitude monitoring networks for snow, ice, springs, and river discharge; process-based modelling that couples downscaled climate projections with cryosphere-groundwater-river interactions; systematic mapping and protection of spring recharge zones; and risk-informed, multi-scale water planning that combines conjunctive use, decentralized storage, and community-based adaptation in the fragile Trans-Himalayan landscapes.

Key words: Glacier hydrology, snow hydrology, spring hydrology, river hydrology, climate dynamics in Ladakh, cryosphere-hydrology interactions, trans-Himalayan region, water security.

Ladakh, situated in the Trans-Himalayan region of northern India, exhibits one of the world's most distinctive climatic and hydrological systems (Thayyen, 2019). Owing to its location in the rain shadow of the Greater Himalaya, the region receives less than 100 mm of annual precipitation in many areas, thereby qualifying as a high-altitude cold desert (Schmidt and Nüsser, 2023). Winters are prolonged, dry, and intensely cold, with temperatures frequently dropping below -20°C , whereas summers are short and comparatively mild. Moisture availability is governed mainly by winter westerly disturbances, which deliver snowfall above 3,500 m elevation and play a critical role in sustaining regional water resources (Fowler and Archer, 2006). In contrast, the influence of the Indian summer monsoon is very limited, resulting in a hydrological regime that differs markedly from most parts of South Asia and exhibits a reversed seasonal cycle (Chevuturi *et al.*, 2018).

Geographically, Ladakh extends approximately between 32° - 37° N latitude and 72° - 80° E longitude, covering an area of about 168,011 km² (Fig. 1). The region is bordered by Tibet to the northeast, Gilgit-Baltistan to the west, and the Wakhan Corridor to the northwest. Administratively, it comprises the Leh and Kargil districts.

The physiography of Ladakh is dominated by rugged high-altitude terrain formed through the continuing convergence of the Indian and Eurasian tectonic plates, a process initiated nearly 50 million years ago (Molnar and Tapponnier, 1975). This tectonic activity has produced a sequence of parallel mountain systems, including the Greater Himalaya, Zaskar Range, Ladakh Range, and the Karakoram Range, giving rise to steep relief, deeply incised valleys, and elevated plateaus (Searle and Tirrul, 1991). Elevation ranges from below 1,000 m in lower valleys to above 8,500 m in the peaks of the Karakoram, with most of the region situated above 3,000 m above mean sea level (m a.s.l.).

Under the Köppen climate classification, Ladakh falls predominantly within the cold

desert to cold semi-arid climatic categories (BWk/BSk) (Köppen, 1936). Due to its position within the Himalayan rain shadow, precipitation remains sparse and occurs mainly as winter snowfall. Consequently, the region experiences long and severely cold winters, while summers remain brief and relatively moderate in temperature (Bhutiyan *et al.*, 2007).

Ladakh possesses a hydrological system that is primarily regulated by seasonal snow, glaciers, perched aquifers, and a limited number of perennial rivers that sustain its sparse yet ecologically and culturally significant valley oases (Nüsser *et al.*, 2012). The region's drainage network is dominated by the Indus River, which flows from southeast to northwest and serves as the principal hydrological artery. Major tributaries, including the Zaskar, Suru, Shyok, Nubra, and Drass rivers, receive substantial meltwater inputs originating mainly from surrounding snowfields and glaciers (Negi and Roy, 2001). Consequently, river discharge in the region is strongly influenced by seasonal snow accumulation and subsequent melt processes.

Understanding the hydrology of Ladakh under changing climatic conditions requires consideration of four interconnected yet distinct components: seasonal snowpack and snowmelt dynamics, glacier mass balance and melt regimes, the recharge and behaviour of springs and shallow aquifers, and river discharge characteristics. Over recent decades, however, climate change has increasingly altered these hydrological systems through rising temperatures, changing precipitation regimes, and shifting storm tracks, thereby affecting water availability, flood hazards, and long-term environmental sustainability (Nüsser *et al.*, 2012; Shafiq *et al.*, 2016; Thayyen, 2019).

Snow hydrology in Ladakh functions as the fastest-responding seasonal storage and a first-order control on spring and early-summer runoff in headwater catchments (Salim and Pandey, 2022). Seasonal snow accumulates over winter at higher elevations and melts in spring to produce the runoff peak that recharges shallow groundwater, sustains springs, and supplies irrigation channels in the valley floors (Passang, 2024). Recent remote sensing studies reveal that snow cover area and duration in the Trans-Himalayan Ladakh region display strong

interannual variability and topographically driven spatial heterogeneity (Salim and Pandey, 2022; Passang, 2024). Also, multiple studies have documented a tendency for shortened snow cover duration and an earlier onset of snowmelt in many Ladakh sub-basins over the past two decades, indicating a shift in the timing of the seasonal water pulse (Gurung *et al.*, 2011).

Glacier hydrology, on the other hand, provides multi-decadal buffering in Ladakh, with glaciers acting as slow-release reservoirs that sustain late-season baseflow and moderate interannual variability in dry years (Schmidt and Nüsser, 2023) this chapter presents a multi-temporal analysis of glacier changes in selected ranges and tributary valleys between 1969 and 2020. The study is based on diverse sets of remote sensing data (Corona, Landsat, and Sentinel). Though the majority of the glaciers in Ladakh are small, they act as critical water reservoirs and are now retreating rapidly (Mongabay, 2023). The glacier response to warming is non-linear: an initial phase of enhanced ablation may increase summer runoff for decades, followed by a long-term decline in glacier melt contribution as ice volume is depleted (Bolch *et al.*, 2019). This transient behavior complicates planning because communities and downstream systems may first experience apparent increases in water availability and later suffer reduced late-season flows. Glacier retreat also promotes the formation and enlargement of proglacial lakes, elevating the risk of glacial lake outburst floods (GLOFs) that threaten downstream settlements and infrastructure in steep valley segments.

In an environment where surface water is seasonal and precipitation is sparse, springs and shallow groundwater systems are disproportionately important for perennial water supply in Ladakh (Dolma *et al.*, 2020). Springs discharge from fractured rock, colluvial storage, talus aquifers and perched water tables sustain domestic drinking supplies, livestock needs, and headwaters for traditional irrigation channels year-round. Spring discharge responds to recharge processes (snowmelt infiltration, glacier melt percolation, episodic monsoon rainfall), the hydrogeological architecture (fracture connectivity, talus and colluvial storage), and evapotranspiration losses in the active layer above permafrost. Shifts in melt

timing and glacier mass reduce late-season recharge and may lower perennial spring discharge, particularly where aquifer storage is limited and extraction is rising due to settlement growth and tourism development. Intense but infrequent rainfall events produce more runoff and less infiltration than gentle, prolonged melt pulses, meaning that a precipitation regime that becomes more episodic tends to reduce net recharge despite similar annual totals. Dar *et al.* (2024) we synthesize the available data to assess the status of groundwater quantity, quality, withdrawal, and contamination in the Leh district of India. The study shows that glacier area has decreased by 40% whereas its volume has reduced by 25% since the Little Ice Age (~1650 AD) noted that rapid urbanization in Leh in recent decades, haphazard drilling of borewells (~115 wells per year), and increasing groundwater extraction have significantly stressed the aquifers. This is corroborated by a (Mongabay, 2023) showing both shrinking glaciers and rising well drilling in urban Ladakh, underscoring vulnerability in groundwater systems.

