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Review Article

ROLE OF GLACIERS IN INDIA'S WATER SUPPLY: A COMPREHENSIVE TECHNICAL REVIEW OF HIMALAYAN CRYOSPHERE HYDROLOGY, REGIONAL WATER SECURITY, AND CLIMATE-DRIVEN CHALLENGES

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Abstract

Glaciers of the Hindu Kush–Himalayan (HKH) region constitute one of the largest repositories of freshwater outside the polar ice caps and serve as the foundational water towers for approximately 1.3 billion people in the Indian subcontinent. This paper presents a comprehensive technical review of the hydrological role of Himalayan and Karakoram glaciers in sustaining India's major river systems — including the Ganga, Indus, Brahmaputra, Yamuna, Beas, Satluj, and Chenab — with particular emphasis on quantifying their contribution to seasonal water availability, agricultural irrigation, domestic water supply, and hydroelectric power generation. The review synthesises findings from four decades of glaciological research, remote sensing studies, hydrological modelling, and field-based mass balance measurements from the Indian Space Research Organisation (ISRO), Wadia Institute of Himalayan Geology (WIHG), Space Applications Centre (SAC), and international collaborators including the International Centre for Integrated Mountain Development (ICIMOD). Inventory data indicate that India's glacierised area spans approximately 75,000 km², comprising an estimated 9,575 individual glaciers primarily distributed across Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, and Sikkim. The paper quantifies the contribution of glacier meltwater to river flow, which ranges from 20% to 70% during the pre-monsoon and dry-season months across different river systems, demonstrating that glaciers function as a critical seasonal buffer, releasing stored water precisely when monsoon rainfall is absent. In the context of accelerating climate change, which has caused measurable and statistically significant glacier retreat across the HKH region at rates of 8–22 metres per year since the 1980s, the paper evaluates the long-term trajectories of glacier mass balance under IPCC RCP 4.5 and RCP 8.5 scenarios, and assesses the downstream consequences for water security, food production, and hydropower capacity. A suite of adaptation strategies — including high-altitude water storage, managed aquifer recharge, artificial glacier programmes, and demand-side agricultural water efficiency improvements — is reviewed and evaluated. The paper concludes that the intersection of demographic water demand growth, agricultural intensification, and accelerating cryosphere degradation represents a water security crisis of continental scale requiring immediate, coordinated policy and infrastructure responses.

Key Words: *Himalayan glaciers; glacier melt; Indian water supply; Ganga; Indus; Brahmaputra; cryosphere hydrology; climate change; glacier retreat; water security; Hindu Kush Himalaya; GLOF; ice-water towers*

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1. INTRODUCTION

Water its abundance, reliability, and seasonal predictability — has shaped the geography of Indian civilisation for millennia. The great north Indian rivers, venerated in ancient texts as the lifeblood of the subcontinent, draw a substantial portion of their flows not from monsoon rains alone but from the slow, steady release of frozen water stored in the glaciers of the Himalaya, Karakoram, and Hindu Kush ranges. This frozen inheritance — accumulated over thousands of years of snowfall compressed into ice — now faces an unprecedented threat from anthropogenic climate change, with consequences that extend far beyond the high- altitude landscapes where glaciers reside.

India is uniquely exposed to glacier-dependent water risk. The country's two most densely populated and agriculturally productive regions — the Indo-Gangetic Plain and the Indus basin — lie downstream of the world's most extensive temperate glacier systems outside Antarctica and Greenland. The Himalayan range contains approximately 15,000–18,000 glaciers; of these, some 9,575 are mapped within the political boundaries of modern India. Their combined ice volume, estimated at 3,400–4,800 km^3 of water equivalent, represents a stored water capital whose gradual depletion will fundamentally reshape India's hydrological future.

The importance of this review is anchored in a fundamental contradiction in glacier hydrology: glacier retreat initially increases meltwater flow — the so-called "peak water" phenomenon — before eventually reducing it as ice volumes become insufficient to sustain elevated summer runoff. India is currently approaching or has already passed the peak water threshold on several of its glacier-dependent tributaries, meaning that the temporary hydrological benefit of accelerated melting will give way to structural water deficits within decades. Understanding this trajectory, its timescales, its regional variation, and the magnitude of its consequences is the central purpose of the present review.

1.1 Definition and Classification of Himalayan Glaciers

Glaciers are perennial masses of ice, formed from the compaction and recrystallisation of accumulated snow over many decades to centuries, that deform and flow under their own weight. Himalayan glaciers are classified hydrologically into four primary categories relevant to water supply: (i) valley glaciers, which flow downslope into river valleys and are the primary source of meltwater to major rivers; (ii) cirque glaciers, which occupy high-altitude bowl-shaped depressions and contribute to headwater streams; (iii) piedmont glaciers, which spread onto flat terrain at valley bottoms; and (iv) ice fields, which cover extensive high-altitude plateaux and feed multiple outlet glaciers. The HKH region contains all four types, with valley glaciers being dominant contributors to India's river system flows.

