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Changing Nature of Hydrological Regime in Greater Himalayas

Abhishek Kumar Jha

TERI University

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Executive Summary

The Himalayas, once thought of as a secure "water tower", are undergoing rapid changes. Problems that were once considered to be climate-related events of the future are already occurring, due to the melting of glaciers and alterations to the hydrological cycle. As a result, the Hindu Kush Himalayan (HKH) Region will soon affect about 1.5 to 2 billion people who rely on its rivers. Similarly, over 50 million people living in the Himalayas in India will be impacted by drying water sources and increased frequency of glacial lake outburst floods (GLOFs).

However, this is more than just a water shortage, it is a crisis of extremes. The region has a complex situation consisting of simultaneous floods, seasonal water stress, and destruction to fragile ecosystems. Current policies on water management are still fragmented, reactive, and do not reflect the reality on the ground. This article explains how India will be hard-pressed without integrating glacier-related changes into water management and community planning as it deals with this issue of increasing severity. This article highlights why the very survival of India's mountain community now depends on the intersection of the accelerated melting of glaciers and urgent intervention to address water stress.

About the Author(s)

Name: Abhishek Kumar Jha
Course: M.A. – Sustainable Development Practice, TERI University, 2nd Year
Research Interests: Water Resource Management, Mountain Sustainability, Cryosphere studies, Peri-Urban Water Regime, Urban Transport/Mobility Policy

1. Introduction:

As one of the most important freshwater systems on Earth, the Indian Himalayan Region (IHR) has been referred to as both "The Water Tower of Asia" and "The Third Pole." The IHR encompasses about 533,000 km2 (16.2% of India's total land area) and is the headwaters of three major river basins: Indus, Ganga, and Brahmaputra, which together support many hundreds of millions of people who live both upstream and downstream.

Historically, the IHR has acted as a natural regulator of water flows through the cryosphere and has supported agriculture, energy generation, and primary production. There are indications that this underlying stability will continue to deteriorate, especially as temperature rises have altered precipitation patterns with a continuation in the shift away from snow to rain, especially in high-altitude areas, which have also contributed to a continual negative mass balance on the glaciers of the Himalayas and a loss of glacier ice storage and glacier boundaries.

These changes are both physical,and will fundamentally alter the timing, quantity, and predictability of water flows in the Himalayas. In the short term, additional melting will create increased flood risks; however, in the long term, there will be a decline in ice storage during dry seasons, thereby affecting the availability of water.

The effects of the transition from cryosphere to hydrosphere will create significant challenges not only in terms of environment, but also of governance and resilience. Current policies tend to be reactive, piecemeal and sectoral i.e. they treat disasters without taking into account their underlying cryosphere. As such, mountain communities and people downstream are becoming increasingly uncertain and vulnerable to future changes in water availability. It is necessary to develop more integrated and future-oriented frameworks in order to manage the current crisis.

To gain a true understanding of the dimensions of the current crisis, it is crucial to go beyond the present day, and understand the long-term evolution of Himalayan hydrology and policies. The current situation is not due to one specific factor but rather multiple contributing factors including long-term climatic shifts, alterations in precipitation patterns and an evolvingpolicy environment that has been unable to handle or keep up with the significant changes occurring in the Himalayas.

2. Background

2.1 Context and History

The current obstacles in the Indian Himalayan Region (IHR), cannot be fully understood without examining how the region has transformed from an historically stable "water tower", to a burgeoning vulnerability hotspot as a result of climate change. The IHR has always provided India with the bulk of its hydrological resources, and fed its three primary river systems of Indus, Ganga, and Brahmaputra, that historically had been thought to be stable repositories of "eternal snow", that supplied predictable amounts of water for downstream livelihoods. However, over the past few decades, this view has changed as the region has been recognised as the "Third Pole", and a climate-sensitive region whose temperature changes are occurring more rapidly than the global average. Long-term trends document the ongoing loss of glacier mass (accelerated since the 1990's) indicating a shift from very gradual change to accelerated transformation of the cryosphere.

