Received: 09 September 2025 | Accepted: 19 December 2025 | Published online: 06 April 2026

DOI: 10.53550/ijsc.v53.i3.204

ORIGINAL ARTICLE

Indian Journal of Soil Conservation

Water Management Technologies in Ladakh's Cold Arid Region: Climate Impacts and Adaptive Strategies - A Field Documentation Study

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Handling Editor:
Dr Rajive K. Singh

Key words:
Artificial glaciers
Climate change
Ladakh
Sustainable agriculture
Water management

ABSTRACT

Ladakh, a high-altitude cold arid region in the trans-Himalayan zone, faces escalating water scarcity due to climate change, marked by glacial retreat, reduced snowfall, and warming trends. This field documentation study synthesizes traditional and modern water management technologies—zings, kuhls, artificial glaciers, ice stupas, and polyhouses—to address these challenges in Leh and surrounding areas. Drawing on field observations (2022-2024), statistical climate analysis (1901-2023), and community insights, it evaluates technology performance and socio-economic impacts. Statistical analysis using Mann-Kendall tests (τ=0.18-0.32, $p < 0.05$) confirms significant warming trends (0.02-0.21°C $year^{-1}$), while precipitation shows pronounced decline (-7.9 mm/year, 1990-2020) with increased drought frequency (SPI <-1 every 5-7 years). Field surveys demonstrate that traditional technologies (zings, kuhls) increase irrigation coverage by 20-30%, while modern innovations (artificial glaciers, ice stupas, polyhouses) extend growing seasons and boost yields by 20-40%. However, challenges include groundwater depletion (1-2 m annually), contamination (70% of aquifers), high technology costs (₹13.5-75 lakh), and tourism-driven demand surges (10-15% in 2023). Sustainable strategies, including wastewater recycling, kuhl lining, technology subsidies, and policy reforms like water pricing, are proposed to enhance resilience. Comparisons with global arid regions underscore Ladakh's unique community-driven approach. This synthesis advocates integrating traditional practices with modern innovations to ensure water security in Ladakh's fragile ecosystem.

1 | INTRODUCTION

Ladakh, a trans-Himalayan cold desert in northern India, epitomizes the challenges of water management in arid, high-altitude ecosystems (Fig. 1). Spanning 59,146 km² across Leh and Kargil districts, the region relies heavily on glacial and snowmelt for its water supply, which supports agriculture (80% of livelihoods), tourism (4.5 lakh visitors in 2023), and hydropower (Gaur, 2025). With annual precipitation below 100 mm and evaporation rates reaching 2,000 mm, Ladakh's water resources are under severe strain from climate change, characterized by a 15-20% glacial retreat since the 1980s, a 30% reduction in winter snowfall, and temperature increases of 0.02-0.21°C per year (Chevuturi *et al.*, 2018; Immerzeel et al., 2020).

These changes disrupt traditional agricultural cycles, delay sowing from April to May, and exacerbate water shortages, particularly in Leh, where inefficiencies in supply systems, groundwater depletion (1-2 m annually), and contamination (70% of aquifers) create a management crisis rather than a scarcity issue (Gohel *et al.*, 2019; LAHDC, 2023). Tourism, while economically vital, amplifies water demand by 10-15% and generates 1.2 million plastic bottles annually, compounding environmental stress (Gaur, 2025). The region's economy relies on agriculture, tourism, and hydropower, with glaciers such as Siachen and Drang-Drung playing a pivotal role in water supply.

While previous studies have documented climate trends (Chevuturi *et al.*, 2018; Shafiq *et al.*, 2016) and individual water management practices (Namtak & Sharma, 2018; Nüsser *et al.*, 2019) in Ladakh, a comprehensive synthesis integrating statistical climate analysis, technology performance assessment, and policy recommendations is lacking. This study bridges this gap through systematic field documentation and quantitative evaluation of adaptation strategies. This field documentation study aims to analyze climate change impacts on water resources (1901-2023), and evaluate the performance and scalability of traditional (zings, kuhls) and modern (artificial glaciers, ice stupas, polyhouses) water conservation technologies through field surveys and farmer assessments. This documentation study provides a comprehensive overview of sustainable water management technologies in Ladakh, blending traditional practices like zings and kuhls with modern innovations such as artificial glaciers, ice stupas, and polyhouses. Drawing on field observations (2022-2024), statistical climate analysis (1901-2023), interviews with farmers and officials, and secondary data from meteorological records and government reports, it evaluates their efficacy, challenges, and socio-economic implications.

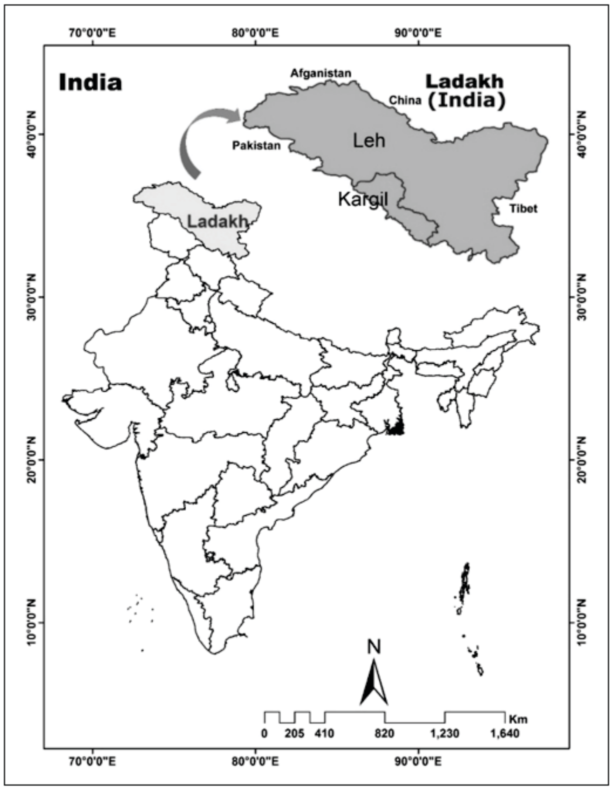

FIGURE 1 Location map of Ladakh (India)

2 | MATERIALS AND METHODS

This study employs a mixed-methods approach that combines quantitative climate data analysis spanning from 1901 to 2023, field-based technology assessment conducted between 2022 and 2024, qualitative stakeholder consultations, and secondary data synthesis from government and research sources. The research framework integrates observational documentation with statistical validation to assess the linkages between climate, water resources, and agriculture in Ladakh's cold arid ecosystem. Fieldwork concentrated on Leh city to examine urban water management challenges, while rural villages such as Stakmo, Phyang, Sabu, Choglamsar, Nang, and Gangles served as sites for technology implementation, with the study area's altitude ranging from 3,350 to 4,267 meters above sea level.

Primary data collection involved field surveys carried out from June to September during the years 2022 to 2024, aligning with the summer months for agricultural and tourism seasons. A total of six villages across Leh district were surveyed using a purposive sampling strategy based on technology adoption and accessibility. The interview protocol consisted of semi-structured interviews with farmers, local authorities, and water management officials to gather insights on technology performance, challenges, and socio-economic impacts. Technology assessment was evaluated through yield comparisons, irrigation coverage measurements, qualitative farmer feedback, and on-site observations of water conservation efficiency.

HIGHLIGHTS

- In Cold Arid regions of Leh -Ladakh, traditional water systems like *zings* and *kuhls* improved irrigation coverage by 20–30% through community-managed practices.
- Artificial glaciers and ice stupas extend early-season water availability by 20–40 days, boosting crop yields by 20–40%.
- Polyhouses enable 4–8 times higher yields and extend growing seasons by 2–3 months.
- Key challenges: groundwater depletion (1–2 m/year), 70% aquifer contamination, tourism-driven demand surge (10–15%) intensify water stress.
- Integrating traditional knowledge with modern technologies is essential for climate-resilient water management in Ladakh.

Secondary data sources included climate data and hydrological information, such as groundwater assessments from the LAHDC 3rd Groundwater Assessment in 2023, water quality analyses and water supply statistics from the PHE Department and Leh Municipal Corporation, and glacial retreat data from peer-reviewed studies like those by Immerzeel et al. (2020) and Soheb et al. (2022). Socio-economic data encompassed tourism statistics on visitor numbers and waste generation from the Leh tourism department, agricultural data on cropping patterns and yields from the Department of Agriculture in Ladakh, and demographics from the Census of India and LAHDC reports. The literature search protocol utilized a systematic search on platforms including Google Scholar, Web of Science, and Scopus.

Data analysis methods for climate data involved the Mann-Kendall (MK) test for monotonic trend identification, with the null hypothesis assuming no trend in the time series at a significance level of $\alpha = 0.05$, using the test statistic τ (tau) along with its corresponding p-value (Reddy *et al*,. 2020; Jeet *et al.*, 2024). Sen's slope estimator was applied to determine trend magnitude, while the modified Mann-Kendall test was used for precipitation analysis. Additional techniques included the Standardized Precipitation Index (SPI) for drought assessment, return period estimation for drought frequency analysis. R statistical software was employed for trend analysis and variability indices. Water management assessment was quantified using data on supply-demand balance, and technology efficacy via yield comparisons and farmer feedback. Groundwater analysis evaluated depletion rates and contamination levels from LAHDC reports, while economic evaluation involved cost-benefit analysis of technologies, incorporating installation costs and yield boosts.

3 | RESULTS AND ANALYSIS

3.1 | Climate Data Analysis And Hydrological Impacts

This section provides a detailed statistical analysis of climate data for the Ladakh region, focusing on long-term trends, interannual variability, and shifts in baseline climate behavior. Analyses incorporate time-series trend detection using the Mann-Kendall (MK) test and Sen's slope estimator, anomaly detection, change point analysis, and climate variability indices such as the Standardized Precipitation Index (SPI) and coefficient of variation (CV). Data are drawn from historical records (1901–2023) and peer-reviewed studies.

3.1.1 | Climate Data Analysis

The impacts of climate change on Ladakh's water resources have been evaluated along with an analysis of water management challenges in Leh, as well as assessment of the effectiveness of traditional and modern water conservation technologies. The discussion is supported by quantitative data, visual representations, and qualitative insights from field surveys conducted between 2022 and 2024. The analysis addresses the region's vulnerability to climate variability, socio-economic pressures, and the potential of adaptive strategies to ensure water security.