1.2 Historical Context of Glacier–Water Relationships in India

The relationship between Himalayan glaciers and India's water supply has been understood in practical terms by Himalayan communities for centuries — reflected in the seasonal agricultural calendars of communities in Ladakh, Spiti, Kinnaur, and the upper Ganga basin, which historically timed their cropping patterns and irrigation schedules around the reliable onset of glacial meltwater in late spring and early summer. Scientific documentation began in earnest in the late nineteenth century with the Survey of India's triangulation campaigns, which first mapped major glaciers such as Gangotri and Zemu. Systematic mass balance measurements began in the 1970s at the Geological Survey of India and Wadia Institute of Himalayan Geology, providing the observational foundation on which contemporary climate change impact assessments are built.

2. GLACIER INVENTORY OF INDIA

A reliable and comprehensive inventory of India's glaciers is fundamental to quantifying their hydrological significance. Multiple inventory datasets now exist, with varying spatial coverage, resolution, and methodological approaches. The most comprehensive national dataset is the Glacier Atlas of India compiled by the Space Applications Centre (SAC), ISRO, using multi-temporal satellite imagery from IRS LISS-III, Landsat TM/ETM+, and Sentinel-2 sensors.

2.1 Spatial Distribution and Area Statistics

India's glacierised area of approximately 75,779 km² is distributed across five principal mountain zones: the Western Himalaya (Jammu & Kashmir and Ladakh), accounting for approximately 65% of total glaciated area; the Central Himalaya (Himachal Pradesh and Uttarakhand), comprising approximately 22%; and the Eastern Himalaya (Sikkim and Arunachal Pradesh), comprising the remaining 13%. The Karakoram ranges of northern Ladakh host some of the world's largest mid-latitude glaciers, including the 76-km Siachen Glacier, which represents the largest glacier in India and one of the most extensively studied high-altitude glaciers on Earth.

The SAC glacier inventory identifies 9,575 individual glaciers within India, compared to 8,511 in earlier surveys, with the difference attributable to improved mapping resolution rather than actual glacier multiplication. Size distribution follows a strongly right-skewed distribution: 75% of individual glaciers have areas below 1 km², while the 50 largest glaciers account for over 40% of total glaciated area. This size distribution has significant hydrological implications, as the smaller glaciers are far more responsive to temperature changes and are projected to disappear entirely within 20–40 years under current warming trajectories.

Glacier Name	**Location**	**Area (km²)**	**Max Elevation**	**Status / Retreat Rate**
Zemu Glacier	Sikkim, East Himalaya	26.0	7,100 m	Retreating ~20 m/yr
Gangotri Glacier	Uttarakhand, Garhwal	30.2	6,672 m	Retreating ~22 m/yr
Siachen Glacier	Ladakh, Karakoram	76.4	5,400 m	Marginally stable
Biafo Glacier	Ladakh, Karakoram	67.0	5,128 m	Slight retreat
Pindari Glacier	Uttarakhand, Kumaon	3.7	5,857 m	Retreating ~14 m/yr

Bara Shigri	Himachal Pradesh	25.0	4,850 m	Retreating ~10 m/yr
Kolahoi Glacier	Kashmir, Pir Panjal	11.5	4,700 m	Retreating ~8 m/yr
Milam Glacier	Uttarakhand, Kumaon	18.0	6,100 m	Retreating ~16 m/yr

2.2 Ice Volume Estimates and Water Equivalent

Accurate ice volume estimation requires either direct ground-penetrating radar (GPR) surveys or area–volume scaling relationships derived from GPR data. For the HKH region as a whole, Radić and Hock (2010) estimated total ice volume using the volume-area scaling equation:

$$V = c \times A^{\gamma}$$

Where V is ice volume (km³), A is glacier area (km²), c is an empirically derived scaling coefficient (0.0365 for mountain glaciers), and γ is the scaling exponent (1.375 for the HKH region, based on Bahr et al.'s analysis of GPR-calibrated datasets). Applying this relationship to India's 9,575 glaciers yields a total ice volume of approximately 4,200 ± 800 km³, equivalent to approximately 3,780 km³ of liquid water — roughly 12 times India's total annual freshwater consumption across all sectors.