India's policy response has evolved in stages but remains incomplete. The 2008 National Action Plan on Climate Change (NAPCC) and the National Mission for Sustaining the Himalayan Ecosystem (NMSHE) marked the first formal recognition of the Himalayas as a distinct climate-sensitive region, though largely focused on research. A decade later, the policy focus began to shift toward local water systems. The 2018 NITI Aayog report on Himalayan springs highlighted that nearly half of the region's springs, primary sources of drinking water for mountain communities, were either drying up or experiencing reduced discharge. This marked a significant conceptual transition from a glacier-centric perspective to one that acknowledged groundwater and spring-shed dynamics as critical components of Himalayan water security. More recently, disaster-focused frameworks have gained prominence in response to catastrophic events such as the Kedarnath floods (2013) and subsequent glacier-related disasters such as South Lhonak lake disaster (Sikkim, 2023) and Dharali GLOF (Uttarakhand, 2025). NDMA's 2020 GLOF guidelines signalled a move toward proactive disaster management. Despite these advances, governance remains fragmented, with limited integration across climate, water, and disaster frameworks.

The current crisis is driven by both climatic and developmental factors. Elevation-Dependent Warming is accelerating glacier melt, while a shift from snowfall to rainfall reduces natural water storage and increases runoff, intensifying both floods and dry-season scarcity. At the same time, infrastructure expansion in ecologically sensitive zones has heightened exposure to these risks. Together, these processes have transformed the Himalayas into a region of growing vulnerability, where interconnected environmental changes are outpacing existing policy responses.

The distribution of the consequences of glacial retreat and hydro-meteorological variability in the Indian Himalayan region is uneven among different stakeholders; some have high exposure to these changes or greater capacities to respond than others.

2.2 Most Affected Group: Indigenous/Local and Mountain Communities

Indigenous and local communities of the Greater Himalayas (including, but not limited to, pastoralists, transhumant herders, and smallholder farmers) will be the most affected by these consequences since they are particularly sensitive to the effects of climate change upon cryospheric processes. Although they contribute very little to these problems, their livelihoods depend heavily upon cryospheric processes.

The effects of climate change caused by glacial retreat will be variable depending on the geographic area affected. For example, the Changpas and Brokpas of the Ladakh region face decreasing availability of grazing areas due to changes in snowfall patterns and permafrost degradation. In the state of Himachal Pradesh (Lahaul - Spiti - Kinnaur), the availability of meltwater used in traditional kuhl irrigation systems is decreasing, causing difficulty for farmers who rely upon these systems. Gaddis and Bakkarwals in Jammu and Kashmir are experiencing disruptions in their migratory routes due to erratic weather and landslides. In Sikkim, decreasing availability of spring water is creating problems for the Lepcha and Bhutia populations who rely exclusively on this source for their water needs, and farmers in Arunachal Pradesh are experiencing changing agricultural growing seasons and loss of agricultural biodiversity due to changes in precipitation patterns caused by climate change.

These changes will not only create water scarcity but will also disrupt the livelihoods, mobility and cultural relationships to living landscapes that exist currently.

Table 1: Evaluating impact of Climate Change on local communities in Greater Himalayan Region

State/Region	Specific Community/Tribe	Impact of Climate Change
Ladakh	Changpas, Brokpas	Loss of permafrost and grazing pastures.
Himachal Pradesh	Lahaulas, Kinnauras, Gaddis	Water stress for apple orchards; disrupted migratory routes.
Jammu & Kashmir	Bakkarwals, Gaddis	Increased landslide risk and unpredictable forage availability.
Uttarakhand	Bhotiyas, Rajis	Vulnerability to GLOFs and drying of mountain springs.
Sikkim	Lepchas, Bhutias	Impacts on sacred landscapes and perennial spring sources.
Arunachal Pradesh	Monpas, Nyishis	Shifts in high-altitude agricultural cycles and biodiversity.