Rivers in Ladakh, principally the upper Indus and its tributaries such as the Suru, Zaskar, Shyok and Nubra - integrate the catchment-scale outputs of snow, glacier and groundwater processes and thus provide the clearest aggregated signal of hydrological change. River regimes here are strongly seasonal: low winter flows, a pronounced spring-summer melt peak driven by snow and glaciers, and variable monsoon influences that are generally weaker than in the southern Himalaya. Recent hydro-observational and modelling work in upper Indus and trans-Himalayan catchments highlights shifts in both the magnitude and timing of stream flows: earlier spring peak flows, increased interannual variability and changing contributions from glacier melt versus snowmelt. These hydrological shifts have practical implications for irrigation schedules, sediment management, infrastructure design, and hazard planning based on historical flow statistics, which are becoming less reliable in a warming climate.

Collectively, these four hydrological dimensions describe a system in flux: earlier melts, transient increases, then declines in glacier contributions, altered recharge to springs and aquifers, and changing river seasonality and

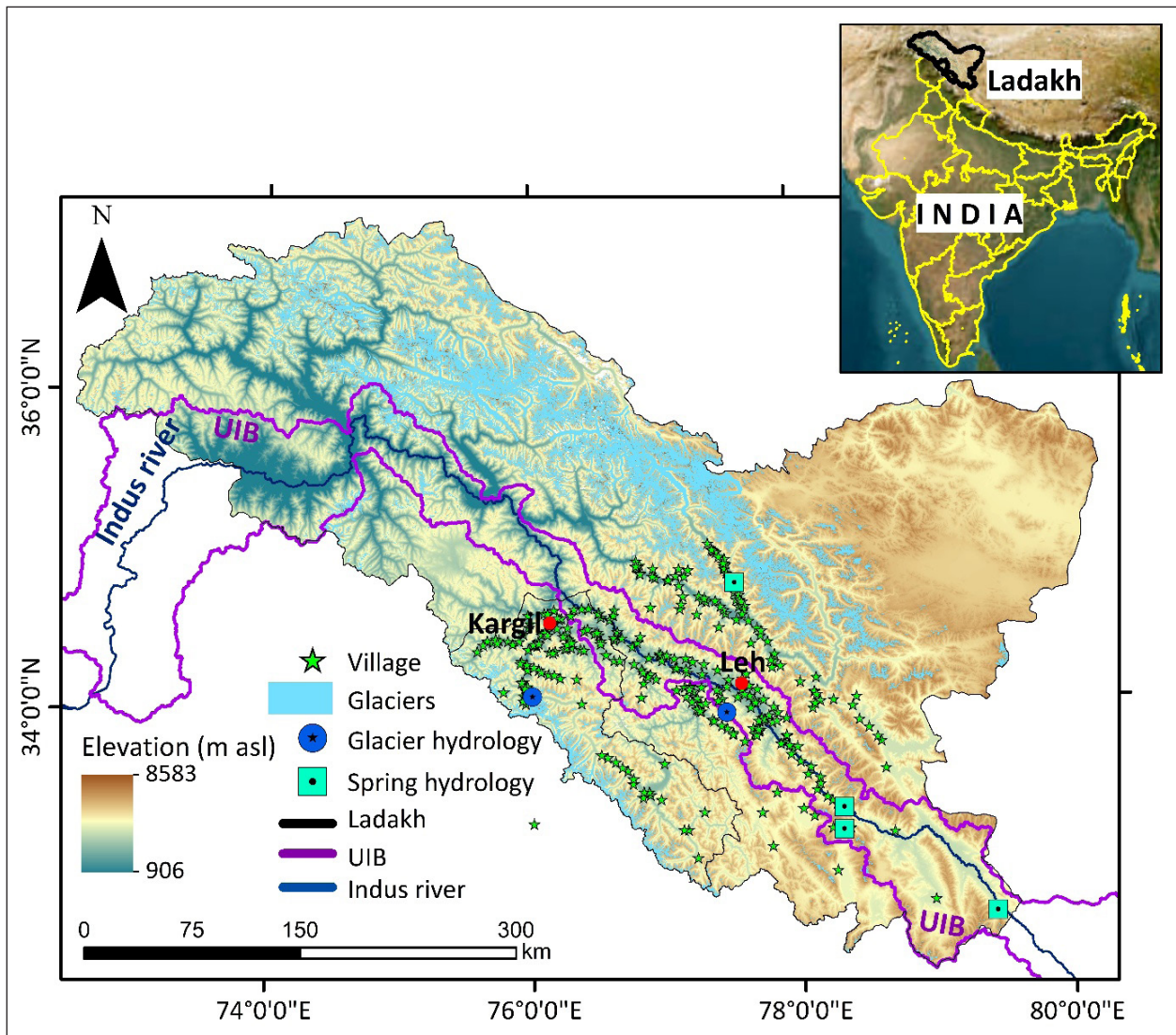


Fig. 1. Geographical overview of the Ladakh region. The map shows the locations of glacier hydrology (cyan square) and spring hydrology (blue circle) studies cited in this work, with appropriate legend symbols. (Source: Administrative Boundary Database, Survey of India, Government of India https://onlinemaps.surveyofindia.gov.in/Digital_Product_Show.aspx; UIB: Upper Indus Basin).

sediment regimes. Research and management must therefore operate at multiple scales, detailed process understanding at the catchment and spring scales, improved remote sensing and in-situ monitoring for snow and ice, and integrated basin planning that couples physical projections with socio-economic adaptation. Only by treating Ladakh's hydrology as an interconnected cryosphere-groundwater-river system can adaptation policies be designed to protect water security, maintain livelihoods and reduce hydro-hazards in a warming world.

Against this backdrop, this article presents an integrated synthesis of existing scientific literature alongside original analyses of India

Meteorological Department gridded hydro-climatic records (1975-2024) to elucidate how climate change is transforming Ladakh's hydrological systems, identify critical knowledge gaps, and highlight urgent priorities for future research and sustainable water resource management.

Materials and Methods

This study adopts a review-cum-research method to understand how Ladakh's water systems are changing under shifting climate conditions. A comprehensive review of peer-reviewed journal articles, institutional reports, and remote sensing-based studies was

conducted to assess four key components of the regional hydrological system: snow, glaciers, springs, and river systems. The literature was analysed using a narrative synthesis approach, focusing on hydrological processes, cryosphere-groundwater interactions, runoff generation mechanisms, and climate change impacts in the region. This synthesis enabled the identification of dominant system linkages, spatial variability, and existing research gaps, thereby providing a conceptual foundation for subsequent data-driven analysis.