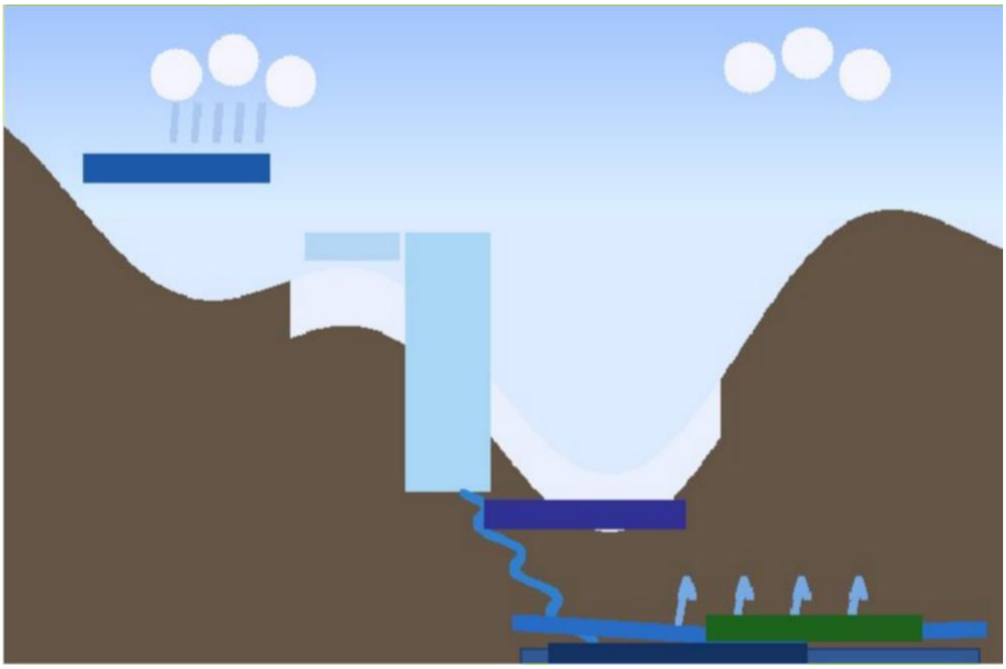
3. HYDROLOGICAL CONTRIBUTION OF GLACIERS TO INDIAN RIVERS

The quantification of glacier contribution to river flow is methodologically challenging because meltwater, rainfall, and groundwater baseflow arrive at a river gauging station as a combined stream that cannot be physically separated without isotopic or chemical tracer analysis. Three primary methods are used in the literature: (i) hydrological modelling using degree-day or energy-balance melt models; (ii) isotopic hydrograph separation using oxygen-18 (^{18}O) and deuterium ratios; and (iii) remote-sensing-based ice loss estimation combined with water balance modelling.

3.1 Seasonal Flow Patterns and Glacial Buffer Function

The most critical and perhaps most underappreciated contribution of glaciers to India's water supply is not their total annual volume but their temporal distribution. The Indian summer monsoon delivers 70–90% of annual precipitation between June and September, but agricultural water demand and domestic supply requirements are highest precisely in the pre-monsoon months of March through June, when rivers would otherwise be at their annual minimum flow. It is during this critical pre-monsoon period that glacier meltwater constitutes the dominant fraction of river flow, sustaining river levels that would otherwise be insufficient for irrigation, urban water supply, and ecological flow maintenance.

Studies using isotopic hydrograph separation on Ganges tributaries in Uttarakhand show that in May– June, glacier meltwater constitutes 35–65% of total discharge at high-altitude stations. By August, when the monsoon is in full progress, this proportion falls to 5–15%, as rainfall runoff dominates. By November– December, glacial melt has ceased and baseflow dominates, fed by groundwater recharged earlier in the year—itself partly sustained by glacial meltwater percolation. This buffering function of glaciers is analogous to a regulated reservoir operating without any human management or infrastructure cost.



Source : https://ndma.gov.in/

Figure 1: Schematic diagram of the Himalayan glacier hydrological cycle showing precipitation input, glacier storage, meltwater generation, river recharge, and groundwater percolation. Note the temporal offset between monsoon precipitation and dry-season melt delivery.

3.2 River-System Specific Contributions

Glacier contributions to individual river systems vary significantly with glacier coverage in the respective catchment, elevation, and regional climate. The following table provides quantitative estimates of glacier meltwater contribution for India's principal glacier-fed river systems.

River System	**Basin Area (km²)**	**Glacier Contribution (dry season)**	**Population Served**	**Primary Uses**
Ganga	505,000	25–45%	~600 million	Drinking water, irrigation, industry
Indus	321,289	40–60%	~300 million	Irrigation-dominant; Pakistan shared
Brahmaputra	651,334	30–50%	~130 million	Flood control & irrigation (Assam)
Yamuna	366,223	20–35%	~180 million	NCR Delhi primary supply
Beas	20,303	55–70%	~20 million	Punjab, Himachal irrigation
Chenab	28,240	50–65%	~25 million	J&K agriculture, hydropower
Satluj	22,275	45–60%	~18 million	Punjab plains irrigation

Source: https://www.hial.org

3.3 The Indus System: Highest Glacier Dependence

The Indus river system is more heavily dependent on glacier meltwater than any other major river in India. The upper Indus basin (above Attock) has glacier coverage of approximately 13%, and isotopic studies by Singh et al. (2016) estimate that glacier meltwater contributes 40–60% of total annual discharge at Srinagar, rising to 65–75% during pre-monsoon months when virtually all flow in the main stem is of glacial origin. The Chenab, Jhelum, and Beas — all tributaries originating in heavily glaciated catchments of Jammu & Kashmir and Himachal Pradesh — exhibit similar patterns.