2.3 Institutional Stakeholders: Research and Monitoring Agencies

The research and monitoring organizations that support the scientific research infrastructure in this region have a crucial role in providing scientific data to develop an understanding of cryosphere processes, particularly with regards to the generation of knowledge on glaciers. Such institutions are exemplified by the GB Pant National Institute of Himalayan Environment (GBPNIHE) and Wadia Institute of Himalayan Geology (WIHG), as well as some of the conservation organizations like the Wildlife Institute of India (WII) and WWF-India, which have developed many scientific approaches to monitor glacial dynamics, to study the impacts of climate change on the ecology (bio-physical environment) of glaciers, and to develop systems for predicting hazards from glacial lake outburst floods (GLOF).

The data provided by these organizations is fundamental to the delivery of effective disaster management response and long-term planning in relation to risk and threat management from such events. However, translating these data and results into actionable policies or localised, accessible interventions continues to prove challenging.

2.4 Government and Regulatory Bodies

At both the central and state levels, the government and regulatory institutions are responsible for the implementation of policies to manage the risks associated with water security, infrastructure and disaster management, including initiatives that include Har Ghar Jal, State Action Plans on Climate Change (SAPCCs) and national frameworks developed by the National Disaster Management Authority (NDMA).
While these governmental institutions have a critical role to play, they deliver their interventions predominantly according to the confines of sectoral boundaries. This restricts their capacity to respond to or address the cross-cutting nature of the changing cryosphere, which concurrently has a significant impact upon water systems, ecosystems, and hazard activity.

A major challenge in terms of governance is the disconnect between the immediate, localised impact of the actions of stakeholders and the fragmented and inadequate responses to those impacts. Bridging the gap between community knowledge, scientific evidence and policy frameworks must improve coordination among these different forms of information in order to produce more contextualised and adaptable responses to changes in the Himalayan environment.

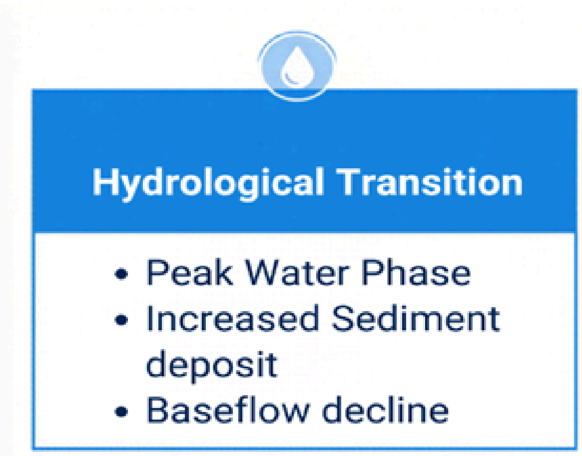
Table 2: Impact of Climate Change on different stakeholders

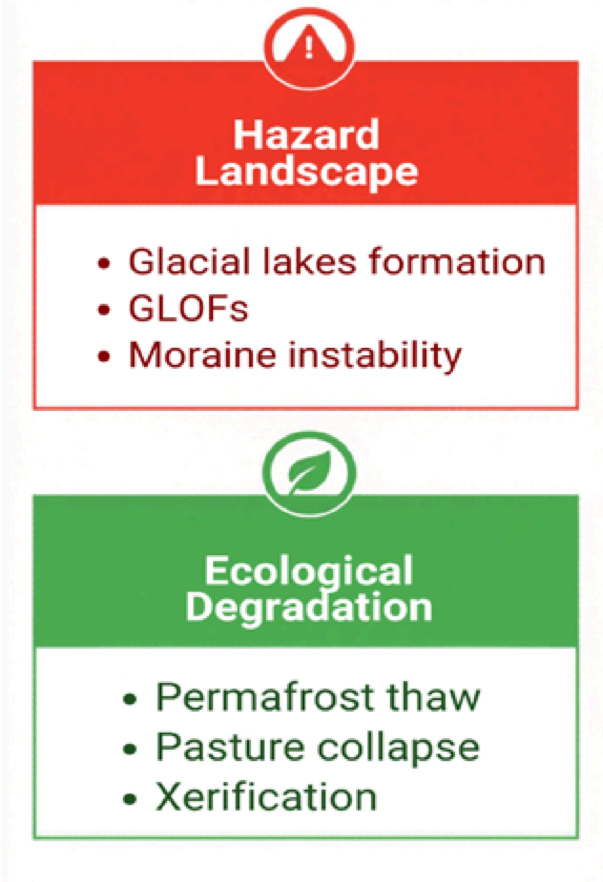
Stakeholder Group	Role / Interest	Impact of Cryospheric Change
Indigenous & Local Communities	Livelihoods, resource stewardship	Water insecurity, loss of grazing lands, cultural and ecological disruption
Scientific & Research Institutions	Monitoring, modelling, risk assessment	Increased demand for data integration, hazard prediction, and early warning systems
Government & Regulatory Bodies	Policy formulation, infrastructure, service delivery	Rising costs of adaptation, infrastructure vulnerability, and disaster management challenges