To complement the review, long-term gridded hydro-climatic datasets of rainfall ($0.25^\circ \times 0.25^\circ$) and temperature ($1.0^\circ \times 1.0^\circ$; maximum and minimum) for the period 1975–2024 were obtained from the India Meteorological Department (IMD), Pune (<https://imdpune.gov.in>) for the study area. A total of 15 grids for the temperature and 264 grids for precipitation were acquired to cover the study area. The datasets were subjected to quality control procedures, including outlier detection and removal of inconsistent grid points to ensure temporal reliability. After scrutiny, 9 grids for temperature and 263 grids for precipitation were considered for further analysis (Fig. 2). The processed datasets were then analysed using robust non-parametric statistical techniques to detect trends, quantify their magnitude, and assess spatial variability across the region. The detailed methodology for trend detection, magnitude estimation, and spatial interpolation is described in the following sections, including the Modified Mann-Kendall (MMK) test, Sen's slope estimator, and Inverse Distance Weighting (IDW) method. The integration of literature-based insights with statistical analysis enables a comprehensive understanding of hydro-climatic variability and its implications for Ladakh's hydrological systems.

Modified Mann-Kendal (MMK) test: The MMK test is commonly used to identify increasing or decreasing monotonic trends in time series data without assuming any data distribution. It was developed by Mann (1945) and Kendall (1975). Since the MK test can be affected by serial correlation, the modified version of the original MK test by Hamed and Rao (1998) was used in the present study at 5% significance level. The equations used are given below.

$$S = \sum_{i=1}^{p-1} \sum_{j=i+1}^p \text{sgn}(y_j - y_i) \quad (1)$$

where, the sign function is:

$$\text{sgn}(y_j - y_i) = \begin{cases} +1 & \text{if } (y_j - y_i) > 0 \\ -1 & \text{if } (y_j - y_i) < 0 \\ 0 & \text{if } (y_j - y_i) = 0 \end{cases} \quad (2)$$

The variance is determined as:

$$\text{Var}(S) = \frac{1}{18} \left[p(p-1)(2p+5) - \sum_{g=1}^q t_g(t_g-1)(2t_g+5) \right] \quad (3)$$

p = length of dataset; t_g = ties groups

The revised variance is:

$$\text{Var}(S)^* = \text{Var}(S) \times \frac{n}{n^*} \quad (4)$$

n/n^* (revised values of auto-correlation coefficient) and formula is as follow:

$$\frac{n}{n^*} = 1 + \frac{2}{p(p-1)(p-2)} \times \sum_{k=1}^{p-1} (p-k)(p-k-1)(p-k-2)r_k \quad (5)$$

r_k = auto correlation coefficient at lag k

Finally, the Z_{mmk} is expressed as;

$$Z_{mmk} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)^*}} & \text{when } (S < 0) \\ 0 & \text{when } (S = 0) \\ \frac{S+1}{\sqrt{\text{Var}(S)^*}} & \text{when } (S > 0) \end{cases}$$

Sen's slope estimator (SSE): The non-parametric SSE method was employed to determine the magnitudes of the trend in rainfall and temperature datasets. The median of the magnitude of the trend was determined as follows (Singh and Kumar, 2024):

$$\alpha = \text{median} \left[\frac{x_j - x_i}{j - i} \right] \quad \text{for } j < i$$

where, x_j and x_i represents data points at j and i , respectively and α is the magnitude of trend

Inverse Distance Weighting (IDW) method: The IDW method is a deterministic spatial interpolation method used to estimate values at unknown location based on known data points. It considers that points closer to the estimated location have more influence than those farther away. The mathematical expression is given below.

$$\hat{z}(y_0) = \frac{\sum_{i=1}^n z(y_i)}{\sum_{i=1}^n \frac{1}{d_i^p}}$$

$\hat{z}(y_0)$ = Estimate value at unknown location

$\hat{z}(y_i)$ = Observed value at known location i

d_i = Distance between y_0 and y_i

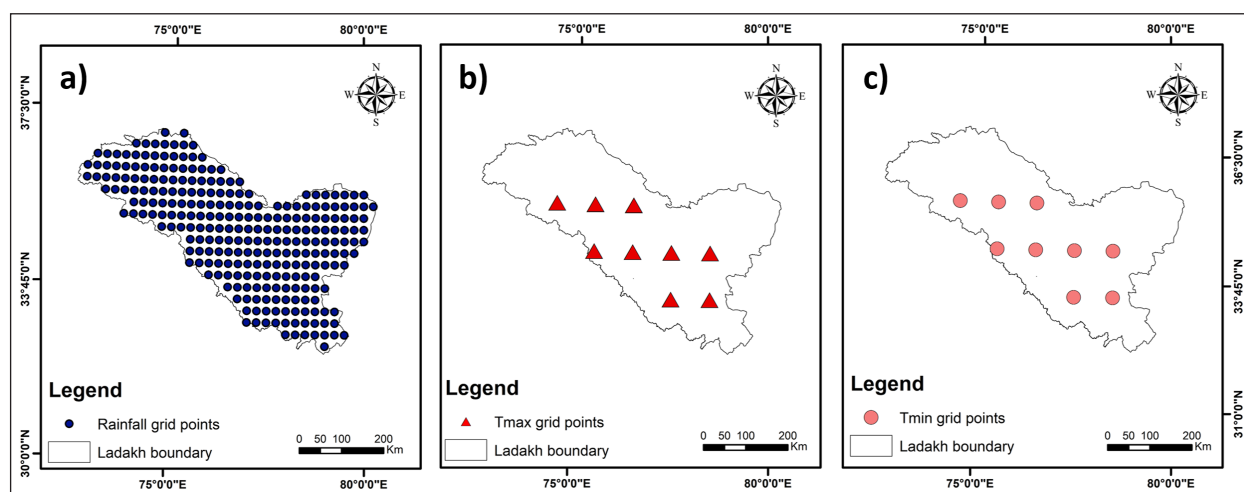


Fig. 2. Grid points used in this study: (a) rainfall, (b) maximum temperature (T_{max}), and (c) minimum temperature (T_{min}).

n = number of neighboring points

p = power parameters that control the influence of the distance

Hydrological Shifts under Changing Climate

Snow hydrology: Snow is the main source of water in Ladakh, the area receives very little rainfall, has long and severe winters, and experiences extremely low temperatures that often fall below -20°C (CGWB, 2015). In many parts of Ladakh, the total yearly precipitation is less than 100 mm (CGWB, 2015; Dahri *et al.*, 2016). Because rainfall is very limited, winter snowfall becomes the most important source of freshwater. This snowfall is mainly brought by Western Disturbances coming from the Mediterranean region (Passang *et al.*, 2022). When the snow slowly melts during spring and summer, it provides water for rivers, farming, ecosystems, and local communities (Passang *et al.*, 2022).

The amount of snow and how long it stays on the ground in Ladakh mainly depend on the landform and terrain. Elevation, slope, and slope direction strongly influence snow cover. High mountain areas situated at about 5,000–6,500 m asl keep snow for most of the year, while lower valley areas at less than 4,500 m asl have snow for a shorter time or may remain snow-free in some seasons (Jain *et al.*, 2009; Passang, 2024). Slopes facing north keep snow longer because they receive less sunlight, while south-facing slopes lose snow faster due to higher solar heating (Jain *et al.*, 2009; Passang, 2024). Satellite data from MODIS between 2000 and 2019 show that, on average, about 42% area

of Ladakh remains covered by snow each year. Snow cover is highest in winter (about 61%) and spring (about 58%) and drops sharply in summer (about 20%) when rapid melting takes place (Passang *et al.*, 2024).