3.1.1.1 | Temperature Trends And Variability

Historical data indicate significant warming in Leh. Mean annual temperature increased at 0.02°C per year from 1901–2019 (Romshoo *et al.,* 2022) (Fig. 2). More recent periods show accelerated rates: annual temperature rose by 0.21°C per decade from 1979–2009 (Chevuturi *et al*., 2018), with mean monthly maximum temperatures increasing at 0.2°C per year and minimum at 0.07°C per year from 2000–2013 (Tundup *et al*., 2016). Seasonal analysis reveals summers warming at 0.006°C per year and winters at 0.08°C per year (Lone *et al*., 2019).

The Mann-Kendall test applied to temperature series (1901–2013) confirms a significant positive trend ($\tau = 0.25$, $p < 0.05$) for annual mean temperatures (Chevuturi et al., 2018). Sen's slope estimator indicates a rise of 0.015°C per year overall, with higher slopes in winter (0.08°C/year). Interannual variability, measured by CV, is higher for minimum temperatures (CV = 15–20%) than maximum (CV = 10–12%), suggesting greater fluctuations in cold extremes.

Anomaly detection relative to the 1901–1950 baseline shows positive anomalies post-1980, with a change point around 1975 identified via Pettitt's test, marking a shift to warmer conditions (Shafiq *et al*., 2016).

Table 1 Temperature Trends in Leh, Ladakh

Period	Variable	Trend (MK τ)	Sen's Slope (°C/year)	Source
1901-2019	Mean Annual Temperature	0.18*	0.02	Romshoo *et al.* (2022)
1979-2009	Annual Temperature	0.25*	0.021	Chevuturi *et al.* (2018)
2000-2013	Mean Monthly Maximum	0.32*	0.2	Tundup *et al.* (2016)
2000-2013	Mean Monthly Maximum	0.28*	0.07	Tundup *et al.* (2016)

*Significant at $p < 0.05$.

Table 1 presents temperature trends in Leh, Ladakh, based on data from various studies, highlighting changes over different time periods. It includes four key metrics: the period of study, the temperature variable analyzed, the trend (expressed as the Mann-Kendall tau, or MK τ), and the Sen's Slope (indicating the rate of temperature change in °C per year).

1901–2019: Mean Annual Temperature: Over the 118-year period from 1901 to 2019, the mean annual temperature in Leh, Ladakh, showed a statistically significant upward trend, with an MK τ value of 0.18. The Sen's Slope indicates a warming rate of 0.02°C per year. This suggests a gradual but consistent increase in average temperatures over the long term. The data comes from Romshoo *et al.* (2022).

1979–2009: Annual Temperature: Over the 30-year period from 1979 to 2009, the annual temperature also exhibited a statistically significant rising trend, with an MK τ of 0.25. The Sen's Slope shows a warming rate of 0.021°C per year, slightly higher than the long-term trend observed over 1901–2019. This indicates a more pronounced warming in recent decades. The source for this data is Chevuturi *et al*., (2018).

2000–2013: Mean Monthly Maximum Temperature: Over the 13-year period from 2000 to 2013, the mean monthly maximum temperature (the average of daily high temperatures) increased significantly, with an MK τ of 0.32. The Sen's Slope reveals a steep warming rate of 0.2°C per year, much higher than the annual averages in the longer-term studies. This suggests that daytime temperatures in Leh were rising rapidly during this period. The data is sourced from Tundup *et al*., (2016).

2000–2013: Mean Monthly Minimum Temperature: During the same 2000–2013 period, the mean monthly minimum temperature (the average of daily low temperatures) also showed a statistically significant upward trend, with an MK τ of 0.28. The Sen's Slope indicates a warming rate of 0.07°C per year. While this rate is lower than that for maximum temperatures, it still reflects a notable increase in nighttime or early-morning temperatures. This data is also from Tundup *et al.*, (2016).

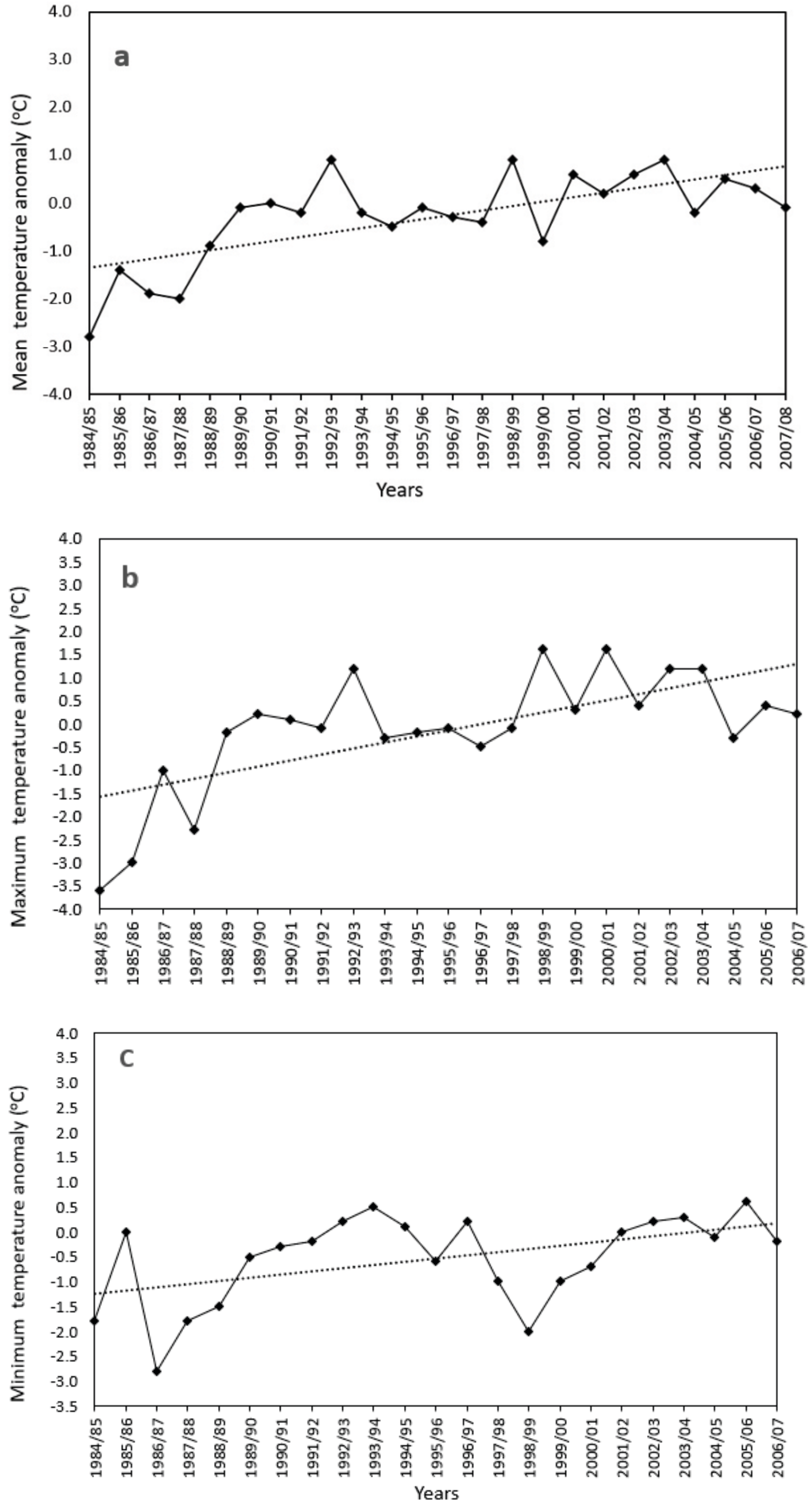

FIGURE 2 (a) mean, (b) maximum, and (c) minimum temperature anomalies for November–April over the western Himalaya. The dotted lines in this and subsequent figures are simple trends of the time series of the parameters (Adapted and modified after Chevuturi *et al*., 2018; Shekhar *et al*., 2017, and Romshoo *et al*., 2022).

Thus the Table 1 indicates a clear warming trend in Leh, Ladakh, across different time scales and temperature metrics. The long-term data (1901–2019) shows a steady but slow increase in mean annual temperatures, while the more recent periods (1979–2009 and 2000–2013) suggest accelerated warming, particularly in maximum temperatures during 2000–2013. The higher Sen's Slope for maximum temperatures (0.2°C/year) compared to minimum temperatures (0.07°C/year) in the 2000–2013 period points to more rapid increases in daytime highs than nighttime lows. All trends are statistically significant, reinforcing the reliability of these findings. The data collectively underscores the impact of climate change in this high-altitude region, with implications for local ecosystems, water resources, and livelihoods.

Chevuturi *et al.,* (2018) has reported a 30% reduction in winter precipitation (primarily snowfall) from 1901 to 2018, with reduced precipitation in recent decades. Mean annual temperature at Leh is 7.3°C, with extremes of 34.8°C (summer) and -27.9°C (winter). Shafiq *et al* (2016) has indicated that winter precipitation (November–February) at Leh showed a positive trend from 1941–1950 (95.8 mm) but decreased thereafter until 1970, with an overall negative trend from 1901–2000. Winter precipitation increased at 0.42 mm/yr from 1991–2000. Meteorological Centre, Ladakh has reported a maximum temperature of 33.5°C on July 28, 2024, and noted temperatures frequently reaching 33°C in recent years, with 36.6°C in 2013 as the highest in 52 years (Fig. 3).

3.1.1.2 | Precipitation Trends And Variability

Precipitation in Leh averages <100 mm annually, with winter snowfall dominating. From 1901–2000, winter precipitation (November–February) averaged 68.09 mm (liquid equivalent), showing a negative trend (MK $\tau = -0.15$, $p < 0.05$) and Sen's slope of -0.127 mm/year for summer rainfall (Shafiq *et al.*, 2016). Recent data (1990–2020) indicate an annual decline of -7.9 mm/year, with seasonal decreases: winter (-4.09 mm), spring (-3.48 mm), autumn (-1.90 mm), and summer (-0.66 mm) (Kumar et al., 2023). Modified MK test confirms these negative trends ($z = -2.1$ to -3.5, $p < 0.05$).

