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Research paper

Vanishing Glaciers, Emerging Crises: A Perception-Based Case Study of Water Scarcity in Ladakh

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ABSTRACT

Ladakh is a high-altitude cold desert whose agriculture, drinking water supply and ecosystems depend on glacier melt and seasonal snow. This study examines how local people perceive climatic and hydrological change, its socio-economic consequences, the role of tourism and urbanization, and the effectiveness of traditional and modern water management. A structured questionnaire was administered to 100 purposively selected respondents (40% farmers, 25% local residents, 20% tourism-related workers and 15% herders), and responses were analysed as percentages. Most respondents reported earlier glacier melting (80%), rising temperature (75%), reduced snowfall (68%) and a decline in drinking water availability (74%). Reduced irrigation (82%), falling income (75%), dependence on external food supply (75%) and food insecurity (73%) were widely reported. About 80% linked tourism and urbanization to rising water demand. Traditional systems (zings and kuhls) were well known (85%) and judged environmentally suitable (82%), yet 68% reported declining use. Ice Stupas were considered suitable for Ladakh by 85%, and 88% supported integrating traditional and modern methods. The findings are perception-based and drawn from a non-probability sample, but they point to a combined climatic and anthropogenic water crisis and support a participatory framework that integrates indigenous knowledge, modern technology and stronger regulation.

1. Introduction

Ladakh lies in the trans-Himalayan region of northern India. It receives very little precipitation and relies on glaciers and seasonal snowmelt to sustain river flow, groundwater recharge and irrigation. For centuries, communities adapted to this environment through indigenous institutions and structures, notably zings (small storage tanks) and kuhls (gravity-fed irrigation channels) managed by customary rules and water managers known as churpons.

This balance is now under strain. The Himalaya has warmed faster than the global average, causing glacier thinning, retreat and reduced snow cover (IPCC, 2021; Bolch et al., 2012). Because glaciers act as natural reservoirs that release meltwater in dry periods, their decline threatens river discharge during critical growing seasons and, with it, agriculture and food security. At the same time, tourism, urban growth and infrastructure development have raised water demand beyond sustainable limits, particularly in Leh and during the summer months when supply is

already limited. The consequences extend beyond hydrology to livelihoods, gender roles, social cohesion and the integrity of fragile wetland ecosystems.

Adaptation responses combine traditional knowledge with modern engineering. The best known is the Ice Stupa, an artificial glacier that stores winter water as ice and releases it in spring. Whether such measures are effective, scalable and socially accepted remains debated. Most studies of the region examine either glacier dynamics or social change; fewer connect physical change, livelihood impacts, human pressures and adaptation options through the experience of affected residents. This paper reports a case study that does so, and it has six objectives: (1) to examine climatic and hydrological trends and their relationship with glacial retreat; (2) to assess the impact of water scarcity on agriculture, livelihoods and food security; (3) to examine the contribution of tourism and urbanization; (4) to document traditional water management practices; (5) to evaluate Ice Stupas and other modern adaptation measures; and (6) to identify policy and community-based solutions.

2. Background: Glacial Change, Traditional Systems and Emerging Pressures

2.1 Glacial dynamics

The Himalayan region, often called the "Third Pole", holds one of the largest stores of ice outside the polar regions, and its rivers support hundreds of millions of people downstream (Immerzeel et al., 2010). In Ladakh, glacier retreat is spatially uneven: higher glaciers may retain some stability, whereas smaller, lower-altitude glaciers, which often contribute disproportionately to local supply, are shrinking quickly. Earlier snowmelt creates a mismatch between water availability and crop demand, and moraine-dammed lakes left by retreating ice raise the risk of glacial lake outburst floods. Black carbon deposited on ice lowers surface reflectivity and accelerates melting (Ramanathan and Carmichael, 2008). The concept of "peak water", the point at which meltwater contribution reaches its maximum before declining, is relevant because some catchments may already be approaching it (Huss and Hock, 2018).