In response to the ongoing climate change, several studies have highlighted substantial changes in snow cover and snowline altitude across the Trans-Himalayan region and the Ladakh Himalaya. Investigations of snow-cover variability during 2000–2019 indicate a modest rise in annual snow cover in the Karakoram ($+0.05\% \text{ y}^{-1}$) and the Western Himalaya including Ladakh ($+0.11\% \text{ y}^{-1}$); however, a declining trend was observed between 2008 and 2018, especially in the Western Himalaya ($-0.08\% \text{ y}^{-1}$). Climatic warming has also contributed to delayed snowfall, earlier onset of snowmelt, shorter snow-cover persistence, and an upward shift of the seasonal snowline (Dharpure *et al.*, 2021; Muhammad *et al.*, 2021). The Phuche and Khardung glaciers, with equilibrium line altitudes (ELAs) of nearly 5480 m and 5500 m a.s.l., respectively, indicate higher snowline conditions (Dharpure *et al.*, 2025). Similarly, the Durung-Drung and Pensilungpa glaciers experienced retreats of approximately 624 ± 547 m and 270.5 ± 27.5 m between 1971 and 2019, together with a rise in ELA, demonstrating persistent glacier recession and upward snowline migration in the Ladakh Himalaya (Mehta *et al.*, 2023). On a wider regional scale, remote-sensing analyses from High Mountain Asia have reported notable increases in glacier snowline altitude (SLA), including an average rise of about 123–151 m in the Karakoram and

190-282 m in the Western Himalayas including Ladakh during 1989-2019, mainly driven by increasing temperatures (Guo *et al.*, 2021).

These changes in snow cover have a direct effect on water flow in rivers. In many river basins of Ladakh, snowmelt provides more than 60%-65% of the total yearly river discharge, which is more than the contribution from glaciers and rainfall (Armstrong *et al.*, 2019). This snowmelt water is especially important in early spring, when farming activities begin and other water sources are limited (Armstrong *et al.*, 2019; Hock *et al.*, 2019). Studies from basins such as the Stok catchment show that snowmelt is the main source of streamflow. Groundwater flow also helps maintain river flow during dry periods and reduces year-to-year variations, showing the important role of snow in keeping the water system stable (Soheb *et al.*, 2023).

Snow is not only important for water but also plays a key role in Ladakh's traditional way of life. Local irrigation systems such as *yuras* and *khuls*, along with small water storage structures called *zings*, are designed to collect and distribute snowmelt water. New methods, such as artificial glaciers and ice stupas, have been developed by local communities to deal with changes in snowmelt timing caused by climate change (Nüsser *et al.*, 2012; 2019). Snow depth and duration also affect grazing areas and livestock movement, especially in regions like Changthang, where pastoral communities depend on snow conditions for their livelihoods (Nüsser *et al.*, 2012). The local names and classifications of snow types show the strong traditional knowledge people have about snow and its use.

From an ecological point of view, snow helps control soil moisture, plant growth in alpine areas, and provides suitable habitats for high-altitude wildlife. Therefore, understanding how snow is distributed, how it changes with seasons, and how much water it provides is very important for protecting Ladakh's water resources, supporting local livelihoods, and improving climate resilience in this fragile mountain environment.

Glacier hydrology: Glacial hydrology examines the movement, storage, and transformation of water within and around glacier systems and has become increasingly important as warming alters high-mountain

cryospheres (Huggel, 2015). In arid and semi-arid mountain regions, glacier runoff provides a disproportionately large share of dry-season streamflow; consequently, changes in glacier mass and melt timing translate directly into water-security, agricultural and ecosystem impacts downstream (Azam, 2021; Nüsser *et al.*, 2012). Glacier systems store winter accumulation as compacted snow and firn are gradually transformed into ice; during the ablation season, this stored water is released as melt and routed through a hierarchy of pathways. Meltwater may flow over the ice surface (supraglacial), through channels and conduits within the ice (englacial), or beneath the glacier along its bed (subglacial) before emerging at the glacier terminus as proglacial streams (Fountain and Walder, 1998). The geometry and connectivity of these pathways, together with firn processes such as percolation and refreezing, control storage, residence time and the seasonal timing of meltwater delivery to downstream systems (Fountain and Walder, 1998).

The buffering capacity of glacierized basins operates across seasonal to multi-decadal timescales and depends on glacier size, hypsometry and regional climate. Unlike seasonal snowpack, which typically melts within weeks to months, glacier ice can store water for years to decades and thereby sustain baseflow during warm or dry periods. This "slow-release" function is especially consequential in basins with weak monsoonal input or highly seasonal precipitation regimes: during drought years or after poor snowfall seasons, melt from glaciers can maintain river flow and support irrigation, livestock and household needs when alternate sources are scarce (Immerzeel *et al.*, 2010). Studies in the Upper Indus Basin and Ladakh indicate that runoff is strongly influenced by snow and ice melt (Fig. 1). Together, these sources are estimated to supply about 62-72% of total runoff in the Upper Indus Basin (UIB) (Azam *et al.*, 2021; Fig. 1), with glacier ice alone accounting for roughly 21-40% depending on sub-basin characteristics (Lutz *et al.*, 2014; Nüsser *et al.*, 2012). Catchment-scale work in Ladakh's Stok catchment explicitly quantifies this partitioning over 2003-2019 snowmelt contributed ~65% of runoff, glacier melt ~19% and rainfall ~16%, while subsurface flow (delayed release) accounted for ~62% of

total discharge (Soheb *et al.*, 2020) reconstruction (between 1978 and 2019). Process-based glacier studies further illustrate how ongoing glacier retreat is modifying meltwater availability. For example, Yadav *et al.* (2025) reported daily mean discharge from the Parkachik Glacier ranging between ~ 3.5 and $4.7 \text{ m}^3 \text{ s}^{-1}$ during 2017-2022, followed by a pronounced increase to $10.0 \pm 1.6 \text{ m}^3 \text{ s}^{-1}$ in 2023, reflecting enhanced ablation under warming conditions (Fig. 1). Notably, over the period 2016-2023, the Parkachik glacier experienced a net frontal retreat of $181 \pm 64 \text{ m}$ ($30 \pm 10 \text{ m y}^{-1}$), with pronounced spatial heterogeneity across the terminus, indicating differential dynamic and climatic controls on meltwater release. Basin-scale syntheses therefore show strong spatial gradients as glacier melt may constitute $\sim 40\%$ of runoff in heavily glacierized headwaters, but declines downstream where rainfall and seasonal snowmelt make larger contributions (Lutz *et al.*, 2014; Nüsser *et al.*, 2012). These values emphasize that seasonal snowmelt commonly dominates immediate runoff generation while glacier melt and groundwater buffering sustain late-season baseflow.