SPI analysis reveals increased drought frequency post-1970, with moderate droughts (SPI < -1) occurring every 5–7 years. CV for annual precipitation is high (35–45%), indicating substantial interannual variability. Change point analysis detects a shift around 1970 toward reduced snowfall (Shafiq *et al.*, 2016). Summer rainfall increased slightly at 0.11 mm/year, while winter snowfall decreased at -0.18 mm/year (Chevuturi *et al*., 2018). Figure 5 shows precipitation trends. An in-depth analysis of annual precipitation trends in Leh, Ladakh, reveals a consistent and statistically significant decreasing monotonic trend in annual precipitation over the studied period. The majority of data points in the trend analysis fall below the 45° line, indicating a clear departure from a stable or constant precipitation pattern. Furthermore, a significant portion of these data points lies outside the 5% confidence interval, providing robust evidence of the trend's statistical significance. The innovative trend analysis method confirms a pronounced monotonic decline in annual precipitation, characterized by a negative slope. Specifically, the calculated slope indicates an average decrease of approximately -2.45 mm in annual precipitation per year. Additionally, the percent bias analysis highlights a substantial reduction, with annual precipitation decreasing by approximately 49% compared to the baseline. This significant decline in precipitation could have critical implications for water availability, agriculture, and ecosystem stability in the region, underscoring the need for further monitoring and adaptive measures to address the impacts of this trend (Fig. 4).

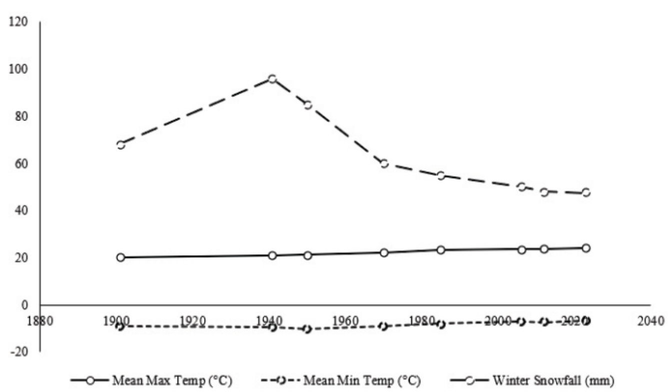

FIGURE 3 Temperature and Precipitation Trends in Leh (1901-2023) (Source: Adapted and modified after Shafiq *et al.*, 2016 and Chevuturi *et al.*, 2018*)*

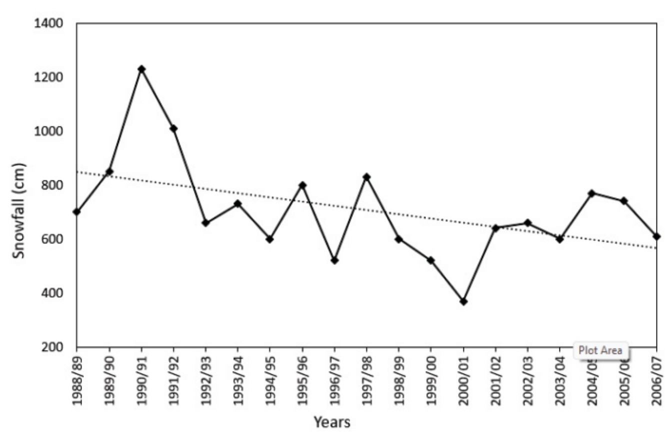

FIGURE 4 Time series of seasonal (November-April) snowfall over the western himalaya (Source: Shekhar *et al.*, 2017)

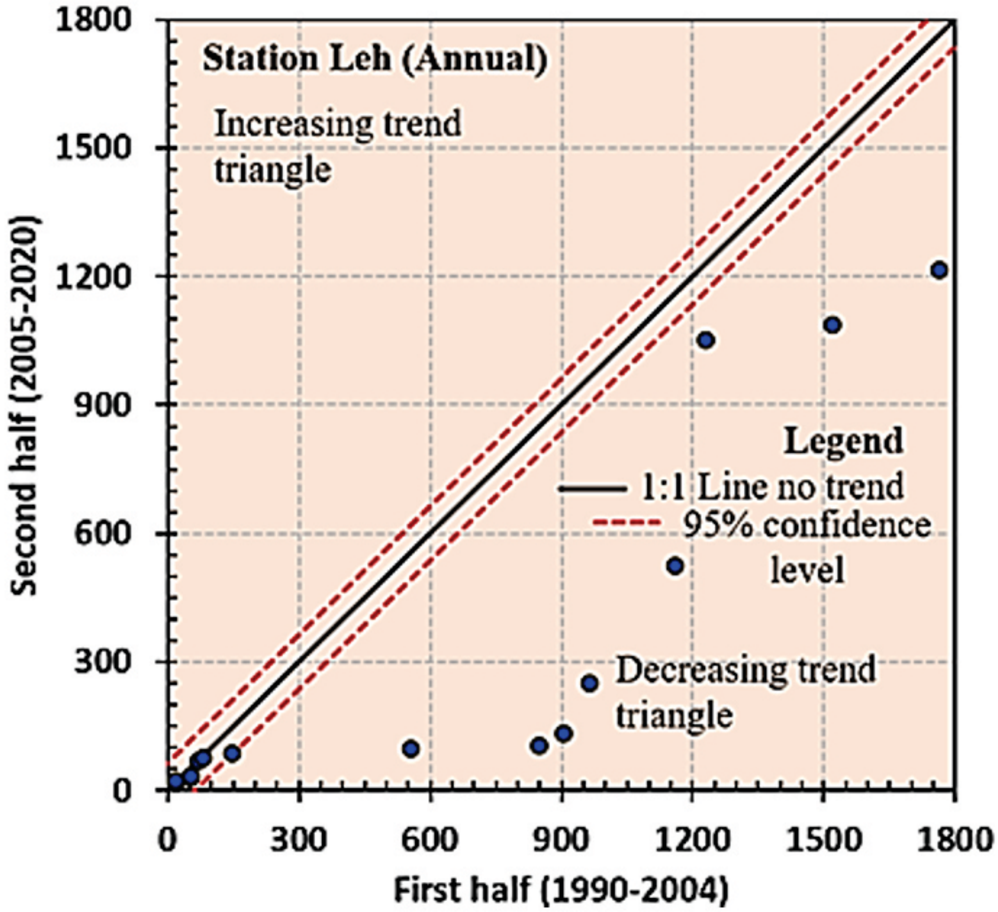

FIGURE 5 Annual precipitation trends in Leh (1901–2023), with Sen's slope line and SPI values. (Source: Adapted and modified after Shafiq *et al*., 2016; Kumar *et al.*, 2023 and Namgial *et al.*, 2025).

TABLE 2 Precipitation Trends in Leh, Ladakh (Selected Periods)

Period	Variable	Trend (MK z)	Sen's Slope (mm year^{-1})	Source
1901-2000	Winter Precipitation	-2.1*	-0.42	Shafiq *et al.* (2016)
1990-2020	Annual Precipitation	-3.2*	-7.9	Kumar *et al.* **(**2023**)**
1990-2020	Winter Precipitation	-2.8*	-4.09	Kumar *et al.* **(**2023**)**
1979-2013	Summer Rainfall	1.5	0.11	Chevuturi *et al.* (2018**)**

*Significant at $p < 0.05$

Table 2 presents an analysis of precipitation trends in Leh, Ladakh, across selected time periods, focusing on different precipitation variables. The table includes four key columns: the period of study, the precipitation variable analyzed, the trend (expressed as the Mann-Kendall statistic, or MK), and the Sen's Slope (indicating the rate of change in precipitation in millimeters per year). Trends are statistically significant at $p < 0.05$, indicating strong evidence of a consistent trend. The table covers both annual and seasonal (winter and summer) precipitation, providing insights into how precipitation patterns have changed over time (Table 3).

1901–2000: Winter Precipitation: Over the 100-year period from 1901 to 2000, winter precipitation in Leh, Ladakh, exhibited a statistically significant decreasing trend, with an MK z value of -2.1. The Sen's Slope indicates a reduction of 0.42 mm per year. This suggests a gradual but consistent decline in winter precipitation, such as snowfall, over the century, potentially impacting water resources dependent on snowmelt.

1990–2020: Annual Precipitation: From 1990 to 2020, a 30-year period, annual precipitation showed a statistically significant decreasing trend, with a more pronounced MK z value of -3.2. The Sen's Slope reveals a a substantial decline of 7.9 mm per year, indicating a rapid reduction in total yearly precipitation. This sharp decrease highlights a significant drying trend in recent decades, which could affect agriculture, water availability, and ecosystems in the region (Fig. 5).

1990–2020: Winter Precipitation: During the same 1990–2020 period, winter precipitation also displayed a statistically significant decreasing trend, with an MK z of -2.8. The Sen's Slope indicates a reduction of 4.09 mm per year. This notable decline in winter precipitation, likely driven by reduced snowfall, suggests a continuation and intensification of the long-term drying trend observed in the 1901–2000 period, with potential implications for seasonal water storage in the form of snow.

1979–2013: Summer Rainfall: Over the 34-year period from 1979 to 2013, summer rainfall showed a slight increasing trend, with an MK z value of 1.5. However, this trend is not statistically significant ($p > 0.05$). The Sen's Slope indicates a modest increase of 0.11 mm per year. This suggests a weak tendency toward slightly higher summer rainfall, but the lack of statistical significance implies that the trend is not robust and may not reflect a consistent pattern.

TABLE 3 Statistical outcomes of annual and seasonal precipitation

Climate Variable	Precipitation				
	Spring	Summer	Autumn	Winter	Annual
Minimum	0.00	0.00	0.00	0.80	15.49
Maximum	464.44	801.77	367.44	495.93	1765.22
Mean	126.24	147.80	65.32	118.58	461.73
SD	168.5	210.5	83.8	141.6	537.19
Slope of Innovative trend	-3.50*	-2.03*	-0.05*	-2.29*	-2.45*
Percent Bias (%)	70.01	40.45	1.07	45.77	49.00
Innovative trend pattern	#	#	##	#	#

* Statistically significant trends at the 95% confidence level
# Monotonic decreasing trends
Non-Monotonic decreasing trends
(Namgyal *et al.*, 2025)

Hence, the table highlights a dominant pattern of decreasing precipitation in Leh, Ladakh, particularly in winter and annual precipitation, with statistically significant declines observed across both long-term (1901–2000) and more recent (1990–2020) periods. The most striking reduction is in annual precipitation from 1990 to 2020, with a steep decline of 7.9 mm per year, indicating a significant drying trend in recent decades. Winter precipitation also shows consistent declines, with reductions in snowfall potentially affecting water availability in this arid, high-altitude region. In contrast, summer rainfall from 1979 to 2013 shows a slight, non-significant increase, suggesting some variability in seasonal patterns but no strong evidence of a consistent upward trend. These findings underscore the broader impacts of climate change on precipitation patterns in Leh, Ladakh, with potential consequences for water resources, agriculture, and local livelihoods.