3. Analysis

3.1 Core Argument: Cryospheric Destabilisation is a Triple-Crisis Affecting the IHR

The hydrological regime of the IHR is undergoing an unprecedented transformation. Instead of functioning as a stable "water tower," it is rapidly becoming characterised by hydrologic instability, newly emerging hazards, and ecological degradation. This transformation demonstrates a trifold cryospheric destabilisation crisis; as (i) Himalayas transition from short-term water surplus to long-term water scarcity; (ii) emergence of a pro-glacial hazard landscape; and, (iii) degradation of high-altitude ecosystems. Each of these three processes are inter-related, and, collectively, reflect a systematic re-organisation of Himalayan environments.





A. From "Peak Water" to Structural Scarcity

The first aspect of this crisis is the paradoxical shift that is occurring from temporary water abundance (from glacial melt) to long-term water scarcity. Glacial temperatures are increasing throughout the Himalayas, resulting in glaciers experiencing long-term negative mass balance due to an upward shift in the Equilibrium Line Altitude (ELA) and expansion of the ablation zone.

In the short-term, melting glaciers generate large amounts of water and ultimately result in enhanced river flow discharge, an event that some scholars describe as the "peak water" phase.

In stark contrast to the temporary abundance of water experienced in short-term bursts of accelerated glacial melt, long-term river discharge and usage will significantly decrease/diminished due to an increase in sediment load and decreased regularity in river flow. Over time, as glacier volumes decline, this phase gives way to reduced melt contributions, particularly during lean seasons. The result is a structural decline in base flows, posing risks to water availability for both mountain communities and downstream populations.

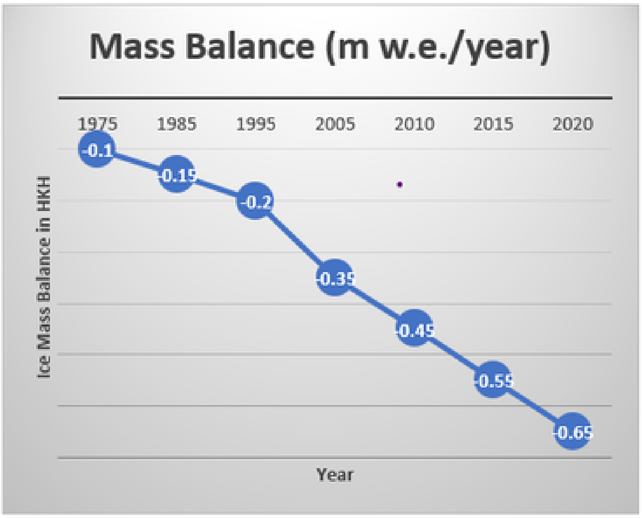


Figure 2: Decreasing ice mass balance in HKH

B. The Rise of a Pro-Glacial Hazard Landscape

In addition to significant changes to the hydrology of the region, glacial retreat is leading to changes to the landscape, which are creating new hazards as the glaciers retreat and leave behind basins that have been eroded and filled with meltwater, creating lakes that are formed behind moraines. The lakes that are formed in this way are inherently unstable, and many have little structural support from the moraine. Any natural events could trigger the failure of one of these lakes (e.g., intense rainstorms, ice avalanches, or earthquakes) resulting in GLOFs that have significant negative impacts to communities downstream. Their increasing number in Greater Himalayas is indicative of the changing systemic risk created by glacial retreat within the various basins in the Himalayas. Recent events, including the Kedarnath flood (2013), the South Lhonak lake outburst (2023) and Dharali flash flood (2025), should serve as examples of the transformation of the Himalayan region into a cascading risk environment due to glacial retreat.