2.2 Traditional systems and their erosion

Traditional systems in Ladakh capture glacial meltwater during peak flow and distribute it in rotation according to crop cycles. Their governance rests on customary rules, collective labour and cultural beliefs that treat water as a sacred, shared resource. Road construction, market integration, out-migration of younger people and a decline in collective labour are weakening these institutions, and with them the transmission of local knowledge. Women, who are traditionally responsible for household water, and marginal farmers and herders bear a disproportionate burden when water becomes scarce.

2.3 Tourism, urbanization and Ice Stupas

Tourism has become a major economic driver, but hotels, guesthouses and urban expansion in Leh increase groundwater extraction and waste generation during the season of lowest supply. Ice Stupas illustrate how traditional storage concepts can be combined with modern engineering. They are, however, limited in scale and need technical expertise, sustained support and community participation to remain effective.

3. Methodology

A mixed-methods design was planned in three phases: physical and environmental analysis, socio-economic assessment, and development of solutions. The empirical results reported here come from the household survey component. A structured questionnaire was administered to 100 respondents selected by purposive sampling to include people directly affected by water scarcity: farmers, herders, local residents and individuals associated with tourism. Most respondents belonged to rural areas. Items were statements on climate and hydrology, impacts, tourism and urbanization, traditional practices, modern measures and policy, to which respondents indicated agreement or disagreement. Responses were tabulated as frequencies and percentages. Participation was voluntary and based on informed consent, confidentiality was maintained and local customs were respected.

Percentages in this paper are the share of the 100 respondents who agreed with each statement; they are not mutually exclusive and therefore do not sum to 100. Because the data are perceptions from a non-probability sample, they indicate how residents experience the problem and cannot by themselves quantify glacier loss or discharge change.

4. Results

4.1 Respondent profile

Table 1 summarizes the sample. Men formed 60% and women 40% of respondents. Farmers were the largest group, consistent with the strong dependence of the local population on agriculture, and most respondents belonged to lower- and middle-income groups, indicating an economically vulnerable study population.

Table 1 Profile of respondents (n = 100)

Characteristic	Category (% of respondents)
Gender	Male 60; Female 40
Age group (years)	18–30: 25; 31–45: 35; 46–60: 25; above 60: 15
Occupation	Farmers 40; local residents 25; tourism-related 20; herders 15
Education	Illiterate 20; primary 25; secondary 30; higher 25
Family type	Joint 55; nuclear 45
Monthly income (₹)	Below 10,000: 30; 10,000–20,000: 35; 20,000–30,000: 20; above 30,000: 15

4.2 Climatic and hydrological change and glacial retreat

Respondents reported clear and consistent change (Fig. 1). Early glacier melting (80%), rising temperature (75%) and irregular rainfall (70%) were widely observed, together with reduced snowfall (68%), reduced stream flow (65%) and longer dry periods (60%). Seasonal water availability had decreased according to 72%, and 78% considered climate change to be affecting agriculture. Hydrological consequences were reported as a decrease in drinking water (74%), drying of local water bodies (71%), difficulty in accessing water (72%) and increased conflict over water within the community (58%).

Respondents also linked these changes explicitly to glaciers: 82% stated that glaciers are shrinking rapidly, 80% that rising temperature accelerates melting, 75% that glacial retreat affects water supply, and 73% that long-term water scarcity is linked to glacier loss. Only 60% considered communities to be aware of glacial change, suggesting a gap between lived experience and understanding of the underlying processes.