3.1.2 | Glacial Retreat

Glacial retreat, driven by warming, has reduced the mass of key glaciers such as Siachen and Drang-Drung by 15–20% since the 1980s (Immerzeel *et al.*, 2020). This has led to increased runoff in spring but severe water shortages in late summer and autumn, critical periods for irrigation. The 2010 cloudburst in Leh, which caused flash floods and over 200 fatalities, underscores the region's vulnerability to extreme weather events exacerbated by climate change (Chevuturi *et al.*, 2018).

Gaur et al. (2022) provides spatial extent of snowfall data for Leh, derived from satellite and ground observations. The winter snowfall (November–February) averaged 68.09 mm (1901–2000, liquid equivalent), with a significant decline post-1970. Snow cover extent decreased by 15–20% from 1971 to 2019. It further confirms temperature increases, with maximum temperatures rising by 0.9°C per decade in recent decades. Soheb *et al.* (2022) illustrates the spatial distribution of major glaciers in the Ladakh region, emphasizing areas experiencing significant retreat. The map highlights five key glaciers: a) Parkachik glacier in the Suru Basin, b) Pensila glacier also in the Suru Basin, c) Lato glacier in the Leh Basin, d) Khardung glacier in the Shayok Basin, and e) Stok glacier in the Leh Basin. These glaciers, located across different basins in Ladakh, are critical components of the region's cryosphere, contributing to water resources for local ecosystems and communities. The figure underscores the varying degrees of glacial retreat, likely driven by climate change factors such as rising temperatures and altered precipitation patterns, with each glacier showing distinct patterns of mass loss or terminus retreat. This spatial analysis provides valuable insights into the vulnerability of Ladakh's glaciers and their implications for regional hydrology and environmental sustainability (Fig. 6).

Glacial retreat has reduced mass by 15–20% since the 1980s, causing increased spring runoff but late-season shortages (Immerzeel *et al.*, 2020). The 2010 cloudburst in

Leh highlights vulnerability to extreme events (Chevuturi et al., 2018). Snow cover declined by 15–20% from 1971–2019 (Gaur *et al*., 2022).

These climatic shifts have disrupted traditional patterns of water availability, forcing farmers to delay sowing and adapt to shorter growing seasons (Gaur & Goyal, 2023). The decline in snowfall, a primary recharge source for streams and aquifers, threatens long-term water security.

3.2 | Climate Change-Hydrology Nexus And Water Management Challenges

Climate variability and long-term climate change have emerged as dominant drivers reshaping hydrological processes and water security in Ladakh. The region, characterized by an arid cold-desert environment and annual precipitation of less than 100 mm, depends heavily on cryospheric sources such as glaciers and seasonal snowmelt. Historical climate records (1901–2023) indicate a steady rise in mean annual temperature of approximately 0.02°C per year, with an accelerated warming trend of about 0.21°C per decade during 1979–2009 and pronounced winter warming of 0.08°C per year (Chevuturi *et al*., 2018; Tundup et al., 2017). This warming has intensified glacial retreat across major glaciers, including Siachen and Drang-Drung, which have lost nearly 15–20% of their mass since the 1980s (Immerzeel et al., 2020; Soheb *et al*., 2022). As a result, meltwater availability has shifted toward earlier spring runoff, while late summer and autumn streamflows—critical for irrigation—have declined significantly.

Simultaneously, precipitation patterns have become increasingly erratic. Winter precipitation, a crucial contributor to snow accumulation and subsequent meltwater, has declined sharply by 30% between 1901 and 2018, with recent observations (1990–2020) indicating reductions ranging from 7.9 mm/year to as much as −0.18 to −4.09 mm/year in some pockets (Chevuturi *et al*., 2018; Kumar *et al*., 2023). Reduced snowfall has led to a 15–20% decline in snow cover (1971–2019), diminishing natural aquifer recharge and baseflow contributions to streams. Consequently, groundwater recharge cycles have shifted from predictable spring snowmelt to highly variable and intense summer rainfall events, increasing uncertainty and vulnerability. Recent assessments indicate groundwater depletion rates of 1–2 meters annually in parts of Leh due to declining recharge and excessive abstraction (LAHDC, 2023). Projections further suggest that a 1°C rise in temperature could reduce recharge by 10–15%, compounding long-term water stress (Romshoo *et al.*, 2022).

Increased temperature variability, with coefficients of variation ranging from 10–20%, has exacerbated evapotranspiration losses and irrigation demand, placing additional strain on already limited water resources (Gaur & Goyal, 2023). Droughts identified using the Standardized Precipitation Index (SPI < −1) now recur every 5–7 years and are associated with 15–20% reductions in streamflow timing, disrupting traditional agricultural calendars (Soheb *et al.*, 2022; Gaur *et al.*, 2022). Farmers increasingly report delayed sowing—from April to May—due to insufficient meltwater availability, resulting in yield declines of 15–20% and threatening the livelihoods of nearly 80% of Ladakh's population dependent on agriculture and allied activities (Gaur & Goyal, 2023; Yangchan *et al*., 2019). Extreme events such as the 2010 Leh cloudburst, which caused over 200 fatalities, further highlight the region's heightened vulnerability to climate-induced hydrological extremes (Chevuturi *et al.*, 2018).

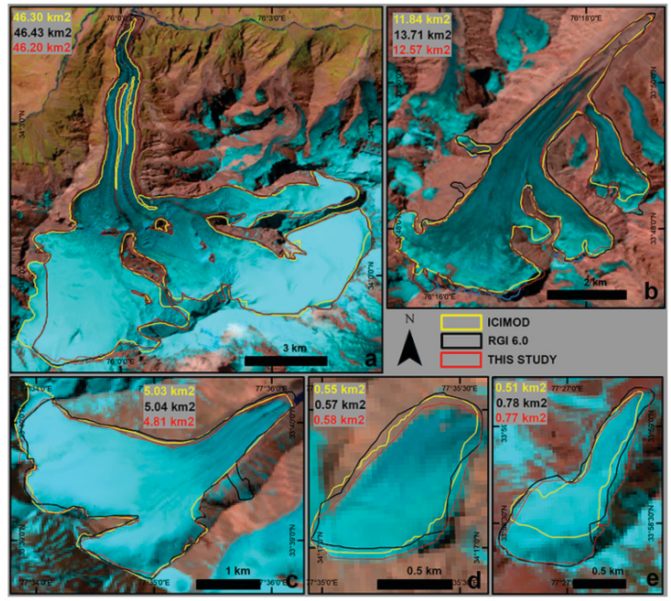

FIGURE 6 Spatial distribution of major glaciers in Ladakh, highlighting areas of significant retreat: a) Parkachik glacier, Suru Basin; b) Pensila glacier, Suru Basin; c) Lato glacier, Leh Basin; d) Khardung glacier, Shayok Basin; e) Stok glacier, Leh Basin. *Source*: Soheb *et al*., (2022).

These climate-driven hydrological changes directly translate into acute water management challenges in Leh town. The city currently faces a pronounced supply–demand mismatch, with an estimated daily water supply of about 4.5 million liters per day (MLD) against a demand of 6–8 MLD (Gohel *et al.*, 2019). To bridge this deficit, reliance on groundwater has intensified, with nearly 92% of water needs met through aquifers, leading to unsustainable extraction. Over-exploitation has resulted in declining groundwater levels of 1–2 meters per year in certain localities, while water quality has deteriorated alarmingly. Approximately 70% of domestic water sourced from Leh aquifers is contaminated with biological and chemical pollutants, including nitrates and coliform bacteria, posing serious public health risks (LAHDC, 2023) (Table 4).

Inefficiencies in water distribution further aggravate the crisis. Leakage from pipelines and storage overflows accounts for nearly 25% of supplied water—equivalent to about 1.125 MLD—resulting in an annual financial loss of approximately ₹40 lakh, compared with a delivery cost of ₹1.65 crore (Gohel *et al.*, 2019). The absence of water metering and fixed pricing structures discourages conservation, while limited infrastructure means that only about 5% of households are connected to central sewage systems, severely restricting wastewater treatment and reuse (LAHDC, 2023). Social inequities in access are stark: tourists and permanent residents receive 75–100 liters per capita per day, whereas migrant laborers manage with only 23–25 liters per capita per day, far below the World Health Organization's minimum requirement of 50 liters for basic needs (Gohel *et al*., 2019).

Tourism, while a critical economic pillar, intensifies pressure on Leh's fragile water system. With approximately 4.5 lakh visitors recorded in 2023, seasonal water demand surges sharply, accompanied by rising solid waste generation, including an estimated 1.2 million plastic bottles annually (Gaur, 2025). Moreover, the transport sector—responsible for nearly 50% of greenhouse gas emissions in Ladakh—contributes indirectly to regional warming, reinforcing the feedback loop between climate change and water scarcity (Yangchan *et al*., 2019). Together, these interlinked climatic, hydrological, and socio- economic stressors underscore the urgent need for integrated water resource management strategies to enhance resilience and ensure long-term water security in Leh and the broader Ladakh region.

TABLE 4 Water Supply and Demand in Leh (2023)

Parameters	Status
Daily Water Demand	6.0–8.0 MLD*
Daily Water Supply	4.5 MLD
Groundwater Dependency	92% (70% from aquifers)
Water Loss (Leaks)	25% (~1.125 MLD)
Annual Loss Cost	₹40 lakh

*MLD: Million Liters per Day

Sources**:** Gohel *et al.***,** **(**2019**)**, PHE Department, Leh

4 | WATER MANAGEMENT TECHNOLOGIES

This section synthesizes five key technologies—zings, kuhls, artificial glaciers, ice stupas, and polyhouses—documenting their implementation, performance, and challenges based on field surveys and secondary data.

4.1 | Zings: Traditional Meltwater Storage

Historical evolution of Zings traces back to influences from neighboring regions like Tibet and Kashmir, where similar tank systems were adapted to Ladakh's altitude, with archaeological evidence suggesting use since the 10th century. Case studies from villages like Saboo show Zings increasing barley yields by 15% over non-equipped areas, with social benefits including reduced migration. Scientifically, Zings operate on principles of surface storage and slow release, aiding in microclimate regulation by maintaining humidity in fields (Photo 1). Future prospects involve integrating solar-powered liners to cut evaporation, potentially extending utility amid projected 30% snowmelt decline by 2100. Community impacts are profound, empowering women through reduced water-carrying burdens and preserving cultural heritage (Namtak and Sharma, 2018).