Regional precipitation regimes and hypsometry further modulate melt contributions. In the Karakoram and adjacent high-altitude sectors, a majority of precipitation at higher elevation arrives as winter snow (up to $\sim 66\%$ of annual high-altitude precipitation in some estimates), storing water that is released during the summer ablation season (Lutz *et al.*, 2014). In Ladakh, the combination of a cold, arid climate (valley-floor precipitation often $< 100 \text{ mm y}^{-1}$), high elevation and a prevalence of small glaciers means that relatively modest ice bodies can make disproportionately large contributions to late-season flows and may threaten local water security (Chudley *et al.*, 2017; Kaushik *et al.*, 2022; Nüsser *et al.*, 2019; Prajapati *et al.*, 2026). Remote-sensing based and in-situ studies show widespread retreat across many Ladakh glaciers in recent decades (Anthwal *et al.*, 2006; Armstrong, 2010; Azam *et al.*, 2021; Bhambri *et al.*, 2013; Ahmed *et al.*, 2026; Azam *et al.*, 2021; Dharpure *et al.*, 2025; Garg *et al.*, 2022; Kunmar *et al.*, 2025; Mandal *et al.*, 2024; Mehta *et al.*, 2023; Soheb *et al.*, 2020). More recent and regionally specific measurements indicate substantially higher rates of ice loss. For example, between 2000

and 2021, western Ladakh glaciers lost mass at a rate of -0.35 to $-0.37 \text{ m w.e. y}^{-1}$, while eastern Ladakh glaciers lost -0.21 to $-0.33 \text{ m w.e. y}^{-1}$ (Mandal *et al.*, 2024). At the glacier scale, even stronger declines have been reported with Khardung Glacier showing a mass balance of -0.63 m w.e. (2014-2017), Phuchoe Glacier -0.17 m w.e. (2014-2017), and Stok Glacier -0.39 m w.e. during 2014-2019 (Dharpure *et al.*, 2025; Soheb *et al.*, 2020). Similarly, Drang-Drung Glacier recorded a mean glacier-wide mass balance of $-0.74 \pm 0.43 \text{ m w.e. y}^{-1}$ during 2021-2023 (Azam *et al.*, 2021), while Pensilungpa Glacier showed a specific balance of $-0.36 \text{ m w.e. y}^{-1}$ over 2016-2019 and $-0.88 \pm 0.04 \text{ m y}^{-1}$ between 2000 and 2017 (Mehta *et al.*, 2023; Garg *et al.*, 2022). In terms of ice volume, area and length changes, Lato Glacier exhibited an $\sim 11.5\%$ reduction in area, a terminus retreat of $\sim 171 \text{ m}$ (4.2 m y^{-1}), and a decline in ice volume from 0.48 to 0.41 km^3 during 1980-2020 (Ahmed *et al.*, 2026). Similarly, Pensilungpa and Durung-Drung glaciers experienced significant recession between 1971 and 2023, with mean retreat rates of $6.7 \pm 0.7 \text{ m y}^{-1}$ and $16 \pm 11 \text{ m y}^{-1}$, respectively, associated with frontal area losses of $2660 \pm 42 \text{ m}^2 \text{ y}^{-1}$ and $23,744 \pm 1124 \text{ m}^2 \text{ y}^{-1}$ (Kunmar *et al.*, 2025). These changes may promote the formation and enlargement of proglacial lakes; while such lakes can store meltwater, they also increase exposure to glacial lake outburst floods (GLOFs), which can inflict sudden and severe damage to downstream settlements and infrastructure in steep valley reaches (Nie *et al.*, 2017). As per the National Remote Sensing Centre reports, there are 3219 glacial lakes in the Ladakh. According to National Disaster Management Authority, there are 263 glacial lakes are ranked for their hazard potential with 18 glacial lakes identified as high-risk lakes in the Ladakh including Jammu and Kashmir. Efforts have also been undertaken to assess and mitigate the risks emanating from these potentially dangerous glacial lakes in Ladakh region. For example, in the Lato catchment of Ladakh, Ahmed *et al.*, (2026) provide a quantitative GLOF risk assessment: the proglacial lake expanded at $0.0047 \text{ km}^2 \text{ y}^{-1}$ (1993-2021) and currently holds $\sim 1.26 \times 10^6 \text{ m}^3$ of water. A worst-case breach would generate a peak discharge of $\sim 1,450 \text{ m}^3 \text{ s}^{-1}$, reaching Lato village in ~ 45 minutes and the Indus River in ~ 3.5 hours. Using a hazard-vulnerability framework, the authors

classify the overall GLOF risk as “Medium” (with a “High” hazard score driven by rapid lake growth and moraine dam geometry) and note that failure probability will rise as the lake continues to expand. Approximately 120-150 people, 3 km of road, and two bridges are exposed. Such probabilistic and impact-based measures are essential for early warning and land-use planning in Ladakh’s rapidly deglaciating catchments. These quantitative estimates confirm that Ladakh’s glaciers are not only retreating but also thinning rapidly, with direct consequences for regional water supply and related hazards.

Adaptation at multiple scales is already underway in Ladakh. Local, low-tech interventions most notably artificially constructed seasonal ice reservoirs or “ice stupas” provide targeted early-season water storage to extend irrigation supply during critical months (Nüsser *et al.*, 2019). Such structures store water on the order of 1,010-3,220 m³ per structure and can meaningfully supplement village water availability during the short melt season (Nüsser *et al.*, 2019). At policy lever, the transient nature of glacier-derived water under warming highlights the urgency for integrated monitoring networks, improved hydrological and mass-balance modeling that couple downscaled climate projections with glacier process models, and risk-informed planning for both chronic scarcity and abrupt hazards (Bolch *et al.*, 2019, ICIMOD, 2017). Conjunctive use strategies, small-scale storage, demand management and community-based GLOF preparedness are practical measures that complement scientific monitoring and modeling (Sattar *et al.*, 2025).

In summary, glacier hydrology in Ladakh and the Upper Indus Basin is characterized by dominant cryospheric contributions to runoff, complex non-linear responses to warming, strong spatial heterogeneity tied to glacier cover and elevation, and coupling to both slow-onset water-security risks and rapid onset hazards. Sustaining livelihoods and infrastructure in this context requires an integrated approach that couples high-resolution observation, transparent uncertainty quantification, process-based modeling and locally appropriate adaptation measures.

Spring Hydrology: In the fragile hydro-climatic environment of Ladakh, springs serve as one of the most dependable and perennial sources of freshwater, supporting domestic water supply, livestock rearing, and limited irrigation. The Aquifer Mapping and Management Plan of Leh District, prepared by the Central Ground Water Board (CGWB), identifies springs as natural groundwater discharge points associated with shallow aquifers that develop in valley-fill deposits, moraines, and fractured lithological units. The CGWB report emphasizes that natural discharge through springs significantly contributes to baseflow in local river systems, which is a crucial factor for water availability in villages and settlements (CGWB, 2023).

In terms of hydrogeology, springs in Ladakh can be broadly categorized into cold springs and thermal (hot) springs, reflecting differences in recharge mechanisms, depth of circulation, and geothermal influence. Cold springs are primarily fed by snowmelt, glacier melt, and shallow subsurface flow through unconsolidated sediments such as sands, gravels, and morainic deposits. These springs are commonly found along valley margins, alluvial fans, and lithological contacts (CGWB, 2023). The hot springs, such as those at Puga, Chumathang, Panamik, and Demchok, are structurally controlled and associated with deep-seated faults that facilitate the ascent of geothermal fluids from depth. These systems indicate prolonged water-rock interaction and elevated subsurface temperatures, distinguishing them chemically and physically from cold springs (Mishra *et al.*, 2023).