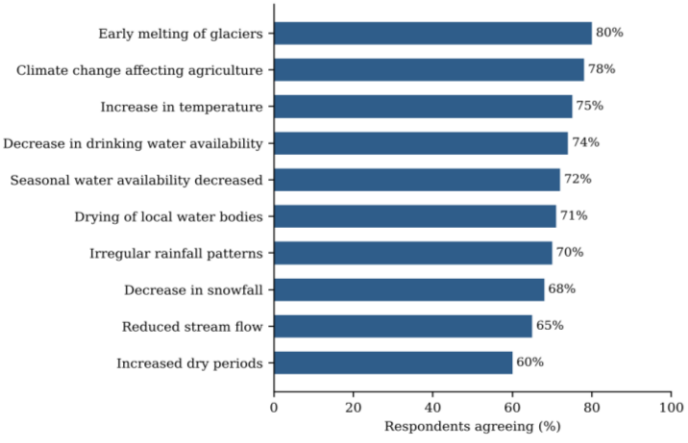


Fig. 1 Perceived climatic and hydrological changes (percentage of respondents agreeing)

4.3 Socio-economic impacts

Water scarcity was strongly associated with agricultural decline (Fig. 2). Reduced irrigation (82%), lower crop production (78%) and crops drying (76%) were the most frequent reports, followed by losses in horticulture (74%), higher farming costs (70%), reduced soil moisture (68%) and delayed sowing (65%). Livelihood effects were also substantial: 75% reported falling income, 74% difficulty sustaining their livelihood, 70% reduced livestock productivity, 68% loss of employment opportunities and 60% migration. Food security was affected, with 75% depending on external food supplies, 73% experiencing food insecurity, 72% reporting reduced food production, 70% higher food prices and 60% a decline in nutritional quality.

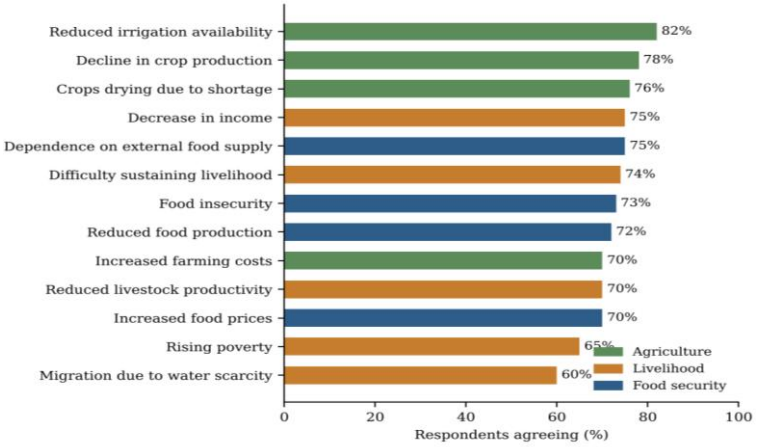


Fig. 2 Perceived socio-economic impacts of water scarcity on agriculture, livelihood and food security

4.4 Tourism and urbanization

Human pressures were seen as an important second driver (Table 2). Eighty-two percent agreed that tourism and urbanization together increase water demand and 78% that the crisis is worsening over time. Hotel consumption, seasonal shortages during peak tourist periods and overuse of groundwater were each reported by roughly three-quarters of respondents. Urban impacts included greater population pressure, higher consumption, construction activity affecting water sources, and pollution from urban waste.

Table 2 Perceived effects of tourism and urbanization on water resources

Statement	Respondents (%)
Tourism and urbanization together increase water demand	82
Increased water demand due to tourism	80
Water crisis is worsening over time	78
Seasonal shortages during tourist periods	78
Increased population pressure on water resources	78
Hotels consume large amounts of water	76
Overexploitation of water resources	76
Higher water consumption in urban areas	75
Construction activities affecting water sources	70
Pollution due to urban waste	69

4.5 Traditional systems and modern adaptation

Awareness of traditional systems was high (Table 3): 85% knew zings and kuhls, 75% used kuhls for irrigation and 70% used zings for storage, and 78% said the practices are passed down through

generations. They were judged suitable for the local environment (82%), helpful for conserving water (80%), supportive of agriculture (76%) and environmentally friendly (79%). Yet 70% cited the influence of modernization, 68% observed a decline in use, 65% lack of maintenance and 60% reduced community participation.