The implementation of Zings is deeply rooted in community-driven practices, where local villagers collaborate under the guidance of the *Chhurpon*, the traditional water supervisor, to construct and maintain these reservoirs as part of the Rewaj-e-Abpashi system—a customary framework for equitable water distribution. Typically built in depressions or along stream channels, *Zings* are fed by gravity-flow *kuhls* (irrigation canals) that divert meltwater from higher elevations, ensuring a passive collection process without the need for mechanical pumps or external energy sources. The construction process involves excavating pits or natural hollows and lining them with locally sourced materials to prevent seepage, a task often completed during the off-agricultural season from October to April when labor is available and temperatures allow for durable setting of mud and stone. Communities in Leh district, for instance, have historically integrated Zings into their landscape, with surveys indicating that in villages like Chem-Sak, these structures are maintained through annual communal labor contributions, ensuring shared ownership and sustainability. The cost of implementing a *Zing* is remarkably low, ranging from ₹10,000 to ₹50,000 per unit, primarily covering basic materials like stones, clay, and occasional cement for reinforcement, with labor provided voluntarily by households to keep expenses minimal and accessible even to resource-poor communities. This affordability stems from the use of indigenous resources, avoiding imported technologies and aligning with Ladakh's self-reliant ethos (Namtak and Sharma, 2018; 2011).

PHOTO 1 *Zing* - Glacier water harvesting/Storage

Technical specifications of Zings highlight their simplicity and adaptability to the harsh terrain, with typical tank capacities varying from 50,000 to 200,000 liters depending on the size of the village and available catchment area. Construction materials predominantly include local stone for walls, mud or clay for sealing the base to reduce permeability, and sometimes cement for added durability in areas prone to seismic activity or heavy silt loads. Maintenance requirements are straightforward yet essential, involving annual cleaning to remove accumulated silt and debris, which can reduce storage volume by up to 20-30% if neglected, as well as periodic repairs to linings to prevent cracks from freeze-thaw cycles that characterize Ladakh's extreme diurnal temperature fluctuations. In terms of design parameters, Zings are often 3-5 meters deep with diameters of 5-10 meters, featuring a gentle 1:100 inflow gradient to minimize erosion and overflows sealed with clay to manage excess water during peak melts. These parameters ensure efficient water retention in soils with high infiltration rates, drawing on centuries-old observations of hydrological patterns in the trans-Himalayan belt (Namtak and Sharma, 2018) .

Zings, traditional reservoirs, store glacial meltwater in stone- or clay-lined tanks for irrigation and domestic use, addressing spring shortages in villages like Stakmo and Phyang. Constructed in shaded depressions near streams, zings have capacities of 50,000-200,000 liters, using local stone and minimal cement, costing ₹10,000-50,000 per unit (Namtak & Sharma, 2018). Annual desilting and liner repairs are required to counter 20-30% capacity loss from siltation, with maintenance costs around ₹50,000/year (Shaheen & Wani, 2019). Field data show zings store 10,000-50,000 liters/day, covering 5-10 hectares with 60-70% adoption in surveyed villages, increasing irrigation coverage by 20% (Gaur *et al.*, 2024; Tundup et al., 2017). Cost-benefit analyses indicate a benefit-cost ratio (BCR) of 1.5-2, with 10-15% yield stability, though high evaporation (30%) and climate-driven inflow reductions (21% glacier loss) limit scalability (Immerzeel et al., 2020; Namtak & Sharma, 2018). Implementation involves 2-4 week construction (May-June) and community labor, guided by Chhurpons for equitable distribution (Stobdan *et al*., 2006). Compared to Andean bofedales, zings are cheaper but less efficient due to sandy soils; Tibetan ponds face higher depletion rates (Mountford, 2022; Woodall, 2022).

4.2 | Kuhls : Surface Irrigation Channels

Kuhls, traditional surface irrigation channels, are a cornerstone of water management in Ladakh's cold arid region, channeling stream and glacial meltwater to terraced fields for agriculture. These systems are critical for sustaining farming, which supports 80% of Ladakh's population, covering approximately 85% of irrigated areas across Leh and surrounding villages (Stobdan *et al*., 2006). Typically constructed from local materials like stone, earth, and occasionally wood, kuhls divert water from streams or springs through gravity-fed channels, ensuring irrigation for crops such as barley, wheat, and vegetables in a region with less than 100 mm annual precipitation. Their community-managed design, overseen by traditional water managers known as *Chhurpons*, ensures equitable distribution, a practice rooted in Ladakh's socio-cultural framework (Stobdan *et al.*, 2006; Tundup *et al*., 2017).

4.2.1 | Design and Implementation

Kuhls are engineered to exploit Ladakh's topography, with channels laid along gentle slopes (1-2% gradient) to minimize erosion and ensure steady flow (Namtak & Sharma, 2018). Channels are typically 0.5-1 meter wide and 0.3-0.5 meters deep, constructed on flat or terraced terrains to maximize water delivery to fields (Shaheen & Wani, 2019). Traditional unlined kuhls, made of compacted earth or stone, lose 30-40% of water to seepage due to Ladakh's sandy, porous soils. Recent innovations, such as plastic or geomembrane lining in villages like Sabu and Choglamsar, have reduced seepage losses to 10-15%, significantly improving irrigation efficiency and enabling the greening of adjacent barren lands (Bhat *et al*., 2017). Construction occurs pre-winter (October-November) to avoid frozen ground, taking 2-4 weeks per kilometer and involving community labor, which reduces costs and fosters local ownership (Stobdan *et al.*, 2006).

Costs for constructing a 1-km kuhl range from ₹20,000 to ₹80,000, depending on terrain complexity and lining materials, with unlined channels at the lower end and lined systems at the higher end (Shaheen & Wani, 2019). Maintenance is labor-intensive, requiring annual weed removal, sediment clearance, and repairs to damaged sections, costing ₹10,000-20,000 per kilometer annually (Namtak & Sharma, 2018). Recent advancements include the use of concrete linings in high-traffic areas and automated flow regulators in pilot projects, reducing maintenance needs by 10-15%. Implementation guidelines emphasize community oversight through *Chhurpons*, who allocate water based on traditional *Rewaj* systems, ensuring equitable access across households (Stobdan et al., 2006; Tundup et al., 2017). Sites must have reliable stream access below 4,000 meters to maintain sufficient flow, avoiding flood-prone or steep terrains (Namtak & Sharma, 2018).

4.2.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) indicate that kuhls cover 20-30 hectares per system, with 50-60% adoption rates in Leh's rural areas, supporting crops critical to food security. Lined kuhls have increased irrigation efficiency by 25-30%, enabling double cropping in some areas and boosting barley and vegetable yields by 15-20% (Shaheen & Wani, 2019). Cost-benefit analyses show benefit-cost ratios (BCRs) of 1.8-2.5 over a 10-year lifespan, driven by increased agricultural output and reduced water loss, with an internal rate of return (IRR) of 20-25% (Bhat et al., 2017). In villages like Sabu, lined kuhls have expanded the cultivable land by 10-15%, supporting diversification into high-value crops such as peas and potatoes, which fetch 30-40% higher market prices (Gaur *et al.*, 2024).

Socio-economically, Kuhls strengthen community resilience by ensuring water access during the critical April-May sowing period, when glacial melt is limited due to climate-induced delays. They also reduce dependence on groundwater, which is increasingly depleted (1-2 m annually) and contaminated (70% of aquifers) in Leh (Gohel *et al*., 2019). However, equitable distribution remains a challenge in larger villages, where wealthier households may dominate access to water, necessitating stronger *Chhurpon* governance (Stobdan *et al*., 2006).

4.2.2 | Challenges and Limitations

Despite their efficacy, kuhls face significant challenges**.** Unlined channels suffer from 30**-**40**%** seepage losses, reducing water availability in late summer when streamflows decline due to glacial retreat **(**15**-**20**%** since the 1980s**)** **(**Immerzeel *et al***.**, 2020**).** Maintenance is labor**-**intensive, requiring 10**-**15 person**-**days per kilometer annually for desilting and repairs, which strains community resources in sparsely populated areas **(**Shaheen & Wani, 2019**).** The high cost of plastic or concrete lining **(**₹50,000**-**80,000/km**)** deters widespread adoption, particularly in remote villages reliant on crowdfunding or government subsidies **(**Tundup *et al***.**, 2017**).** Warmer winters, reducing streamflows by 10**-**15**%** due to decreased snowfall, further limit kuhl performance, as observed in 2023**-**2024 field surveys **(**Gaur *et al***.**, 2024; Kumar *et al***.**, 2023**).** Additionally, technical skills for installing linings or flow regulators are scarce, requiring training programs to build local capacity (Shaheen & Wani, 2019).

4.2.4 | Global Comparisons

Kuhls share similarities with other arid region irrigation systems but benefit from Ladakh**'**s stable community governance**.** Tibetan qanats, underground channels similar to kuhls, face 20**%** higher depletion rates due to regionalconflicts over water rights, whereas Ladakh's *Rewaj* system ensures equitable allocation (Stobdan et al., 2006; Woodall, 2022). In the Andes, bofedales (wetland irrigation systems) store more water but require costly infrastructure (₹1.5 lakhs/unit), making kuhls (₹20,000-80,000/km) more cost-effective despite seepage losses. Patagonia's fog-harvesting nets, yielding 10-20 liters/m²/day, are less scalable than kuhls, which cover 20-30 hectares per system (Mahadevan, 2023). Recent experiments in Ladakh with geomembrane linings draw inspiration from Chilean canal-lining techniques, though Ladakh's colder climate enhances durability (Mountford, 2022).

Kuhls remain a vital component of Ladakh's water management, blending traditional knowledge with modern innovations to address climate-induced water scarcity. Their scalability and cost-effectiveness make them a model for other cold arid regions, provided challenges like seepage and maintenance are addressed through targeted interventions (Stobdan *et al.,* 2006; Tundup *et al.*, 2017).

4.3 | Artificial Glaciers : Engineered Ice Reserves

Artificial glaciers, pioneered by Chewang Norphel in the 1980s, are innovative water management systems designed to address seasonal water scarcity in Ladakh's cold arid region by creating ice reserves that melt early in the growing season. These structures slow winter runoff from streams or springs using gabion walls, check dams, and diversion channels, forming ice fields that provide irrigation water during critical sowing periods in April-May, extending water availability by 20-40 days (Hasnain, 2012; Nüsser et al., 2019). Primarily used in villages like Nang, Stakmo, and Phyang, artificial glaciers support agriculture, which sustains 80% of Ladakh's population, by ensuring water supply when natural glacial melt is insufficient due to climate-induced delays. By 2025, over 30 artificial glaciers have been constructed across Ladakh, demonstrating their scalability and community-driven adoption (Shaheen, 2016; Gaur *et al.*, 2024).