For the approximately 10 million people in the Kashmir valley whose domestic water supply draws from the Jhelum and its tributaries, and for the 7 million hectares of irrigated agriculture in Punjab and Haryana served by the Indus canal system, this degree of glacier dependence is a profound and underappreciated vulnerability. A 50% reduction in glacier volume — a conservative projection for 2070 under RCP 8.5 — would reduce pre-monsoon Indus flows by an estimated 15–25%, a decline that current infrastructure has no capacity to compensate.

3.4 The Ganga System: Partial but Critical Contribution

The Ganga basin has lower fractional glacier coverage (approximately 7% in the headwater catchments) than the Indus, but its scale — serving approximately 600 million people — means that even a partial reduction in glacial contribution carries catastrophic water security implications. The Bhagirathi (Gangotri Glacier) and Alaknanda (Satopanth, Tipra Ban, Chaturangi glaciers) are the two main glacially fed tributaries of the Ganga's headwater reach.

An important nuance in Ganga glacier hydrology is the Gangotri Glacier — the largest individual glacier in the Ganga basin and the mythologically significant source of the Bhagirathi. Gangotri has retreated approximately 2.2 km since systematic measurement began in 1780 and is currently retreating at 22 metres per year. The glacier feeds directly into the Bhagirathi at Gangotri town (3,050 m altitude), and its meltwater is detectable isotopically at Rishikesh (372 m altitude) — a longitudinal distance of over 250 km — confirming that glacial meltwater remains a significant component of the Ganga's composition far into the plains.

3.5 The Brahmaputra: Glacial Contribution in a High-Rainfall Context

The Brahmaputra basin receives some of the world's highest monsoon precipitation — 2,000–4,000 mm annually in Assam and Arunachal Pradesh — and as a result the fractional contribution of glacier meltwater to annual discharge is lower (15–25%) than in drier western river systems. However, the importance of this contribution lies in the pre-monsoon period (March–May) when glacial melt sustains navigation, fisheries, and early Boro paddy cultivation in Assam. Tibetan plateau glaciers feeding the Yarlung Tsangpo (the upper Brahmaputra) also contribute significantly to dry-season flows that sustain base flows in the Indian reach of the river.

4. GLACIER RETREAT AND MASS BALANCE CHANGE

The empirical documentation of Himalayan glacier retreat constitutes one of the most extensively studied and methodologically diverse bodies of literature in contemporary earth sciences. Evidence sources include: direct field measurements of terminus positions; area change mapping from multi-temporal satellite imagery; mass balance measurements through stake networks and geodetic methods; GRACE (Gravity Recovery and Climate Experiment) satellite gravimetry providing regional ice mass change estimates; and modelling studies constrained by these observations.

4.1 Observed Retreat Rates (1980–2020)

A comprehensive analysis of 2,018 Himalayan glaciers using Landsat imagery by Kulkarni et al. (2011) at SAC, ISRO, documented an overall area reduction of 21% between 1962 and 2001, with a mean retreat rate that has accelerated from approximately 12 m/year in the 1980s to 20–25 m/year in the 2010s. The WIHG long-term monitoring program at Chorabari, Milam, and Pindari glaciers has recorded continuous annual retreat since 1990, with mean recession of 14–18 m per year over the 1990–2020 period.