Cold springs in the Ladakh region exhibit measurable average discharge rates. According to the CGWB aquifer mapping outputs, the average discharge of perennial cold springs ranges from approximately 0.2 to 1.2 liters per second (L s⁻¹), change in discharge rates depends on the location and season. Some perennial springs exhibit discharge of about 1 L s⁻¹ during peak flow periods and during dry seasons, the discharge ranges from 0.2 to 0.5 L s⁻¹. These cold springs are typically tapped near their emergence points using fundamental catchment structures, and their flow is influenced by seasonal snowmelt and shallow groundwater recharge from adjacent morainic and alluvial deposits (CGWB, 2023).

The chemical facies of springs of Ladakh show substantial spatial variability. Cold springs generally show low total dissolved solids (TDS ~150-400 mg L⁻¹), near neutral to slightly alkaline pH (~7.1-8.3), and bicarbonate-dominated hydrochemical facies, which makes water from these springs suitable for drinking and domestic use without any major treatment (CGWB, 2023). Thermal springs, however, show higher mineralization, high pH, and dominance of sulfate, carbonate, and borate species. Geochemical analysis of the Demchok hot springs reported substantially alkaline waters (pH ~9.3-9.5) with low TDS, suggesting limited residence time despite high temperatures (~75°C). But in the case of the Puga geothermal field, they show higher TDS values (>1200 mg L⁻¹) and are rich in hydrothermal mineral deposits, including borates and sulfates, which reflect substantial water-rock interaction at depth (Mishra *et al.*, 2023; Sarkar *et al.*, 2022).

Researchers are now also focusing on the organic and microbiological aspects of hot springs of Ladakh (Roy *et al.*, 2020; Choudhary *et al.*, 2024). These hot springs host diverse thermophilic microbial communities and contain complex dissolved organic compounds such as carboxylic acids, esters, alcohols, and bioactive molecules. The organic and microbial signatures of high-altitude hot springs are distinct from those of cold springs and low-altitude geothermal systems, reflecting extreme environmental adaptation. Such outcomes have attracted interest in geomicrobiology and astrobiology, with Ladakh's hot springs proposed as terrestrial analogues for early Earth and extraterrestrial hydrothermal environments (Sarkar *et al.*, 2022; Anu *et al.*, 2024; Roy *et al.*, 2020).

Springs hold a significant place in Ladakh's traditional water management systems. Cold springs serve as primary sources of drinking water, livestock supply, and irrigation in villages where surface water is seasonal or inaccessible (Angchok and Singh, 2006; NITI Aayog, 2018; Kumar and Yangchan, 2021). To effectively distribute spring water, communities frequently maintain old channels and storage facilities. Established community calendars for agriculture and animal trough filling are based on the consistent discharge rates of cold springs, despite their seasonality. Hot springs, on the

other hand, are primarily valued for therapeutic and recreational purposes. Local populations and visitors commonly use geothermal pools for bathing, believing in their curative effects for skin ailments, joint pain, and general well-being. While these therapeutic benefits are largely based on cultural practice rather than clinical validation, they contribute significantly to local livelihoods through tourism (Angchok and Singh, 2006; BORDA and LEDeG, 2019, n.d.; CGWB, 2023).

Springs in Ladakh face many risks and vulnerabilities despite their importance. Physical hazards associated with thermal springs include high temperatures and unstable ground. High quantities of dissolved minerals, such as sulfates, borates, and other trace elements, make geothermal waters unfit for irrigation and drinking, without treatment. Additionally, there are microbiological hazards, particularly in thermal springs where non-potable thermophilic organisms dominate. Cold water springs are safer overall, but livestock contamination (BORDA and LEDeG, 2020, n.d.), unplanned urban growth (Pandey, 2024), and recharge zone degradation driven by shifting land use patterns (Mishra *et al.*, 2014), are all posing a growing threat to cold springs. These hazards become worse by changing climate, which modifies groundwater recharge processes, glacier melt dynamics, and snowfall patterns (NITI Aayog, 2018; Kumar and Yangchan, 2021; CGWB, 2023; Dar *et al.*, 2024).

The Aquifer Mapping and Management Plan is a major proponent of spring rejuvenation and conservation strategies, including the construction of artificial recharge structures and infiltration cavities, the protection of recharge areas, and continuous monitoring of groundwater levels and quality. Actions like these are crucial to preserve springs as long-term water sources, considering the growing stresses from tourism, urbanization, and climatic variability (CGWB, 2023). Very little research has been conducted on the cold springs of Ladakh, with limited published data available (Dar *et al.*, 2024; Kumar and Yangchan, 2021), creating a significant research gap to better understand their hydrology and critical importance in people's lives as primary drinking water sources in arid Ladakh. A vital strategy for ensuring sustainable spring

management in Ladakh is the integration of scientific knowledge with traditional knowledge and community involvement (NITI Aayog, 2018).

River Dimension: The river systems of Ladakh were recognized as the principal hydrological framework of this cold-arid Trans-Himalayan region, where surface water availability remained spatially constrained and subject to pronounced seasonal variability (Kumar and Srivastava, 2017; Phartiyal and Nag, 2022). Owing to Ladakh's aridity, resulting in river discharge being largely sustained by snowmelt and glacier melt processes, with only limited and episodic contributions from summer monsoonal rainfall (Bookhagen and Burbank, 2010; Archer and Fowler, 2004; Lone *et al.*, 2021). The Indus River functioned as the primary axial trunk system, entering the region near Demchok and flowing westward across high-relief terrain, while major tributaries such as the Zaskar, Shyok, Nubra, and Suru rivers expanded the drainage network by routing meltwater from the glaciated source areas of the Karakoram and Zaskar ranges into the main channel system, thereby integrating basin-scale hydrological inputs (Jonell *et al.*, 2017; Nag and Phartiyal, 2014; Immerzeel *et al.*, 2010).

From a hydrological standpoint, rivers in Ladakh exhibited marked seasonal asymmetry in discharge, with peak flows occurring during late spring and summer in response to intensified cryospheric melt, followed by sharp reductions in winter when subfreezing temperatures promoted partial ice formation within river channels (Bookhagen and Burbank, 2010). Basin-scale investigations across the Upper Indus River Basin consistently demonstrated that meltwater constituted the dominant source of river discharge during the ablation season, thereby maintaining perennial flow conditions despite minimal annual precipitation and distinguishing these systems from ephemeral channels typical of arid environments (Kumar and Srivastava, 2017; Phartiyal and Nag, 2022; Archer and Fowler, 2004; Lone *et al.*, 2021; Lone *et al.*, 2023). Proxy-based reconstructions and long-term observational datasets further indicated that interannual variability in river discharge was closely associated with fluctuations in glacier mass balance and snowpack accumulation (Mandal *et al.*, 2024; Giese *et al.*, 2022). Hydrochemical analyses

revealed that river-water composition was primarily controlled by basin lithology, while seasonal dilution by meltwater exerted a strong influence on temporal variations in water quality (Ali *et al.*, 2025; Lone *et al.*, 2023).