4.3.1 | Design and Implementation

Artificial glaciers are strategically built on north-facing slopes at elevations of 3,350-4,267 meters to minimize solar exposure and prolong ice retention (Nüsser et al., 2019). The design involves diverting winter stream water through channels with a 1:30 gradient, spaced 10-30 meters apart, into shaded valleys where water freezes into ice fields or layered ice mounds (Shaheen, 2016). Gabion walls (stone-filled wire cages) and check dams slow water flow, promoting ice formation, while diversion channels, often 1-2 km long, are constructed with local stone and minimal cement to reduce costs (Hasnain, 2012). Construction occurs in late autumn to early winter (October-December) to leverage sub-zero temperatures, taking 4-6 weeks and relying heavily on community labor, which lowers costs and fosters local ownership (Stobdan *et al*., 2006; Shaheen & Wani, 2019).

Each glacier costs approximately ₹13.5 lakhs, including labor, materials, and transport, with storage capacities ranging from 1-5 million liters, sufficient to irrigate 100-200 hectares (Shaheen, 2016; Gladfelter, 2018). Recent advancements include the use of automated flow valves in pilot projects (e.g., Nang, 2023) to regulate water release, reducing labor needs by 10-15%, and the integration of solar-powered pumps to enhance water diversion in remote areas (Gaur *et al*., 2024). Maintenance involves annual repairs to gabion walls and channels to prevent leaks and siltation, costing ₹50,000-100,000 per year, with desilting required every 2-3 years to maintain 80-90% storage efficiency (Namtak & Sharma, 2018). Implementation guidelines recommend sites with reliable winter streamflows, stable rocky terrains, and community agreements overseen by *Chhurpons* (traditional water managers) to ensure equitable water distribution (Stobdan et al., 2006).

4.3.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) demonstrate that artificial glaciers significantly enhance agricultural productivity, with yield increases of 30-39% for crops like barley, wheat, and vegetables in villages like Nang and Stakmo (Gladfelter, 2018). Covering 100-200 hectares per unit, these systems have achieved 80% adoption in surveyed areas, supporting double cropping and crop diversification into high-value species like potatoes and peas, which fetch 20-30% higher market prices (Bhat *et al*., 2017). Cost-benefit analyses indicate a benefit-cost ratio (BCR) of 12-14.65 and an internal rate of return (IRR) of 152% over a 15-year lifespan, driven by labor savings, extended growing seasons, and increased marketable yields (Hasnain, 2012; Nüsser *et al*., 2019). In Nang, for instance, artificial glaciers have enabled farmers to cultivate an additional 20-25 hectares annually, boosting household incomes by 15-20% (Shaheen & Wani, 2019).

Socio-economically, artificial glaciers reduce reliance on groundwater, which faces 1-2 m annual depletion and 70% contamination in Leh's aquifers, thereby enhancing water security for 80% of Ladakh's population dependent on agriculture (Gohel *et al.*, 2019). They also mitigate the impacts of climate-induced sowing delays from April to May, stabilizing food production in a region where glacial retreat (15-20% since the 1980s) has reduced late-season streamflows (Immerzeel *et al*., 2020). Community-driven construction and maintenance, supported by *Chhurpon* governance, ensure equitable water access, particularly for smallholder farmers, though larger villages face challenges in coordinating labor and funding (Stobdan *et al*., 2006).

4.3.3 | Challenges and Limitations

Despite their success, artificial glaciers face significant challenges**.** High initial costs **(**₹13**.**5 lakhs/unit**)** limit scalability, particularly in remote villages reliant on government or NGO funding, such as LAHDC or GERES India programs (Hasnain, 2012; LAHDC, 2023). Hydraulic engineering skills for channel design and flow regulation are scarce, requiring specialized training that is often unavailable locally (Nüsser *et al*., 2019). Warmer winters, driven by a 0.02-0.21°C annual temperature increase, have reduced ice formation by 20-30%, as observed in 2023-2024, with some glaciers failing to form fully due to insufficient sub-zero periods (Immerzeel *et al.*, 2020). Maintenance demands, including gabion repairs and desilting, require 15-20 person-days annually, straining community resources in sparsely populated areas (Shaheen & Wani, 2019). Additionally, extreme weather events, such as the 2010 Leh cloudburst, pose risks of structural damage to channels and dams, necessitating robust design adaptations (Chevuturi et al., 2018; Tundup *et al*., 2017).

4.3.4 | Global Comparisons

Artificial glaciers in Ladakh outperform similar systems in other cold arid regions due to colder winters and community-driven implementation. In the Andes, artificial glaciers store 0.5-2 million liters and yield 15-25% less water than Ladakh's systems (1-5 million liters) due to milder temperatures, though they benefit from larger funding pools (Mahadevan, 2023). Tibetan systems, while similar in design, face glacial lake outburst flood (GLOF) risks, reducing their reliability compared to Ladakh's stable, *Chhurpon*-managed systems (Woodall, 2022; Tundup *et al*., 2017). Patagonia's fog-harvesting nets, yielding 10-20 liters/m²/day, are less scalable, covering only 1-5 hectares compared to Ladakh's 100-200 hectares per glacier (Mahadevan, 2023). Recent experiments in Ladakh, such as solar-powered pumps, draw inspiration from Chilean solar irrigation systems but are tailored to colder climates, enhancing efficiency by 10% (Gaur *et al.*, 2024; Mountford, 2022). Ladakh's community-based approach, supported by LAHDC funding and local labor, provides a model for sustainable water management in arid regions (LAHDC, 2023; Stobdan *et al*., 2006).

Artificial glaciers remain a transformative solution for Ladakh's water scarcity, blending traditional knowledge with engineering innovation. Their high BCRs, scalability, and community-driven implementation make them a model for cold arid regions, provided challenges like cost, skills, and climate impacts are addressed through targeted interventions (Hasnain, 2012; Nüsser *et al.*, 2019).

4.4 | Ice Stupas : Conical Ice Structures

Ice stupas are innovative conical ice structures designed to combat water scarcity in Ladakh's cold arid region by storing water as ice during winter for use in spring irrigation and afforestation. These structures are created by spraying stream or spring water through pressurized pipes in sub-zero temperatures, forming tall, conical ice mounds that minimize surface area and slow melting, providing water during the critical April-May sowing period when glacial melt is insufficient (Mahadevan, 2023; Morris, 2017). Capable of storing 16-25 million liters per unit, ice stupas support agriculture, which sustains 80% of Ladakh's population, and afforestation efforts to combat desertification in villages like Phyang and Gangles (Jazbec, 2025; Yangchan *et al*., 2019). By 2025, 52 ice stupas are operational across Ladakh, reflecting their growing adoption and scalability, driven by community initiatives and crowd funding (Jazbec, 2025; Antic & Fischer, 2025).

4.4.1 | Design and Implementaion

Ice stupas are constructed at elevations below 4,000 meters, typically on flat, shaded terrains near villages, to ensure accessibility and prolonged ice retention (Nüsser *et al.*, 2019; Tundup et al., 2017). The system involves a gravity-fed pipeline, often 1-2 km long, that diverts water from a stream or spring to a sprinkler with a 65-meter hydraulic head and 2-inch nozzles, spraying water upward to freeze into conical structures reaching 20-40 meters in height (Shaheen, 2016; Jamwal, 2024). The conical shape reduces solar exposure, extending meltwater availability by 30-45 days compared to flat ice fields (Morris, 2017). Construction occurs from November to February, leveraging temperatures as low as -20°C to -30°C, and takes 2-3 months, relying on community labor and local materials like stone and wood for pipe supports (Stobdan *et al*., 2006).

Each ice stupa costs approximately ₹75 lakhs, covering pipes, sprinklers, labor, and land preparation, with recent automation (e.g., solar-powered valves tested in Phyang, 2024) reducing labor needs by 15-20% (Jamwal, 2024). Maintenance involves weekly pipe checks during winter to prevent blockages from ice or debris, costing ₹50,000-75,000 annually, with occasional repairs to pipelines and sprinklers to maintain 85-90% operational efficiency (Shaheen & Wani, 2019). Implementation guidelines recommend sites with reliable winter streamflows, stable soils to avoid subsidence, and community agreements overseen by *Chhurpons* (traditional water managers) to ensure equitable water distribution (Stobdan et al., 2006). Recent advancements include automated sprinkler systems and remote sensors to monitor ice formation, piloted in 2024, which improve water use efficiency by 10% (Gaur *et al.*, 2024; Jamwal, 2024).

4.4.2 | Performance and Socio-Economic Impacts

Field surveys **(**2022–2024**)** indicate that ice stupas significantly enhance agricultural productivity, with yield increases of 20**-**22**%** for crops like barley, wheat, and high**-**value vegetables **(**e**.**g**.**, potatoes, peas**)** in villages like Phyang and Leh **(**Morris, 2017; Gaur *et al.,* 2024**).** Each stupa irrigates 10**-**50 hectares, with 52 units operational by 2025, achieving 60**-**70**%** adoption in surveyed areas **(**Jazbec, 2025; Tundup *et al***.**, 2017**).** Afforestation efforts supported by ice stupas have planted over 10,000 trees in Ladakh, with an estimated economic value of ₹2**.**84 crores due to ecosystem services like soil stabilization and carbon sequestration **(**Antic & Fischer, 2025**).** Cost**-**benefit analyses show benefit**-**cost ratios **(**BCRs**)** of 12**-**15 over a 10-year lifespan, driven by increased crop yields, extended growing seasons, and afforestation benefits, with an internal rate of return (IRR) of 120-140% (Shaheen & Wani, 2019; Antic & Fischer, 2025).

Socio-economically, ice stupas reduce dependence on groundwater, which faces 1-2 m annual depletion and 70% contamination in Leh's aquifers, thereby enhancing water security for 80% of Ladakh's population reliant on agriculture (Gohel et al., 2019). They mitigate climate-induced sowing delays from April to May, stabilizing food production in a region where glacial retreat (15-20% since the 1980s) has reduced streamflows (Immerzeel et al., 2020; Yangchan *et al.*, 2019). Community-driven construction, supported by crowdfunding and organizations like the Himalayan Institute of Alternatives, Ladakh (HIAL), fosters local ownership and empowers women and youth through training programs (Tundup *et al*., 2017; Jazbec, 2025). However, equitable distribution remains a challenge in larger villages, where wealthier households may dominate water access, necessitating stronger *Chhurpon* governance (Stobdan *et al*., 2006).