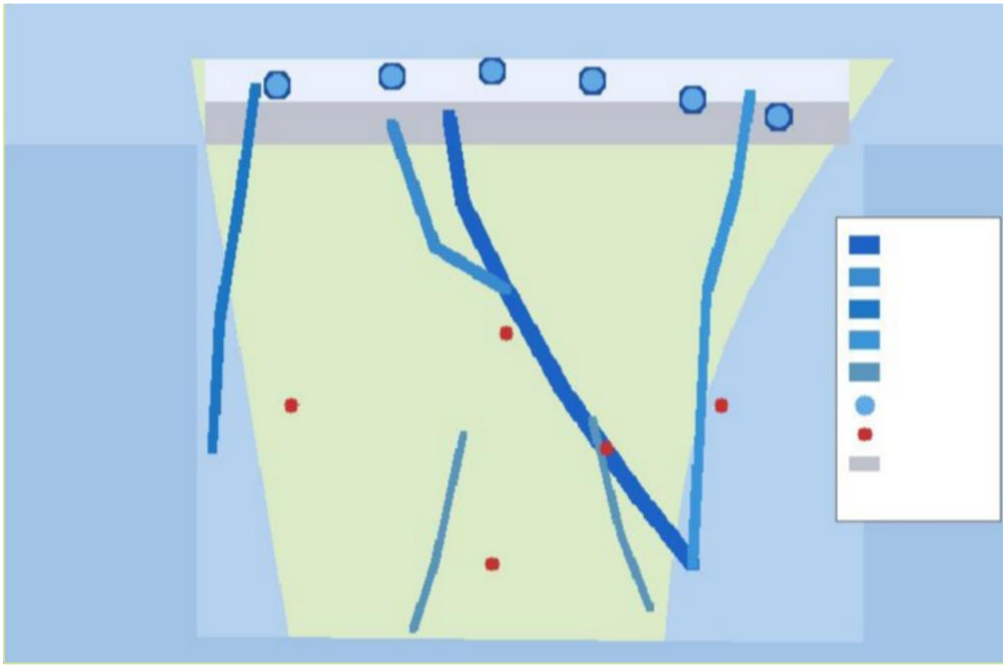


Figure 2: Schematic map of major glacier-fed river basins of India showing principal glacier locations (blue circles) in the Himalayan arc, main river corridors, and the approximate downstream extent of glacier-influenced water supply.
Glacier size is indicative, not to scale.

Soyrce: https://www.icimod.org/resource/hkh-assessment-report/

4.2 Mass Balance Measurements

While area and terminus retreat provide qualitative evidence of ice loss, quantitative water supply implications require mass balance data — the net gain or loss of ice expressed in metres of water equivalent per year. Long-term mass balance measurements from the WIHG network show that Indian Himalayan glaciers have maintained consistently negative mass balances since at least the 1980s, with a clear acceleration of ice loss from approximately −0.20 m w.e./yr in the 1980s to −0.65 m w.e./yr in 2015–2020. The Karakoram glaciers of northern Ladakh are a notable exception, exhibiting neutral to slightly positive mass balances due to increased winter precipitation — the so-called "Karakoram Anomaly" — though the physical basis and future persistence of this anomaly remain subjects of active scientific debate.

The geodetic mass balance — estimated from DEM (Digital Elevation Model) differencing using SRTM (2000) and CryoSat-2/TanDEM-X (2010–2020) data — provides a more spatially complete picture. Brun et al. (2017) estimated a basin-wide mass balance for the eastern and central Himalaya of −0.43 ± 0.08 m w.e./yr over 2000–2016, implying a total ice loss of approximately 5,000 km³ from the broader HKH region over this period.

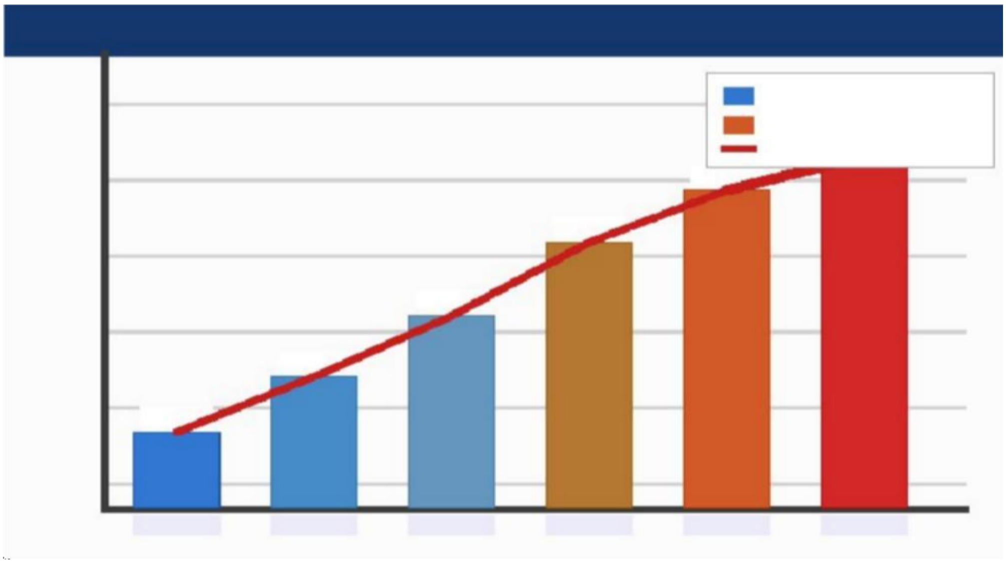


Figure 3: Himalayan glacier area reduction index (1990–2020) for monitored Indian glaciers, expressed relative to 1990 baseline. The accelerating trend (red line) reflects temperature-driven ablation rates increasing faster than replenishment from winter snowfall.

Source: https://www.ipcc.ch/report/ar6/wg1/

4.3 Glacial Lake Outburst Floods (GLOFs)

An important and often underappreciated hydrological consequence of glacier retreat is the formation and catastrophic drainage of proglacial lakes — bodies of water that accumulate behind unstable morainal dams as glacier termini retreat. GLOFs represent one of the most acute and immediate water hazards in the Himalayan region, capable of releasing millions of cubic metres of water within hours, destroying downstream infrastructure and communities with little warning.