Ecologically and socio-economically, the narrow floodplains and alluvial terraces bordering the Indus River and its tributaries were shown to support concentrated zones of agriculture, settlement, and transportation. At the same time, sediment supplied by tributaries such as the Zaskar and Shyok rivers influenced channel width, depth, and planform characteristics along the Indus corridor (Jonell *et al.*, 2017; Nag and Phartiyal, 2014; Kumar *et al.*, 2023). Over longer temporal scales, stratigraphic and sedimentological evidence demonstrated that variations in river discharge and sediment load responded sensitively to Late Quaternary climatic fluctuations and tectonic forcing. These responses drove geomorphic adjustments including valley incision, sediment aggradation, and alluvial fan development, which collectively shaped patterns of resource availability and heightened vulnerability to hydrological hazards (Kumar and Srivastava, 2017; Phartiyal and Nag, 2022; Phartiyal *et al.*, 2021; Bhattacharya *et al.*, 2021). Thermochronological constraints on Indus Group sediments further linked long-term erosion histories to sustained river incision across Ladakh (Bhattacharya *et al.*, 2021). In recent decades, accelerated glacier mass loss, consistent with projections for the Asian water towers, was inferred to pose increasing risks to this meltwater-dependent hydrological regime, while also accentuating spatial contrasts in streamflow behavior across glacierized sub-basins (Immerzeel *et al.*, 2010; Lone *et al.*, 2023).

Climate Dynamics in Ladakh

Ladakh, a high-altitude cold desert located in the Trans-Himalayan region, is highly sensitive to climatic fluctuations due to its fragile cryosphere systems, limited precipitation, and strong dependency on snow and glacier meltwater (Norphel and Tashi 2014; Priya *et al.*, 2016; Chevuturi *et al.*, 2018). In recent decades, multiple hydro-climatic indicators have highlighted a shift in Ladakh's environmental stability, suggesting that the region is undergoing accelerated climate change impacts compared to other parts of the Indian

Himalaya (Kumar and Yangchan, 2021). The most prominent climate change signals are recorded in temperature trends, precipitation variability (Machiwal and Jha, 20217), and the increased frequency of extreme events (Shafiq *et al.*, 2016; Chevuturi *et al.*, 2018).

Overview of temperature patterns reported in the Ladakh region: Globally, rising temperatures are driving widespread glacier shrinkage and permafrost thaw, reducing their overall stability (Jorgenson *et al.*, 2015; Ding *et al.*, 2019). Faster warming rates intensify ice melt and accelerate permafrost degradation, leading to increasing environmental instability (Oliva and Fritz, 2018). The temperature rise is one of the clearest hydrological signals of climate change and adverse effects on traditional agricultural practices in Ladakh (Le Masson and Nair, 2012; Kumar and Yangchan, 2021; Namgyal and Sarkar, 2025). An increase of approximately 1°C in land surface temperature between 1990 and 2015 was associated with a reduction of ~98422 ha in snow cover and an upward shift of the snowline by ~445m, leading to diminished snow accumulation at lower elevation below ~5600 m (Husain *et al.*, 2022). For example, in Leh, the region's main town, average temperatures have risen by about 1°C since 1973 (Barrett, 2014). This warming has caused the snowline to shift upward by more than 150 m, while nearby glaciers have receded

by up to 10 km approximately over the past century (Vince, 2010; Barrett 2014). Variation in the temperature directly influences glacier mass balance, river discharge timing, and reduced water supply in regions like Ladakh (Soheb *et al.*, 2020; Kumar and Yangchan, 2021; Mandal *et al.*, 2024).

Overview of precipitation patterns reported in the Ladakh region: Ladakh historically receives low precipitation, primarily in the form of winter snowfall brought by western disturbances. However, climate datasets suggest a gradual but uncertain change in precipitation patterns (Shafiq *et al.*, 2016). While some regions show a declining pattern in summer rainfall (Shafiq *et al.*, 2016). The shift from snow-dominated precipitation to rain-dominated events poses a significant challenge to water availability and flood hazards in mountainous regions (Maina and Kumar, 2023). The study conducted by Dar *et al.* (2024) demonstrated that groundwater storage has decreased by 26 times over the last few decades due to human intervention and climate change. In addition, the number of bore wells and the groundwater draft increased at rates of approximately 115 wells y⁻¹ and 7 million cubic meters per year, respectively, particularly in the Ladakh Himalaya. Two major types of extreme hydro-meteorological events (02) were reported in Ladakh's fragile landscape (Bhan *et al.*, 2015). This Hydrological intensification

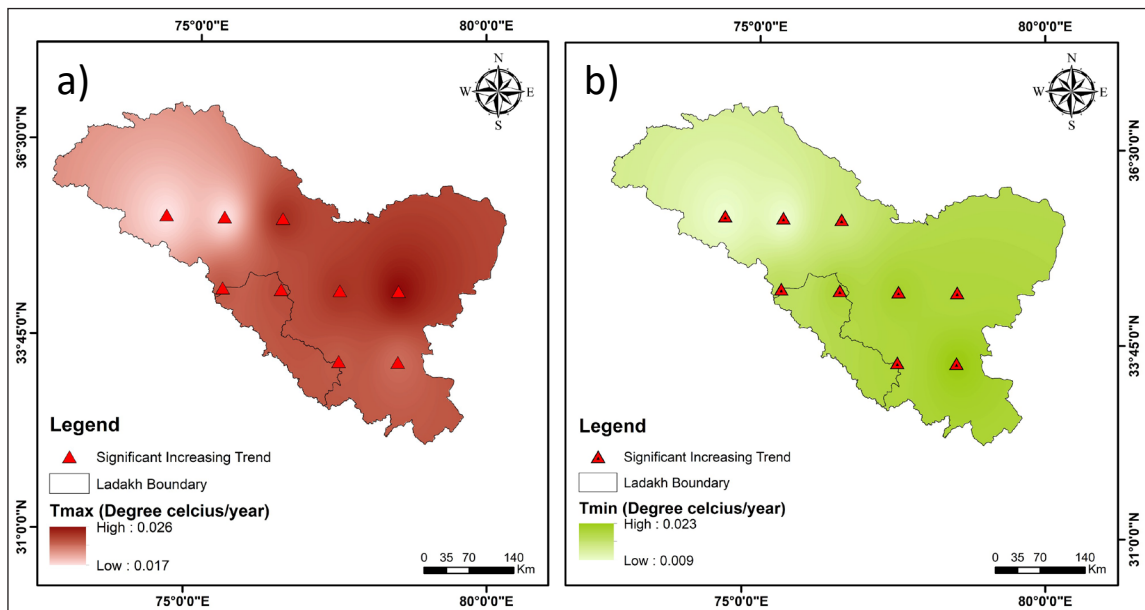


Fig. 3. Significantly increasing trend in the maximum (Panel a) and minimum (Panel b) temperatures from 1975 to 2024 in Ladakh based on India Meteorological Department's gridded climate data.