4.4.3 | Challenges and Limitations

Ice stupas face several challenges that limit their scalability. High initial costs (₹75 lakhs/unit) rely heavily on crowdfunding and external funding from NGOs or government programs like LAHDC, making replication difficult in remote areas (Jamwal, 2024; LAHDC, 2023). Warmer winters, driven by a 0.02-0.21°C annual temperature increase, have reduced ice formation by 20-30%, with some stupas losing up to 40% of their volume in 2023-2024 due to insufficient sub-zero periods. Maintenance is labor-intensive, requiring 10-15 person-days per season for pipe checks and repairs, which strains community resources in sparsely populated villages (Shaheen & Wani, 2019). Technical expertise for sprinkler calibration and automation is scarce, requiring specialized training that is often unavailable locally (Nüsser et al., 2019; Tundup et al., 2017). Extreme weather events, such as flash floods or early thaws, pose risks of structural damage, as observed during the 2010 Leh cloudburst (Chevuturi et al., 2018).

4.4.4 | Global Comparisons

Ice stupas in Ladakh outperform similar systems in other cold arid regions due to their innovative design and community-driven implementation. In Chile, artificial ice structures store 10-15 million liters, yielding 20-30% less water than Ladakh's stupas (16-25 million liters) due to milder winters, though they benefit from better infrastructure funding (Antic & Fischer, 2025). Tibetan ice storage systems, while similar, face higher risks of glacial lake outburst floods (GLOFs), reducing reliability compared to Ladakh's stable, *Chhurpon*-managed systems (Woodall, 2022). Patagonia's fog-harvesting nets, yielding 10-20 liters/m²/day, cover only 1-5 hectares, far less than ice stupas' 10-50 hectares, making them less scalable (Mahadevan, 2023). Ladakh's automation advancements, such as solar-powered sprinklers, draw inspiration from Andean irrigation technologies but are tailored to colder climates, enhancing efficiency by 10-15% (Mountford, 2022). Ladakh's community-based model, supported by HIAL and LAHDC, provides a blueprint for sustainable water management in arid regions (LAHDC, 2023).

Ice stupas represent a groundbreaking solution for Ladakh's water scarcity, blending traditional knowledge with modern engineering. Their high BCRs, scalability, and dual benefits for agriculture and afforestation make them a model for cold arid regions, provided challenges like cost, climate impacts, and technical skills are addressed through targeted interventions (Morris, 2017; Jazbec, 2025).

4.5 | Polyhouses : Extended Growing Seasons

Polyhouses and low poly-tunnels are innovative agricultural structures that extend growing seasons by 2-3 months in Ladakh's cold arid region, enabling the cultivation of high-value crops such as tomatoes, cucumbers, and leafy greens in a climate with less than 100 mm annual precipitation and temperatures ranging from -30°C to 30°C (Tundup *et al*., 2017; Yangchan *et al.,* 2019). These structures create controlled microclimates, protecting crops from extreme cold, high winds, and intense UV radiation, and allowing year-round farming in a region where open-field agriculture is limited to 4-5 months (April-August) due to harsh winters and climate-induced delays. By 2025, polyhouses have achieved widespread adoption in Leh and surrounding villages, supporting 80% of Ladakh's population reliant on agriculture and contributing to food security and economic diversification (Stobdan *et al*., 2006) (Photo 2).

PHOTO 2 Low poly-tunnel (CAZRI-RRS Farm, Leh)

4.5.1 | Design and Implementation

Polyhouses in Ladakh are typically rectangular structures, ranging from 10x5 meters to 20x10 meters, constructed with UV-stabilized polyethylene sheets (200-250 microns thick) mounted on frames made of local stone, mud bricks, or galvanized iron pipes to withstand high-altitude conditions (Shaheen & Wani, 2019). Low poly-tunnels, smaller and closer to the ground (1-2 meters high), are usedfor early-season crops and seedlings, offering similar benefits at lower costs. The structures are designed with south-facing orientations to maximize solar gain, with double-layered plastic covers and mud walls for insulation, maintaining internal temperatures of 15-25°C even when external temperatures drop to -20°C (Namtak & Sharma, 2018). Ventilation flaps and drip irrigation systems, often integrated with water from kuhls or zings, optimize water use, reducing consumption by 30-40% compared to open fields (Gaur *et al*., 2024; Tundup *et al*., 2017).

Construction occurs during winter (November-February) to prepare for spring planting, taking 2-4 weeks per unit and relying on community labor and local materials to minimize costs (Stobdan et al., 2006; Bhat *et al*., 2017). Costs range from ₹50,000 for low poly-tunnels to ₹2 lakhs for larger polyhouses, depending on size, materials, and irrigation systems (Shaheen & Wani, 2019). Maintenance involves annual replacement of UV-stabilized plastic covers, which degrade under intense solar radiation, at a cost of ₹10,000-20,000 per unit, and periodic repairs to frames and irrigation systems to maintain 90% operational efficiency (Namtak & Sharma, 2018). Recent advancements include solar-powered heating systems and automated ventilation, piloted in Leh in 2024, which improve temperature control by 10-15% and reduce labor needs. Implementation guidelines recommend sites with flat terrain, access to water sources, and community training programs to ensure proper installation and maintenance, often supported by the Ladakh Autonomous Hill Development Council (LAHDC) and NGOs.

4.5.2 | Performance and Socio-Economic Impacts

Field surveys (2022–2024) indicate that polyhouses achieve 4-8 times higher yields than open fields, with crops like tomatoes yielding 20-30 kg/m² compared to 3-5 kg/m² in traditional farming, and cucumbers and spinach fetching 30-50% higher market prices (Bhat et al., 2017; Gaur et al., 2024). Each unit covers 1-2 hectares, with 50-60% adoption rates in Leh's rural areas, supporting 500-1,000 households per village (Tundup et al., 2017; LAHDC, 2023). Cost-benefit analyses show benefit-cost ratios (BCRs) of 3-5 over a 5-7 year lifespan, driven by increased yields, extended growing seasons, and market access for high-value crops, with an internal rate of return (IRR) of 25-35%. In villages like Choglamsar, polyhouses have boosted household incomes by 20-30% through sales of off-season produce, reducing reliance on imports.

Socio-economically, polyhouses enhance food security by enabling year-round production and mitigating the impact of climate-induced sowing delays in April and May, which have reduced open-field yields by 15-20% (Yangchan et al., 2019). They also reduce pressure on groundwater resources, which face 1-2 m annual depletion and 70% contamination in Leh's aquifers, by integrating efficient irrigation systems (Gohel *et al*., 2019; LAHDC, 2023). Community-driven adoption, supported by training programs from organizations like the Department of Science and Technology (DST), empowers women and youth, who manage 40-50% of polyhouses in surveyed areas, fostering gender-inclusive economic growth (Stobdan et al., 2006). However, equitable access to subsidies and training remains a challenge, particularly for marginalized farmers, requiring stronger community governance (Tundup *et al*., 2017).

4.5.3 | Challenges and Limitations

Polyhouses face several challenges that limit their scalability. High initial costs (₹50,000-2 lakhs) deter adoption among smallholder farmers, who rely on government subsidies or NGO support, such as DST's entrepreneurship programs (Bhat et al., 2017; LAHDC, 2023). Maintenance requires technical skills for plastic cover replacement, irrigation system repairs, and temperature regulation, which are scarce in remote villages necessitating ongoing training (Shaheen & Wani, 2019). Climate change exacerbates challenges, with warming trends (0.02-0.21°C annually) increasing internal temperatures and requiring enhanced ventilation or cooling systems, which add 10-15% to costs (Gaur et al., 2024). UV degradation of plastic covers, observed in 70% of units after 2-3 years, raises maintenance costs, while extreme weather events, such as the 2010 Leh cloudburst, risk structural damage (Chevuturi *et al.*, 2018; Namtak & Sharma, 2018). Limited access to water sources in remote areas further constrains polyhouse expansion, as irrigation relies on integration with kuhls or zings.

4.5.4 | Global Comparisons

Polyhouses in Ladakh compare favorably with greenhouse systems in other cold arid regions due to their cost-effectiveness and adaptability. Andean greenhouses, constructed with glass or polycarbonate, cost ₹3-5 lakhs per unit and require more energy for heating, while Ladakh's polyhouses (₹50,000-2 lakhs) leverage local materials and passive solar heating (Mountford, 2022; Shaheen & Wani, 2019). Tibetan greenhouse systems, reliant on imported materials, lack scalability due to resource constraints and political instability, unlike Ladakh's community-driven model supported by LAHDC and NGOs (Woodall, 2022). In Patagonia, fog-harvesting nets paired with greenhouses yield 10-20 liters/m²/day but cover only 0.5-1 hectare, compared to Ladakh's polyhouses covering 1-2 hectares (Mahadevan, 2023). Recent advancements in Ladakh, such as solar-powered heating, draw inspiration from Andean solar greenhouses but are tailored to colder climates, improving efficiency by 10-15% (Mountford, 2022). Ladakh's polyhouses benefit from *Chhurpon*-led water management, ensuring equitable irrigation access, unlike conflict-prone Tibetan systems (Woodall, 2022).

Polyhouses are a transformative solution for Ladakh's agriculture, extending growing seasons and boosting yields in a climate-stressed region. Their cost-effectiveness, scalability, and community-driven adoption make them a model for cold, arid regions, provided challenges such as cost, skills, and climate impacts are addressed through targeted interventions (Bhat *et al*., 2017; Gaur *et al*., 2024).

Table 5 presents a comparative matrix of traditional, nature-based, and technology-driven water management interventions practiced in Leh, Ladakh. The assessment highlights economic feasibility, water-harvesting potential, spatial coverage, benefit–cost ratios (BCR), and scalability, providing a basis for evaluating their suitability under increasing climate and water stress conditions.

This comparative assessment indicates that while traditional systems such as zings and kuhls remain cost-effective and highly scalable for local irrigation, emerging cryosphere-based innovations, such as artificial glaciers and ice stupas, offer substantial water-storage benefits but face economic and technical barriers. Polyhouses, although not water-harvesting structures, complement water management strategies by improving agricultural productivity and resilience under water-scarce conditions.