Modern measures were also well received. Around 78–80% of respondents were aware of Ice Stupas and 78% were interested in adopting modern methods. Eighty-five percent considered Ice Stupas suitable for Ladakh, 82% said they store water effectively and 80% that they reduce seasonal shortages. Support for combining the two approaches was strong, with 88% agreeing on integration.

Table 3 Assessment of traditional practices and modern measures

Indicator	Respondents (%)
Traditional: aware of zings and kuhls	85
Traditional: suitable for the local environment	82
Traditional: help conserve water	80
Traditional: environmentally friendly	79
Traditional: knowledge passed through generations	78
Traditional: usage declining	68
Traditional: lack of maintenance	65
Modern: Ice Stupas suitable for Ladakh	85
Modern: Ice Stupas store water effectively	82
Modern: Ice Stupas reduce seasonal shortages	80
Support for integrating traditional and modern methods	88

4.6 Policy and community solutions

Respondents called for stronger regulation (80%) and better planning and monitoring (78%), and 70% reported insufficient government support (Fig. 3). Community participation was considered essential by 85% and as improving water management by 84%. Awareness programmes (82%), conservation practices (88%), long-term planning (90%) and long-term water security (90%) received the strongest endorsement.

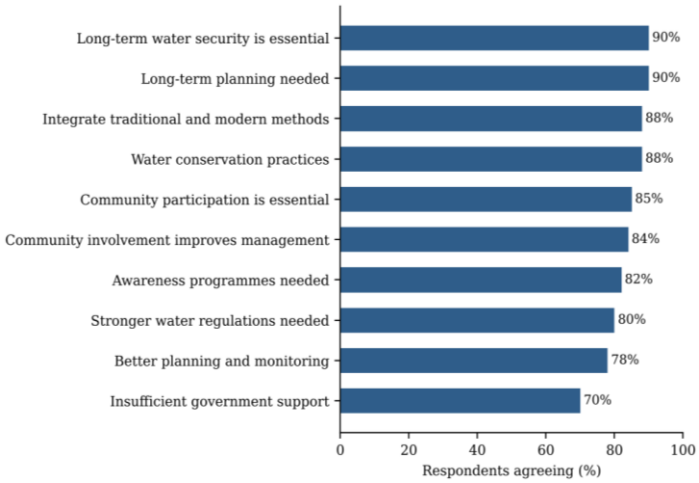


Fig. 3 Support for policy and community-based solutions

4.7 Summary of results by objective

Table 4 summarizes the principal finding for each objective. Taken together, the survey supports a clear chain from climatic change and glacial retreat to reduced water availability, then to agricultural, livelihood and food-security impacts, intensified by tourism and urbanization, and moderated by traditional and modern adaptation measures.

Table 4 Principal findings by objective

Objective	Principal finding
1. Climatic and hydrological trends	Early glacier melt (80%), warming (75%) and reduced stream flow (65%) widely reported; 82% see glaciers shrinking rapidly
2. Socio-economic impacts	Reduced irrigation (82%), falling income (75%), external food dependence (75%) and food insecurity (73%)
3. Tourism and urbanization	82% agree that together they increase water demand; 78% report seasonal shortages in tourist periods
4. Traditional systems	Well known (85%) and environmentally suitable (82%), but use is declining (68%) and maintenance is poor (65%)
5. Modern adaptation	Ice Stupas judged suitable (85%) and effective in storing water (82%); 88% support integration with traditional methods
6. Policy and community	80% want stronger regulation; 85% see community participation as essential; 70% report insufficient government support

5. Discussion

The results portray water scarcity in Ladakh as the product of interacting physical and human drivers. The pattern of perceived change, namely warming, reduced snowfall, earlier melt, falling stream flow and longer dry periods, is consistent with the glaciological literature on negative mass balance, earlier snowmelt and the approach of peak water (Immerzeel et al., 2010; Huss and Hock, 2018). That residents independently report these trends is valuable, since local observation can complement sparse instrumental records in remote high-altitude catchments. However, perception data cannot establish magnitude or causation, and the study should be read alongside hydrological monitoring and remote-sensing assessments.