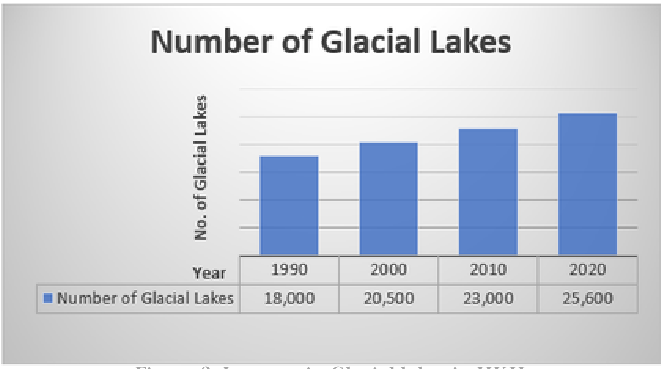


Figure 3: Increase in Glacial lakes in HKH

C. Cryospheric Degradation and High-Altitude Xerification

The third dimension of this crisis is in the ecological systems of the region. As the cryosphere melts away, permafrost degrades. This has an important function within high altitude environments of holding soil moisture and providing ecological balance. Because of glacial retreat, melting of the permafrost, it negatively impacts the ability to hold subsurface moisture as a function of permafrost melt occurring, consequently leading to increased drainage and drying of soil (i.e., high altitude xerification). These processes degrade high altitude ecosystems, as alpine meadows become drier and less productive areas of land. Because vegetation has diminished in the alpine meadows, the land loses its ability to hold moisture and continues a cycle of degrading the land. Therefore, both pasture and agricultural communities will see the ability of grazing lands decrease and their ability to produce from the ecosystem will diminish, resulting in the loss of livelihood of the communities that depend on that production.

These three dimensions are not independent entities; they are part of a larger cycle that is an outcome of the same critical process occurring (cryosphere destabilisation). The hydrological cycle, hazard formation and ecological degradation have created compound risks because the impact created in one area of the system increases the vulnerability of another area of the system. The interconnected nature of these three processes presents a significant challenge to existing policies developed to address water scarcity, disaster risk reduction and ecosystem damage as independent issues. The science shows that an integrated, systems approach is needed to develop policies that recognise the Himalayas as a dynamic, interlinked socio-ecological system.

3.2 Counter arguments and Limitations

Himalayan hydrology has the argument that glaciers provide only a small percentage of total annual river flow, especially in the case of monsoon-dominated watersheds like the Ganga. When looking at the number of glaciers providing water to rivers, it is understandable to think of glacier retreat as not having an immediate impact on the whole water supply level due to glacial summer melt water. This may be true; however, it does not consider the role of glacial melt on maintaining the low-flow periods of the rivers when there is little or no rainfall and much water is needed. Even a small amount of glacial summer melt can have a larger effect during periods of low flow than it does at all other times, particularly for upstream communities and irrigation systems in downstream locations.

Another limitation is associated with the uncertainty that exists within the research data used to describe the Himalayas due to the extreme topographical features of the terrain, sparse monitoring networks and changing climate. While there is uncertainty in the information collected for the glaciers, changes in glacier mass balance, precipitation patterns and an increase in the frequency and magnitude of natural disasters are all observing the same trend in research studies. In fact, the uncertainty of the ongoing change in the glaciers increases the justification for implementing adaptive and precautionary policies as soon as possible.

Third limitation is the idea that local communities have successfully adapted to environmental variability, and will do so again with the current changes to the cryosphere. However, the rate and magnitude of the change occurring to the cryosphere today is much faster and greater than anything that has ever happened previously.

4. Implications

The study shows that disaster management in the Indian Himalayan Region (IHR) must change from a reactive, centralised to a localised, anticipatory, and technology-based resilience system. Evidence from the Upper Beas Valley indicates that even though mountain communities have historically adjusted to seasonal variability, the extent and speed of today's cryospheric change have exceeded the traditional coping capabilities of mountain communities.