The National Disaster Management Authority (NDMA) of India has identified 188 potentially dangerous glacial lakes in the Indian Himalaya, with the highest concentrations in Sikkim, Uttarakhand, and Himachal Pradesh. The 2013 Kedarnath disaster, which killed over 6,000 people and destroyed infrastructure worth USD 1.5 billion, was partly triggered by GLOF events combined with extreme monsoon precipitation

—a compound hazard that is projected to increase in frequency and magnitude as both glacier retreat and monsoon intensity extremes increase under climate change.

5. SECTORAL USES OF GLACIER-DERIVED WATER IN INDIA

5.1 Agricultural Irrigation

Agriculture is by far the dominant user of water in India, accounting for approximately 80% of total freshwater withdrawals. In the northern plains, the canal irrigation systems fed by the Indus and Ganga river networks collectively irrigate over 50 million hectares — the largest irrigated agricultural system in the world. The reliability of these canal systems for kharif (summer) and rabi (winter) irrigation is directly contingent on adequate river flows, which in turn depend on the seasonal glacier melt contribution during the pre-monsoon period.

The Punjab and Haryana states, which together produce over 50% of India's wheat and 30% of its rice, depend on a combination of canal water (from the Indus tributaries) and groundwater for irrigation. Canal water availability in May and June — when standing rabi wheat crops require water for grain filling and newly transplanted kharif rice requires flooding of paddies — is predominantly sustained by glacier melt. A 30% reduction in this flow would require an equivalent expansion of tube-well pumping at costs estimated at USD 800 million annually in additional energy expenditure.

5.2 Drinking Water Supply for Urban and Rural Populations

The glacier-fed rivers of northern India serve as the primary drinking water source for hundreds of millions of urban and rural residents. Delhi, with a population of 32 million, draws 55–60% of its raw water supply from the Yamuna river — which receives a substantial glacial melt contribution from the Yamunotri glacier and associated Bandarpunch group. Haridwar, Rishikesh, Allahabad, Varanasi, and Patna — all major cities on the Ganga — similarly depend on river water whose minimum-season volume is underwritten by glacial flows.

For rural mountain communities in Uttarakhand, Himachal Pradesh, and Jammu & Kashmir, glacial meltwater and spring flows fed by glacial percolation often constitute the only reliable year-round drinking water source. Field surveys by the People's Science Institute document 4,000–6,000 springs in the Uttarakhand hills, approximately 40% of which show signs of reduced discharge since 2000, directly correlated with upslope glacier retreat.

5.3 Hydroelectric Power Generation

India's installed hydroelectric capacity exceeds 47,000 MW, with an additional 14,500 MW under construction — the bulk located in Himalayan states where glacier-fed rivers provide reliable, high-head water flows. The 1,520-MW Nathpa Jhakri project on the Satluj, the 2,000-MW Teesta Stage-IV project in Sikkim, and the proposed 1,000-MW Dibang project in Arunachal Pradesh are all directly dependent on glacier-fed hydrology for their design-flow assumptions.

NTPC and NHPC project documents for Himalayan hydropower plants typically assume design flows based on historical gauge records that reflect 20th-century glacier conditions. As glacier volumes decline, these design assumptions become progressively less valid. A modelling study by Mishra et al. (2020) estimates that under RCP 8.5, Himalayan hydropower generation capacity utilisation will peak around 2040–2050 and then decline by 15–25% by 2080 as glacier-sustained base flows diminish.

5.4 Ecological Water Flows and Riverine Biodiversity

Glacier meltwater sustains minimum ecological flow requirements in Himalayan rivers that are critical for the survival of endemic aquatic biodiversity, including the Mahseer (Tor putitora), the snow trout (Schizothorax spp.), and the Gangetic dolphin (Platanista gangetica). Cold, turbid, oxygen-rich glacial meltwater creates unique thermal and chemical niches in upper Himalayan river reaches that are not replicable from monsoon runoff or groundwater baseflow, and the simplification of seasonal flow regimes consequent on glacier retreat is already documented to be altering macroinvertebrate communities and fish species distributions in the upper Ganga and Yamuna.

6. CLIMATE CHANGE PROJECTIONS AND FUTURE WATER SUPPLY SCENARIOS

The future trajectory of Himalayan glacier volumes, meltwater flows, and their consequences for downstream water supply depends critically on the global greenhouse gas emission pathway followed over the coming decades. The IPCC's Representative Concentration Pathways (RCPs) provide standardised scenarios against which glacier models can be run. The HKH region is among the world's most climatically sensitive areas, with projected warming rates approximately 1.5–2.0× the global average under all RCP scenarios — a phenomenon attributed to the elevation-dependent warming effect, by which high-altitude regions warm faster than sea-level areas.