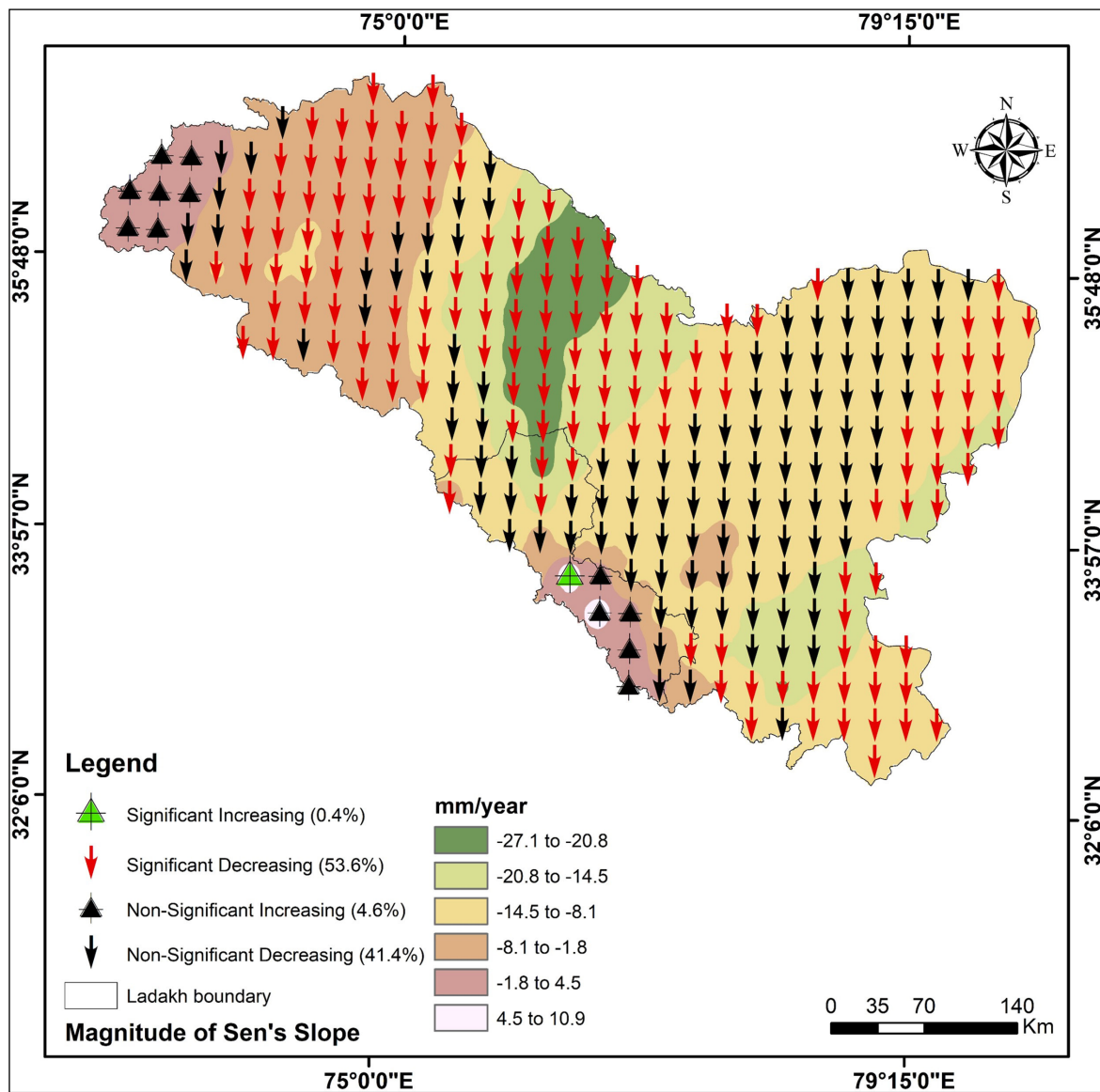


Fig. 4. Map showing significantly increasing/decreasing and a non-significantly increasing/decreasing trend in the rainfall pattern from 1975 to 2024 in Ladakh based on India Meteorological Department's gridded climate data.

complicates water resource planning (Ficklin *et al.*, 2022) and increases hydrological stress on local communities (Agarwal *et al.*, 2012; Lone and Jeelani, 2020; Soheb *et al.*, 2024).

Climatic patterns of rainfall and temperature in Ladakh based on 50 years of long-term meteorological data: The climate data analysis shows statistically significant increasing trend at most grid points for maximum and minimum temperatures (Fig. 3). The magnitude of the significant trend in maximum temperature varies from 0.017 to 0.026°C y⁻¹. Similarly, the magnitude of the significant trend at 5% significance level in minimum temperature varies from 0.009 to 0.023°C y⁻¹. The outcomes of

this study indicate significant increasing trends at most of the grid points for both maximum and minimum temperatures, providing clear evidence of rising temperatures in the Ladakh region.

For the precipitation, a very small percentage of a significantly increasing trend (0.4%) was observed, while a significant decreasing trend with a higher percentage (53.6%) was recorded at the 5% level of significance (Fig. 4). Similarly, for non-significant increasing trends, the percentage is 4.6%, and for non-significant decreasing trends, it is approximately 41.4%. We further noticed that most trends in rainfall patterns in Ladakh are characterised by a decline

in rainfall. However, a very small percentage of the trend is observed in the Ladakh region. The magnitude of this trend varies from -27.1 to 10.9 mm per year. The results of this study suggest that the trend is predominantly declining, indicating that the rainfall pattern in the Ladakh region decreased from 1975 to 2024 time period. Machiwal and Jha, 2017 reported significant change points in annual and wet seasonal rainfall during 1941-1955 and in dry season rainfall around 1973-1975, indicating that rainfall behaviour before and after these periods differ substantially. Consequently, long-term analysis covering 1901-2002 may reflect on the overall monotonic (increasing or decreasing) trend by incorporating both wetter and drier phases. The difference between the present study and earlier studies based on 1901 to 2002 is primarily attributed to the non-stationary nature of rainfall and the influence of the selected analysis period. Rainfall in Ladakh does not exhibit a uniform long-term linear trend; rather, it is characterised by distinct phases of increase and decrease associated with climatic variability and regime shifts. For example, the present study shows an increasing trend in the Kargil region of Ladakh, while other regions show decreasing trends, consistent with findings reported in previous studies (Shafiq *et al.*, 2016; Namgyal *et al.*, 2025; Namgyal and Sarkar, 2025).

Conclusions and Future Recommendations

This study synthesizes current knowledge on the hydrological dimensions of Ladakh and demonstrates that the region's water security is intrinsically linked to interactions among climate, cryosphere, groundwater, and river systems. The study highlights that seasonal snowmelt remains the dominant and most responsive source of runoff, while glaciers provide critical late-season buffering that moderates interannual variability. However, rising temperatures and erratic precipitation patterns, coupled with consequent reducing snow cover and glacier decline, altering the timing, magnitude, and reliability of water availability. The transient phase of enhanced glacier melt masks an emerging long-term risk of reduced dry-season flows, increased dependence on stressed springs and aquifers, and heightened exposure to hydro-hazards such as flash floods and glacial lake outburst floods. Groundwater and spring systems,

which underpin perennial water supply for settlements and agriculture, are shown to be particularly vulnerable to altered recharge regimes, urban expansion, and unregulated abstraction.

Future research and management should prioritize: (i) establishment of integrated, high-altitude monitoring networks for snow, glaciers, springs, and river discharge; (ii) process-based modelling that couples downscaled climate projections with cryosphere-groundwater-river interactions; (iii) systematic mapping, protection, and rejuvenation of spring recharge zones; and (iv) risk-informed planning for both gradual water scarcity and extreme events. Strengthening conjunctive water-use strategies, small-scale storage, and community-based adaptation—while integrating scientific insights with traditional knowledge—will be essential for enhancing long-term resilience and sustainable water management in the fragile Trans-Himalayan environment of Ladakh.

Competing Interests

The authors declare no competing interests.

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