As can be seen from Table 3, a considerable amount of the population remain exposed to this change, thereby demonstrating an urgent need to transition toward early warning systems (EWS), high-altitude monitoring systems, and real-time climate information systems particularly in areas of high hazard. In addition, mountains are often the primary source of drinking water for a large number of people and therefore their dependence on spring systems to provide that water demonstrates an additional, less visible layer of vulnerability. The anticipated decrease in snowfall also indicates that traditional forms of natural water storage will continue to decline, making it necessary to improve climate monitoring and precipitation assessment systems. Concurrently, the large number of glacial lakes in the region indicates that the extent of hazard exposure is enlarging, which means that more proactive, decentralised risk mitigation strategies need to be implemented.

Parameter	Quantitative Substantiation	Source
Vulnerable Population	~51–52 million residents in the IHR directly affected by cryospheric changes	NMSHE / ICIMOD
Spring Dependency	Up to 80% of rural households depend on springs, nearly half of which are now seasonal or drying	NITI Aayog (2018)
Snowfall Reduction	Projected 30%–70% decrease in snowfall under high-emission scenarios	HKH Assessment (2019)
Hazard Density	Over 25,000 glacial lakes across the HKH region requiring monitoring and early warning systems	ICIMOD Glacial Lakes Report

Table 3: Cryospheric Risk and Vulnerability in the IHR

Evidence indicates that building resilience among Himalayan communities requires more than just implementing high-tech solutions. It will take "innovative" systems that rely on current scientific methods and local traditional knowledge. Communities in Kullu and Lahaul-Spiti already have active roles as first responders during extreme events. To amplify their first responder capabilities, they need additional investment in decentralized infrastructure, local health systems, and community preparedness mechanisms, which will all continue to operate during any interruptions caused by flooding, landslides or isolation.

At the same time there needs to be increased convergence between institutions dealing with these issues today. Although scientific organizations, such as GB Pant National Institute of Himalayan Environment and Wadia Institute of Himalayan Geology, produce invaluable information concerning cryospheric changes, as of now very limited integration has taken place between this information and applicable governance frameworks supported by existing agencies. Bridging this disconnect will require establishment of scientific expertise as part of

Key Takeaways

• Localized Climate Resilience: Strengthening early warning systems and high-altitude monitoring infrastructure is essential to enable communities to anticipate and respond to climate-induced hazards.

• Hybrid Water Systems: Reviving traditional water conservation practices such as kuhls in Spiti and zings in Ladakh and integrating them with modern technologies can provide sustainable solutions to localized water stress, particularly during lean seasons.

• Institutional Convergence: Bridging the gap between scientific research and community-level action is critical for building an integrated and adaptive governance framework in the Himalayas.

5. Conclusion

The IHR, or the Indian Himalayan Region, is experiencing a major shift in their hydrological and cryospheric systems that will have profound effects on water security throughout the Sub-Continent, India. As we've demonstrated, glacial retreat is already happening and will continue to happen as both encouraging hydrological instability; increasing risk of harmful natural disasters and creating environmental degradation. In this way, the dramatic loss of an iconic and previously predictable source of glacier-based water storage represents a critical failure of the traditional function of the Himalayas as the World's "Water Towers", which will have serious future implications for both the mountain communities and downstream.

To address this transformation, we need to go beyond the current practices of reactive governance and adopt integrated approaches to adaptive resilience. These include building stronger systems of early warning for natural disasters, supporting local governance when it comes to water resource management, and increasing collaboration, communication and coordination between scientific agencies and people living and working at the community level. In short, the changing Himalayan cryosphere should not be considered as an independent regional issue but rather as one of the broader relationships between climate and water security. Its maintenance and sustainability will ultimately rely on aligning science, policy, and local knowledge in ways that provide both short-term and long-term benefits.

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Jindal School of Government and Public Policy, O.P. Jindal Global University
Sonipat Narela Road, Near Jagdishpur Village, Sonipat, Haryana 131001, India
Email: info@jgu.edu.in · Instagram: instagram.com/jindalpolicyresearchlab

Website: jgu.edu.in/jsgp/jindal-policy-research-lab