6.1 Temperature and Precipitation Projections for the HKH Region

CORDEX-South Asia regional climate model ensemble projections show warming of 1.2°C above 2010 levels by 2030 and 2.0°C by 2050 under RCP 4.5, rising to 2.5°C by 2050 and 4.5°C by 2100 under RCP 8.5. Winter snowfall — the primary source of glacier mass input — is projected to decrease by 10–20% by 2050 across the western Himalaya under RCP 8.5, further reducing glacier replenishment rates. Summer ablation seasons are projected to lengthen by 3–6 weeks by 2050, substantially increasing net annual ice loss.

6.2 Glacier Volume Change Projections

Huss and Hock (2018) applied a global glacier model calibrated with regional mass balance data to project HKH glacier volume changes, finding median volume reductions of 43 ± 14% by 2100 under RCP 4.5 and 68 ± 11% under RCP 8.5. For India specifically, modelling by Immerzeel et al. (2020) in the landmark Science paper 'Importance and vulnerability of the world's water towers' placed the Indus basin as the globally most vulnerable water tower system, with a projected water tower index decline of 35–45% by 2050.

Projection Year	Temp. Rise (RCP 8.5)	Glacier Volume Change	Runoff Regime	Policy Implication
2030	+1.2°C	-15 to -20%	Increased peak flow	Moderate risk — buffer zones needed
2050	+2.0°C	-30 to -40%	Peak flow earlier	Significant — storage augmentation critical
2070	+3.1°C	-50 to -65%	Flow declining	Severe — groundwater emergency plans
2100	+4.5°C	-70 to -90%	Minimal melt contribution	Crisis — alternate supply infrastructure essential

Source: https://science.nasa.gov/earth/earth-observatory/

6.3 Peak Water and Post-Peak Decline

The concept of "peak water" is essential for interpreting short-term versus long-term hydrological trajectories. As a glacier retreats, the larger proportion of its exposed ablation zone initially generates more meltwater annually — a temporary hydrological surplus that can actually reduce irrigation water deficits in the near term. However, once the glacier has shrunk beyond a critical threshold — estimated at approximately 50% of initial volume for HKH glaciers — annual melt output falls below current levels and continues declining toward zero as the glacier disappears entirely.

Modelling studies suggest that most small-to-medium Indian glaciers (area below 5 km²) will pass their peak water threshold between 2020 and 2040. Larger glaciers, including Siachen, Gangotri, and Zemu, are projected to maintain meltwater output near current levels until 2050–2060 before entering terminal decline. This temporal variability means that different regions of India will experience glacier-related water stress at different times, requiring geographically differentiated adaptation planning timelines

7. ADAPTATION STRATEGIES FOR GLACIER WATER DEPENDENCY

The long-term reduction in glacier-derived water supply cannot be prevented; it can only be managed through a combination of supply augmentation, demand reduction, storage enhancement, and institutional reform. The following table summarises the primary adaptation strategies evaluated in the literature for India's glacier-dependent regions.

Adaptation Measure	Mechanism	Target Region	Effectiveness
Glacial Lake Dams (GLOF barriers)	Early warning + downstream protection	Uttarakhand, Sikkim	High — immediate safety benefit
High-altitude water reservoirs	Store peak melt for dry- season use	J&K, Himachal Pradesh	Very High — long-term storage
Fog collection systems	Supplementary mountain water harvesting	North-east India	Moderate — scalable in humid zones
Managed Aquifer Recharge (MAR)	Inject monsoon surplus to groundwater	Indo-Gangetic Plain	High — drought resilience
Crop shift and micro- irrigation	Reduce irrigation water demand	Punjab, Haryana, UP	High — demand-side management
Interbasin water transfer	Redirect surplus basin flows	National (multi-state)	High but politically complex
Artificial glacier construction	Build ice stupa mounds for spring water	Ladakh highlands	Moderate — proven at local scale

7.1 Artificial Glaciers and Ice Stupas

The "ice stupa" concept, developed by Sonam Wangchuk of Ladakh — and recognised internationally with the Rolex Award for Enterprise in 2016 — addresses the specific problem of spring water scarcity in Ladakhi villages. By diverting winter river water through a pipe to a cone-shaped structure at a lower elevation, and allowing it to freeze in the cold winter air, a conical ice tower (resembling a Buddhist stupa) accumulates over winter and melts slowly through spring and early summer, providing irrigation water precisely when it is needed for crop establishment.

Field evaluations by the Himalayan Institute of Alternatives Ladakh (HIAL) document ice stupa volumes of 5,000–15,000 m³ at successful sites, providing 50–150 kL of meltwater per day during the critical April–June agricultural window. The technology is low-cost (approximately USD 2,000–10,000 per installation), community-buildable, and directly replicable across hundreds of Ladakhi villages facing water scarcity resulting from upstream glacier retreat.