The impact results show that scarcity is felt first in agriculture, then in income and food access. The high share of respondents dependent on external food supplies and reporting food insecurity indicates that water stress translates directly into household vulnerability, particularly because the sample is dominated by farmers and lower-income groups. Reports of conflict, employment loss and migration suggest erosion of social cohesion, a theme that deserves dedicated qualitative study.

Respondents attributed a large share of the pressure to tourism and urbanization, which raise demand at the time of year when supply is lowest.

This implies that adaptation cannot rely on supply-side storage alone; demand management, enforceable standards for hotels and construction, and planning of urban water infrastructure are also needed.

A notable finding is that traditional systems and modern interventions are not seen as competitors. Zings and kuhls are valued but declining through modernization, weak maintenance and lower participation, whereas Ice Stupas are viewed as effective and suitable. The 88% support for integration suggests acceptance of a hybrid model in which community institutions maintain and govern infrastructure, while modern technology and monitoring add capacity. The principal limitations are the small purposive sample, reliance on agreement-based items, the absence of site-level breakdown and the lack of measured hydrological data; the findings should therefore be treated as exploratory.

The findings also matter for environmental and occupational health. Reduced drinking water availability (74%) and difficulty in accessing water (72%) can compromise hygiene, sanitation and water quality, and longer collection distances add physical burden, especially for women. Farmers and herders, who dominate the sample, face occupational and economic stress as irrigation and pasture decline. Health outcomes and water quality were not measured in this study, so these implications should be tested in future work.

Table 4 Synthesis of drivers, survey evidence and adaptation responses

Driver or issue	Key survey evidence	Adaptation response
Glacier retreat and climate change	Early melt 80%; warming 75%; reduced snowfall 68%	Monitoring, early warning, rainwater harvesting
Agricultural water shortage	Reduced irrigation 82%; lower production 78%	Drip irrigation, Ice Stupas, revived kuhls
Livelihood and food insecurity	Income decline 75%; external food dependence 75%	Livelihood diversification, water-efficient farming support
Tourism and urban demand	Combined effect on demand 82%; seasonal shortage 78%	Water-use standards, urban water planning
Weakening traditional institutions	Declining use 68%; poor maintenance 65%	Community committees, churpon-led governance
Policy and governance gaps	Insufficient support 70%; stronger regulation 80%	Enforcement, inter-departmental coordination

6. Recommendations

1. Revive traditional systems. Repair and maintain zings and kuhls, support churpon-led governance and collective labour, and document elders' knowledge.

2. Scale modern storage carefully. Expand Ice Stupas with technical and financial support and local training, evaluating performance at each site.

3. Regulate tourism and urban demand. Set water-use standards and monitoring for hotels and commercial establishments, and plan urban water supply, drainage and waste management.

4. Improve agricultural efficiency. Promote drip and controlled irrigation, rainwater harvesting and conservation practices, with training and financial assistance.

5. Strengthen governance and monitoring. Form community water committees, enforce regulations, coordinate between departments and monitor water availability to give early warning of shortages.

6. Build awareness. Use schools, community centres and campaigns to promote conservation and understanding of glacial change.

7. Conclusion

Water scarcity in Ladakh is both an environmental and a socio-economic problem. Residents perceive warming, reduced snowfall, early glacier melt and declining stream flow, and they report serious consequences for irrigation, income, food security and community cohesion. Tourism and urbanization intensify the pressure. Traditional systems remain valued but are weakening, while Ice Stupas are viewed as promising yet limited in scale. Respondents strongly favour an integrated approach combining indigenous knowledge, modern technology, effective policy and community participation. Future work should pair perception surveys with measured hydrological and glaciological data, use probability sampling across districts, and evaluate the long-term performance of integrated management interventions.

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