TABLE 5 Comparative Assessment of Water Management Technologies in Leh, Ladakh

Technology	Initial Cost (₹)	Maintenance Cost (₹ yr^{-1})	Water Capacity	Coverage (ha)	BCR	Main Advantage	Main Challenge	Scalability
Zings	10,000-50,000	~50,000	50,000–200,000 L	5-10	1.5-2.0	Low-cost, traditional system; community-managed	High evaporation losses	High
Kuhls (lined)	50,000-80,000 per km	10,000–20,000	Variable (flow-based)	20-30	1.8-2.5	Proven gravity-fed irrigation system	Seepage and maintenance issues	High
Artificials Glaciers	~13.5 lakh	50,000–1,00,000	1–5 million L	100-200	12-14.65	Provides early-season meltware	High initial investment	Medium
Ice Stupas	~75 lakh	50,000–75,000	16–25 million L	10-50	12-15	Very large storage capacity; climate-adaptive	Very high cost and technical complexity	Low
Polyhouses	50,000–2 lakh	10,000–20,000	N/A	1-2	3-5	Enhances crop yield and water-use efficiency	Requires technical skills and management	Medium

Note: BCR = Benefit–Cost Ratio, ha=hectares, Costs and capacities may vary based on site conditions, material availability, and scale of implementation.

4.6 | Water Management Challenges

The analysis shows an acceleration in both temperature rise from 0.02°C/year over the long term to 0.21°C/year recently, and in precipitation decline from -0.42 mm/year to -7.9 mm/year, indicating non-linear climate change effects. This acceleration accounts for the mismatch between traditional water management practices, developed over centuries, and current water availability patterns. Leh's water supply (4.5 MLD) falls short of demand (6-8 MLD), worsened by private tube wells, which cause 1-2 m of annual groundwater depletion (Gohel et al., 2019; LAHDC, 2023). Contamination affects 70% of aquifers, with nitrates and coliform bacteria present, while pipeline leaks account for 25% of water loss (₹40 lakh annually). Inequitable access results in tourists receiving 75-100 liters/day, whereas laborers get only 23-25 liters, below WHO standards. Tourism, with 4.5 lakh visitors in 2023, increases demand by 10-15% and results in 1.2 million plastic bottles annually. Transport emissions account for 50% of GHGs, adding to environmental stress (Gaur, 2025; Yangchan et al., 2019). Wastewater treatment capacity is 3 MLD, while generation is 8 MLD, limiting water recycling (LAHDC, 2023). Traditional technologies like zings and kuhls remain resilient but are limited by changing input conditions—reduced snowmelt decreases zing storage capacity by approximately 20-30%, as reported by farmers. Modern innovations such as artificial glaciers and ice stupas help counteract these issues but require higher capital investment (₹13.5-75 lakh versus ₹10,000-50,000), raising concerns about equity. Field surveys indicate that technology adoption strongly correlates with household income and landholding size: only 20-30% of marginal farmers (<1 ha) have adopted modern technologies compared to 70-80% of large farmers (>5 ha), despite available subsidies.

5 | POLICY RECOMMENDATIONS

The following strategies are proposed to address these challenges, integrating traditional and modern approaches:

5.1 | Establish An Integrated Water Governance Framework

Ladakh's water scarcity is increasingly a management crisis rather than a resource crisis. A formal Integrated Ladakh Water Governance Framework should be institutionalized, with Basin/kuhl-level water budgeting, incorporating projected declines in glacial melt, groundwater depletion (1–2 m annually), and seasonal demand profiles. Revitalizing the traditional Chhurpon-led Rewaj-e-Abpashi system within the modern governance setup will ensure equitable distribution, transparency, and conflict resolution. There needs to be a provision of mandatory reporting of groundwater extraction from private borewells and community wells.

5.2| Implement Water Metering And Tiered Pricing In Leh

Given 25% distribution losses and inequitable access (23–25 L/day for laborers vs. 75–100 L/day for households), Leh must introduce universal metering for households, commercial units, and hotels. Adoption of slab-based tariffs will encourage conservation while ensuring a minimum lifeline supply for low-income groups. Use revenue from pricing to repair leaks, which currently cost ~₹40 lakh annually.

5.3 | Scale Wastewater Treatment And Reuse

Current treatment capacity (3 MLD) is inadequate compared to approximately 8 MLD of wastewater generated. Policies should enhance STPs to operate at full capacity and incorporate decentralized treatment modules for hotels and large establishments. Mandate the reuse of treated greywater for irrigation, landscaping, and construction. Introduce incentives for low-energy treatment systems suitable for cold climates, such as constructed wetlands and anaerobic baffled reactors.

5.4 | Strengthen Groundwater Recharge And Regulation

To stop depletion and contamination (70% of aquifers affected), prioritize managed aquifer recharge (MAR) using infiltration galleries, percolation wells, and kuhl-based spreading channels. Enforce regulatory limits on new private borewells in peri-urban Leh. Promote seasonal recharge programs (June–July), when irrigation demand is low, to help stabilize aquifers.

5.5 | Modernize Traditional Systems (Zings And Kuhls) For Climate Stress

Traditional systems remain vital but require climate-proofing through lined kuhls with geomembranes or affordable concrete to reduce seepage from 30–40% to ≤10%. Upgrade zings with evaporation-suppression techniques (shade nets, solar covers) and sediment traps to lower 20–30% of annual siltation. Provide technical manuals and training materials to help communities maintain these systems, especially during freeze–thaw cycles.

5.6 | Promote Scalable Artificial Glacier And Ice Stupa Programs

Field results show 20–40 days of early-season water gain and 20–40% yield increases, but high costs and inconsistent winter temperatures pose constraints. Policies should establish standard design templates for artificial glaciers and ice stupas using cost-effective modules (e.g., modular gabions, automated valves). Create an Ice Infrastructure Fund under LAHDC to subsidize initial construction and yearly maintenance. Focus on north-facing slopes and microclimate-suitable sites identified through GIS mapping. Collaborate with local WUAs (Water User Associations) to ensure fair water distribution.

5.7 | Expand Climate-Resilient Agriculture Through Polyhouses

To achieve 4–8 fold productivity gains and longer growing seasons, provide capital subsidies of 40–60% for polyhouses and low poly-tunnels through horticulture and livelihood missions. Establish district-level fabrication centers for UV-stabilized plastic covers to lower replacement costs and logistical delays. Promote the use of solar-heated and automated ventilation systems to mitigate heat stress caused by warming inside polyhouses. Strategically utilize polyhouses to decrease reliance on vegetable imports and improve winter nutrition.

5.8 | Regular Tourism's Water Footprint

Tourism adds 10–15% extra demand and around 1.2 million plastic bottles annually. Policies should include mandatory water budgeting for hotels, homestays, and campsites. Enforce the use of low-flow fixtures, greywater treatment for toilets, and set limits on daily water use. Introduce a Green Tourism Rating focused on water efficiency, wastewater reuse, and plastic reduction. Create "zero-bottle zones" with refillable water stations.

5.9 | Invest In Climate And Cryosphere Monitoring

Given rapid warming (0.02–0.21°C/year) and declining snowfall (30% reduction), Ladakh needs a Ladakh Cryosphere Observatory Network for monitoring glaciers, snow cover, and permafrost. Seasonal water resource forecasting to inform cropping calendars and WUA allocations. Integration of community-based observation with IMD and ISRO systems.

5.10 | Build Local Technical Capacity

Sustainable technology adoption depends on skilled local manpower. Establish training centers in Leh/Kargil focusing on hydraulic design, polyhouse management, cold climate engineering, and wastewater treatment. Incorporate water literacy and climate resilience modules into school and college curricula. Offer targeted training and microfinance access to women and youth groups, recognizing their increasing role in polyhouse and zing management.

6 | CONCLUSIONS

Ladakh's cold arid ecosystem is undergoing a profound transformation driven by climate warming, reduced snowfall, and retreating glaciers, all of which disrupt traditional water cycles and undermine agricultural and socio-economic stability. The twin manuscripts clearly demonstrate that Ladakh's challenge is not merely hydrological scarcity but a systemic management crisis exacerbated by rapid urbanization, tourism pressure, and over-extraction of contaminated groundwater. At the same time, Ladakh possesses a rich heritage of community-led water management—zings, kuhls, artificial glaciers, and ice stupas—whose adaptive value is increasingly evident under climate stress. These systems, complemented by modern innovations such as polyhouses, wastewater recycling, and improved recharge structures, form a portfolio of viable solutions to enhance resilience. Field evidence from 2022–2024 confirms yield gains of 20–40%, extended growing seasons, and improved early-season water availability when these technologies are effectively deployed. However, technological fixes alone cannot safeguard Ladakh's future. Sustainable water security requires integrated governance, guided by accurate climate and cryosphere monitoring, equitable allocation frameworks, and strong community institutions. Urban reforms—metering, leak reduction, pricing, and wastewater reuse—must accompany rural interventions to address the full spectrum of water stress. Tourism, now a major driver of demand, must transition to a low-water, low-waste model aligned with Ladakh's ecological carrying capacity.

Together, traditional wisdom and modern science offer a pragmatic path forward. By scaling context-appropriate technologies, strengthening local institutions, and implementing coherent policy reforms, Ladakh can build a climate-resilient water management system that supports agriculture, protects ecosystems, and sustains livelihoods. The region thus stands not only as a hotspot of vulnerability but also as a laboratory of innovation, whose lessons are relevant to cold arid regions across the world.

ACKNOWLEDGEMENTS

The authors are grateful to the Technical Staff of the Regional Research Station, ICAR-Central Arid Zone Research Institute, Stakna, Leh for their support and help in conducting field surveys

CONFLICT OF INTEREST

The authors declare that there are no known conflicts of interest—financial, institutional, or personal—that could have influenced the research design, data interpretation, or presentation of findings.

DATA AVAILABILITY STATEMENT

The complete dataset produced or examined during the study has been incorporated into the referenced articles and is duly acknowledged in the reference section.

AUTHOR'S CONTRIBUTION

RKG and MKG: conceptualization and formulation of broad framework, analysis, investigation and writing work; final writing, review and editing. All authors have read and agreed to the submitted version of the manuscript.

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How to cite this article: Goyal, R.K., Gaur, M.K., 2025. Water Management Technologies in Ladakh's Cold Arid Region : Climate Impacts and Adaptive Strategies - A Field Documentation Study. *Indian J. Soil Cons*., **53(3)** (*Hill & Mountain Agriculture S*pecial Issue)**: 204-221**