7.2 High-Altitude Reservoirs and Check Dams

The construction of small storage reservoirs at altitudes of 3,500–5,000 m to capture peak melt flows for release during low-flow periods represents a conventional engineering solution to the temporal mismatch between glacier melt peaks and irrigation demand peaks. The National Water Mission has identified 20 priority sites in Uttarakhand, Himachal Pradesh, and Ladakh for feasibility assessment of high-altitude storage schemes. A critical design consideration is the sediment load of glacial rivers, which can be 10–50 times higher than equivalent non-glacial streams, requiring efficient sediment exclusion or regular desilting operations.

7.3 Managed Aquifer Recharge

The Indo-Gangetic Plain overlies one of the world's largest alluvial aquifer systems, with an estimated storage capacity of 6,700 km³. Systematic managed aquifer recharge (MAR) — injecting surplus monsoon river water into this aquifer during peak flow periods — can significantly augment groundwater levels that are currently declining by 0.5–2.0 m per year in Punjab, Haryana, and western Uttar Pradesh due to over-extraction for irrigation. MAR can effectively replace the buffer function of glaciers by using the aquifer as a large seasonal storage reservoir, with water recharged during monsoon surplus periods and extracted during pre-monsoon deficit periods.

8. POLICY AND INSTITUTIONAL FRAMEWORK FOR GLACIER WATER MANAGEMENT IN INDIA

India's institutional response to glacier-related water security challenges is fragmented across multiple ministries, agencies, and state governments, reflecting the historically siloed nature of water, environment, and disaster risk management in the country. The National Water Policy 2012 recognises climate change as a factor in water planning but does not specifically address glacier retreat. The National Action Plan on Climate Change (NAPCC) includes the National Mission for Sustaining the Himalayan Ecosystem (NMSHE), which mandates glacier monitoring, but its annual budget of approximately USD 15 million is widely regarded as grossly insufficient relative to the scale of the challenge.

8.1 Institutional Responsibilities and Gaps

Glacier monitoring in India is distributed among the Wadia Institute of Himalayan Geology (WIHG), the Space Applications Centre (SAC), the Geological Survey of India (GSI), the National Institute of Hydrology (NIH), and university-based research groups. While each produces valuable data, the absence of a unified national glaciological observing network with standardised protocols means that inter-agency data comparability remains limited. India has less than 30 active mass balance monitoring sites across its 9,575 glaciers — a ratio that compares unfavourably with Switzerland (22 sites for 1,800 glaciers) and Norway (30 sites for 2,600 glaciers).

8.2 International Dimensions: Indus Waters Treaty

The Indus Waters Treaty (1960) between India and Pakistan — brokered by the World Bank and widely regarded as one of international water law's most durable agreements — allocates the waters of the six Indus tributaries between the two countries. However, the Treaty was negotiated under the assumption of stationary hydrology. Climate change-driven changes in glacier volumes and seasonal flow regimes will alter the natural water availability underlying the Treaty's water allocations, creating potential for bilateral disputes at precisely the period of maximum water stress. Legal scholars and hydrologists have called for a supplementary protocol to the Treaty addressing climate-driven hydrological change, but negotiations have not advanced.

9. CONCLUSIONS

This review has documented the central and indispensable role of Himalayan glaciers in sustaining the seasonal and interannual water availability of India's major river systems — a role that extends from agricultural irrigation and urban drinking water supply to hydroelectric power generation and ecological flow maintenance. The key conclusions are:

- Glaciers constitute India's largest single-source seasonal buffer against pre-monsoon water deficits, providing 20–70% of total river flow across major north Indian river systems during the critical March–June period when monsoon rainfall is absent and agricultural demand is at its peak.
- India's 9,575 mapped glaciers are in sustained and accelerating retreat, losing approximately 0.43 m water equivalent per year in the 2000–2020 period — a rate that represents a 60–80% acceleration over 1980s values and is statistically consistent with HKH regional warming trends.
- The phenomenon of peak water means that most small Indian glaciers have already passed their maximum meltwater output, while larger glaciers will reach peak water by 2050, after which glacier- derived river flows will decline structurally and irreversibly on human-civilisation timescales.
- Approximately 600 million people in the Ganga basin, 300 million in the Indus basin,

and 130 million in the Brahmaputra basin face measurable long-term water security risks from progressive glacier volume decline under current climate trajectories.

- Glacial Lake Outburst Floods represent an acute near-term hazard that is projected to increase in frequency as morainal lake formations multiply in response to continued glacier retreat.
- A portfolio of adaptation responses — including high-altitude storage, managed aquifer recharge, ice stupas, demand management, and updated interstate and international water-sharing frameworks — is technically available and economically justified, but requires institutional coordination and budgetary commitment far exceeding current levels.

9.1 Research Priorities

Critical knowledge gaps identified by this review include: systematic mass balance measurements at representative glaciers across all hydrological zones of the Indian Himalaya; improved quantification of glacier contribution to baseflow and groundwater recharge; socioeconomic vulnerability assessments at the watershed level integrating glacier hydrology projections with agricultural production and population growth models; and integrated modelling of compound hazards (GLOF, extreme monsoon, drought) in glacier-dependent basins.

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